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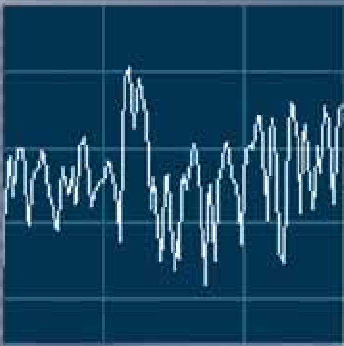

Handbook

SPECTRUM MONITORING

Radiocommunication Bureau

THE RADIOCOMMUNICATION SECTOR OF ITU

The role of the Radiocommunication Sector is to ensure the rational, equitable, efficient and economical use of the radio-frequency spectrum by all radiocommunication services, including satellite services, and carry out studies without limit of frequency range on the basis of which Recommendations are adopted.

The regulatory and policy functions of the Radiocommunication Sector are performed by World and Regional Radiocommunication Conferences and Radiocommunication Assemblies supported by Study Groups.

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HANDBOOK

SPECTRUM MONITORING

Edition 2011

Radiocommunication Bureau

PREFACE

In 2006, Radiocommunication Study Group 1 agreed with Working Party 1C decision to revise some parts of the Spectrum Monitoring Handbook (edition 2002) taking into account the latest developments in digital radio systems and the needs of spectrum management regulatory authorities, in particular, those of developing countries.

The work was carried out by a first Group of Experts and resulted in the publication in 2008 of a Supplement to the Handbook including complete and self-contained revision of Chapter 3 (Monitoring Equipment and Automation of Monitoring Operations), Sub-chapter 5.1 (Spacecraft Emission Monitoring) and Annex 1 (Monitoring system planning and Tenders) of the Handbook.

In 2008, Radiocommunication Study Group 1 agreed with Working Party 1C decision to revise the other parts of the Handbook and mandated Working Party 1C to prepare and approve the next complete edition with necessary changes to the parts published in the Supplement.

A second Group of Experts was established to prepare this fifth edition of the Handbook. Containing the latest information on all aspects of monitoring, the Handbook represents a valuable reference manual for the spectrum management community.

The updated six Chapters and Annex 1 describe in detail the key elements of spectrum monitoring and its relationship to spectrum management. In addition, the Handbook contains many references that can be consulted for additional details.

The Handbook on Spectrum Monitoring is intended for the use by administrations of both developing and developed countries and by the Radiocommunication Bureau. The Handbook will also be useful to radiocommunication engineers everywhere.

François Rancy
Director
Radiocommunication Bureau

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FOREWORD

Due to the growing demands on the radio frequency spectrum, it is of great importance that spectrum monitoring techniques keep track with advances in radiocommunication technology and to disseminate such information the world over. Since the 2002 edition of this Handbook, significant improvements in monitoring techniques have taken place. Accordingly, Radiocommunication Study Group 1 entrusted Working Party 1C (WP 1C) with the task of revising the Handbook on Spectrum Monitoring for the benefit of developing and developed countries.

The radio frequency spectrum is a limited natural resource and it is essential that it is used in the most effective and efficient manner by all radiocommunication users the world over. This is so that various radiocommunication networks can function in an interference-free radio environment. Radiocommunication technology is advancing at a rapid pace. With the emerging of new technologies and the phenomenal growth of radiocommunication services, requirements for the radio frequency spectrum and the satellite orbit are increasing at an astronomical rate. Effective and efficient spectrum management is the key element for ensuring the co-existence of various radiocommunication networks, without causing interference to each other.

Spectrum monitoring is one of the essential tools of spectrum management. Spectrum monitoring techniques are developed to ensure that technical parameters and standards for radiocommunication systems are adhered to. In addition spectrum monitoring assists in promoting the efficient utilisation of the radio frequency spectrum and the satellite orbit. Spectrum monitoring techniques are different from those of a radiocommunication network in that they are carried out in non-optimal situations and in an unknown environment.

This Handbook has been developed covering all essential features of spectrum monitoring techniques and activities including the establishment of monitoring facilities. The Handbook is expected to be of great value to administrations and spectrum monitoring agencies. It is considered to be equally valuable to the developing as well as to developed countries.

We convey our great appreciation to Mr. Ralf Trautmann (Germany), Chairman of the WP 1C Rapporteur Group on the complete revision of the Handbook, Mr. Alain Jacquet (France), Chairman of the WP 1C Rapporteur Group responsible for the development of the Supplement to the 2002 edition of the Handbook, sub-coordinators, contributors, participants and all those who have been instrumental in the development of this Handbook and without whose efforts this Handbook would not have been a reality. Our special gratitude is also due to Mr Philippe Aubineau, Counsellor of the Radiocommunication Bureau who has played a key role in the development of the Handbook.

It is hoped that this Handbook will prove to be a great asset in the field of spectrum management and spectrum monitoring for establishment and operation of monitoring facilities. It should provide essential tools for spectrum management and for the performance of radiocommunication networks in an interference-free environment.

Rob Haines

Chairman, Study Group 1
Spectrum Management

Jan Verduijn

Vice-Chairman, Study Group 1
Chairman, Working Party 1C
Spectrum Monitoring Techniques

ACKNOWLEDGEMENTS

We would like to express appreciation to all ITU Member States, Sector Members and companies who supported the development of this Handbook for their contributions, participation and hosting of meetings.

We want to acknowledge the following individuals named in alphabetical order who sent contributions to this new edition of the Handbook on Spectrum Monitoring and to the Supplement of the 2002 edition of the Handbook, which has been incorporated in this new edition. The relevant Chapter and Section numbers are given in parentheses for the authors who accepted responsibility as Chapter Rapporteur or Section Rapporteur.

Mr. Mubarak Al-Sawafi, Sultanate of Oman (Chapter 5); Mr. Uzi Ben-Yakov, Tadiran Electronic Systems (Section 2.7); Mr. Robert Cutler, Agilent Technologies, Inc; Mr. Francois Delaveau, Thales; Mr. Saad Dera, Kingdom of Saudi Arabia (Chapter 1); Mr. Pierre-Jean Dumay, France; Mr. Tamas Egri, Hungary; Mr. Thomas Hasenpusch, Federal Republic of Germany (Sections 4.9, 5.3, 5.7); Mr. Roland Heister, Federal Republic of Germany; Mr. James Higgins, United States of America (Sections 2.4, 2.6); Mr. Alain Jacquet, France (Supplement), Mr. Sungmoon Kim, Republic of Korea; Mr. Fryderyk Lewicki, Telekomunikacja Polska; Mr. Zhuoran Liu, People's Republic of China (Section 5.1); Mr. Yvon Livran, Thales; Mr. Fabio Santos Lobao, Brazil (Sections 5.2, 5.6); Mr. Haim Mazar, Israel, (Chapter 2 and Sections 6.1, 6.2, 6.3, 6.4, 6.11); Mr. Klaus Mecher, Federal Republic of Germany; Mr. Philippe Mege, Thales; Mr. Makoto Miyazono, Japan; Ms. Soon Hee Park, Republic of Korea; Mr. David Pasquereau, Thales (Section 4.7); Mr. Alexander Pavlyuk, Russian Federation (Chapter 6); Mr. Olivier Pellay, France (Chapter 4 and Section 6.9); Mr. Ulrich Pennig, Federal Republic of Germany (Section 4.10); Mr. Christof Rohner, Rohde & Schwarz; Ms. Mi-Kyung Suk, Republic of Korea; Mr. Peter Tomka, Hungary (Annex 1); Mr. Erik van Maanen, Kingdom of the Netherlands; Mr. Zhixin Wang, People's Republic of China (Section 2.5); Mr. Roy B. Woolsey, TCI International, Inc. (Chapter 3).

We would also like to thank the many others who have contributed to the Handbook by participating in meetings and providing fruitful advice and comments.

INTRODUCTION

The development of this edition ...

The last edition of the Handbook (HB) on Spectrum Monitoring had been published in 2002. Due to developments in telecommunication and monitoring technology, Working Party 1C (WP 1C) decided at its meeting in October 2006 to install a Rapporteurs Group (RG) chaired by Mr. Alain Jacquet (France) for the revision of parts of that Handbook. In its June 2008 meeting, WP 1C approved new texts for Chapter 3 on monitoring equipment and automation of monitoring operations, Section 5.1 on spacecraft emission monitoring and Annex 1 on monitoring system planning and tenders, which were published as a Supplement to the Handbook on Spectrum Monitoring, Edition 2002.

In order to review also the remaining parts of the 2002 Handbook, WP 1C installed a new RG chaired by Mr. Ralf Trautmann (Germany). The objective of the new RG was to publish a complete new edition of the Handbook, including the text of the Supplement, and to complete its work before the 2010 meeting of WP 1C, for approval of the new complete edition of the handbook at that meeting.

To organise the work, the RG held 4 meetings, 25 February to 4 March 2009 in Seoul, 16-23 September 2009 in Geneva, 1-10 February 2010 in Geneva and 3-9 June 2010 in Mainz.

More than 165 input documents submitted by Member States, Sector Members and SG 1 Associates (e.g. equipment manufacturers) resulted in amendments to and revisions of existing sections and complete new sections. These contributions in turn resulted in proposals for the modification and improvement of the HB structure. Due to this interdependence the HB structure was continuously further developed. As a result the RG refined the HB text substantially and improved in particular the logical delimitation between the various Chapters.

The text of this Handbook was approved by WP 1C during its meeting in September 2010 in Amsterdam.

The Handbook consists of the following parts with the responsible Chapter Rapporteurs indicated on the right:

Chapter 1	Spectrum monitoring as a key function of a spectrum management system	Mr. Saad Dera (Saudi Arabia, Kingdom of)
Chapter 2	Organization, Physical, Structures and Personnel	Dr. H. Mazar (Israel)
Chapter 3	Equipment	Dr. Roy B. Woolsey (TCI International, Inc)
Chapter 4	Measurements	Mr. O. Pellay (France)
Chapter 5	Specific monitoring systems and procedures	Mr. M. Al-Sawafi (Oman, Sultanate of)
Chapter 6	Fundamentals and supporting tools	Dr. A. Pavlyuk (Russian Federation)
Annex 1	Monitoring system planning and tenders	Mr. P. Tomka (Hungary)

A short historical retrospect ...

The CCIR published the first edition of the Handbook for Monitoring Stations in 1968 (supplemented in 1971). The next edition was published 20 years later in 1988. Just a few years later in 1995 there was a need for the publication of a further edition with a major revision of the HB structure. Still there was no clear separation between sections related to equipment and measurement procedures. This problem was first solved by the 2002 edition. The structure of that edition still forms the basis for the new edition. With this new edition the separation between the various chapters was further improved. Old material was up-dated and a lot of new material was incorporated, e. g. the introduction of radar measurement techniques and measurements on time difference of arrival.

Purpose of this Handbook ...

The radio spectrum is used literally by everybody. There are a lot of applications like burglar alarm, cordless headphones and microphones, radio LAN, remote keys, remote switches and other remote controls in our personal environment. Some users may not be aware that these are radio applications and a service degradation of these applications may be perceived as malfunction instead of radio interference. Other applications like cellular radio and broadcasting and radio operators as police, ambulance, air traffic control and armed forces are more intuitively linked with radio. Anyway, the vital importance of the radio spectrum for modern societies has been extensively discussed elsewhere and is commonly accepted and understood.

Radio monitoring, in contrast, requires much more explanation. The purpose of spectrum monitoring is to support the spectrum management process in general and to solve interference problems. And in addition it has to be clearly stated that spectrum monitoring has nothing in common with radio surveillance. In spectrum monitoring the content of an emission may be used to identify a radio station or to determine the service quality. However, the message as such is of no interest.

The purpose of this Handbook is to provide information and to give guidance to all those who are involved in the process of spectrum monitoring: managers, operators, maintenance staff, instructors and procurement managers.

In whose interest the Chapters are ...

Chapter 1 of this Handbook describes the relationship between spectrum monitoring and spectrum management and the involvement in the international monitoring system. Chapter 2 continues with the tasks of a spectrum monitoring service, its structure and organisation and finally leading to the various types of monitoring stations including personnel for operation and maintenance. These two Chapters may be the most important ones for those who are involved in the design and the management of a spectrum monitoring system.

Chapter 3 describes the equipment which is needed to perform the measurements as described in Chapter 4. These two Chapters are mainly of interest for monitoring operators and staff involved in the procurement of equipment.

Chapter 5 describes specific monitoring systems and procedures that are usually not carried out by all spectrum monitoring stations. This Chapter is of special interest for those who are involved in these fields, e. g. monitoring of spacecraft emissions, broadcasting monitoring and monitoring of cellular systems.

Chapter 6 contains a lot of supplementary and basic information about various issues such as maps, modulation, Fast Fourier Transform and the required documentation. This Chapter is particularly useful for monitoring operators.

Last not least, Annex 1 on monitoring system planning and tenders supplements Chapter 3. Annex 1 is essential for those who are involved in the process of equipment procurement.

Conclusion ...

Taking into account that there are diverging views and interests of the various parties involved in the work of the Rapporteurs Group, the text of the HB represents a high level compromise. Finally the new HB text is seen to be suitable to serve for the coming years the demands of readers from both developing and developed countries, who want to gather up-to-date information about a radio monitoring service's organisation, equipment and measurement techniques.

I would like to thank all Chapter and Section Rapporteurs, all contributors and participants of the various meetings and the WP 1C Chairman for their valuable contributions, comments and advice. Last but not least, I would like to thank Mr. Philippe Aubineau, the Counsellor for ITU-R SG 1, for his support. Without his incredible precision and speed in identifying any inconsistencies the handbook would have not been available so quickly and in this quality.

Ralf Trautmann

Rapporteur of the RG on Spectrum
Monitoring Handbook Issues

CHAPTER 1

SPECTRUM MONITORING AS A KEY FUNCTION OF A SPECTRUM MANAGEMENT SYSTEM

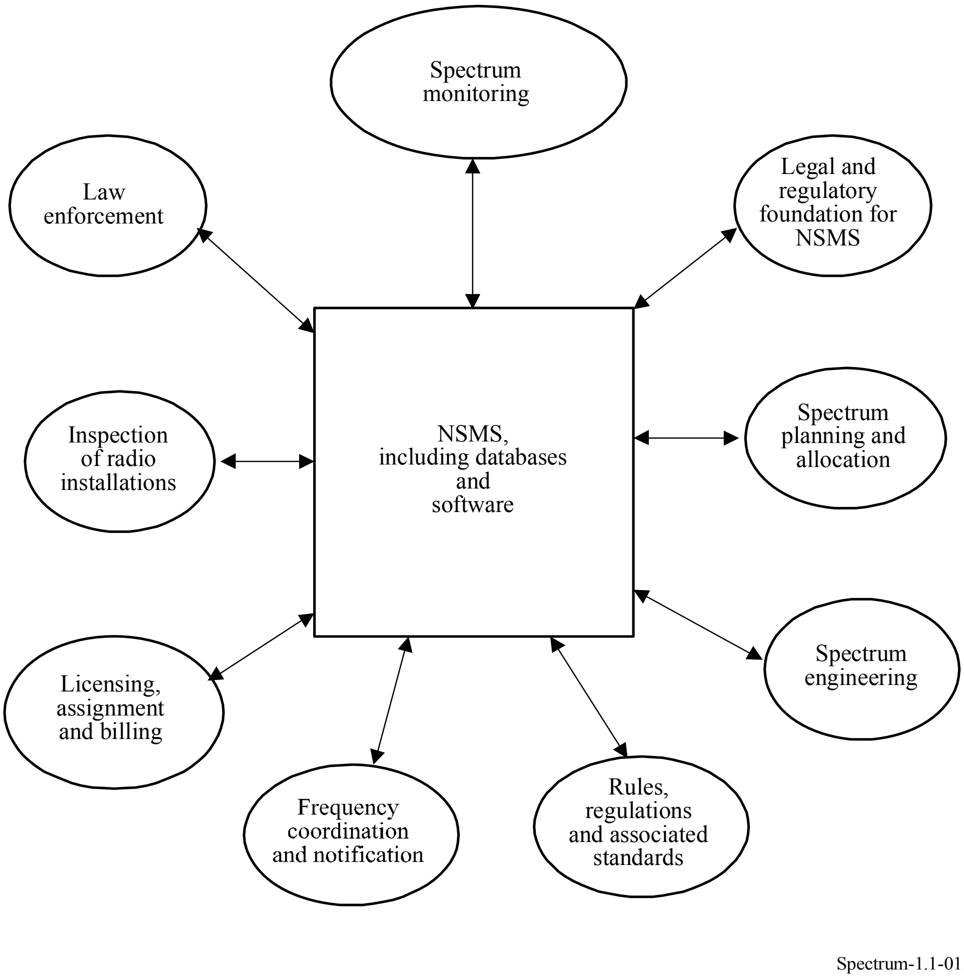
Page

1.1 Spectrum management

The purpose of this section is to provide a brief overview of the spectrum management process and the role of spectrum monitoring as a key function in spectrum management. The following discussion of national spectrum management systems (NSMS) is meant as a general overview (see Fig. 1.1-1).

FIGURE 1.1-1

Simplified national spectrum management system



The reader should refer to the ITU Handbooks, on National Spectrum Management (Edition 2005) and on Computer-Aided Techniques for Spectrum Management (CAT) (Edition 2005), Reports ITU-R SM.2012, ITU-R SM.2015, ITU-R SM.2093, ITU-R SM.2130 and ITU-D, Resolution 9 (Rev. Doha, 2006) for more information on these related spectrum management issues.

1.1.1 Description of spectrum management

Spectrum management is the combination of administrative, scientific and technical procedures necessary to ensure the efficient operation of radiocommunication equipment and services without causing interference. Simply stated, spectrum management is the overall process of regulating and administering use of the radio frequency spectrum. The goal of spectrum management is to maximize spectrum efficiency, minimize interference and eliminate unauthorized and improper use of the spectrum. Rules and regulations, based on relevant legislation, form a regulatory and legal basis for the spectrum management process. Databases of information, including details of all authorized users of the spectrum, provide the administrative and technical basis for the process. Analysis of the information in these databases facilitates the spectrum management process resulting in decisions for spectrum allocations, frequency assignments, and licensing. Spectrum monitoring, inspection, and law enforcement provide the necessary means to maintain the integrity of the spectrum management process.

1.1.2 Spectrum monitoring

1.1.2.1 Purpose of spectrum monitoring

Spectrum monitoring serves as the eyes and ears of the spectrum management process. It is necessary in practice because in reality, authorized use of the spectrum does not ensure that it is being used as intended. This may be due to the complexity of the equipment, interaction with other equipment, a malfunction of equipment, or deliberate misuse. This problem has been further exacerbated due to the accelerating proliferation of terrestrial wireless and satellite systems and of equipment that may cause interference, such as computers and other unintentional radiators. The monitoring system provides a method of verification and "closes the loop" on the spectrum management process.

Use of the spectrum occurs around the clock throughout the year, whether locally, regionally, or globally. Likewise, spectrum monitoring should also be on a continuous basis if the purposes and goals of monitoring are to be appropriately fulfilled.

The purpose of spectrum monitoring is to support the spectrum management process in general, including frequency assignment and spectrum planning functions. Specifically, the goals of monitoring (not necessarily in priority order) are to:

– assist in the resolution of electromagnetic spectrum interference, whether on a local, regional or global scale, so that radio services and stations may coexist compatibly, reducing and minimizing resources associated with installing and operating these telecommunication services while providing economic benefit to a country's infrastructure through access to interference- free, accessible telecommunication services;
– assist in ensuring an acceptable quality of radio and television reception by the general public;
– provide valuable monitoring data to an administration's electromagnetic spectrum management process concerning the actual use of frequencies and bands (e.g., channel occupancy and band congestion), verification of proper technical and operational characteristics of transmitted signals (license compliance), detection and identification of illegal transmitters and potential interferers, and the generation and verification of frequency records;
– provide valuable monitoring information for programmes organized by the ITU Radio-communication Bureau (Bureau), for example in preparing reports to Radiocommunication Conferences, in seeking special assistance of administrations in eliminating harmful interference, in clearing out-of-band operations, or in assisting administrations in finding suitable frequencies.

1.1.2.2 Relationship between spectrum monitoring and spectrum management

The functions of spectrum monitoring and spectrum management are closely related. Linking these functions through an integrated computer system can result in significantly increased effectiveness and cost-efficiency for both. It is critically important in implementing a spectrum management system to first develop a system structure that maintains the integrity of the process, and the database that contains all relevant information to support the process. In the case of an inadequate database, the combination of monitoring and enforcement techniques and procedures can be effectively used to obtain critical information and thereby, help improve the database and the overall spectrum management process.

Monitoring is closely associated with inspection and compliance in that it enables the identification and measurement of spectrum usage, interference sources, the verification of proper technical and operational characteristics of radiated signals, and detection and identification of illegal transmitters, producing data on the effectiveness of spectrum management policies.

Monitoring further supports the overall spectrum management effort by providing general measurement of channel and band usage, including channel availability statistics of a technical and operational nature, thereby giving a measure of spectrum occupancy. Monitoring is also useful for planning, in that it can assist spectrum managers in understanding the level of spectrum use as compared to the assignments that are registered on paper or in data files. A monitoring and measurement system can help in some instances where a solution to a problem requires more than knowledge of authorized or designed characteristics of radio systems. A monitoring and measuring system also obtains information on the operation of individual stations, for regulatory, enforcement, and compliance purposes, and can be used to establish the location and identity of stations causing interference.

In general terms, monitoring gives feedback to spectrum management on whether the practical use of the spectrum matches the national policy. Monitoring can also identify the need for future requirements for spectrum management officials. In this case monitoring gives feed-forward information to spectrum management.

1.1.3 Databases

An integral component of spectrum management is the ability to store, maintain and access information about individual communication networks. This information can form one of the spectrum management system databases, which is a description of all of the relevant parameters of individual radiocommunication facilities. This database enables the governing agency to conduct various engineering and managerial analyses to ensure spectrum efficiency, operational compliance with rules and regulations, and interference free operation between systems. Without accurate database records, the integrity of the spectrum management process would be compromised.

The spectrum monitoring service must have access to the complete central database of authorized users. This allows a means of verifying the licensing and assignment conditions, and identifying unauthorized uses of the spectrum. The monitoring service can also create its own databases of monitored transmission activity and measured characteristics. This information can be used for event records and later correlated to the central databases.

1.1.4 Software

Spectrum management and monitoring systems may contain a significant amount of software to automate data collection, processing, evaluation, and interference analysis tasks. Using software to save spectrum monitoring results in relational databases and correlating this information with the central database of authorized users can save considerable research time while increasing accuracy.

1.1.5 Legal and regulatory foundation for a national spectrum management system

Because of the rapid advance of radio technology and the central role that technology plays in the life of each nation, laws covering the spectrum resource are becoming as important as those that govern land and water use. Therefore, the use and regulation of radiocommunications must be covered within each nation’s body of law. The radiocommunications law is a basic document establishing concepts, authorities, broad goals and objectives, and responsibilities, but should not stray into detailed delineation of regulations and procedures. This law should give recognition to the fact that the radio spectrum is a national resource and that there is a need to govern it in the interest of all citizens. It should therefore establish the right of the national government to regulate radiocommunications use, including authorization for use and enforcement of spectrum management rules, primarily controlled through monitoring and inspection. In order to carry out these functions, spectrum managers should be granted the authority to identify sources of interference and to require that they be turned off or confiscated under an appropriate legal mechanism. The limits of the authority should also be specified.

The radiocommunications law should establish the right of both citizens and government to own and operate radiocommunications equipment. National, regional, or local government may best operate some communication systems. These are most often systems that support the missions of the government organizations themselves. However, many of the needs of society can be met by commercial ventures or individuals, and the quality and availability of communication services may be linked closely to the kinds of activity and the level of freedom granted to service providers.

Elements that also should be covered within the national radiocommunications law are the requirements for public access to the spectrum management decision process and for government responsiveness to the public input. The specific processes whereby the public presents its spectrum requirements or its position on spectrum issues to the spectrum manager, may be described elsewhere, but the right to access, and any limits to that access, could be established in the law. Based on the spectrum manager's basic mission to manage spectrum use in the national interest, by responding to public input, is essential. Therefore, the radiocommunications law should require that the spectrum management authority provide the public with information on its decisions, including written explanation of the basis for its decisions. In addition, the law should provide a process for review and appeal of decisions in accordance with established criteria and procedure.

The primary day-to-day tools of spectrum management are the set of published regulations and procedures promulgated and adopted by the national spectrum regulator. These regulations serve as the basis for daily conduct of radiocommunications use and enable the spectrum users to understand the manner in which their operations are governed. The regulations provide a method of interaction with the spectrum management authority. These regulations and procedures should cover areas such as procedures for obtaining and renewing a licence, emission standards, equipment authorization procedures, channelling plans, and operational requirements, as well as procedures for spectrum monitoring, inspection and enforcement.

1.1.6 Spectrum planning and allocation

Spectrum allocation is the process of distribution of radio frequency spectrum among different radiocommunication services on either an exclusive or shared basis and on either primary or secondary principals. At the international level this allocation is governed by World Radiocommunication Conferences (WRCs) and reflected in Article 5 of the Radio Regulations (RR). Based on its international Table of Frequency Allocations, administrations may establish a national frequency allocation table, allocate frequency bands to radiocommunication services and authorize specific systems.

To use the spectrum efficiently, it is essential to allocate frequency bands that will meet the propagation requirements of the intended service. For example, services that are typically required to provide omni-directional coverage over a large area, such as broadcast television, are allocated frequency bands that are relatively low in the spectrum; private mobile radio (PMR) services are allocated VHF/UHF frequency bands to ensure limited local coverage; and for global aeronautical and maritime services, which require worldwide coverage, HF frequency bands are allocated. These allocations are sometimes subdivided into channel plans to ensure that specific loading, channel and frequency re-use requirements are met.

In response to requests from particular users, administrations should follow these allocation tables to assign appropriate frequencies for the needed radio system, issue relevant licences and produce appropriate records in the database. Technical procedures of frequency assignment should allow effective channel and frequency re-use, based on permissible interference concepts or necessary frequency-distance separation criteria between radio networks.

1.1.7 Spectrum engineering

Spectrum management involves decisions pertaining to a field of technology and engineering that is required to adequately evaluate the information, capabilities and choices involved. Though social, economic, and political considerations enter into most decisions, many spectrum management issues can be analysed, and spectrum management decisions made, based on engineering and technical factors. Therefore, a part of the organization versed in these analysis techniques, and knowledgeable in technological developments, is needed to provide unbiased assessments to those within the policy and planning groups who must consider other factors such as economics and national policy. They may identify and recommend solutions to interference problems, determine equipment technical characteristics necessary to ensure compatibility between systems, or in some cases, encourage the use of alternative technologies. An important aspect involves the use of models with input information supplied by appropriate databases, to perform analysis pertinent to spectrum management such as frequency assignments. Models can be used to predict whether compliance with rules and regulations (e.g., satellite power flux-density limits) is possible, and to assess the potential for sharing by analysing the probability of interference.

1.1.8 Rules, regulations and associated standards

ITU has established general rules and regulations regarding international spectrum allocation and spectrum management. These are contained in the Radio Regulations published by the ITU (http://www.itu.int/publ/R-REG-RR/en).Taking into account these international regulations, each member nation creates its own legislation and relevant rules and regulations to accommodate its national radiocommunication infrastructure and goals. The intent of these rules is to provide a necessary framework for administration and enforcement of the spectrum management process. The regulations should include the process of authorization of equipment, including specifications and standards for transmitter characteristics.

1.1.9 Frequency coordination and notification

Because the radio spectrum is a limited resource and the demand from both private and government users continues to increase, it is necessary to create a mechanism by which frequencies can be assigned to particular services and systems whereby the greatest number of users can be accommodated. This is implemented through a frequency coordination process.

Frequency coordination starts with the process of selecting frequencies for a system that is not likely to cause interference to other existing systems. This information can then be exchanged or "coordinated" with appropriate parties to insure compatibility between systems. The purpose of this process is to maximize frequency reuse while minimizing operational interference between communication systems.

There are several key elements to consider in the frequency coordination process. First, the administration must define the rules and regulations, which will become the basis for the process. Next there must be an exchange of information between the applicant for a new service and the coordinators. The information must contain sufficient technical data so that the coordinators can perform an analysis to assure that the new service will not cause harmful interference into existing services, and that new services can operate compatible with existing services. The effectiveness of frequency coordination is directly related to the accuracy and currency of the records contained in the database and the ability to accurately predict the operation of the existing and proposed systems.

Frequency coordination and compatibility studies between existing and proposed radio facilities are necessary parts of an effective spectrum management system, whether carried out at the national or international level.

International frequency coordination is a procedure that should be implemented before giving a frequency assignment to a station that might conflict with that of another country. This frequency coordination procedure is usually under a special agreement concluded between two or more countries as it is described, for example, in Recommendation ITU-R SM.1049. Global, general rules for the assignment and use of frequencies, and special agreements are described in RR Articles 4- 9 and 11.

1.1.10 Licensing, assignment and billing

The necessary administrative steps in the process of licensing and frequency assignment are defined by the rules and regulations identified previously. A government agency usually controls the licensing function or process. Once the agency has determined that the proposed communication system complies with these rules, authorization is normally granted through the issuance of a licence or equivalent. If any significant changes are made to a licensed system, rules usually require the user to notify the regulatory agency of these changes so that a revised licence may be issued. If these procedures for licensing are followed, they will ensure that the integrity of the spectrum management database is maintained by reflecting changes made in operational systems in a timely manner. Data on decommissioned systems can be moved in the database to an inactive section for temporary, future reference, and eventual elimination.

The licensing and administrative functions of an effective spectrum management system have benefits that go beyond merely creating and maintaining a database of technical parameters. The licensing process can be a source of revenue for the administration in the form of fees when the initial licence is granted, fees for renewal of existing licences. It can also be a source of revenue in terms of fines and penalties for operating without the proper licence, operating outside of the licensed parameters or operating in defiance of the established rules and regulations.

1.1.11 Inspection of radio installations

The inspection of radio installations is an effective means of regulating and ensuring more efficient use of the spectrum because it ensures that radio facilities are installed and operating in accordance with their assigned operating parameters. Stations operating outside their authorized operating parameters (for example, excessive power, or an error in the transmitter location) have greater potential for causing interference, and will impact new authorizations on co-channel and adjacent channel frequencies.

A number of different approaches may be taken by administrations in planning and implementing inspections of radio facilities. The approaches include plans such as:

– inspection of all newly authorized installations;

– inspections based on cause (for example, increased number of interference reports, or discovery of rule infractions), and

– inspecting a percentage of all stations on a random sampling or other statistical basis.

An example of an effective approach is to inspect a percentage, or "sample" of existing authorized facilities/transmitters. The facilities included in the sample could be selected randomly for different services. The results of the inspections would then be evaluated in accordance with the national regulations and standards. The compliance level of the sample would provide an estimated measure of overall compliance with national regulations. In future years, the sample sizes and categories of facilities subject to inspections may be adjusted based on the compliance results of the previous year. In other words, if compliance were relatively high in a particular service, the number of samples could be reduced; alternatively, if compliance were low, a larger sample could be undertaken.

A more detailed discussion of inspection planning methods, statistical sampling determination, Equipment for inspections and detailed inspection procedures can be found in Report ITU-R SM.2130.

1.1.12 Law enforcement

The benefits of a spectrum management system cannot be realized if the users fail to comply with their licence(s) and the appropriate rules and regulations. Rules and regulations should include provisions defining the actions that can be taken if a user is found to be in non-compliance. Based upon the severity of the violations, penalties could range from warnings, to fines, to revocation of licences and terminating operation of systems and, in accordance with and depending on national legislation, even legal prosecutions. Without effective enforcement procedures, the integrity of the spectrum management process would be compromised. The ability of an administration to enforce established rules and regulations pertaining to the operation of radiocommunication systems is clearly dependent upon both an effective spectrum management system and an effective spectrum monitoring and inspection system. When a complaint concerning interference is received, the interfering signal can be monitored to determine the location of the signal, the type of transmission and other technical parameters that may aid in identifying and locating the source of interference which then can be farther investigated. The spectrum management database can be searched to determine if the source of interference is a licensed transmitter that is operating outside of its authorized technical parameters, or is from an illegal operator.

1.2 Spectrum management considerations

1.2.1 Efficient use of spectrum

The rapid growth of demand for worldwide communication services, driven by the move towards an information-based society, could lead to a serious shortage of available spectrum unless measures are taken to manage the spectrum effectively on national, regional and international levels. Because frequency spectrum is a limited resource, required growth must be achieved through efficient use of the available spectrum.

Efficient use is achieved by strategically allocating portions of the spectrum to meet the requirements of users without creating any waste of the spectrum. Conservation of spectrum will allow for future growth and the emergence of new wireless technologies.

1.2.2 Spectrum sharing

The ability of one or more users or services to share a segment of the frequency spectrum without interference is an important consideration in spectrum management. Sharing of spectrum effectively increases the amount of spectrum available for the wide variety of services. Sharing can be facilitated by power control, geographical separation of users, separation of radiation patterns, time separation of users, by permitting some interference when it can be tolerated without becoming harmful, or use of newer technologies that allow coexistence of multiple transmissions on the same frequency. However, efficient sharing requires a good coordination between national bodies which manage the spectrum utilization, and may also require coordination between administrations at international level near country borders. Allocation of spectrum to users with geographical restrictions takes advantage of the limitations of signal propagation. The simplest example of geographical restrictions is the differences in allocations between the ITU Regions. On a smaller scale, geographical separation is also the basis of frequency planning for a cellular system, which allows for frequency re-use after an appropriate physical separation between cells and between emission patterns has been achieved.

Time separation is also an effective method of facilitating sharing through the use of time-agile technologies and trunking systems. In these systems, one or more channels may be shared by many users that have delineated transmission time requirements. Many systems are capable of coexisting in the same time and space segment of the spectrum, depending upon the specific modulation and interference threshold or multiple access scheme of each system (e.g., code division multiple access (CDMA)). For example, one of the primary advantages of spread spectrum technology is its increased resistance to interference. This characteristic allows multiple transmissions to occupy the same spectrum at the same time without disruption but, of course, within system limitations.

1.2.3 Economic aspects

Radiocommunications have become an increasingly vital part of the telecommunications infrastructure and economy of a country and economic approaches to national spectrum management are becoming essential. These approaches promote economic, technical, and administrative efficiency, and help ensure that radio services are able to operate on a non-interference basis. In order to have effective radiocommunications, a country must have an effective spectrum management system.

The starting point for an effective spectrum management system is to obtain adequate financial resources. These resources can be obtained from the administration or from fees collected from the use of the radio spectrum. The collection of fees varies from the fee for the processing of a radio licence to the auctioning of a portion of the radio spectrum. Fees can promote efficient use of the spectrum provided that they incorporate the correct economic incentives and are not so low as to be negligible in the eyes of spectrum users or so high as to exceed what a market would set, in which case spectrum may sit idle and generate no benefits.

Auctions may be most appropriate when there are competing applicants for the same frequency assignment. Auction revenues may vastly exceed spectrum management costs but the auction approach holds potential for an accurate reflection of the value of the spectrum. Auctions may not be appropriate for services in which there is limited competition for spectrum assignments, for socially needed services such as safety and national defence, and for some other specific services, e.g., international satellite services. Since recent auctions have placed significant values on spectrum, sometimes in the billions of dollars, administrations have to ensure that an auctioned spectrum band is acceptable for use, whether by moving existing users or through the implementation of sharing conditions. Monitoring such bands in the appropriate coverage areas will support this activity.

A number of administrations have implemented various forms of support for national spectrum managers. These include:

– communication groups with a direct interest in spectrum such as advisory committees, trade associations, professional organizations, and quasi-governmental associations;

– frequency coordinators and designated spectrum managers;

– spectrum management consultants, and support contractors.

These supporting methods have potential for saving government financial or human resources, increasing the efficiency of spectrum use, improving the efficiency of frequency assignment and coordination, and supplementing the expertise of the national spectrum manager.

For details on spectrum economics see Report ITU-R SM.2012.

1.3 National monitoring goals

The purpose of spectrum monitoring, as previously described, is to assist in the resolution of interference, in ensuring acceptable quality of radio and television reception, and to provide monitoring information to spectrum management.

Historically, it was because of more and more intensive use of high frequencies for international links that countries met to lay down rules for frequency allocation and procedures for dealing with interference. RR Article 16 describes the procedure and facilities to be used for international monitoring as noted in § 1.4. To implement the provisions of RR Article 16, it is recommended that countries establish a centralizing office and HF monitoring station(s).

Nowadays, although it is still necessary to monitor at HF, the need to pay special attention to VHF/UHF/SHF monitoring is becoming more and more urgent. These frequencies are increasingly used for radiocommunication networks whose range is, by their very nature, limited roughly to line-of-sight, or around a 100 km, depending on the frequency, power, propagation conditions, and antenna (transmitting and receiving) height.

The best way to site monitoring stations, in the light of the limited range of the transmitters to be monitored, is considered in Chapter 2. National use of these facilities is described below, while their international use is dealt with in § 1.4.

1.3.1 Monitoring for compliance with national rules

The purpose of monitoring is to identify those transmissions that do not conform to requirements either because the transmission is unlicensed or because of some technical non-compliance of the transmission with national rules and regulations.

There are a number of reasons for this type of work:

– an unauthorized or defective transmission causes other users poor service through interference;

– unauthorized transmissions represent loss of licence income to the administration and a disincentive for other users to seek licences, and they complicate the resolution of interference;

– planning can only effectively proceed in a stable and coordinated environment;

– the public has a right to an acceptable level of broadcast, mobile radio and paging services.

1.3.1.1 Verification of technical and operational parameters

Monitoring is used to obtain detailed information on the technical and/or operational characteristics of radio systems. This might typically include a detailed measurement of the emitted spectrum of a transmitter and/or its antenna pattern. These measurements can be made to provide information needed in a particular electromagnetic compatibility (EMC) analysis, to verify conformance with the characteristics authorized in a particular frequency assignment record or as part of a type-acceptance process to ensure that a particular kind of equipment will operate compatibly with other equipment in the frequency band. Finally, measurements might be made to ascertain that a given transmitter was operating within specified limits.

Although many types of technical parameters can be measured, probably the most important one is the emitted spectrum of a transmitter. A measurement technique must be selected that will allow various types of signal modulation to be quantitatively measured in a useful way. Thus, a measurement system should have a variety of bandwidths, filters, attenuators and other parameters that may be selected individually for the signal being measured. Vector signal analysis capabilities are required for some of these measurements.

1.3.1.2 Resolution of interference and identification of unauthorized transmitters

Spectrum monitoring data are useful in identifying and resolving the cause of interference to authorized transmitters. Such measurements may detect the presence of unauthorized transmitters causing the interference or, for example, detecting intermodulation interference resulting from a combination of transmitters and unintended spurious emissions. Although a wide variety of combinations of spectrum measurements and engineering analyses may be needed to resolve some types of interference, spectrum monitoring data often play a key role in this process. Aural monitoring will often be useful in learning the identity of transmitters involved in the interference.

Unauthorized transmitters may be suspected as a cause of interference. For this reason, there will often be a close association between the ability to solve interference problems and the ability to detect and identify unauthorized transmitters. A major problem with the detection of unauthorized transmitters is that it is often difficult to separate legal signals from those that are unauthorized. This is especially difficult in crowded bands where authorized and unauthorized transmitters share the same band and have similar modulation characteristics.

Detection of unauthorized signals can sometimes be accomplished by aural monitoring on frequencies where authorized users have complained of interference or where frequency assignment records show no legally-assigned users. Direction finding, mobile-tracking vans and information derived from aural monitoring are helpful in identifying and locating illegal transmitters after their operation has been detected.

1.3.2 Monitoring to aid spectrum management-policy

Good spectrum management can only satisfactorily proceed if the planners are adequately informed on the current usage of the spectrum and the trends in its demand. While much data is collected from prospective users on licence application or renewal forms, it is seldom completely adequate for spectrum management purposes. These records will only indicate that the use of a frequency is authorized, but may not give adequate information on whether or how the frequency is actually used. Therefore, a frequency band that appears crowded on the basis of frequency assignment records may or may not, in fact, be crowded. Nowadays many countries, in procuring new automated spectrum management systems require also a direct connection with the monitoring system, in order to store the monitoring results in the central database. The monitoring data is then directly available to frequency planners and also the monitoring operators have online access to the license database. This may lead to an efficient work process.

1.3.2.1 Spectrum usage (occupancy) data

Usage or channel occupancy data indicates how much of the time a particular frequency or band has had a signal present during a specified observation interval. Measurements on a single frequency can be combined to show how usage varies during a 24 h day (including busy hour and hours of peak, average and minimum usage). Data from many frequencies can be combined to show the average usage for all frequencies in a band, or for a selected group of users.

Channel occupancy and band congestion information is a valuable tool for several spectrum management functions. This information can be used to identify vacant channels in a band, and can be used to prohibit adding more assignments to heavily used channels. Such data can also be used to prompt an investigation, either when signals are present on unassigned channels, according to the frequency management records, or when no usage is seen on frequencies with assignments. Changes with time-of-occupancy statistics, for the same band in the same geographical area, can reveal trends. Finally, this type of information can be used to help anticipate and plan for the allocation of additional bands when existing bands become too crowded.

Spectrum usage measurements are particularly helpful in the land mobile radio bands or similarly channelized communication bands. Other mobile bands would also be good candidates for usage measurements. Standards of use could be established by the spectrum management process for reference purposes in each of the services involved.

The relationship between monitoring information and spectrum management records is not always straightforward. Channel occupancy information tells us only that a frequency is used. It does not indicate which transmitter is producing the signal. The existence of an assignment at a particular frequency and the presence of a signal at that frequency do not necessarily mean that the measured signal was transmitted by the assigned transmitter. Aural monitoring for call signs or similar information to identify a transmitter may be needed to resolve any ambiguity. Alternatively, direction finders make it possible to compute occupancy measurements on a per transmitter basis with the identification relying on geographical fix information. The absence of a signal during the measuring time, however, does not necessarily indicate the absence of a frequency assignment or that the frequency is unused. An assigned transmitter may not have been used during the monitoring period.

1.3.2.2 An aid to new assignments

The level of use by each licensee varies according to the relevant business, the time of day and the day of the week. Licensing data can be used to predict levels of use with some degree of success depending on the sophistication of the prediction model and the accuracy of the data. As congestion increases the model may become progressively less adequate in identifying the least used channels. Monitoring data from the geographical area of the proposed assignment will be invaluable in identifying a frequency most suited to the prospective purpose.

1.3.2.3 An aid to developing better management models

Monitoring data may be expensive to collect and analyse. Therefore, despite being a valuable tool, it is impractical to utilize monitoring data for all assignments. Lightly used areas of the country may be adequately served by modelling based on available licence data. Monitoring data collected in the busier areas can be compared to the levels predicted by the model with the results used to identify suspect licensing data, and then to refine the model so that it best fits the total picture. By this means, the model can be validated and subsequently, better applied. Accordingly, monitoring can be better targeted to those areas most in need of assistance.

1.3.2.4 An aid to dealing with complaints and queries

As congestion grows, the users will become less satisfied with the service available. By being able to monitor in areas attracting disproportionately large numbers of complaints, the true nature of a problem can be ascertained and the best remedial action devised. It will also be possible to substantiate or refute allegations regarding the quality of service perceived.

1.3.2.5 An aid to categorizing and interpreting interference and propagation effects

The VHF and UHF bands are not immune to the effects of anomalous propagation. The result may be interference from distant services normally considered too distant to warrant great efforts in coordination.

These effects are short-lived and while statistical data on them are available, it is only by monitoring that the implications for particular services can be accurately assessed. It may well be that only a few services are affected by only a few distant transmitters. The appropriate cure may be case-specific. Good monitoring data will greatly aid in identifying the causes of a problem.

1.3.2.6 An aid to spectrum sharing

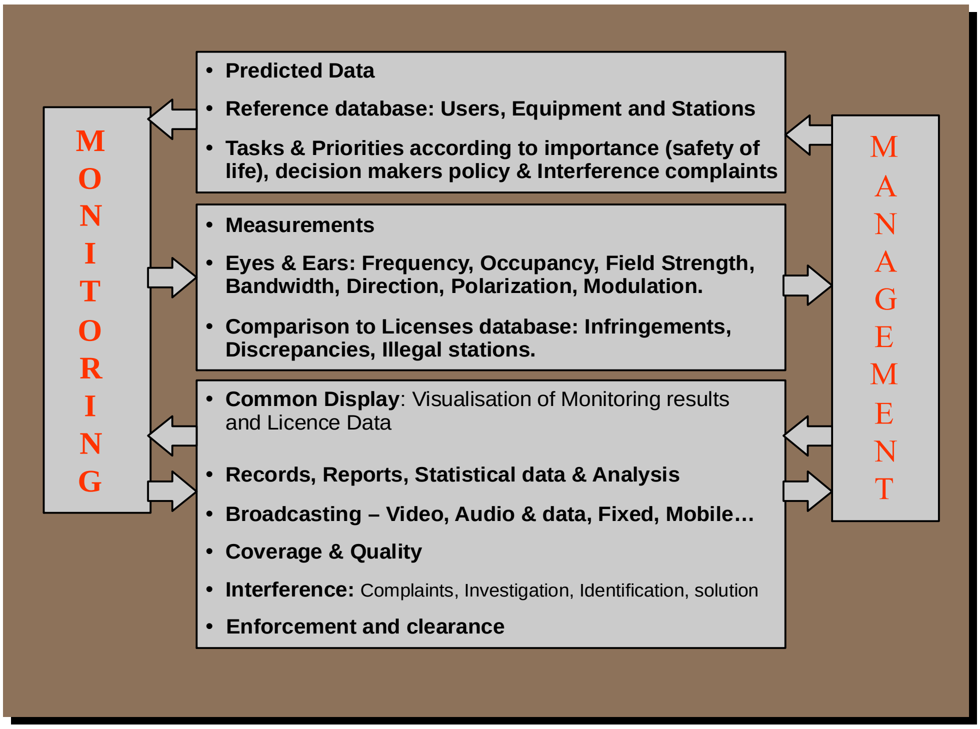
The demand on the spectrum is now such that services are expected to share. Some service types are clearly incompatible, but often the matter is borderline. Trials could be carried out to determine the degree of compatibility. Monitoring the conduct of a trial will give information such as relative signal levels that will aid analysis of the system performance.

1.3.2.7 Spectrum monitoring functions within spectrum management system

The relation between the spectrum management and monitoring is presented in Fig. 1.3-1. The management data provides the predicted data, the reference database of users (licensees), equipment (RF, power) and stations (coordinates, identification, altitude above sea level, altitude above ground level, antenna gain, azimuth and elevation angles). It offers the tasks and priorities according to importance (e.g. safety of life), decision-makers policy and interference complaints. The measurements, the eyes and the ears of the spectrum management, deliver the frequency, occupancy, field strength, bandwidth, direction, polarization and modulation. The comparison of measurements to licences indicates the infringements, discrepancies and illegal stations. A common display may visualise the monitoring results and licence data: records, reports, statistical data and analysis of services, such as broadcasting, mobile and fixed; their coverage and quality of service may be depicted, including the digital terrain mapping. The interference: complaints, investigation, identification and solution become visible; enforcement and clearance are mandatory in case of unauthorised stations.

FIGURE 1.3-1

Interrelation of spectrum management and monitoring functions



Spectrum-1.3-01

1.3.2.8 Activity flow and database consideration

For optimal cooperation of the spectrum management and monitoring activities, immediate direct access of the spectrum monitoring to the spectrum management database is proposed. Maintenance of the database is the responsibility of the spectrum management authority. However, in order to more effectively empower the spectrum monitoring department with real-time information, the on-line read-only access to specific tables of the database can be provided to the monitoring department, in order to plan monitoring activities and to evaluate results.

Similarly access of the spectrum management to the spectrum monitoring database (mainly monitoring results) is suggested.

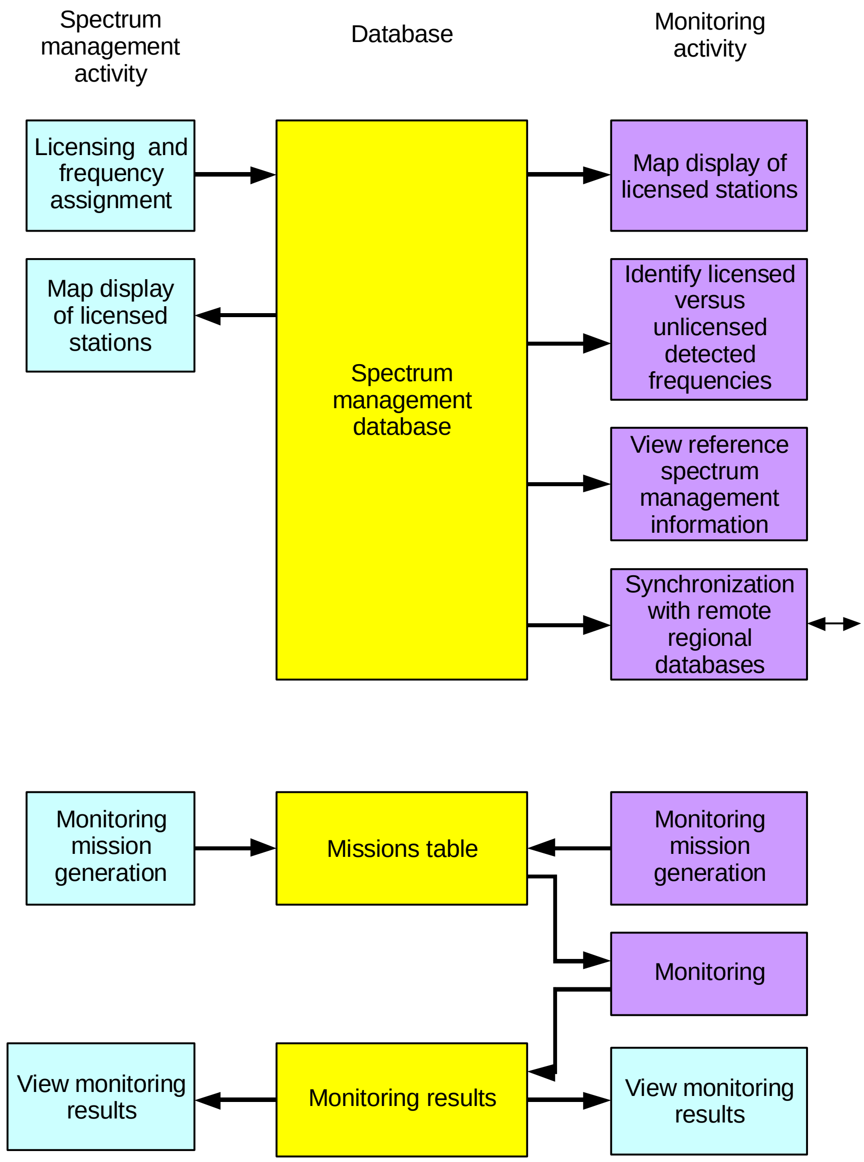
This might reduce the number of messages between the spectrum management and monitoring, and will support seamless use of the information by both applications, regardless of which one has generated the data, see Fig. 1.3-2.

The spectrum management database accessible to the monitoring service may consist of:

– Stations and Networks (license) data;
– Frequency assignment information;
– Equipment data;
– Other data.

FIGURE 1.3-2

Spectrum management and monitoring cooperation flow



Spectrum-1.3-02

By using this information the monitoring department will be able to do the following:

– Display subset of the licensed stations over a map background, graphically depicting the location of each station;

– Identify licensed versus unlicensed stations and transmission activity;

– Analyze license infringements;

– View reference data, such as equipment specifications or user details.

Monitoring Missions and Tasks

– It will be possible for the spectrum management system to prepare monitoring missions and Tasks for execution by the monitoring system. The requested missions and tasks will be saved within the database.

– It is proposed to set thresholds/tolerances on parameters to be measured (i.e. bandwidth) when defining the missions and tasks. These thresholds/tolerances will be used to alert the operator when deviations occur from the expected (licensed) value.
– The monitoring service will use these instructions for scheduling of automatic activities (as well as initiating interactive operations) and for saving the results in the database.
– The saved results will be available for analysis and report preparation by both spectrum management and/or monitoring staff members.

The shared database described herein is to be implemented at the spectrum management department level, as specified in Chapter 3 of ITU National Spectrum Management Handbook, Edition 2005. This Chapter relates to those components of the database that are relevant to the spectrum monitoring department, in order to support the Integration of the spectrum monitoring system with the spectrum management system, as has been described in Recommendation ITU-R SM.1537.

Note that the distribution of relevant information to the remote monitoring stations (i.e. update a mobile monitoring station on licensed stations and assigned frequency list at an area before this mobile monitoring station is going to a work session at that area), and the transfer of measurement results from the remote stations to the national centre will be the responsibility of the monitoring service.

1.3.2.9 Database verification and correction

Integrity of databases requires regular updates and verification. Monitoring data can be utilized to help verify the accuracy of spectrum management databases and to help bring them up-to-date, through a manual procedure. Also, monitoring capability of checking the data helps provide some added motivation for better database maintenance.

1.4 International monitoring

1.4.1 The international monitoring system

As can be appreciated from different Chapters of this Handbook, the monitoring of emissions is an essential component of the frequency spectrum management system. Each country should operate monitoring facilities as essential tools for ensuring efficient spectrum management at the national level. On the other hand, since aims of the ITU include ensuring efficient and economic use of the frequency spectrum and help towards the rapid elimination of harmful interference, administrations have decided to cooperate in the development and operation of an international monitoring system and, to that end, have adopted appropriate regulatory provisions.

RR Article 16 contains the provisions governing the establishment and operation of the international monitoring system.

The international monitoring system comprises only those monitoring stations that are designated as such by administrations. Such stations may be operated by an administration, a public or private agency, a monitoring service established jointly by several countries or by an international organization. The administrations responsible determine whether the technical standards observed by stations are in accordance with the ITU-R Recommendations and communicate the information to the ITU. It is to be noted in this respect that administrations may authorize the participation of stations observing lower technical standards in order to meet some particular needs for monitoring data.
A centralizing office must be designated by each administration, by a group of administrations in cases where a joint monitoring service has been set up, or by an international organization participating in international monitoring. Requests for monitoring information must be sent to the centralizing office, which then assembles the monitoring results for transmission to the Bureau or other centralizing offices. In accordance with RR Article 20, information on such stations is published by the ITU in the List of International Monitoring Stations (also known as List VIII), together with the name of the centralizing office.

In addition to that List VIII, includes information about the different functions that each monitoring station is able to perform, both in the terrestrial and in the space radiocommunication services.

List VIII is an indispensable document for operating in the international monitoring system, because the information it contains enables rapid contact to be made between centralizing offices, particularly in the case of harmful interference. It is therefore important for administrations to carefully update (upon periodic request by the Bureau) the information in List VIII and notify the Bureau immediately of any significant change. Supplements to List VIII are published regularly and, in addition, information received between publications of the supplements is published in the ITU Operational Bulletin and also in the Web site, (http://www.itu.int/ITU-R/ go/terrestrial-monitoring-listVIII/index.html).

1.4.2 Coordination role of the Bureau

The international monitoring system is a means for coordinating monitoring activities to satisfy international needs relating to the collection, exchange and publication of information. Monitoring activities within the system are carried out in response to a request by either Administrations or by the Bureau. The Bureau plays an essential role in the operation of the system by coordinating the organization of regular and special monitoring programmes, collating and studying the results and making the necessary arrangements for communicating them to administrations. Since 1999, the Bureau publishes the reports of monitoring information received from administrations in the ITU Web site, (http://www.itu.int/ITU-R/go/terrestrial-monitoring/en), and the corresponding electronic files can be downloaded free of charge.

The Bureau organizes different types of monitoring programmes on a world or regional basis, as well as limited programmes confined to a smaller area or a few administrations.

1.4.3 Use of international monitoring information by the Bureau

The Bureau needs monitoring data to perform the following tasks:

- assisting in clearance of unauthorized or out-of-band operations;
- assistance to administrations in cases of harmful interference;
- guidance to administrations in selecting frequencies;
- preparation for Radiocommunication Conferences, in particular those responsible for allocating frequency bands, by providing reports on spectrum occupancy.

Because of the different propagation characteristics in different parts of the frequency spectrum, the monitoring data used by the Bureau generally relates to the terrestrial services in the frequency bands below 28 MHz or those frequency bands used in space radiocommunications. In some special cases, however, particularly when intervening in cases of interference, the Bureau must be able to obtain data relating to any frequency band.

In this connection, it should be emphasized that with the increasing use of the frequency spectrum by the space radiocommunication services, there is a growing need for monitoring information concerning the bands used by these services. Recommendation 36 (WRC-97) invites ITU-R to study and make recommendations concerning the facilities required to provide adequate coverage of the world with a view to ensuring efficient use of resources, and invites administrations:

- to make every effort to provide monitoring facilities as envisaged in RR Article 16;
- to inform ITU-R of the extent to which they are prepared to cooperate in such monitoring programmes as may be requested by ITU-R;
- to consider the various aspects of monitoring emissions originating from space stations to enable the provisions of RR Articles 21 and 22 to be applied.

It is also essential that those administrations already having space monitoring facilities participate in the international monitoring system and to this effect notify to the Bureau of the particulars of their monitoring stations for inclusion in List VIII (Section III).

1.4.3.1 Assisting in clearance of unauthorized or out-of-band operations

From time to time the Bureau organizes special monitoring campaigns with the purpose of identifying unauthorized or out-of-band operations and encouraging administrations to take the necessary action to eliminate the emissions concerned.

The frequency bands for which these campaigns are organized are usually those allocated to safety services. During these campaigns, the Bureau asks Administrations to intensively monitor the bands concerned over a limited period of time (generally one week). The type of data required is explained in a BR Circular Letter. The Bureau for facilitating further analysis summarizes the reports so obtained. If the Bureau is able to determine with reasonable certainty that the operating unauthorized or out-of-band station is under the jurisdiction of a particular administration, it will draw the attention of this administration to the reported operation and to the interference potential of such emissions to safety services.

Interfering emissions are sometimes due either to spurious emissions resulting from maladjustment of a transmitter working in another band or to stations recorded in the Master International Frequency Register (Master Register) as operating on a "non-interference basis" as foreseen in RR No. 4.4. Administrations are therefore generally able to clear the resulting interference.

As an example, a special campaign has been in progress since 1987, pursuant to Resolution No. 205 (Rev. Mob-87), in the 406-406.1 MHz band allocated exclusively to satellite emergency position-indicating radiobeacons. This campaign has produced very positive results. Statistics about the number of interfering emissions that have been detected and further suppressed are appropriately published in the BR annual reports and the reports are also made available at the Web site, (http://www.itu.int/ITU-R/go/resolution-205/en).

1.4.3.2 Assistance to administrations in cases of harmful interference

Pursuant to RR Article 15, an administration may request the assistance of the Bureau in solving cases of harmful interference. In the studies it conducts for that purpose, the Bureau frequently uses information secured through international monitoring, often obtained by organizing special programmes involving only a few monitoring stations.

The Bureau may require two types of information in cases of harmful interference:

– The first of these concerns the identification and location of possible sources of harmful interference. In this case, the Bureau will request those administrations that have monitoring stations suitably equipped and located to make the necessary observations and measurements.

– The Bureau evaluates the results of the measurements thus obtained so as to determine the location of the interfering stations and hence, to identify the administration under whose jurisdiction it appears to be operating. The administration responsible is approached with a view to securing rapid elimination of the interference.

– The second use of monitoring information in connection with cases of harmful interference is the measurement of the field strength of the interfering station. This may be necessary when there is some uncertainty as to the degree of harmful interference experienced, or if specific criteria in the RR or an ITU-R Recommendation, might apply. The Bureau will, in cases of this type, request the assistance of administrations whose monitoring stations are suitably located and equipped to make the measurements required.

1.4.3.3 Guidance to administrations in selecting frequencies

If requested by any administration in accordance with RR No. 7.6, and particularly by an administration of a country in need of special assistance, the Bureau will use the information recorded in the Master Register, together with monitoring information received in the context of regular or special monitoring programmes in order to identify potential frequencies that could be assigned to their stations in the fixed or mobile services.

Special attention will be given to cases where replacement frequencies are needed for the regular operation of stations in the aeronautical or maritime mobile service due to unresolved cases of harmful interference.

1.4.3.4 Preparation for radiocommunication conferences

As part of the preparations for a radiocommunication conference, particularly if the conference has to make decisions on changes in the Table of Frequency Allocations, the Bureau may organize special monitoring campaigns designed to supplement the data in the Master Register. Results would be reported to the conference in the form of a report so that it can evaluate the impact of the proposed changes in spectrum use.

In addition, a radiocommunication conference may request the Bureau to organise special monitoring campaigns not only with a view to providing information concerning the use of a specific part of the spectrum but also to supporting studies concerning interference caused to safety communications for further analysis by a subsequent conference.

1.4.4 International monitoring programmes

1.4.4.1 The regular programme

Since the introduction of the Table of Frequency Allocations adopted by the Atlantic City Radio Conference in 1947, the ITU maintained a regular programme of monitoring in the HF bands between 2 850 and 28 000 kHz. The first issue of the "Summary of Monitoring Information" appeared in 1953 and these summaries have been published since then on a regular basis. The main objectives of the regular monitoring programmes of the International Monitoring System can be summarized as follows:

– to assemble information on spectrum utilisation at the location of the monitoring stations and to derive there from an indication of how the spectrum is used;

– to identify stations whose emissions are not in conformity with the RR No. 16.8;

– when requested by a radiocommunication conference, to assemble information on the use of the bands exclusively allocated to specific services (i.e. broadcasting, maritime, aeronautical) for consideration by appropriate, future radiocommunication conferences;

– to provide administrations, which do not have monitoring facilities, with information for frequency management purposes.

Several administrations normally contribute reports to the Bureau for the preparation of summaries of regular monitoring. The Bureau validates the information received and prepares a compiled database in the form of quarterly files, which are continuously updated and published on the ITU Web site, (http://www.itu.int/ITU-R/go/terrestrial-monitoring/en).

1.4.4.2 Special programmes

From time to time, the Bureau organizes special monitoring programmes covering certain frequency bands and time intervals. These are carried out over several two- to three-week periods, each near in time to at least one equinox and two solstices.

Each such special programme is announced in a circular letter sent to all administrations, inviting them to make all the necessary arrangements well in advance for effectively participating in the campaign. The Circular Letter also contains a list of the different parameters which monitoring stations are invited to collect, and indicates the format in which the data should be communicated to the Bureau.

1.4.5 Global monitoring coverage

One of the main conditions for successful operation of the international monitoring system is to achieve a uniform coverage of all parts of the world by monitoring stations adequately equipped and taking an active part in these ITU monitoring programmes. For the time being, this coverage is very uneven, particularly in some areas of the world from where the collection of monitoring information is often an essential requirement.

Resolution ITU-R 23 refers to the need for extension of the international monitoring system to a worldwide scale and in particular resolved that:

– all administrations now participating in the international monitoring system, including for monitoring of space stations emission levels, should be urged to continue to do so to the maximum extent possible and to provide data to the Bureau for the preparation of summaries of monitoring in application of RR Article 16;

– administrations, which do not at present participate in the international monitoring system, should be urged to make monitoring facilities available to that system, in accordance with RR Article 16 using the relevant information contained in this Handbook;

– cooperation between monitoring stations of different administrations should be encouraged and improved with a view to exchanging monitoring information concerning terrestrial and space stations emissions, and to settling harmful interference caused by transmitting stations that are difficult to identify or cannot be identified;
– administrations, located in those areas of the world where monitoring facilities are inadequate, should be urged to promote the establishment of monitoring stations for their own use and make them available for international monitoring, in accordance with RR Article 16;
– data supplied by the monitoring stations participating in the international monitoring system may be used by the Bureau to prepare summaries of useful monitoring data in application of RR Article 16;
– administrations with more advanced terrestrial and space monitoring systems should be urged to accept officials from other administrations to train them in the techniques of monitoring, direction finding and location. Initial contact for training may be made to the appropriate centralizing office as incorporated in List VIII.

1.5 Collaboration among monitoring stations of different countries

As mentioned above, one of the objectives spelled out in Resolution ITU-R 23 by the Radiocommunication Assembly is the cooperation between monitoring stations of different administrations. This cooperation is particularly useful in areas where monitoring stations of different countries are relatively close to one another. Different forms of cooperation can be envisaged. Two examples of such cooperation are described in §§ 1.5.1 and 1.5.2.

1.5.1 Collaboration below 30 MHz

In order to avoid overlapping of activities by monitoring stations covering the same area, close cooperation can be organized between these stations so that they can take part, in turn, in a specific monitoring programme. For this purpose, the part of the spectrum to be monitored can be divided into sub-bands that each monitoring station taking part in the programme will explore in turn in accordance with a predetermined timetable, for instance once a week. Some common operational rules have to be defined so that a uniform method is used in conducting all operations, including the appraisal of reception quality. It is advisable that all these operations be coordinated by one of the participating monitoring stations.

Such arrangements can be implemented either for particular purposes, for instance during special monitoring programmes organized by the Bureau, or they can be of a more permanent nature.

Another field of activity where close coordination between monitoring stations may be essential is the determination of the location of a transmitter and its identification, particularly in the case of harmful interference. In such a case the most important factors are the speed and accuracy of intervention. It is thus essential that administrative and operational arrangements be concluded, a priori, among the administrations of the countries in which the monitoring stations are located. As soon as the need arises, these stations can then establish direct contact between themselves in order to perform simultaneous measurements of the same emission including, as necessary, taking bearings on the transmitter concerned.

Again, one of the monitoring stations should take a leading role in the exercise but it, of course, does not need to be the same station in all cases. Normally, the station that requests the investigations would take the leading role.

1.5.2 Collaboration above 30 MHz

Neighbouring countries are increasingly endeavouring to provide harmonized radiocommunications to facilitate cross-frontier operations by adopting common specifications. This phenomenon is a very marked one, at least in Europe, and should encourage the countries concerned to set up harmonized or even integrated monitoring facilities by using identical procedures and, under certain circumstances, a common infrastructure. This would make monitoring services more efficient and also lead to lower and, therefore, more readily acceptable financial investments for monitoring infrastructure.

Collaboration between technicians of different countries in the definition and development of a common operational system could also have a major positive impact on technical innovation and the quality of inter-personal and related international relations.

As mentioned in § 2.6, countries need to introduce VHF/UHF monitoring stations that are carefully sited, having regard to the normal, limited range of transmitters in these bands.

Neighbouring countries might be advised to conclude special agreements between one another on the basis of RR Article 16, with a view to optimizing the monitoring procedures and facilities to be introduced in frontier area(s). Such bilateral or even multilateral agreements may be classified in three categories.

The first category is to be regarded as the initial step while the second and third categories constitute longer-term objectives. The main issues to be covered are the following:

First category:

– cases in which the regional authorities on both sides of the frontier are authorized to enter into direct contact, for example, only when the frequencies concerned are the direct responsibility of the regional centre (frequencies to be specified), on the basis of RR No. 16.3;
– in such cases, methods for informing the centralizing offices (RR No.16.3);
– exchange of list of actions authorized by the regional authorities, e.g.:
  – carrying out measurements from their own territory on transmitters in the neighbouring country, at its request, and transmitting the results to it;
  – authorizing a mobile team from the neighbouring country to come and take measurements itself;
  – mutual assistance in both cases.

Second category:

– joint establishment of a plan for the distribution of monitoring stations in frontier areas;
– definition of the interfaces to enable each country to take measurements of transmitters located on its own territory from any station in the frontier area;
– establishment of a schedule for installing harmonized monitoring facilities.

Third category:

– exchange of lists of authorized networks in the frontier areas of each country, together with their technical characteristics, so that "foreign" transmitters are no longer regarded as unknown;
– exchange of such lists using automatic remote data transmission procedures.

Arrangements of this kind exist in many parts of the world, particularly in congested areas. The long-standing arrangements among Canada, Mexico, and the USA constitute a typical example of such cooperation.

The need for such collaboration is also exigent in the European area where, for instance, France, Germany and Switzerland entered into an agreement of the first category in 1993. A detailed description of this arrangement is given in Annex 1 to this Chapter.

In developing its national spectrum monitoring system, France's aim is, in particular, to make access to its system easy and automatic, both for authorized national users and for users from agreeing countries.

ANNEX 1 TO CHAPTER 1

Agreement for direct co-operation among radio monitoring stations

Agreement among the Administrations of France, Germany and Switzerland on the direct co-operation between radio monitoring stations

AGREEMENT

Among the signatory administrations on the direct co-operation between radio monitoring stations

The following has been determined by the signatory Administrations within the scope of their responsibilities as defined by Articles[1] 20, 22 and 24 of the Radio Regulations for the settlement of problems of harmful interference or unauthorized emissions:

1. If the assistance of another country is deemed necessary, the centralizing office of the country concerned shall turn to the centralizing office of the other country in accordance with the Radio Regulations (No. 1875 of the Radio Regulations).

2. The bodies responsible for radio monitoring shall designate radio monitoring stations which, when deemed appropriate, may establish direct contact with each other (Nos. 1946 and 1956 of the Radio Regulations).

3. The Administrations give their consent for mobile monitoring equipment of the radio monitoring stations mentioned in **2** above to cross the common borders of their countries in the fulfilment of radio monitoring tasks.

Consent from the other country is to be obtained in each case.

Stations may use their own monitoring equipment.

The use of means of communication is not covered by this Agreement.

4. No official acts may be performed directly towards citizens within the territory of the other country.

5. The radio monitoring stations shall mutually support each other in the application of this Agreement.

6. The bodies responsible for radio monitoring shall stipulate the terms regarding the application of this Agreement in a protocol.

NOTE 1 – Replaced by Articles 16, 15, and 18, respectively.

Paris, 16 September, 1993

For the Minister responsible for Telecommunications in France:

The Director of the Réglementation Générale:

Bern, 15 October, 1993

For the General Directorate of the Swiss PTT Operators:

The Director of the Directorate for Radio and Television:

Bonn, 9 November, 1993

For the Federal Minister of Posts and Telecommunications:

PROTOCOL

Regarding the Agreement of 1993 among the Administrations of Germany, Switzerland and France on the direct co-operation between radio monitoring stations

1. Participants in the co-operation

– for Germany: the radio monitoring stations in Constance and Darmstadt;

– for France: the *services régionaux des radiocommunications* of Lyon-St André de Corcy and Nancy and the international radio monitoring centre in Rambouillet;

– for Switzerland: the radio monitoring stations in Basel, Bern, Châtonnaye, Geneva, St. Gallen and Zürich.

2. Form of the co-operation

The direct co-operation provides for the following possibilities for the countries participating in the Agreement:

– to carry out measurements with fixed and mobile monitoring equipment at the request of a neighbouring country on their own territory;

– to carry out measurements with their own mobile monitoring equipment outside their territory;

– to exchange measurement results.

3. Procedure for the co-operation

The request for measurements shall be transmitted among the monitoring stations by telephone, by fax or by telex. If measurements with mobile monitoring equipment have to be carried out on foreign territory, a distance of 50 km from the border may not be exceeded.

4. Limits of the co-operation

The direct co-operation of the monitoring stations shall end when the request can no longer be treated on the grounds that the matter lies outside the competence of the monitoring station.

It shall also end

– when the measurements with fixed monitoring equipment are expected to require more than three hours;

– when the measurements with mobile monitoring equipment are expected to require more than nine hours or more than one monitoring vehicle.

In both cases, the requests are to be addressed to the centralizing office.

Paris, 16 September, 1993	Bern, 15 October, 1993	Mainz, 29 November, 1993
For the Direction de la Réglementation Générale;	For the General Directorate of the Swiss PTT Operators;	For the BAPT;
Le Service National des Radiocommunications:	Directorate for Radio and Television Department for the State Radiocommunications Monopoly:	The Centralizing Office of the Radio Monitoring Service:

NOTE – Due to reorganisation of telecommunication authorities, the name of the signing authorities have changed. Nevertheless, the agreement is still in use.

References

ITU-R texts:

NOTE – In every case the latest edition of the Report should be used.

ITU-R Handbook [2005] National Spectrum Management.

ITU-R Handbook [2005] Computer-Aided Techniques for Spectrum Management (CAT).

Recommendation ITU-R SM.1049 – A method of spectrum management to be used for aiding frequency assignment for terrestrial services in border areas.

Report ITU-R SM.2012 – Economic aspects of spectrum management.

Report ITU-R SM.2015 – Methods for determining national long-term strategies for spectrum utilization.

Report ITU-R SM.2093 – Guidance on the regulatory framework for national spectrum management.

Report ITU-R SM.2130 – Inspection of radio stations.

Resolution ITU-R 23-1 – Extension of the international monitoring system to a worldwide scale.

ITU-D Resolution 9 (Rev. Doha, 2006) – Participation of countries, particularly developing countries, in spectrum management.

CHAPTER 2

ORGANIZATION, PHYSICAL STRUCTURES AND PERSONNEL

Page

2.1 Tasks and structure of the monitoring service

2.1.1 Tasks of the monitoring service

2.1.1.1 Tasks derived from the Radio Regulations

The following monitoring service tasks derive from the Radio Reulations (RR):

– monitoring emissions for compliance with frequency assignment conditions;

– frequency band observations and frequency channel occupancy measurements;

– investigating cases of interference;

– identifying and stopping unauthorized emissions.

Regularly monitoring national emissions for compliance with conditions and subsequently eliminating any non-compliance aims to prevent radio interference. Technical parameters such as frequency, bandwidth, frequency deviation and class of emission, and – with certain radiocommunication services – communications content needs to be monitored. For example, monitoring amateur radio communications should aim in particular to ensure that call signs are regularly used and no broadcasts are made.

Frequency band observations aim to determine which frequencies/channels are used by whom and how. By contrast, channel occupancy measurements aim to determine the degree to which and when frequencies are used – and hence also which frequencies are unused – and involve identifying emissions and their basic characteristics. Knowledge of actual spectrum use is essential for the frequency management aim of ensuring efficient, interference-free frequency use and for deciding whether or not a certain frequency can be assigned to additional users. These data also form the basis for national and international frequency coordination.

In view of the increasing role played by radio applications in every area of life, swiftly and effectively investigating and eliminating radio interference is a task of economic importance. Special priority is to be given to eliminating interference to safety services such as the aeronautical, police and fire services.

Stopping unauthorized emissions aims primarily to prevent radio interference but also to guarantee income, since fees are paid only by authorized frequency users.

2.1.1.2 Tasks on a national basis

Additionally to the tasks indicated in § 2.1.1.1 the monitoring service is also often charged with the following tasks not directly derived from the RR:

– assistance on special occasions such as major sporting events and state visits;

– radio coverage measurements;

– radio compatibility and EMC studies;

– technical and scientific studies.

At state visits, Formula One races and other large-scale events, a large number of radio equipment are used within a confined space. The users are often not aware that they need a frequency assignment or that they may not be able to use the same frequencies in each country. In the interests of preventing interference and intervening immediately should interference occur, it is expedient for the monitoring service to be on site to monitor spectrum use and act swiftly to investigate and eliminate any interference. Crucial for success is timely coordination with the organizers and the staff responsible for frequency assignment, who also need to be on site to assign frequencies at short notice if necessary.

Many Administrations also see radio coverage measurements as the monitoring service’s task. This involves measuring field strength and, in some cases, quality parameters such as bit error rate (BER) and adjacent channel power. However, other Administrations see such measurements as the task of the radio network operators and not the monitoring service, as the market guarantees sufficient radio coverage quality.

Before frequencies are allocated for a new radio application, compatibility with existing radio systems must be ensured. Purely theoretical radio compatibility studies are often not adequate. The monitoring service may often be called upon to assist with the necessary practical studies if it has the required measurement equipment and expertise. It may likewise be called upon to assist in certain scientific studies such as long-term observations of propagation conditions.

2.1.1.3 Tasks usually assigned to the radio inspection service

The following tasks are usually assigned to the radio inspection service and not the monitoring service:

– inspecting radio equipment on site;

– measuring radio equipment to rule out health hazards from electromagnetic radiation;

– processing cases of electromagnetic compatibility (EMC) relating to non-radio equipment;

– market surveillance activities when radio equipment or other electronic equipment is put on the market.

Regarding market surveillance, radio and telecommunications equipment used worldwide is required to respect regional or national requirements in order to ensure they are operating in compliance with relevant technical regulations or restrictions (frequency band, power levels, etc.).

Failure to respect these regulations and restrictions creates a risk the equipment will cause harmful interference. Therefore it may be among the task of administrations to control products using "market surveillance". Typically, random product samples are obtained in retail stores and are then tested in the administration's testing laboratories or an independent private test laboratory under contract with the administration.

2.1.1.4 Co-operation of radio monitoring and inspection services

The radio monitoring and inspection services should cooperate closely and, if possible, have access to a common database. In searching for sources of harmful interference it is, for example, helpful for the monitoring service to also have details of the radio equipment, which the inspection service has found to be non-compliant. Conversely, the monitoring service can trigger inspections by recording the same parameters that would be recorded during an inspection. Monitoring results obtained in this way can be used to select candidates for an on-site inspection. This in turn may substantially reduce the amount of on-site inspections needed.

Monitoring can further support the radio inspection service by determining whether or not a faulty radio station has been repaired, without the inspection service having to re-inspect the equipment on site.

The monitoring service has high measurement equipment costs compared to the inspection service. Hence many Administrations base their monitoring service at fewer locations than their inspection service. Since the inspection service is usually closer to the customers, the inspection service could do the final investigating of interference cases which have initially been investigated by using fixed direction finders.

There is no need for a strict division between the two services. For financial reasons it may even make sense, in particular for smaller countries, not to separate the radio monitoring service from the radio inspection service at all. In fact, the integration or merger of monitoring and inspection into one organisation may simplify the overall organisation.

2.1.1.5 Cooperation with other bodies

The monitoring services in most countries do not have any police powers. Cooperation with the police and courts is therefore essential for confiscating illegal transmitters and imposing penalties for violations of conditions. Past experience has shown that it is helpful if the police and the courts are involved in advance and are made familiar with the major provisions of telecommunications law.

It is assumed that it is not necessary here to detail the need for close cooperation between the frequency management and the monitoring service.

2.1.2 Measurement tasks and essential equipment

In order to carry out the tasks mentioned in § 2.1.1, the monitoring stations must be capable of identifying and locating emissions and measuring their essential characteristics.

The most important measurement tasks, which a monitoring station should at least be able to perform, are:

– frequency measurements;
– field strength and power-flux density measurements at fixed points;
– bandwidth measurements;
– modulation measurements;
– spectrum occupancy measurements;
– direction finding.

Consequently, it is proposed that the measurement equipment of a monitoring station fulfils the functions of the following equipment:

– omnidirectional antennas;
– directional antennas;
– receivers;
– direction finders;
– frequency measuring equipment;
– field-strength meters;
– bandwidth measurement equipment;
– channel occupancy measurement equipment;
– frequency spectrum registration equipment;
– spectrum analyzers;
– vector signal analyzers or modulation analyzers;
– decoders;
– signal generators;
– recording equipment.

It should be noted that modern measurement equipment can often fulfil more than one function, which results in a reduced number of cabinets. Many functions can also be realised in software.

Generally, the measurement equipment should cover the frequency range 9 kHz-3 GHz. If separate HF and VHF/UHF monitoring stations are planned, the frequency range may be divided up into, for example, 9 kHz-30 MHz for HF monitoring stations and 20 MHz-3 GHz for VHF/UHF monitoring stations.

Further measurement equipment, including equipment for higher frequencies, may be required, depending on a monitoring service's additional and more specific tasks such as:

– field strength measurements along a route;
– monitoring of broadband technologies operating above 3 GHz, such as some Wi-Fi, WiMAX and WLAN/RLAN systems;
– television measurements on video signals (e.g. luminance and chrominance);
– measurement of specific parameters of digital networks;
– monitoring of fixed link emissions;
– measurement of satellite signals;

Chapters 3-5 and 4 contain detailed information on measurement methods and equipment.

2.1.3 Structure of a monitoring system

2.1.3.1 Centralising office and international cooperation

According to RR Articles 15 and 16, each Administration or common monitoring service established by two or more countries, or international organizations participating in the international monitoring system, must designate a “centralising office” to which all requests for monitoring information must be addressed and through which monitoring information will be forwarded to the Bureau or to other Administration’s centralising offices. It is essential that Member States exercise the utmost goodwill and mutual assistance in the settlement of problems of harmful interference.

The centralising office staffs therefore needs to meet a number of basic requirements. The staff must be authorized to issue direct instructions to the monitoring stations, must be available round the clock, and must be familiar with the monitoring station’s essential working procedures and technical facilities.

If these requirements are met, it is irrelevant whether the centralising office belongs to a ministry or other organization or whether it forms part of a monitoring station.

Where practicable and subject to agreement by the Administrations concerned, cases of harmful interference may be dealt with directly by their specially designated monitoring stations. Many European Administrations endorse direct cooperation between the monitoring stations.

An example for an agreement allowing monitoring stations to request foreign monitoring stations to make measurements not only in cases of interference and also to use their vehicles in the other country is given in Annex 1 to Chapter 1.

Cooperation and support are based on the principle of mutuality, and hence are free.

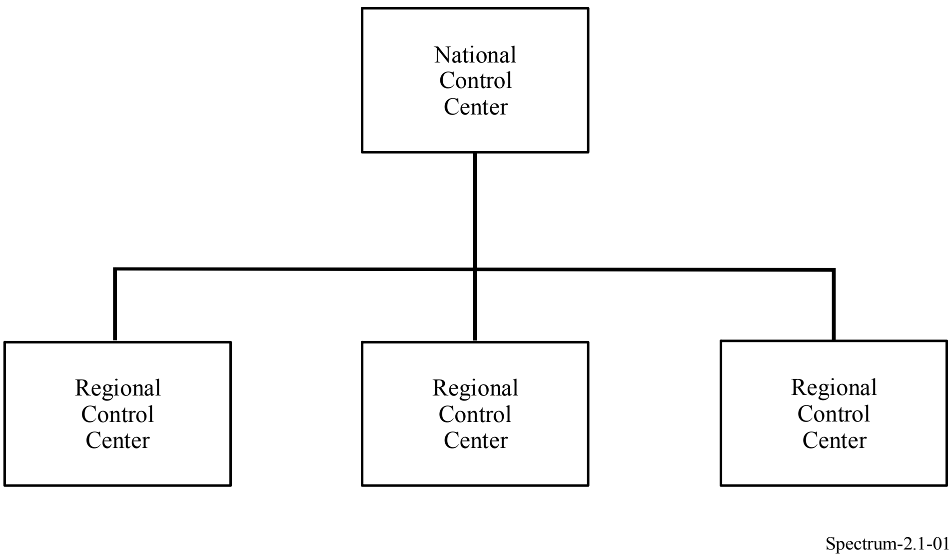
However, individual Administrations also have special facilities such as satellite monitoring stations which are extremely expensive. A contractual agreement may be concluded enabling other Administrations to use such facilities against payment of the costs.

2.1.3.2 Organizational structure

A monitoring system can be structured in various possible ways, although the range of possibilities actually feasible in each case is restricted by the number of monitoring stations and the Administration’s organizational form (see Fig. 2.1-1).

FIGURE 2.1-1

Organizational structure



This section only relates to manned monitoring stations which are also assumed to have access to remote-controlled and mobile facilities. Subordinate monitoring stations may be remote controlled.

The management of the whole monitoring service at the top level (sometimes called the National Control Center) defines the monitoring station's tasks and provides resources. In some countries Regional Control Centers are responsible for a certain region. Their resources may include manned, remote controlled and mobile monitoring stations. The Regional Control Center should be co-located with a manned monitoring station. Frequently, only one HF monitoring station is available which is then of course responsible for the whole territory. Similar other special tasks could be assigned nationwide to only one Regional Control Center.

The centralising office may be assigned either to the National Control Center or to one of the Regional Control Centers. The inspection service may be a separate organization, although it has proved expedient to integrate any co-located monitoring and inspection services. Furthermore, the centralising office or even the whole radio monitoring service may be part of the frequency management department.

2.1.3.3 Geographic configuration of monitoring stations

The number of monitoring stations in a country depends on the tasks, the geography, and not least the financial resources. It would be ideal if every point in a country were covered by at least two direction finders, enabling every emission to be located. On account of the unaffordable costs of the required number of direction-finding stations, this is not practicable, and so concessions must be made. The following sections provide additional thoughts taking account of the different frequency ranges. The planning and optimization of spectrum monitoring networks by using software tools is described in § 6.8.

2.1.3.3.1 HF range

If there is more than one HF monitoring station, depending on the frequency band and propagation conditions each station can at times provide global coverage.

2.1.3.3.2 VHF/UHF range

In light of the limited range of VHF/UHF waves of normally not more than a few tens of kilometres, monitoring stations should be located near to where the work is most concentrated. The manned monitoring stations should be supplemented by remote-controlled direction finders to enable transmitter location.

Each manned monitoring station disposing of fixed and mobile equipment should cover an action area of approximately 150 to 200 km radius to enable those teams, which have to intervene at the boundary of the area to make their movements within a day. This radius should be adapted depending on the available transport means, the geographical relief, the road network conditions and the significant road traffic specific to some regions and of the urban areas.

Any areas not covered by fixed direction finders must be covered by direction-finding vehicles. The mobile teams should have the appropriate means to conduct the interference search and the compatibility and coordination measurements at the borders.

2.1.3.3.3 Satellite signals

From a technical viewpoint, a satellite monitoring station can provide extensive coverage of both geostationary and non-geostationary satellites depending on the satellite footprint, thereby covering at times the territory of several entries, and therefore it is recommended that the national Administrations cooperate.

2.2 Operation

This section deals with monitoring station processes relating to terrestrial services, covering the tasks set out in § 2.1 and involving stationary, remotely controlled and mobile measuring equipment. In view of the high amount of money involved in radio monitoring systems and considering that radio monitoring services are usually funded by taxes or by the fees paid by license holders, there is a need to organise their efficient and traceable work. Hence the management should document its strategies, systems, programmes, procedures and instructions to the extent necessary to ensure quality of the whole monitoring system permanently. This should be communicated, understood and available to the appropriate personnel.

2.2.1 Work instructions and forms

For routine tasks it is advisable to establish work instructions describing workflows, rights and obligations for standard procedures. Such work instructions serve as reference material for both new and experienced staff. In drawing up such instructions, a pragmatic approach should be adopted to ensure unambiguous and easily comprehensible guidelines, motivating staff by giving them a certain degree of leverage for individual decisions. Obviously, the degree of detail will depend on the qualification of the staff and regulatory requirements in individual countries. Separate instructions should be compiled for specific cases and non-routine tasks not described in the work instructions.

Forms serve as a useful aid when dealing with matters of a more or less regular nature by ensuring uniformity and clarity. They should therefore be structured logically and provide sufficient space for handwritten notes. For example, the form used for registering interference complaints received by telephone should enable staff to ask for all necessary details. Here again, exceptional cases may occur which are not covered by the form. It is therefore important that there should be sufficient space to record further information.

Work instructions should also include a reference to the applicable safety regulations or a quotation thereof. Taking care of the personnel's health and safety is an important management task.

2.2.2 Work schedules

The tasks can be split up into stationary and mobile measurements. In the work schedules the following distinctions need to be made:

– scheduled tasks which cannot be postponed;

– scheduled tasks which can be postponed;

– unforeseen tasks which can be postponed;

– unforeseen tasks requiring immediate action.

The first category covers tasks such as field strength measurements, needed by the frequency administration by a certain date for licensing or international coordination purposes. Routine measurements such as general measurements verifying adherence to assignment conditions are not normally subject to a deadline and may therefore be postponed. The third category includes non-critical interference reports such as Citizen Band (CB) or amateur service interference. If, however, safety-related services such as COSPAS/SARSAT, police radio are affected, immediate action is required.

The human and technical resources needed to deal with the tasks then need to be assessed and coordinated. The work schedule should therefore be compiled and published as early as possible for staff to be adequately prepared. In case of urgent interference reports, the work schedule has to be modified at short notice. This also applies in case of illness or equipment failure.

When compiling the plan, attention must also be paid to the following:

– If large areas need to be covered, it may be expedient for mobile measurement teams to remain in the area and be accommodated in a hotel rather than returning on a daily basis, to avoid costly and unproductive time on road travel.

– The availability of the monitoring service must be ensured around the clock, since interference may also occur at night. In some countries the monitoring stations are hence staffed 24 h/day, in others availability is assured either by round-the-clock staffing of a single monitoring station or by automatic call forwarding to staff on call at home. However, availability does not only imply being reachable over the telephone: it is not sufficient to staff a monitoring service with one person only who would be unable to undertake urgent field work as the station would then be left unmanned.

– Vehicles and equipment need to be maintained on a regular basis or may require unexpected repairs, which means that they will be temporarily taken out of service.

– Regular staff meetings are essential to brief staff about any organizational changes or changes and developments in services, frequency assignments or regulatory matters. Such meetings also offer the opportunity to instruct staff in the use of new radio technologies, licenses and monitoring equipment (if no other training arrangements, e.g. by the manufacturer, are foreseen).

The afore-mentioned considerations are also valid in case the responsibilities assigned to monitoring team include the task of performing on-site inspection; thus, it is advisable to plan the work of monitoring and inspection together, to be carried out during the same visit. The work schedule should be presented in a form allowing each staff member to identify immediately who will carry out which task where, the vehicle to be used and how radio contact will be maintained. A computer system containing the work schedule to which all staff members has access may be used, but a simple notice board or even old-fashioned blackboard is a cheap alternative which functions equally well.

2.2.3 Typical procedure for dealing with interference complaints

Interference processing is not only the most important task, but also a very complex task, justifying a detailed description of the procedures involved.

2.2.3.1 Interference report

Interference is normally reported by telephone, fax or email. The operator then has to inquire about the details. The key items of information needed are:

– name, address telephone number and email address of the party experiencing the interference;
– data about the interfered-with device: frequency, type, coordinates, location, license number and other relevant data;
– data about the occurrence of the interference (when first noticed, time, regular or sporadic);
– description of the interference (humming, hissing, etc.);
– suspected source of interference;
– is it a case of interference which needs to be dealt with by the monitoring service or is merely an equipment fault involved, in which case the operator of the equipment or a repair service ought to be called in?.

2.2.3.2 Preliminary diagnosis

The priority accorded to the case depends on the interfered-with service and the number of interfered-with devices. The description of the interference will be used to decide on the various steps and measurements required to solve the interference. Other operators of the same radio frequency in the nearby area may be asked if they are also interfered.

Many operators of different services (e.g. satellite, broadcasting, mobile, fixed) tend to have their own monitoring equipment utilized to assess the quality of service. The Administration may use this infrastructure and advance self-monitoring, in order to assist the interfered party: the interfered site may serve as the best fitted, to monitor the interference; location, altitude above ground and sea level of the antenna and retrieving the modulation.

As a rule, fixed and remotely controlled measurement equipment should be used to ascertain whether the interference can also be heard at the monitoring station. With direction-finding means it should be possible to roughly identify the location of the interference's source. Location and other features such as modulation and bandwidth usually suffice to limit the number of possible sources to relatively few with the help of frequency assignment databases. The operators of the suspected interference sources are contacted and asked about a change in their activities and to switch off their transmitter for a short time. This procedure is repeated until a change in the interference or spectrum clearly identifies the actual source. This approach is the cheapest and fastest way of eliminating interference.

2.2.3.3 Localization of the source by mobile means

If the source of the interference cannot be determined as described above, it will be necessary to deploy vehicles. Especially in the case of sporadic interference or interference to cellular operators, localization efforts may prove to be very time-consuming.

2.2.3.4 Measurements of emissions and possible sources

Once the source or interfering emission has been localised and identified, the technical characteristics responsible for the interference must be measured to determine the nature of the interference, i.e. whether the case involves co-channel interference, adjacent channel interference, receiver intermodulation, receiver saturation or conducted interference at the mains input. During these measurements the equipment used and their settings must be recorded accurately to be able to verify in the next step whether the interfering system or device is being operated in violation of the frequency assignment conditions or exceeds threshold values. Standards and recommendations contain detailed specifications of the measurement procedures for a wide range of parameters.

2.2.3.5 Measurement evaluation and necessary action

The measurement results must subsequently be compared with the frequency licence, assignment conditions or relevant standards. Depending on the outcome, the interfering system or device may either have to be taken out of operation altogether or its operation modified, or the system or device may have to be rectified, or the interference may have to be accepted. In many countries the outcome will indicate whether a fine or other penalty is payable.

National regulations, which vary from one country to another, specify whether the measurement team or another entity within the Administration is responsible for actions such as law enforcement to be taken. The requisite actions should not only conform to the law but also be reasonable. If a defective relay contact in a heating system turns out to be the cause for minor interference, it would be inappropriate in winter to demand that the system be shut down immediately. Instead, a reasonable period should be specified for eliminating the defect.

2.2.3.6 Interference involving foreign or military stations

Special provisions apply to cases of interference involving foreign stations. In this connection reference is made to RR Article 15 (Interferences), RR No. 16.3 and RR Appendix 10 (Report of harmful interference). It may also be expedient to specify specific procedures to be adopted in cases where military stations are involved.

2.2.3.7 Final check-up

In many cases the monitoring service will be able to check whether remedial action has been taken, using fixed or remotely controlled equipment. Where this is not possible, an on-site inspection may be necessary. The simplest way of dealing with the matter is by asking the interfered-with party whether the interference has stopped.

2.2.4 Identification and disconnection of illegal radio stations

Transmitters which are being operated without the prescribed license or frequency assignment are potential sources of interference and must therefore be taken out of service. Locating such transmitters may be initiated by any of the following:

– observation of such a transmitter by the monitoring service during routine measurements;
– interference complaints;
– other indications.

The initial steps taken are identical to those in interference processing. First of all, as much information as possible must be gathered about the transmitter through the evaluation of the measurement results. Since the operators of pirate radio stations are normally aware of the fact that they are violating the law, they will make every effort to remain undiscovered. They may employ the following tactics:

– incorrect and misleading data about the transmitter location including camouflage;
– remote operation of the transmitter;
– misrepresentation and disinformation;
– sporadic, irregular emissions;

– use of different frequencies;
– change of location.

Compared with “normal” interference cases, these tactics make it much more difficult to localise and identify the transmitter. The monitoring service has to adapt itself to circumstances and take appropriate measures, such as exact evaluation of the message content. Details, which may first appear irrelevant, assist to identify the illegal station and prosecute the accused.

Another difference is that the operator of an interfering station is usually keen on eliminating the interference and will therefore be willing to help solve the problem. However, operators of pirate radio stations are most unlikely to cooperate in view of the consequences of their behaviour (penalty and confiscation of their equipment). It is therefore important for the monitoring service to collect unambiguous proof that can be used in court as evidence to support the claim that unlawful transmissions have been made by the defendant. Seizure of the equipment during an actual transmission obviously constitutes irrefutable proof of illegal use; such an action, however, is contingent upon close coordination with the police.

The chances of being successful in combating the operation of pirate radio stations depends entirely on the legal frameworks in each country which should provide the basis for prosecuting the operators of such transmitters and confiscating their equipment.

2.2.5 Case documentation

Many engineers and technicians view measurements as their primary obligation and consider the associated documentation as a job of secondary importance. It is therefore essential to repeatedly stress the high value of documentation as an essential part of the staff’s responsibility. If at any time doubts arise as to the reliability of measurement values, these doubts can only be dispelled by submitting a complete set of documentation proving the validity of the values.

Example: The quantified measured input power value is only meaningful if antenna height, terrain profile and range from emitter to monitoring receiver, bandwidth, type of detector, measurement location, used antenna and its k factor, and the setting of any attenuators are also known.

The documentation serves as a reference document for past measurements, offers lessons to prevent future interference, and provides updated data needed in the database used as the management information system (see § 2.3).

From the above it follows that the documentation must comprise the following items:

– task number;
– task content;
– entity requesting the task or source of interference complaint;
– staff involved in the task;
– date(s) and time(s) at which the task was carried out;
– precise measurement locations (e.g. coordinates);
– measurement equipment and antennas used (serial number or inventory number must be indicated to be able to determine whether the equipment was calibrated at the time it was used);
– chosen settings (e.g. attenuator activated);
– measurement set-up (block diagram, sketch);
– measured values (with units!) of frequency, bandwidth, power flux density (or field-strength), bearings, etc. and observations, e.g. call signs and violations;
– any measurement protocols, spectrum analyzer plots, data files, etc.;
– environmental conditions possibly affecting the measurement accuracy;
– vehicle(s) used;
– Records such as videos, audios and photos.

Signature or the author's initials should confirm the correctness of the data in the work report. Depending on the type of task, the documentation should also include a summary of the conclusions, decisions, further action taken and associated reports.

2.3 Management information system

Management information system as used for monitoring purposes provides information as a key factor in directing and decision-making at a managerial level. The management process can be considered either as a feedback structure or as a combined top-down and bottom-up process. A management information system, consisting of a database and associated reporting system, will provide relevant information on time. On the basis of this information a working plan can be created which ideally would form the basis for a resource plan. Nevertheless, due to insufficient information and budget, it may be more appropriate to set up a resource plan first and take it as a basis for the working plan. Practical experience shows that the road to success will be in-between.

2.3.1 Database

In order to gain an overview of the overall volume of tasks, the time required dealing with them, and their regional distribution, the following information could be stored in the monitoring database:

- unique task number;
- code for the type of task (e.g. interference report, occupancy measurements);
- date of receipt and completion of task;
- entity requesting task or source of interference report with address, telephone, fax number and e-mail address;
- identification of the location of the interference or measurement by name and numerical code, such as postcode or coordinates;
- task description or content of the interference report;
- affected service or application;
- frequency or frequencies;
- call sign;
- frequency license numbers, if individually assigned;
- category of the station (such as fixed, mobile);
- in interference cases, cause and source of the interference.

It may be expedient to input further data such as manufacturer, type and serial number of the interfering or interfered-with device, any foreign countries or military locations affected, steps taken (e.g. fines imposed), recipient of the final report, names of personnel involved in the measurements, etc.

Uniform and unambiguous analysis of the data should be guaranteed by using a hierarchically structured menu for inputting type of task, service involved, source and cause of interference, as illustrated in the example below:

Layer 1	Layer 2	Layer 3
1 Terrestrial services	1-1 Fixed service	...
	1-2 Mobile services	1-2-1 Land mobile service 1-2-2 Aeronautical mobile service 1-2-3 ...
	1-3 Broadcasting service	...
2 Space services	1-4 …	

The hours worked, split up into in-house and fieldwork, and mileage can be recorded for each individual task. Depending on the type of analysis for which the data is required it may also be necessary to note the equipment used.

As the data referred to in this section forms the basis for the management information system analyses, other data such as field strengths, occupancy rates and other measurement results is ignored in this context. Nevertheless, the data mentioned in § 2.2.5 can be stored in the same database (monitoring database), thus allowing both individual cases to be analysed and statistical analyses to be carried out.

2.3.2 Reporting system, statistical analyses

Once the aforementioned data has been keyed into a database, various types of analysis are possible. For planning purposes it is important to have an idea of the time needed for the various tasks. Graphs covering several years clearly indicate typical trends. For example, should working hours invested in occupancy measurements decline, because management demand for such values has decreased or because remotely controlled equipment is being used to a greater extent, manpower will be available for other tasks.

Unless such information is supplied to management well ahead of time, there is a risk of incorrect decision-making as management may not be familiar with the details of monitoring procedures and techniques. Increasingly, Administrations also require exact data about the total number of tasks dealt with and the resources used and hence the costs for determining the fees payable by various frequency user groups, and, should the need arise, as evidence in court.

The format of standard reports and statistics should be specified to ensure uniform data compilation and data comparability. However, this does not imply that the information should be distributed to all recipients in the same format. The information requirements of the head of a monitoring station are usually quite different from those of his superior (head of the Administration). The data therefore needs to be tailored to individual recipient's needs.

An analysis of statistical data often leads to further questions. It must hence be possible to carry out non-standardised, individual database queries without the need for additional programming.

For example, when identifying the most interfered-with service, the question automatically arises as to the primary source of the interference, which then leads to the question regarding the mechanism actually causing it. The answers to these questions may well be of importance in the context of radio equipment inspections, standardisation and market surveillance. Above all, they will indicate whether remedial measures need to be taken in relation to interfered-with or interfering equipment.

When designing a reporting system hypertext mark-up language (HTML) techniques should be taken into account. The key feature of HTML is its capability of handling different types of data such as text, pictures and graphs and presenting them in a unified layout by using a simple browser.

2.3.3 Working plan

When developing a working plan a distinction is to be drawn between tasks, which can and cannot be planned. While it is usually possible to predict the number of and time required for frequency occupancy measurements made for the spectrum management department, it is not possible to accurately predict the number of incoming interference reports and the time required to eliminate interference.

Planning is based on the previous year's working plan, taking account of any noticeable increase and/or decrease in tasks. Early consultation with the entities requesting such tasks is necessary to be able to accommodate changes. Changes in the regulatory framework affecting telecommunications also need to be taken into consideration.

In order for the working plan to be drawn up, all individual tasks need to be recorded on database to enable a statistical analysis of the volume of and time required for the tasks. The working plan must in any case leave scope for unpredictable requirements, and may need to be revised in the course of the year.

2.3.4 Resource planning

The working plan forms the basis for resource planning which constitutes another complex task involving a number of functional inter-relationships. A comparison with the previous year's working plan will indicate any increase or decrease in the demand for personnel, training, vehicles, and measurement equipment.

The automation of measurements in newer models and the integration of several functions in a single device may lead to a decrease in the number of staff required and to smaller vehicles. However, it should be borne in mind that such developments may call for additional training in order to improve the qualifications of the operators and maintenance staff.

The matter is further complicated by the fact that changes in telecommunications and technical measurement requirements emerge at such short notice that they cannot always be taken into account adequately in medium-term budgetary planning (3-5 years).

From experience the following advice seems relevant: when replacing equipment, special attention must be paid to those items of equipment for which spare parts are no longer available. Any equipment taken out of service should be physically removed from the monitoring station to avoid additional costs through maintenance and used storage capacity.

2.4 Types of monitoring station

The following three types of monitoring station are defined:

– fixed monitoring stations;

– mobile monitoring stations;

– transportable monitoring stations.

2.4.1 Fixed monitoring stations

Fixed monitoring stations are the central element of a monitoring system. In their coverage area they generally allow all measurements to be carried out, without limitations such as insufficient working space, inadequate possibilities to set up antennas and limited power supply.

There are two approaches for determining the location of a fixed monitoring station. It can be established either at a place where a minimum of interference from man-made noise and radio emissions is expected, or in highly populated regions where many emissions, including low-power emissions, can be received. The first approach is particularly suitable for HF monitoring stations because they are very sensitive to interference, and propagation conditions allow them to be located far from transmitter sites. For VHF/UHF monitoring stations the second option will be chosen as the propagation conditions do not permit such stations to be located far from transmitters. However, great care must be taken not to overload the receivers by strong signals, e.g. from broadcasting transmitters, and create intermodulation products. In practice, different requirements will make it necessary to find a compromise.

Details regarding buildings and property are contained in § 2.6. For the special requirements of satellite monitoring stations see § 5.1.

The main drawback of fixed, manned monitoring stations is the very fact that they are fixed and that, for financial reasons, they cannot be established in sufficient numbers. Therefore such stations are frequently complemented by remote controlled monitoring stations, which may be equipped with measuring receivers and/or direction finders, depending on their purpose. Advanced equipment not only allows stations to be operated by a remote operator, but also allows measurement programmes to be carried out automatically, with results being transmitted to the manned monitoring station at a later time or an alarm going off when certain limits are exceeded. A more detailed description of the remote control of equipment and automation of monitoring is given in §§ 2.5 and 3.6.

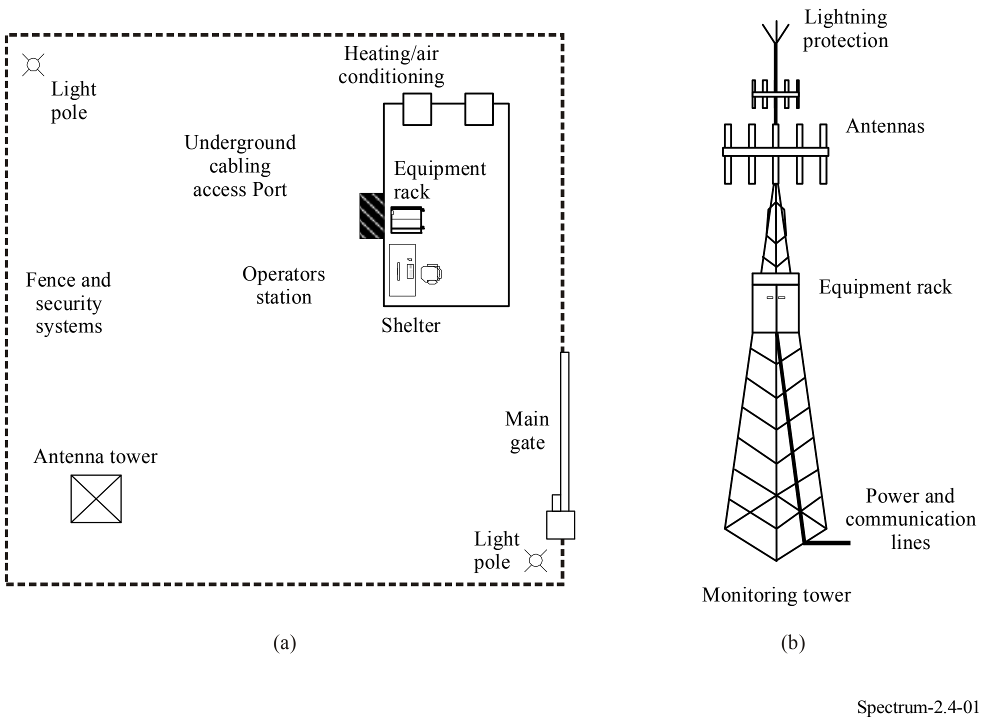
Figure 2.4-1 presents sketches of configuration for remote fixed stations, either with a larger container space that allows temporary local operation or without this space, allowing only remote controlled operation.

Furthermore, in some situation it might be difficult for administrations to find appropriate sites to install fixed stations, and solutions allowing minimum infrastructure work may be necessary.

For example, solutions allowing simple installation of a fixed station on the top of a private building, with very few infrastructure works and minimum nuisance to inhabitants, could be requested by administrations.

FIGURE 2.4-1

Fixed Monitoring Stations Diagrams, (a) Larger site with shelter for local operation (b) Smaller site with all equipment attached to the tower.



Such fixed stations have the following main characteristics:

– remote controlled;

– neither a building nor large shelter is required next to the mast;

– reduced power consumption for a whole fixed station.

2.4.2 Mobile monitoring stations

Mobile monitoring stations have the function to carry out all those monitoring operations where the low power of the transmitters, the high directivity of the antennas and the particular propagation characteristics make it impossible for measurements to be made by fixed stations.

This section deals with the special aspects of monitoring tasks due to the mobile application only, because the considerations being common to all siting, measuring, networking, data handling, etc. problems can be found in the appropriate chapters.

The design of mobile monitoring stations varies considerably according to their purpose, scope and operating conditions. The complexity of the equipment and its proper operation together with the problems of weight and power consumption usually necessitate a specially equipped vehicle capable of rapid movement. In some cases, the mobile unit must carry additional portable equipment for making specialized measurements in locations that are not readily accessible by the vehicle.

2.4.2.1 Navigation and positioning systems

Contrary to fixed monitoring stations, whose position remains unchanged, all mobile monitoring stations should be equipped with a positioning/navigation system so that their exact location can be determined any time and anywhere. This will ensure the location of the test system can be identified at the moment data is recorded. Moreover, if the mobile monitoring station is equipped with directional antennas and/or direction finders, it is also necessary to know the orientation (bearing) of the vehicle.

The accuracy required of the positioning information varies depending upon the goals of the measurement and the type of system being measured. For example, accuracy within 100 m may be sufficient for performing the coverage contours of a TV or radio broadcasting station. Accuracy within several meters may be required when mapping the signal coverage and quality of a "micro-cell" system.

Navigation systems like GPS and Global Navigation Satellite System (GLONASS) require no interaction from the operator and can be used in vehicles, on ships and on aircraft. Account should, however, be taken of the fact that these systems rely on the satellite's visibility and hence cannot determine the position of a vehicle in, for example, a tunnel.

To overcome loss of satellite navigation signals, systems are commercially available, which use a gyrocompass and a rotational transducer coupled to a vehicle's drive train to derive vehicle position. A combination of different systems may be appropriate.

All positioning systems on board should be equipped with a communication interface so that the positioning data can be stored together with the measured data in a process controller, e.g. field-strength values paired with coordinates and time.

Further details regarding the different navigation and positioning systems are given in § 6.1.

2.4.2.2 Vehicles

2.4.2.2.1 General considerations

Before a vehicle is selected, it should be established what functions the vehicle is to be used for and in what circumstances it is to be used.

The advantage of a general-purpose vehicle for all kinds of measurement task is that it can be employed for a variety of functions. There will always be special measurements, however, which cannot be carried out using a general-purpose vehicle. Measuring equipment that has been mounted in racks can be easily adapted to the requirements of a given task, provided there is sufficient space. The main disadvantage of a general-purpose vehicle is its large size, required to accommodate all the necessary apparatus and antennas, and the resulting difficulty in manoeuvring the vehicle in cities and off-road.

Specialized vehicles offer the benefit of being equipped with apparatus perfectly suitable for the measurement task to be performed, and of frequently being smaller than other vehicles. As they can only be used for special functions, however, they will often be parked idly in the garage.

If a vehicle is to be used for missions that last several days, it must be considered where the staff will sleep and wash. Where hotel accommodation is not provided, the vehicle will have to meet additional requirements, which will considerably influence its size and price.

A vehicle's crew generally consists of two persons: an operator and a driver/assistant who may have only basic knowledge of radio engineering. If only one person were on the vehicle, that person would have to drive the car and simultaneously handle the measuring equipment, a combination that should be avoided for safety reasons. Moreover, it has proved useful to have a second person as a witness. It may even occur that three people are on board, for instance when a new colleague is trained. This does not result in additional requirements, however, as most vehicle types have at least three seats.

2.4.2.2.2 Antennas for mobile monitoring stations

For monitoring antennas and their characteristics, please refer to Chapter 3. This section only describes the limitations and auxiliary attachments taking into account characteristics specific to antennas for mobile monitoring stations.

The types of antenna used in mobile monitoring vehicles will vary according to the frequency and the nature of the measurements carried out. They must also be adapted to the traffic conditions and the installation requirements.

The limitation on the antennas of a mobile monitoring station concerns the size and the number. Owing to the inevitable lack of space, the antennas will have to be small unless, as is sometimes the case, collapsible antennas are used which can be set up on the ground near to where the vehicle is stationed.

It must be taken into consideration during the measurements that the vehicle itself has a distorting effect on the characteristics of the antenna. A "clean" (unmodified) antenna pattern can only be obtained at a sufficient distance from the vehicle, or at a sufficient height above the roof when the antenna mast is extended. The problem concerns the polarisation as well.

Omnidirectional antennas can be used and are particularly suitable for general scanning of the spectrum. Directional antennas can be used in order to improve the directivity, the signal/noise ratio or to increase gain and thereby to reduce interference in field-strength measurements, as well as for direction-finding activities.

A wide variety of directional and direction-finding antennas are available from HF up to the GHz frequency range capable of meeting all the requirements of a mobile monitoring station.

As antennas for frequencies above 1 GHz have a small aperture, which may be in the order of down to 1° only, depending on the frequency, hydraulic supports may be needed for the measuring vehicle unless a separate tripod is used.

Directional antennas permitting a rough determination of the direction must be distinguished from the special direction-finding antennas available for the various frequency ranges.

The directional antennas however must be arranged to be easily steerable from the inside of the vehicle towards the direction of reception either by hand or by electric motor. The operator must be able to check the orientation of the antenna easily. For automatic measurements the position information must be available for remote control. A rotor, which can be controlled by the process controller, is recommended.

One method to rotate the antenna is to rotate its whole support system (mast or tower). A more useful alternative solution is to place a rotating unit in the head assembly of the tower. The remote control of the polarisation is also possible this way.

It must be possible to raise the antenna to a certain height above the roof to improve the sensitivity, reduce the influence of the vehicle upon the measurements and raise the antenna above any obstacles to wave propagation. This applies particularly to antennas intended for VHF and UHF reception. The height to which antennas can be raised should be 8 m at least.

For this purpose, special telescopic masts are used, consisting of a series of closely fitting steel tubes, which are driven upwards by a pneumatic or hydraulic system. Other widespread solutions use a wire-rope system driven manually or by an electromotor. When choosing the system the weight of the antenna must be taken into consideration along with the measurement method to be used (fixed-site measurement with the mast extended during a long period or measuring from point to point and extending the mast again and again). The mechanical construction of the antenna supports (masts) fixed into or onto the vehicle has an important role because of the heavy stress they must bear.

The instantaneous antenna height must be readable from inside the vehicle. To simplify height-dependent field-strength measurements, a mast steered by a process controller is recommended with the instantaneous antenna height being available at the processor.

Proper precautions must be taken when hoisting a mast of this height and allowance must be made for the weight of the mounted antenna or wind pressure, which might cause dangerous swaying of the support and so threaten its stability. **When raising the mast, care should be taken to see that there are no overhead electric wires in the vicinity**.

Apart from antennas for use on open ground, which can be dismantled, the antennas of a mobile monitoring unit are normally mounted on the roof of the vehicle, which must therefore be easily accessible by means of a small outside ladder, or better still, from inside the vehicle through a trapdoor in the roof to which easy access can be provided by means of an inside ladder.

To make the antennas easily interchangeable, it is wise to adopt some form of standard fixing system, for example of the bayonet type, which can be used for all the station antennas. The antenna must also have a suitable connector to which the down lead can be connected.

A single length of flexible cable can be used, which hangs down parallel to the mast and is wound up on a reel inside as the mast is lowered.

To avoid complications when making field-strength measurements, it is essential to choose a cable, which has the correct characteristic impedance and is of a low-loss type. The attenuation of each length of cable at the various frequencies must be known and allowed for.

Interference Considerations for Mobile Monitoring: In conducting mobile monitoring, one must consider the radio frequency environment, especially in RF environments where strong signals such as broadcast transmitters are present. The strong signals can generate intermodulation distortion within the monitoring or measurement system, making it difficult to make accurate signal measurements in such environments. This may be particularly important with radio direction-finding equipment installed in monitoring vehicles, since those systems often use internal amplifiers and active antennas, which are more susceptible to internally generated intermodulation effects from strong signals.

In these RF environments, there are usually no problems using systems which use passive (non-amplified) antennas. However, monitoring systems which use low noise amplifiers and/or active (preamplified) antennas are much more susceptible to intermodulation. In this situation two approaches can be used separately or together to assure that systems are not impacted by strong signals:

Dual mode Antenna

A dual-mode antenna can switch over from active (amplified) mode to passive (non-amplified) mode. It operates normally as an active antenna, and in areas where strong signals are present, it switches into passive mode, so its operation is not impaired.

Inserting a Band Rejection Filter

Installing a band rejection filter (BRF) for a portion of the frequency band where strong signals are present is another possible solution. The BRF is installed in front of the first signal preamplifier in a signal distribution system and can prevent strong signals from affecting the system. Of course, when a BRF is used, the corresponding frequency band blocked by the filter is not able to be measured. Also, consideration must be given to any effects the filter may have on gain, signal group delay, or other filter characteristics that may affect monitoring or direction-finding systems.

Intermodulation effects are discussed in more detail in Chapter 3.3 on receivers.

2.4.2.2.3 Requirements to be fulfilled by the vehicle

The choice of vehicles for mobile monitoring stations is governed by a variety of factors. Each individual purchasing authority will prioritise these factors according to their own needs, but as a minimum, the following should be considered before specifying vehicles.

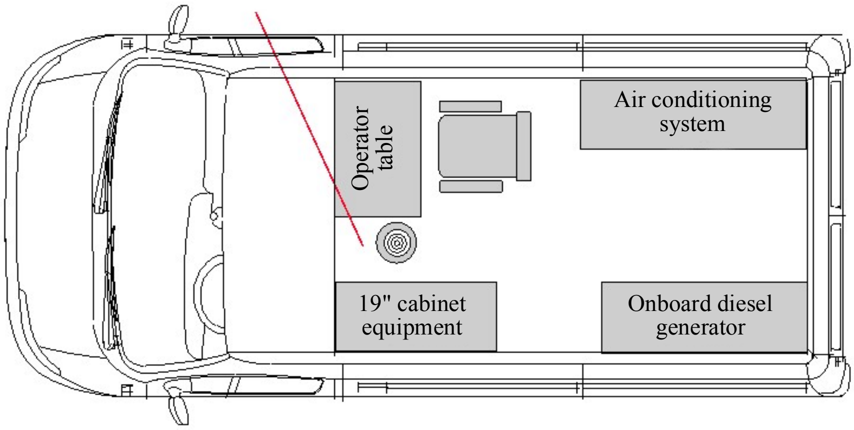
Mobile monitoring stations can be developed from a variety of commercial vehicles. A production vehicle with standard drive train components will offer the lowest life cycle costs. The availability of spare parts should be part of the vehicle specification. It is advantageous to procure vehicles from manufacturers who have local service facilities already in place. Vehicles intended for use also on unpaved roads and off-road will need four-wheel drive and sufficient road clearance.

There must be sufficient leg-room for both the driver and the operator. During measurements carried out on the move, the operator should sit facing forward. In any case, the vehicle will have to contain everything needed to ensure that the measurements can be carried out easily. The equipment must be arranged in a handy way so that personnel are able to carry out measurements with minimum movement. The operating equipment must be near at hand. The dimensions of larger vehicles should allow the operator to stand upright.

A bus-type structure as shown in Fig. 2.4-2 without a partition between driver's cabin and operator's room is preferable so that the driver, who must often work in close conjunction with the operators while the vehicle is on the move, can have direct contact with the operator's room. This also gives operators a view of the direction in which they are moving and gives the driver a chance to go to the laboratory part without actually having to get out of the vehicle.

FIGURE 2.4-2

Interior of a mobile monitoring station



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Windows in the operating area of the vehicle should be included to provide natural lighting for the operators and to give them an all-round view. Curtains or shutters should be provided, however, so outside light can be excluded in those cases where it interferes with viewing of displays such as spectrum analyzers, computer monitors or televisions.

Great importance should be attached to safety. Every seat should be equipped with a safety belt and equipment must be securely fastened so that it cannot shift and cause injury while the vehicle is in motion or in case of a minor collision. If there is a seat for the operator in the rear of the vehicle, it must be possible to lock that seat. The roof of large vehicles should be fitted with a folding safety rail to protect staff from falling down.

The interior of the vehicle should be equipped with equipment mountings to secure the electronics and to offer some protection against shock and vibration. Equipment may be mounted in standard 19 inch racks, or by special rails and suitably shaped fasteners. This latter may result in a more flexible solution. Whatever the mounting technique, equipment should be easily removed for repairs. Power and signal leads should be properly dressed behind the equipment to the greatest extent possible, to reduce clutter in the work area and to enhance operator safety. Equipment layout should be studied and planned so that the controls and displays used most frequently by the operators are in the most convenient locations.

The body of the vehicle, regardless of design, must have adequate thermal insulation to ensure both proper conditions for the equipment inside, and comfort to the crew. Good thermal insulation will also typically serve as acoustic insulation. The normal vehicle heater and air conditioner will be satisfactory for the driver's comfort, but larger units should be furnished for the equipment and crew compartments. Propane, petrol, or electrical heaters can provide additional heating capacity. Air conditioning of the vehicle itself and of extra cabins, if necessary, can be powered by the vehicle's electrical system, by external mains input, or by an on-board generator.

The vehicle should be fitted with sufficient interior lighting so that the operators may work without eye strain. Low-voltage fluorescent lighting can be powered by the vehicle's electrical system. Normal incandescent or fluorescent lighting can be powered by an on-board generator or by external mains power where available.

A vehicle's weight is the most critical factor in vehicle selection. A passenger car (estate) has the advantage of being highly maneuverable, able to pass through narrow streets, and allowed on squares and streets that are closed to trucks. The vehicle's maximum load capacity of some 500 kg for staff, measuring equipment and additional power supply systems together with its small interior considerably restricts the range of possibilities for its use. However, vehicles of this type have been successfully employed for searching mobile sources of interference or illegal transmitters. The direction-finding antenna can be disguised as luggage, and antennas of a lower sensitivity can even be completely integrated into the roof so as not to be recognized.

Vehicles with a maximum total weight of 2.8 tonnes, which are still considered passenger cars under the road traffic regulations of many countries and have a load capacity of more than 1 000 kg, offer much more flexibility. They can be easily used as universal vehicles, fitted with measuring equipment, mast and direction finders, and offer space for additional antennas and a portable power generator in the rear part of the vehicle. The interior may be formed into a complete mobile measuring station but it often suffices to have an occasional version of vehicle in which the instruments are interchangeable. However, the power supply, the computer access (e.g. IEC bus), the position determination system, the measuring antennas with their movable supports, and the appropriate means of communication must be ensured in both cases.

Large trucks will be chosen for long-term, quasi-stationary measurements requiring a powerful built-in generating set, or if it should be possible for the staff to stand upright or to sleep in the vehicle. A truck is also required where dish antennas with very small apertures, which require a solid flat platform, are used; in this case the truck should also have hydraulic supports.

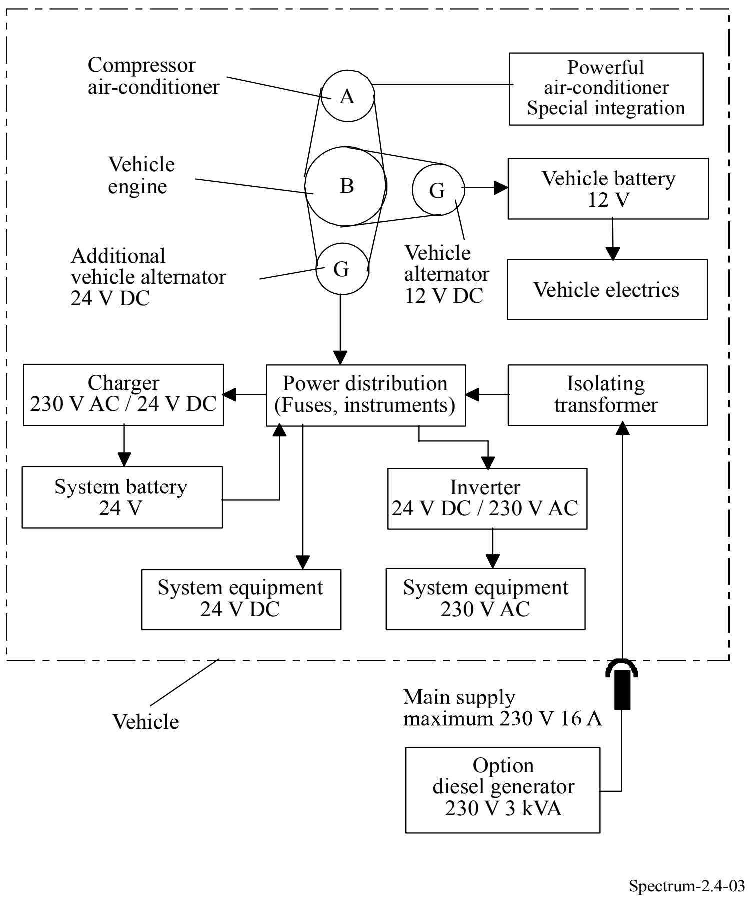
Even in full load conditions the vehicle should be able to reach a speed of at least 80 km/h on level roads so as not to be an obstacle to traffic. This requires adequate motor power. If the manufacturer offers a reinforced clutch it should be used, in order to prevent an early failure of this part as a result of the mostly heavy load.

2.4.2.2.4 Power supply

A variety of power sources for equipment in mobile stations are available. A well-equipped mobile station will use at least two sources for redundancy. An example is shown in Fig. 2.4-3.

FIGURE 2.4-3

Example of a power supply system of a general-purpose vehicle



The power consumption of modern equipment has eased the mobile unit power problem considerably. As examples, the following typical power consumption figures are for commercially available equipment in the categories cited in the following table. This equipment might be available as separate parts or as a combined system that includes several items, with combined power usually lower than the sum of each part, e.g. a signal processing system consisting of radio frequency distribution, receiver(s) and processor might demand as little as 200 W:

Equipment type	Power consumption (W)
Spectrum analyzer	150
Oscilloscope	120
Signal generator	150
DF	250
HF receiver	80
VHF/UHF receiver	100
Industrial personal computer (PC) with colour display monitor	200

Electronic equipment has also become lighter and more compact. These combined size and power features allow a great deal of capability to be included in a mobile unit, which generates its own power. In many cases, however, equipment must be operated remotely from the vehicle. Such equipment must be capable of battery-powered operation. There is modern test and communications equipment in almost all categories (analysers, oscilloscopes, receivers, signal generators, direction finders, computers, etc.), which can be operated on battery power. Most such equipment can also be operated inside a mobile unit on a.c. power.

Compact gasoline-powered generator sets with up to at least 2 kVA are available which can easily be fitted into the rear compartment of a cargo van. Some electronic news gathering vans include two such generators. Thus, power consumption should no longer be the critical factor in equipment selection for mobile units.

Batteries or secondary cells

Power supply from batteries or rechargeable batteries is the only solution for portable equipment for use in remote places, which are inaccessible to vehicles. This situation often occurs in the case of field-strength measurements.

Alternators coupled to the engine – Inverters

Since most of the electronic equipment employed for measurement purposes is designed for direct supply with a.c. current from the mains at 115 V/60 Hz or 220-230 V/50 Hz, the vehicle must be equipped with a generator capable of providing an adequate supply of power with these characteristics.

A solution is to use an inverter supplied from a battery in the vehicle. An auxiliary battery of higher capacity may also be used if this is needed to ensure the requisite independence of operation. This, however, raises additional problems of maintenance and periodic recharging.

The high efficiency, operating reliability, silence, high stability of both the frequency and the voltage generated and the absence of electrical interference which can be obtained from a modern inverter system using entirely solid-state elements suggest that these are the most suitable devices to use at least up to the 500 VA limit.

For higher outputs, the size and weight of the batteries required guaranteeing the necessary independence from the mains supply and the inevitable maintenance difficulties involved detract from their utility as power sources for mobile monitoring stations.

Generating sets

Mobile monitoring stations generally need a power supply of more than 500 VA. Current is required not only for the electronic equipment, but also for the ancillary equipment: small electric motors, fans, lighting, not to mention radiators, air-conditioning plant, etc. The connected load of a medium-sized mobile monitoring station can easily reach, and in some cases even exceed, 2.5 kVA. This load may be required for many hours, and sometimes days, of independent operation. Under these conditions, the most convenient solution is a generating set driven by an internal combustion engine.

The drawbacks common to all low-power petrol engines are: noise, tendency to vibrate and, sometimes, to cut out, owing to their operating characteristics and weight distribution problems. Moreover, the ignition system can easily cause electrical interference if not fitted with adequate suppressors. Therefore diesel engines should be preferred.

The installation of a generating set on the vehicle calls for particular care to prevent its noise reaching the cabin and becoming a nuisance to the operators to the detriment of measurement accuracy. Normally, it is housed in a fully sound-proofed compartment at the side of the bodywork and secured by an elastic suspension system. Access to the set for the purpose of inspection, maintenance and starting is from the outside by means of a flap, which must be very carefully fitted so as to prevent noise leaks.

When the generating set is intended for intermittent use only, for example, to operate the air-conditioning plant from time to time, to recharge the batteries during a long series of measurements, or to cover temporary power peaks, it may be advisable not to install a generating set on the vehicle but to make use of a portable model which can, if necessary, be placed at some distance from the vehicle, with a cable connection so that its operation will cause no serious disturbance.

Mains supply

Even when a mobile monitoring station can be equipped with an independent power source, it is always preferable to take advantage of direct supply from the mains whenever possible. This should be done in order to keep the auxiliary lighting and air-conditioning plant in good running order, or, of course, to recharge the service batteries and the built-in instrument batteries through their respective charging devices.

Evidently, connection to the mains replaces the vehicle-borne generators since both power sources obviously cannot be used in parallel. The electrical equipment of the vehicle must necessarily be designed in such a way as to make it mechanically impossible to connect both systems at once.

There should be an isolating transformer on board to avoid the inconvenience of having to earth the vehicle and measuring instruments. Any mains outlet should include a suitable automatic switch set for the maximum current needed.

2.4.2.2.5 Example of a vehicle concept

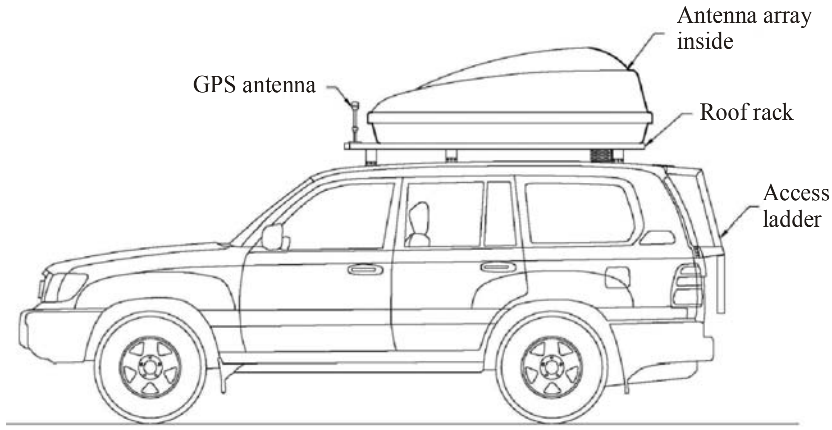
The vehicle concept should be prepared taking account of the above considerations, the volume of tasks (see § 2.3.4) and the number of sites; the financial resources available will generally necessitate compromises with regard to the concept's realization.

Although the vehicle requirements of various countries may differ, several examples of vehicles for mobile monitoring stations are illustrated in Fig. 2.4-4.

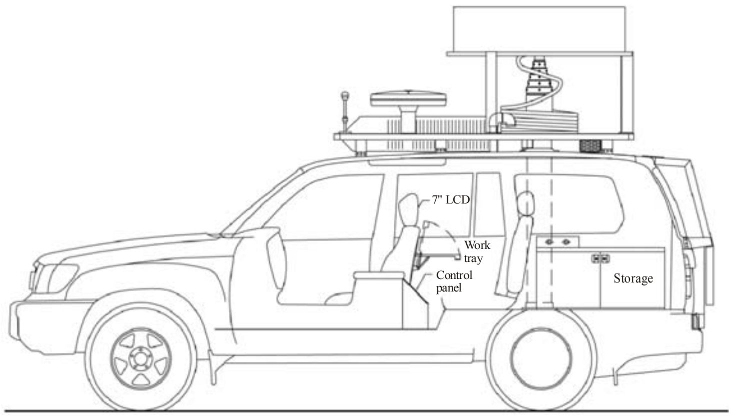
The vehicle types in this Handbook are classified into three types, as described on the following items:

Type 1: These vehicles are passenger cars (or estate wagons) used to carry passengers, equipment and antennas. The antenna array used for DF and monitoring is mounted in an unobtrusive roof-top carrier mounted directly to the luggage rack on the roof of the car. The monitoring and DF equipment is mounted in the luggage area at the rear of the car, and the operator can be seated anywhere in the passenger area of the car and control the equipment from his laptop. This type of station can operate while in motion or stationary. The measurement results are stored on the hard drive or flash memory of the laptop, and can be downloaded to the fixed station database when the car returns to its home station at the end of the measurement session. Alternatively, with a communications connection the data can be transferred directly to the central station. Typically the monitoring station can be operated locally, but it can also be remotely controlled by the central station.

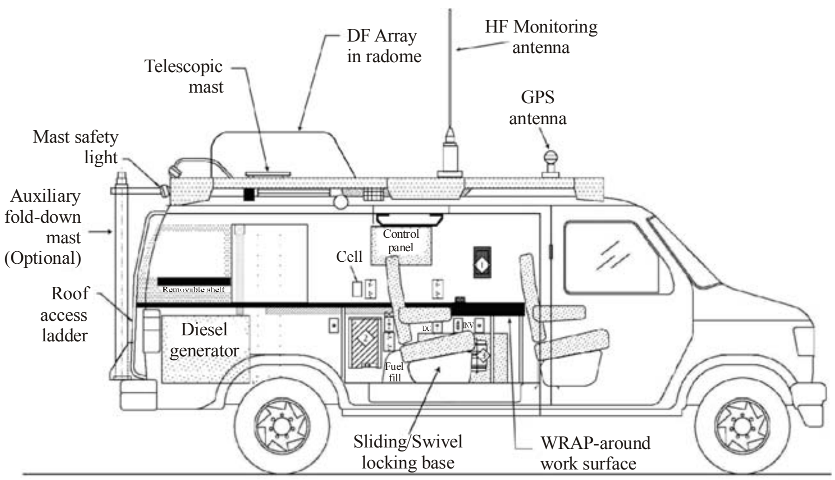
FIGURE 2.4-4
Examples of mobile monitoring stations



Type 1



Type 2



Legend: ① Breaker box ② 70 APH battery charger W/temp. probe ③ 1 800 Watt inverter

Type 3

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A printer can also be provided inside the car. Almost any passenger car or estate wagon can be used as a Type 1 vehicle, especially if it is factory equipped with a roof rack. Because they look like ordinary passenger cars and do not attract attention, these types of mobile stations are especially useful when searching for illegal transmitters.

Type 2: These are heavy duty 4 x 4 utility vehicles to be used on difficult road conditions where neither Type 1 nor Type 3 vehicles can go (desert areas, mountains, etc.). They contain equipment capable of both monitoring and direction finding while in motion or stationary. These vehicles are equipped with a telescopic mast compatible with the difficult road conditions the vehicle is used for and the compactness of the equipment compartment. A typical mast can then extend the antenna used for monitoring and DF up to approximately 6 m above ground level. The operator can be seated anywhere in the passenger area of the vehicle and can control the equipment from a laptop. With the mast down, this type of station can operate while in motion or stationary. During normal operation, the electrical power is provided by the high current alternator mounted on the engine of the vehicle, and environmental control is provided by the on-board vehicle air conditioner and heater. There is generally not enough room for permanently mounting an auxiliary electrical generator inside the vehicle. However, these types of vehicles can be equipped with an external generator mounted on a special purpose platform at the rear of the vehicle. This vehicle type is the standard vehicle for rural and mountain area operations where access would be difficult for passenger cars or large vans.

Type 3: These are heavy-duty utility vans. They are intended for universal use and are therefore equipped with the same type of monitoring and direction-finding equipment as the Type 2 vehicles, including a mast which can be raised up to approximately 10 m above ground level. An optional mast can be added to raise additional monitoring antennas if needed. When the mast is not raised, the Type 3 vehicles can operate while in motion as a homing station. In addition, the auxiliary generator is built into the vehicle and properly shielded for noise and electromagnetic interference. Type 3 vehicles use a.c. power, either from the on-board generator or from the mains when vehicle is stationary. This vehicle can easily accommodate one passenger in the front and 2 or 3 operators in the back. This vehicle type is the standard vehicle of the monitoring service, primarily used for investigating interference. It may also accommodate transportable/portable equipment to perform monitoring and direction finding tasks equipment to be used outside the vehicle to reach an area inaccessible to vehicles.

Other vehicle types, of course, may be used. Examples include trucks, equipped with a shelter that provides space for more monitoring positions.

For the sake of completeness, the vehicles of the radio inspection service should also be mentioned here. This service might uses Type 2 vehicles equipped with a mast but not direction finders. These vehicles are mostly used for investigating interference to broadcasting transmissions and for inspecting radio installations. For this reason they have special television broadcasting antennas, but they also cover the whole frequency range up to 3 GHz. Portable equipment for the inspection of radio installations is also available.

2.4.2.3 Airborne monitoring stations

The use of airborne radio monitoring stations instead of land mobile monitoring stations allows accomplishment of the monitoring tasks with some advantages as well as disadvantages, as shown in Table 2.4-1.

2.4.2.3.1 Operations of airborne monitoring stations

General purpose procedures

Flight missions should be duly scheduled and well planned. This implies that some coordinating activities should take place following the general guidelines listed below:

a) Request for flight mission, indicating duration

Monthly or weekly schedules can be fixed only when the activities to be performed and the relative task-time are known, together with aircraft and crew's availability. The term "aircraft" here comprises aeroplanes, helicopters, airships, etc.

TABLE 2.4-1

Advantages and disadvantages of airborne radio monitoring stations

Advantages of air mobile monitoring	Disadvantages of air mobile monitoring
1. Quick exploration of broad geographical areas 2. Opportunity to obtain geographic direction using one station by obtaining several lines of bearing from different locations 3. Better opportunity to perform measurements due to line of sight 4. Rapid location of emergency beacons, interferers and Earth stations which sometimes cannot be detected from ground 5. All means of measurement of aeronautical flight aid transmissions	1. Cost of flight 2. Limitations in weight, power, size, cooling 3. Limited by weather, winds 4. Limited flight time due to fuel limitations 5. Requires accurate azimuth and depression angle, fast DF capability and antenna tracking 6. Frequency compensation for relative velocity may be needed

b) Flight activities coordination

Aeronautical authorities responsible for air spaces where radio monitoring should take place, together with those in charge of aircraft and crew logistic support, must be notified in advance. Flight procedures required for monitoring may in fact require some special coordination, especially in heavy air-traffic areas. Similarly, ground fixed and mobile radio monitoring stations should also be taken into account during joint coordinated activities.

c) Pre-flight activities

In addition to operational planning and preparation of flight mission (flight plan, aircraft checkout, fuelling, etc.) data obtained from measurements made in previous missions, or available from other sources, should be carefully examined in order to select the functions and the automatic procedures of the monitoring equipment to be used during the flight.

Operational procedures

Monitoring flight mission implies different operational procedures depending upon the requested activities to perform. Such procedures must be carefully planned before each mission.

For instance, it is likely that during monitoring missions, the aircraft will have to fly on predetermined paths, such as loops, at suitable speed and altitude.

Mission altitude can determine the area to be monitored, while speed influences the accuracy of the direction-finding measurements. Moreover, as regards detection of mobile interfering radio signal sources, it could be necessary to perform position by homing the source at low altitudes and speeds.

2.4.2.3.2 Applications – Examples

Mobile measuring systems installed on board an aircraft, an airship or a helicopter is well suited to plot the radiation pattern of antenna towers in both the horizontal and vertical planes. It may also be necessary in a few cases to use a helicopter or an airship fitted with measuring equipment suitable for locating sources of interference that cannot be identified by ground monitoring facilities as earth stations or leakage from cable TV, for analysing phenomena that may result from closely spaced high-power VHF transmitters and for measuring antenna radiation patterns.

In some situations in large cities where mobile ground facilities are "obscured" by obstacles such as high-rise buildings which mask the source of the signal or produce numerous reflections, a properly equipped helicopter or airship provides a high-level of precision in positioning and/or organising the movements of facilities on the ground.

It must be ensured that:

– the height and the distance (or the navigation data, as appropriate) can be registered;
– the antennas are fixed in a reliable way;
– the measuring instruments are installed suitably;
– the necessary data can be collected;
– the instruments are supplied with power during the flight.

2.4.2.3.3 Aircraft operational requirements

Taking into consideration the general needs of spectrum monitoring activities and measurements to be performed the operational requirements of an aircraft housing an airborne monitoring system should be as follows:

– flight capability for all weather operations;
– manoeuvrability and good stability at low speed/altitude;
– adequate load capacity in order to accommodate all necessary equipment and monitoring staff.

2.4.2.3.4 Aircraft technical requirements

Technical characteristics required for an aircraft housing an airborne monitoring system should satisfy the following criteria:

– autopilot facilities should permit surveillance operations by pre-planned procedures (e.g. grid or circular patterns);
– avionics navigation equipment on board should allow full instrument flight operations; an independent instantaneous aircraft position and altitude computation system should be interconnected to the monitoring processing unit;
– range should be possible to operate for at least 2 h in the area under observation in full load conditions, considering altitude levels even below 6 000 ft (1 800 m);
– speed range large enough to allow both quick transfers and homing procedures at low altitudes.

2.4.2.3.5 Antennas

For practical airborne applications, the antenna array considerations dominate the engineering effort and the cost integrating the DF system into the aircraft. These issues begin with determining antenna locations that are physically compatible with the airframe, engineering the antenna hardpoints into the aircrafts to carry the mechanical loads generated by the antennas, impact of the antennas upon the flight characteristics of the aircraft, airworthiness certification of the aircraft, and peripheral issues such as antenna de-icing requirements. As a result, simplification of the antenna array yields significant reduction in the complexity of the system integration.

a) Passive airborne antenna systems

High performance airborne DF systems using passive antenna arrays have been integrated with aircraft that range in size and capabilities that span the full range of aircraft used in multi-mission roles. The scimitar shape for the VHF antennas adds effective antenna length without increasing the protruding length from the aircraft surface. The system operates principally with signals that are approximately vertically polarized. As a result, the antennas of choice are usually either monopoles or dipoles.

b) Active airborne antenna systems

Active antennas offer extremely wide bandwidth and antenna physical size reduction while maintaining constant sensitivity compared to passive antennas. Active antennas have become practical with the newer generation active devices, primarily field effect transistors (FETs) that permit active impedance transformation while maintaining high circuit dynamic range.

2.4.2.3.6 General requirements for on-board systems

The whole airborne systems set-up must be designed and implemented very carefully in order to ensure maximum safety and reliability of the aircraft. It is important to mention that equipment used in aeroplanes must comply with both ICAO and national regulations.

Some of the parameters, which can directly influence flight operation, are:

– weight and location of equipment on board, so as to avoid any upset of aircraft flight stability;

– structural strength and stiffness of the aircraft after modifications;

– aircraft aerodynamics following installation of the monitoring system antenna;

– thermal and electrical power balance.

The above-listed parameters show the importance of accurate cross-checking, to be performed in order to improve the system reliability and limit operating cost.

Also, simplified maintenance (modular design and built-in test system) and possibility to remove and substitute faulty equipment easily for laboratory checks and calibrations, is the normal procedure in the aeronautical field; that philosophy of maintenance requires adequate availability of spare parts and equipment subsystems.

2.4.2.3.7 Aircraft radio monitoring station set-up criteria

The main station subsystems should be based on the following criteria:

a) Automatic position determination system

The aircraft must be able to determine its own position in order to perform signal source position fixing without any special external auxiliary navigation systems beyond existing radio aids. Its navigation system must therefore be self-sufficient.

Moreover, by coupling the navigation system (e.g. inertial and/or satellite system, multi-distance measuring equipment (DME) technique) to the radio-monitoring processing unit, it will be possible to compute the position of radio signal sources for all possible headings of aircraft. However, an independent position and altitude computation system in conjunction with the monitoring processing unit is of advantage.

b) Efficient man-machine interface

Aircraft radio-monitoring operations generally involve limited task-time and minimum personnel on board. Therefore monitoring equipment must be capable of performing programmable and automatic measuring procedures, reserving manual operations only for very specific tasks.

In any case, data presentation should permit immediate interpretation so that an instinctive cognisance of current aircraft position should be possible for the monitoring staff in flight.

2.4.2.4 Maritime monitoring stations

The marine environment presents one advantage as well as unique equipment problems that must be considered. The primary advantage to marine mobile monitoring is that the area surrounding the marine vessel is generally very quiet from a radio frequency point of view. Problems include the corrosive atmosphere, multipath due to sea state reflections of radio energy, antenna mounting, and radio frequency ducting over warm bodies of water.

A moist corrosive environment will dramatically shorten the life of electronic devices if not specifically designed for marine use. This usually requires sealed controls, filtered housings and fungus treatment. Alternatively, equipment can be placed in a conditioned environmental location. To prevent moisture build-up a very small amount of heat, often in the form of a small nightlight or leaving the equipment turned on, has a beneficial effect. Left unattended in an unconditioned area electronic equipment not specifically designed for the environment will corrode and develop electrical breakdowns.

Electrical grounding (Earth) is often difficult to achieve on board marine vessels.

Direction finding equipment must be specially installed and calibrated for the vessel. Mobile, carry on – carry off, gear is not recommended. The direction finder antenna should be placed at a high point on the vessel and, to the extent possible, clear of surrounding obstructions. A particular problem resulting from the antenna being at the top is that nulls occur in the vertical radiation pattern at small elevation angles and wavelengths that correspond to about twice the mast length. Changing the antenna position will improve reception only in part of the frequency range. To solve the problem, it is expedient to mount two antennas at different heights and switch between them as required. The actual calibration should be performed by swinging the ship a full 360°. Satellite navigation and North references are needed to obtain accurate lines of bearing and fixes.

While motion of the vessel can cause problems in instantaneous direction-finding, the effect of pitching and rolling of the vessel can be compensated by determining average line of bearing.

Multipath of radio frequency signals over water is affected by the sea state. While even smooth water will cause multipath difficulties, the multipath effects increase as the sea state worsens.

Ducting is a phenomenon in which radio frequency energy is trapped in, or reflected by a "duct" in the atmosphere. Over warm (above about 20° C) bodies of water, ducts tend to be formed and increase in strength when the water and air temperature increases. During marine mobile monitoring, the effects of ducting can cause failure to intercept signals, and also to intercept very distant signals which proceed in the duct with very little attenuation.

2.4.3 Transportable monitoring stations

Transportable monitoring stations combine some of the features and advantages of fixed stations with some of the features and advantages of mobile stations. They can have larger aperture antennas that are generally available to fixed stations and they can offer larger operator work areas than are available in mobile stations, yet they can be redeployed to different locations as needed by the monitoring service.

The equipment for transportable stations is typically installed inside of an equipment shelter, as described in § 2.6.2.2. Shelters may be small, allowing space for just equipment that may be remotely controlled, or may be larger, allowing work space for one or several operators. VHF/UHF antennas for transportable stations may be installed on a transportable mast so they may be elevated several meters above the ground.

Transportable stations may include HF DF capability, using transportable antennas that are deployed on an adjacent field. These antennas allow the transportable system to provide high aperture and therefore highly accurate DF results. The antennas can then be removed when it is desired to move the transportable station.

A transportable station may be placed in a particular location, such as on the ground or on the roof of a building, for an extended period of time, and then may be moved to another location as required by the needs of the monitoring service. Such a station does not need a dedicated vehicle as does a mobile monitoring station; a vehicle or other means of transportation is only needed when it is desired to move the transportable station from one location to another.

Typically this type of monitoring station can be operated local but also remote controlled by the central station. Via communication connection the measurement data can be transferred directly to the central station.

2.4.4 Additional support equipment

To provide greater flexibility on monitoring activities, most monitoring stations, specially mobile, may also be equipped with portable equipment, such as spectrum analyzers and small sized measurement antennas, portable receivers and handheld directional antennas. Their moderate weight makes it possible to carry them walking to locations inaccessible to vehicles, e.g. to the interior of a building or to the roof of a house.

Such instruments are necessary to determine the exact location of interference, or to verify compliance of radio equipment with the relevant technical parameters on site.

Portable apparatus can be found on the market for field measurements in the frequency range 150 kHz to 30 MHz, with loop antennas directly connected to the receiver input. The accuracy can be better than ± 2dB and the apparatus is quite suitable for monitoring purposes with the object of checking whether the Radio

Regulations are being obeyed. However, its sensitivity is inadequate for operations involving the measurement of very low field strengths such as those of spurious emissions from a transmitter; for these operations, narrow-band apparatus of higher sensitivity must be used.

Portable apparatus operating between 20 MHz and 3 GHz or more is available. This portable apparatus can be equipped with a small panorama display and small broadband antennas, which are well suited for portable applications. However, if more sensitive and accurate measurements are required it is essential to use a more sophisticated monitoring receiver or spectrum analyzer.

2.5 Remote control of monitoring equipment

A modern spectrum monitoring system may consist of a number of attended and unattended fixed and mobile monitoring stations. Automation and remote control of networked monitoring stations considerably improves the efficiency of the whole system, such as allowing resource sharing between different operators and advanced functions such as the automatic location of transmitters. The monitoring equipment in vehicles can be controlled by operators in a fixed control centre and manned monitoring stations. Remote control of equipment can also be found in vehicles to allow front side passenger access to equipment installed in the rear.

Details on automation of monitoring are contained in § 3.6 where its limitations and an example of a practical realisation are given. This section deals with the specification of the communication architecture.

2.5.1 Remote modes of operation and exchange of information

A remote monitoring station should be able to be operated in different modes.

On-line control of a station enables an operator to operate the remote station in a similar way as if it were a local station. It may involve monitoring of the audio signal and data exchange for the control of the equipment. To establish the link between the station and the operator may take some seconds (up to 1 min e.g. for GSM), but afterwards the operator should have continuous and real time control of the station.

This mode is particularly suited for the investigation of interference problems and for the identification of unauthorized users.

Although the use of commercial general purpose remote desktop software might be useful for remote maintenance tasks, it is not generally a good alternative as a remote operation tool, since it has a higher communication bandwidth demand when compared to a dedicated server-client architecture that is properly implemented.

In *batch or scheduled mode* it is possible to load a set of parameters for an automatic measurement to be performed during a given period and to retrieve the results later (file transfer). Batch or scheduled mode does not require a permanent link but needs data transfer capability at the beginning of the task as well as at the end of the task.

This mode is particularly suited for tasks such as frequency occupancy measurements. However, depending on various factors, e.g. the duration of the measurements, the amount of data to be transferred may be very high. Therefore pre-processing and other data reduction methods may be applied before the data transfer.

As scheduled tasks may occupy a monitoring station for a long period, it is necessary that the system allows interruption and re-starting of a batch or scheduled process for higher priority tasks, e.g. interactive direction findings.

2.5.2 Network architecture and communication lines

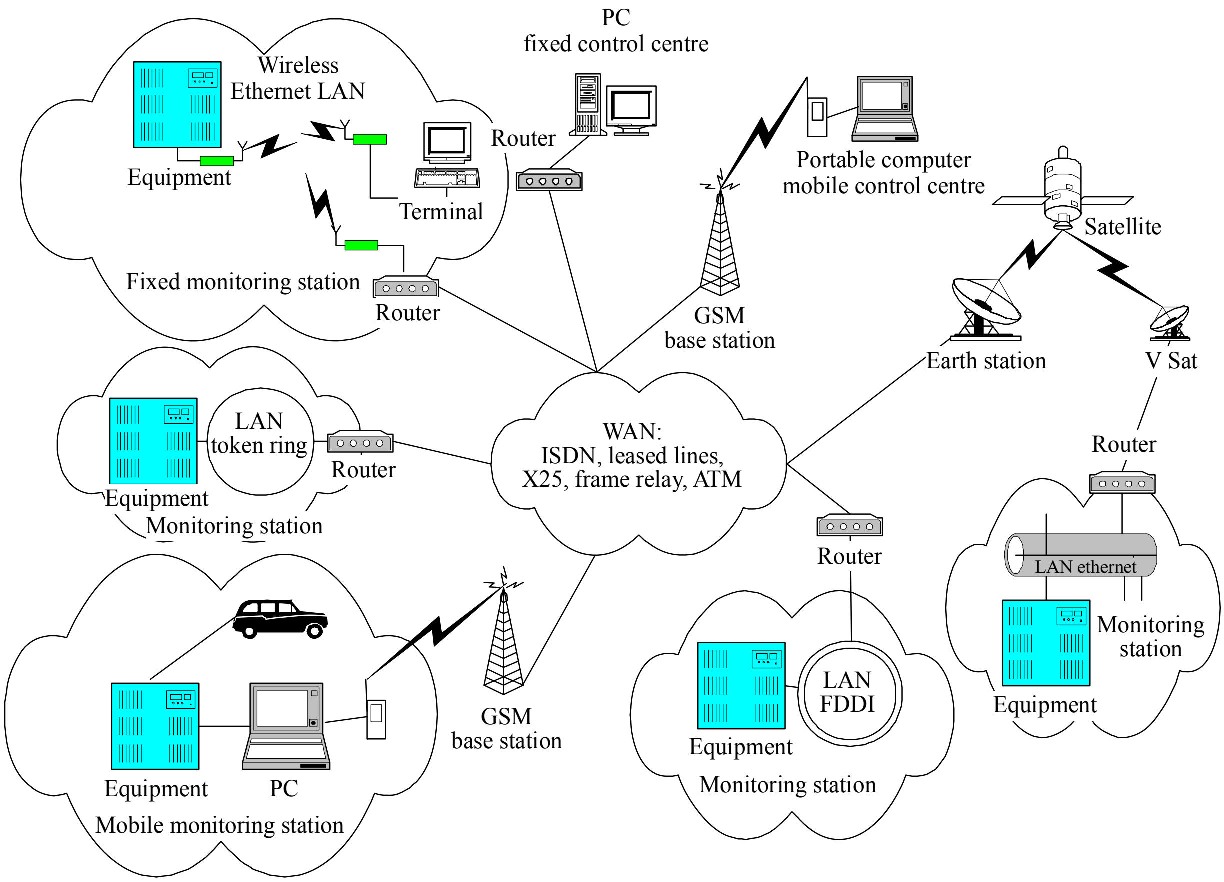
The choice of the network architecture depends on several requirements in terms of set-up or access time (in case of switched networks), data rate, time delay, link availability and link quality. The nature of the information to be transferred, which can be digital or analogue, is also important. As modern equipment usually also digitizes analogue data such as audio, almost all data transfer will be digital.

The design of the network architecture has to take into account two network levels (see Fig. 2.5-1). The first level is the interconnection of different devices such as receivers and analyzers with a computer on a local basis (via direct connection to equipment or connection through a local area network, called a LAN).

The second level is the wide area network (WAN), which enables the networking of distant sites and mobile monitoring/DF stations to access other DF stations for the purpose of location. Using a star-shaped network structure on the second level, all monitoring stations have a direct link to the control centre which improves call setup and latency times during data transfer.

FIGURE 2.5-1

Example for a network architecture



WAN: usually made up of a number of LAN's connected together using ISDN, X25, frame relay, ATM network.

Spectrum-2.5-01

2.5.2.1 Interconnection of equipment on a local basis

Almost all modern monitoring equipment such as receivers and direction finders can be linked to a personal computer via some kind of interface.

The formerly-used RS232 interface, used for direct connection of some equipment to PCs, offers only limited data rates of up to 115 kbit/s. Furthermore, this interface is no longer supported by most standard PCs and laptop computers and is therefore not favourable as a means to remote control monitoring equipment.

IEEE488 (commonly known as GPIB or IEC bus) is an equipment connection standard still used frequently in older monitoring equipment. It allows connection of up to 15 devices and data rates in the range of 1 Mbit/s to 8 Mbit/s at a maximum cable length of 5 m. However, special interface hardware is required for computers to enable this type of connection.

USB is a local connection standard implemented in all modern PCs and laptops, offering data rates of up to 240 Mbit/s (USB 2.0). However, this interface is not commonly implemented in monitoring equipment for remote control.

The most common interface present in all PCs and widely adopted by manufacturers of monitoring equipment is Ethernet/LAN. Depending on the network architecture and cables used (coaxial cable, twisted pair, or fibre-optic cable), data rates from 10 Mbit/s up to 1 000 Mbit/s can be achieved.

2.5.2.2 Long distance telecommunication network

Wide area network (WAN) access can be realised via fixed telecommunication networks or via radio (terrestrial and satellite). The actual solution will depend on the technical requirements, the availability of a specific system and its costs.

2.5.2.2.1 Fixed telecommunication network

A fixed telecommunication network is appropriate for fixed, transportable and in special cases also for mobile monitoring stations (if operated quasi-stationary).

Analogue public switched telephone network

The public switched telephone network (PSTN) network is characterized by a call set-up time of some seconds, which may be a factor for monitoring control. Achievable speeds are adequate for basic equipment control (tuning, setting parameters, uploading and downloading monitoring settings, etc.).

Analogue leased lines

Analogue leased lines are permanent links, which have characteristics similar to that of PSTN, except for a null call set-up time. Cost is usually relatively low, and dependent on distance.

Digital leased lines

Digital leased lines are digital point-to-point links, which are generally available at speeds from 56 kbit/s on. Such links may not be available in some regions or in some countries. Digital leased lines can offer large capacities, low time delay and good reliability. Cost is usually relatively high, and depends on data rate and distance.

Integrated services digital network

Integrated services digital network (ISDN) is a digital switched telephone network providing two B channels of 64 kbit/s each as well as one D channel of 16 kbit/s. B channel cost is usually duration and distance dependent. Call set-up time is typically less than 1 s.

X25 public packet network

X25 public packet networks offer a permanent or semi-permanent data link, with a cost, which is usually volume dependent and distance independent. It is also well suited for sporadic short messages.

Frame relay network

A packet network service, relying on the data integrity inherent in digital transmission to speed up transmission (up to 2 Mbit/s); it was created to avoid long time delays in X25 networks.

XDSL (ADSL, VDSL)

Digital subscriber line (DSL) technologies (DSL, ASDL, VDSL) allow digital data to be added to existing copper pair cables used by PSTN circuits. The DSL signalling runs in parallel with voice calls on the PSTN line pairs, allowing an increase in the data carrying capacity of existing cables.

ATM (asynchronous transfer mode) network

ATM technologies are capable of handling multimedia information including voice and video data with its associated time constraints, at very high speeds (25 Mbit/s-2.4 Gbit/s). It is equally suitable for LAN and WAN thus including the ability to connect machines across LANs and WANs using the same technology end to end.

2.5.2.2.2 Radio telecommunication networks

A radio telecommunication network is appropriate to connect transportable and remote fixed monitoring stations installed in isolated areas where no wired telecommunication links are available, and to connect mobile monitoring stations to the network.

2G public mobile radio links

Radio networks based on 2G standards, e.g. GSM, IS-95 are widely deployed; they easily offer connections with a standard data rate of 9.6 kbit/s. They can be sufficient to have on-line control of simple equipment (no screen image and no big file transfer). 2.5G public mobile radio standards like GPRS and EDGE offer improved data rates up to 473 kbit/s.

3G public mobile radio links

Radio networks based on 3G/3.5G standards, requested by ITU-R IMT-2000, e.g. UMTS and CDMA 1X. Extensions like high speed packet access (HSDPA, HSUPA) allow data rates of up to 14.4 MBit/s.

3.9G and 4G public radio links

The latest developments in digital wireless communication networks are designed to provide the highest possible data rates starting at 20 MBit/s. These rates provide live control of monitoring equipment including I/Q data, video, audio and heavy file transfer. Examples of associated technologies are WiMAX and LTE.

WLAN (IEEE 802.11)

This private wireless data communication standard offers data rates of several 10s of Mbit/s using very cheap commercially available equipment. Possible distances are generally limited by the range of line-of sight. As these links usually operate in ISM bands, reliability is low as interference from co-channel users may occur.

All radio telecommunication networks emitting in and near the station may disturb active monitoring antennas, receivers, DF systems and other monitoring equipments in the monitoring station. Careful consideration should be given to wireless technologies used for monitoring to ensure they will not have an adverse impact on monitoring activities.

2.5.2.2.3 Satellite networks

Very small aperture terminals networks

Very small aperture terminals (VSAT) can provide data transmission over extremely wide areas without the need for a terrestrial communication infrastructure. VSATs are well suited to link stations scattered over large countries, at locations not properly serviced by public telecom networks at data rates from 64 kbit/s up to 2 Mbit/s. A characteristic of VSAT networks is their relatively long time delay (approximately 600 ms and more).

2.5.3 Data flow and possible realisation

Transmission of data between units of a monitoring system may have the following characteristics:

– From the monitoring stations to the control centre, essential information such as bearings and field-strength levels can be transmitted using a data rate as low as 9 kbit/s. For the transmission of video, audio, spectral graphical displays, I/Q spectra, remote desktop access, and the transfer of large files, additional capacity is required.

– From the control centre to the monitoring stations, it will be necessary to transmit monitoring assignments, instructions for synchronised direction finders, responses to requests of the centre's database and service information. Typically, each control centre will generate a data rate of at least 9 kbit/s towards each monitoring station but additional capacity may be required.

– Between control centres, data from local databases and service information may be exchanged and will generate data rates of around 10-150 kbit/s. This estimate does not consider other network needs of the control centres (internet access or electronic mail).

The above list makes it evident that, in terms of required data rate, traffic between monitoring units is often asymmetrical. The data from a monitoring station to the control centre usually places the highest demand on the bandwidth of the communication line. Table 2.5-1 lists some typical measurement applications, the required data rates and possible communication techniques that may be used to realize them. The values given should only serve as a general guideline, because in actual implementations, they may vary considerably, depending on:

- the software implementation of the remote control functions (full screen updates or only changed data);
- data compression techniques;
- desired update rates;
- the particular implementation of these technologies by network/service providers as well as other factors.

TABLE 2.5-1

Typical data rates and communication implementation

Transfer of…	**Typical data rates**	**Suitable wired communication links (minimum)**	**Suitable wireless communication links (minimum)**
Commands and measurement results (on single frequencies); DF results (single frequency)	9 kbit/s – 64 kbit/s	Analogue PSTN, leased lines, ISDN	HF/VHF/UHF private radio links; TETRA; GSM
Control Functions described above, plus return path for digitized audio (narrowband)	16 kbit/s – 128 kbit/s	Digital leased lines; ISDN	GSM with (GPRS/EDGE), IS95
Frequency scan results, Live spectra or IF displays (standard resolution); Remote computer control (transfer of screen contents); DF results (multiple frequency)	64 kbit/s – 1 Mbit/s	Frame relay network, ADSL VDSL	IS95; CDMA 1X; UMTS; VSAT
Wideband raw spectrum information (I/Q data)	1 Mbit/s to greater than 1 Gbit/s (depending on signal bandwidth)	VDSL, ATM, LAN	UMTS with HSPA; WiMAX; LTE; WLAN Microwave links

Offline transfer of measurement tasks and results is not time critical. In this case any available data rate can be used. Note that result files may be many Mbytes in size and slow data lines may lead to unacceptable transfer times.

2.5.4 Protocol and software advice

As seen above, a large variety of different telecommunication networks are available and allow a flexible configuration, so that the selection of a specific telecommunication network can be based on the actual situation. Operation is usually totally transparent by using the TCP/IP protocol, and the handling and control of the communication link is done by modern communication equipment (routers), thus allowing the terminal or measurement equipment to concentrate on other processes.

Although different network systems and protocols may be used in a LAN, for more convenient network administration during operation, it is advisable to use the same operating system in all units of the network.

Different manufactures have developed different kinds of software for their monitoring equipment. However, it may be useful to develop a general (integrated) software which is adapted to the majority, if not all, of the monitoring equipment that is remotely controlled Operators are then only confronted with one familiar user interface to control different equipment efficiently.

If many operators access the monitoring network, a multi-level access control scheme may be useful in order to avoid operational conflicts.

2.5.5 System security and access method

Networked computerised spectrum monitoring systems are vulnerable to "computer hackers" and risk damage to data. Attacks can be by access to the computers or consoles, through a computer network from a remote location, or simply passive monitoring of data being sent over a communications link. The attack could compromise data integrity and confidentiality or interrupt system operation. Securing the system after the attack can incur increased costs because of the time required to locate and repair the corrupt data in the system.

The threat of attacks can be minimised by using a level of standard computer security techniques appropriate to the potential loss. Examples are:

– Securing the computer and network equipment in a locked area (physical security).
– Using access control techniques such as passwords and multi-level privileges to restrict access by users to system functions (software security).
– Performing regular system maintenance functions such as backups, security checks etc. as recommended by the manufacturer (software security).
– Information which is sent to telecommunication network can be encoded, but unfortunately this solution can decrease the speed of the process (software security).
– Using communications links and routers that can be secured against external attack (software security).
– Setting up a virtual private network (VPN) if public network technologies are used. VPNs automatically enclose user data in an additional protocol layer and restrict access to "known" system components. This technique is supported by many modems and routers today and can be used in all physical communication means mentioned in § 2.5.2.2.

2.6 Siting, buildings, facilities

2.6.1 Siting of monitoring stations

2.6.1.1 General considerations

This section provides general guidelines for monitoring station site selection, and identifies some of the pitfalls to be avoided. Some fundamental decisions must be made known to the planning group in advance of the actual selection of a site, so that the station may adequately serve its intended purpose. These include:

– the frequency ranges and geographical areas to be covered (see also § 2.1.3.3);
– whether domestic monitoring or monitoring of signals from outside national borders is more important;
– requirements for special installations such as long-range direction finders, field-strength recording facilities or directional antennas;
– acceptable on-site field strengths from nearby transmitters in the frequency ranges of concern;
– administrative considerations such as availability of housing, shopping facilities, schools for dependants, local transport and utilities;
– land costs.

The importance of administrative considerations should not be minimised. Experience has shown that it is difficult to retain qualified technical personnel at civilian monitoring facilities if normally expected amenities are not within reach. Demographic changes and physical growth projections of an area under consideration for a monitoring station should also be taken into account for siting decisions to prevent undue encroachment.

2.6.1.2 Desirable minimum site criteria for a station

Sites for spectrum monitoring stations must have suitable RF conditions and comply with three major principles. They should be:

– located in places suited to the zone to be monitored (suitable geographical coverage);

– protected against obstacles;

– electromagnetically protected.

As far as possible, a site should be selected where the field strengths of the emissions to be recorded will be relatively undisturbed by the local structures or terrain features. Particularly sites used for measurements below about 30 MHz should consist of level terrain situated in a relatively level area with relatively high conductivity and free of gravel or outcroppings of rock. Nearby overhead conductors, buildings, large trees, hills and other man-made and natural features may seriously distort or disturb the wave front of the emission. The degree to which these conditions limit the validity of the measurements depends on a number of factors including the frequency range and the type and orientation of the antenna used. At VHF and UHF frequencies, where highly directional antennas are used, it is important that the path in the general direction of the signal source be clear; additionally multiple-path reception due to local reflection or re-radiation of the wanted signal must be minimized.

If the site itself does not comply with the above-mentioned principles at ground level for VHF/UHF the set-up of antenna towers providing sufficient clearance with respect to nearby obstacles may improve the situation substantially. In order to avoid bearing errors and other undue mutual influence of the antennas it will not always be possible to group all antennas on one tower. Antenna masts can be lattice towers or be made of concrete. Depending on the local circumstances the erection of a lattice tower may be less expensive but the recurring maintenance costs should also be taken into account. A tower must withstand the weather conditions in the area, e.g. wind- and ice-loading. The antenna tower must allow easy and secure access to the antennas, to amplifying, filtering and switching equipment installed near the antennas and to the lightning rod on top of the tower.

The site should be remote from existing or potential industrial or congested residential districts. At least 1 km clearance is desirable and even greater spacing may be required from certain types of industrial plants utilising electrical welders, high power industrial heating devices, diathermy equipment, smoke precipitators and other machines with significant levels of radio-frequency energy. With respect to protection from strong fields from radio transmitters, see § 2.6.1.4.

High-tension power transmission lines may be a source of wide-band noise interference if they are near either the monitoring building or the antennas. A minimum of 2 km clearance from lines exceeding 100 kV is desirable and much greater clearance (up to 10 km) may be required for extremely high-voltage lines or where extensive monitoring of very weak signals is planned.

Proximity to airports or heliports is usually undesirable, especially at the higher frequencies, because low-flying aircrafts reflect sufficient energy to cause out-of-phase, multipath reception of signals being monitored. Experience has shown that airports should be more than 8 km distant in the direction of the runway approaches, or 3 to 4 km in other directions.

Roads with heavy traffic should be sufficiently remote from the monitoring facilities (including antennas) to minimise ignition interference (e.g. 1 km). The site should be accessible by an all-weather road and adequate utilities such as commercial electric power, telephone service and water should be available or obtainable. If the monitoring station must include a direction finder, then the highest priority consideration must be given to the direction-finder site criteria given in § 2.6.1.3. Direction-finder site criteria cannot be compromised if accurate bearings are required.

2.6.1.3 Additional desirable site criteria for stations equipped with direction finders

If a direction finder is to be installed in addition to the criteria mentioned above, it is desirable that no mountains, hills, large man-made structures or other obstructions project to a vertical angle of more than 3° above the horizontal as viewed from the proposed site or the direction finder. There should be no valleys or other major depressions within 1 000 m from the site of the direction finder, and even greater spacing to such natural terrain features is desirable.

Maximum terrain deviation from the reference ground elevation at the centre of the direction finder should not exceed about 1 m within a 200 m distance so as to avoid expensive ground preparation costs when constructing the direction finder. When the direction finder is completed, the land within several hundred metres of the direction finder should be essentially flat (or slightly crowned to facilitate water drainage).

The selected site for the direction finder should avoid locally concentrated areas of wet or exceedingly high conducting soil. To the extent that discontinuities in the substrata can be discovered, particularly when obvious surface features imply them, such irregularities should be avoided.

Large buried conduits or metal pipes (such as petroleum transmission lines) may, unless deeply buried, cause direction-finding errors if they are in the immediate area of the direction finder. A minimum separation of 200 m is recommended.

Any single half-wave ($\lambda/2$) structure, resonant at any frequency within the operating frequency range of the DF should be removed by at least 15 wavelengths. Any single quarter wave ($\lambda/4$) structure, resonant at any frequency within the operating frequency range of the DF and positioned in the same polarization plane should be removed by at least 7 wavelengths. For example, at an operating frequency of 25 MHz (where $\lambda = 12$ m), a conducting object with a length of 6 m ($\lambda/2$) should be at least 180 m distant from the DF.

NOTE 1 – When more than one of the quarter wave or half wave structures referred to above are noted at any reasonable distance from the DF, a special study may be required.

Wind turbine operation in the vicinity of direction finders may deteriorate the performance of the direction-finders. Scattering from the blades consists of a slow low amplitude variation at the geometric rotation repetition frequency (one-third the rotation rate) of the blades, as well as a large amplitude but short duration (about 30 ms) interference. In the forward scatter region, the receiver antenna pointing towards the monitored transmitter also points towards the wind farm, and the antenna directivity is of little benefit in reducing interference effects. The height of the monitoring antenna can be critical, as ground reflections can result in significant signal reduction (see Report ITU-R BT.2142 – The effect of the scattering of digital television signals from a wind turbine, p.47).

Below 30 MHz, the additional "man-made" noise from wind turbines may also impair the sensitivity. If the wind turbines obstruct the Line of Sight between the monitoring antenna and the transmitted signal, they may decrease the accuracy of the measurement:

a) Direction finders below 30 MHz

The requirements listed below and in Table 2.6-1 are of particular importance when choosing a site used for DF stations below 30 MHz. In general, the site should have a soil of uniformly high conductivity, a flat surface, sufficient distance from all metal obstacles, in particular high-tension power lines, sufficient distance from all metal piping or conduits even when buried, sufficient distance from railway lines, public highways, built-up areas, trees, buildings, etc.

The best sites will be on flat ground in areas where the water table is near the surface. When the country is fairly hilly, the best choice is a plateau, with the highest possible soil conductivity, overlooking the surrounding countryside.

TABLE 2.6-1

Minimum distances between obstacles and direction finder

Obstacle	Minimum distance (m)
Non-metallic one-storey building: – a single building – a group of buildings	 100 (in HF depending on the size and the shape of the antenna more than 100) 200
Two- or three-storey non-metallic buildings	250
Non-metallic buildings of over three storeys	300 and over depending on height
Small buildings with metal roofs	250
Metal structures (small sheds, etc.)	800
Reservoirs, large metal structures, metal bridges	1 500
Open-wire telephone lines, low-tensions lines	250-300
High-tension lines with pylons 20 m high	1 000
High-tension lines with pylons of 30 m and over	2 000-10 000
Railway or tram lines	1 000
Wind turbines	2 000 from individual wind turbines 5 000 from wind farms
Isolated trees	100
Small groups of trees	200
Forests	800
Metal fences	200 (in HF depending on the size and the shape of the antenna more than 200)
Small antennas	200
Large antennas	400
Lakes, ponds, rivers	1 000

As far as possible, the following rules should be used as a guide:

– the terrain should be chosen to avoid gradients of more than 1% within a radius of 100 m for HF installations and 250 m for MF and LF installations;

– outside this zone, the slopes can become steeper as the ground drops away, but excessive or sudden changes in ground level should be avoided;

– the angle between the horizontal and a line joining the direction finding antenna and the top of any obstacle should not exceed 2° or 3°;

– the ground should be completely clear within a radius of at least 200 m of the antenna;

– all incoming cables connected to the direction finding antenna should be 1 or 2 m underground within a distance of 30 m from the centre of the antennas. This depth can be reduced to about 0.5 m between 30 m and 250 m.

DF antennas should be located as far away as possible from other monitoring antennas as the receiving antennas of the monitoring station obstruct the regular propagation of radio waves, thus introducing errors into the bearings obtained.

If an Adcock system is used, the cables in the first section should lie along the line formed by an antenna pair or, if this is not possible, they should be laid at an angle of 45° with respect to each pair.

Table 2.6-1 gives comprehensive information on the minimum distances required between obstacles and the centre of the antennas, in order to prevent excessive interference with bearings.

b) Direction finders above 30 MHz

For VHF/UHF DFs the minimum distances of Table 2.6-1 may be reduced.

Since VHF/UHF monitoring stations often have to be installed in congested urban areas or in their vicinity, e.g. on house tops, the definition of protection zones may be appropriate. Two different types of zone have to be considered.

In the first, smaller zone the use of fixed and mobile radios may be restricted. For practical reasons it will be difficult to enforce such a rule outside the station's area. In a larger zone the use of high power ISM equipment and the build-up of major obstacles such as multi-storey buildings and industrial plants may be restricted. The legal prerequisites for the creation of such restrictions are completely different from country to country.

2.6.1.4 Protection from strong transmitter fields

Monitoring sites should be free from strong emissions and other sources of interference because, dependent upon the frequency ranges to be covered, the presence of nearby radio transmitters may severely limit the monitoring capabilities due to intermodulation and blocking effects.

In evaluating the possible adverse effects of such transmitters, not only the field strength of the fundamental signal but also that of harmonics should be taken into account. The presence of two or more transmitters has to be considered, even if their operating frequencies are far away from the frequencies of interest of the monitoring station because the resulting intermodulation products may fall in the frequency range of the monitoring station.

Based on experience a root-sum-square value of 30 mV/m for multiple signals within the passband of the monitoring receiver can be regarded as an acceptable field strength level corresponding to a distance of about 5 km between a 1 kW transmitter and the monitoring station depending on frequency, terrain and equipment used.

Spectrum managers should carefully investigate all licence applications for fixed transmitters within a 5 km radius, and within even a 50 km radius for transmitters exceeding 1 kW and not issue licences for any kind of radio transmitter exceeding a level of 30 mV/m at the monitoring station(s).

If a monitoring station has to be built in a strong signal area, at least the installation of active antenna devices should be avoided.

2.6.1.5 Protection from local computer systems

It has been found in many cases that various components of computer systems may emit electromagnetic radiation and cause interference to the monitoring and measuring equipment. Although special low-interference computer equipment for radio monitoring systems has become available, most of the computers in use are standard PCs.

After the installation of a computer system it is very difficult to detect the source of interference since the computer equipment and its peripheral components are normally distributed throughout several rooms or even the whole monitoring building. The interfering signals may be emitted by the components and/or conducted via the computer cables. Furthermore, interfering signals may often also occur not only on the fundamental (clock) frequencies but also on the harmonic frequencies. The most appropriate way to detect the interfering source is to subsequently shut down and disconnect the various computer components.

In any case the monitoring service should observe the following recommendations:

– Only double shielded coaxial cables should be used for connections between the antennas and the receiving equipment.
– Shielded cables should also be used to connect the individual components of the computer system.
– Where possible, general purpose computer components should not be installed near receiving and measuring equipment.

– In the case of interference, any computer equipment which is not needed should be disconnected or closed down.

– In general, monitoring offices should be situated close to the antennas and be separated from administrative offices.

– Measures to avoid or minimise interference caused by computer equipment should be incorporated into the planning phase of the monitoring station. It is recommended to seek advice from monitoring services with experience in this field.

2.6.1.6 Land requirements

The amount of land required for a monitoring station and the layout of its facilities will depend to a large extent on the mission and activities assigned to the station and whether it is manned or not. A station used for HF monitoring requires much more space for the antennas of the DF system than a station for VHF/UHF direction finding or if local monitoring is the most essential task. Stations engaged in signal field-strength recording will require additional land to provide adequate clearance from overhead conductors and other obstructions for the antennas.

The use made of adjacent property is also an important factor. For instance, where a monitoring station is to be situated in a farming or cattle-rearing area, there may be less likelihood of interference to the operations than in an area where factories or similar sources of potential interference are in existence or contemplated. To avoid possible deterioration of a monitoring site due to erection of interference sources in close proximity to the direction finder or antennas, it is often desirable to obtain additional land to provide the necessary isolation from such sources. This area can be leased to farmers and agriculturally used.

Provided that adequate protection from potential noise sources is ensured by agricultural or unused land around, an area of 40 000 to 160 000 m^2 is sufficient for a manned monitoring station equipped with a VHF/UHF direction finder and with limited requirements for MF or HF directional antennas. A separate area of another up to 90 000 m^2 is needed for the installation of an HF direction finder, depending on its design. Taking into account the figures of minimum distances in Table 2.6-1 it becomes obvious that areas of 400 000 m^2 or even more are needed if adequate protection cannot be otherwise guaranteed and all equipment and facilities have to be situated on a coherent plot of land. For monitoring stations with an exceptional need for a large, long range DF used at frequencies below HF, a limited number of large directional monitoring antennas, and with radiocommunication facilities, an area of 320 000 m^2 to 640 000 m^2 may be needed, depending on antenna designs. In some exceptional cases where monitoring stations have several large directional monitoring antennas, isolated field-strength recording facilities, and separate radio-net control or relay duties, an area of up to as much as 1 200 000 m^2 may be needed.

The area needed for the installation of a remote controlled VHF/UHF monitoring station is primarily determined by the size of the antenna tower. An area of 30 m^2 may be sufficient for the antenna tower and a equipment shack. If the antenna mast has a height of e.g. 80 m, more than 100 or 200 m^2 may be required.

Also legal aspects related to operational safety and public safety may have to be considered. Icicled antenna elements for example can pose a threat and require fencing at some distance to the mast, which of course increases the demand for land.

2.6.1.7 Roadways

In addition to access roads from public streets to the monitoring stations and its buildings, service roads should normally be provided to all DFs, antennas, field-strength recorder booths and other outlying facilities so that motor vehicles may be used to convey equipment to and from these sites. These should be all-weather roads suitable for the terrain and soil conditions, so as to ensure operation throughout the year.

2.6.1.8 Fencing

Fences may be desirable to protect the plant from livestock or wild animals and, in some cases, from human intruders. Depending upon the local circumstances, the entire property may be fenced, or it may be determined that only the building area requires fences.

If a decision is reached to install metallic fences, they should be sufficiently remote from critical installations, such as long-range DFs and field-strength measurement installations (usually 200 m or more) to avoid possible interference to the proper operation of such devices.

Metallic fences should be well grounded to ensure that there are no floating conductors that can resonate and re-radiate stray electromagnetic energy.

2.6.2 Buildings and auxiliary facilities

2.6.2.1 Buildings

2.6.2.1.1 Monitoring buildings for manned monitoring sites

Depending on the separation from the monitoring antennas or direction finder, it is recommended that the building should have no more than three storeys above ground level. If a multi-storey building or a single-storey building with a basement is selected and if a large quantity of equipment is contemplated at the monitoring station, the design should take account of the concentrated weight of the monitoring racks and equipment and the need for an adequate capacity for the floor loading in those areas.

In the case of unmanned stations provisions for the protection of the building and the equipment from vandalism have to be made, e.g. by using concrete buildings with trellised windows. Remote monitoring units for the detection of intrusions, power breakdown and fire alarm should also be considered.

In the case of manned monitoring stations there are basically two different concepts possible. Some administrations concentrate their monitoring operations in a single room; others have found it expedient to separate certain functions from the main monitoring room. For example, if there is sufficient staff and if there will be extensive associated communication activities; it may be desirable to install the communication terminal equipment and operating position in an adjoining room. On the other hand, where there are limited staffs, the communications operations will normally be performed by the monitoring personnel as a collateral duty, so that the communication facilities should be readily accessible from the monitoring position. Similarly, if there is extensive special work (e.g. long-term propagation studies) to be performed in addition to the normal monitoring and measurement duties, it may be desirable to perform such operations in a separate room.

2.6.2.1.2 Allocation of space

Not only the amount of land required but also the space requirements of the monitoring building very much depend on the mission of the station. National legislation related to occupational health, other safety aspects and ergonomics may largely expand the minimum space requirements as the following example indicates. From the technical point of view equipment must have sufficient distance from the wall so that maintenance teams are able to replace the equipment. From the job safety point of view additional space may have to be allocated enabling staff to pass by even when all cabinet doors are open. Two different examples A and B are presented below, and may be considered as possible starting points for planning. It should be stressed that these examples are for reference and will need to be adapted to individual administration needs.

Example A

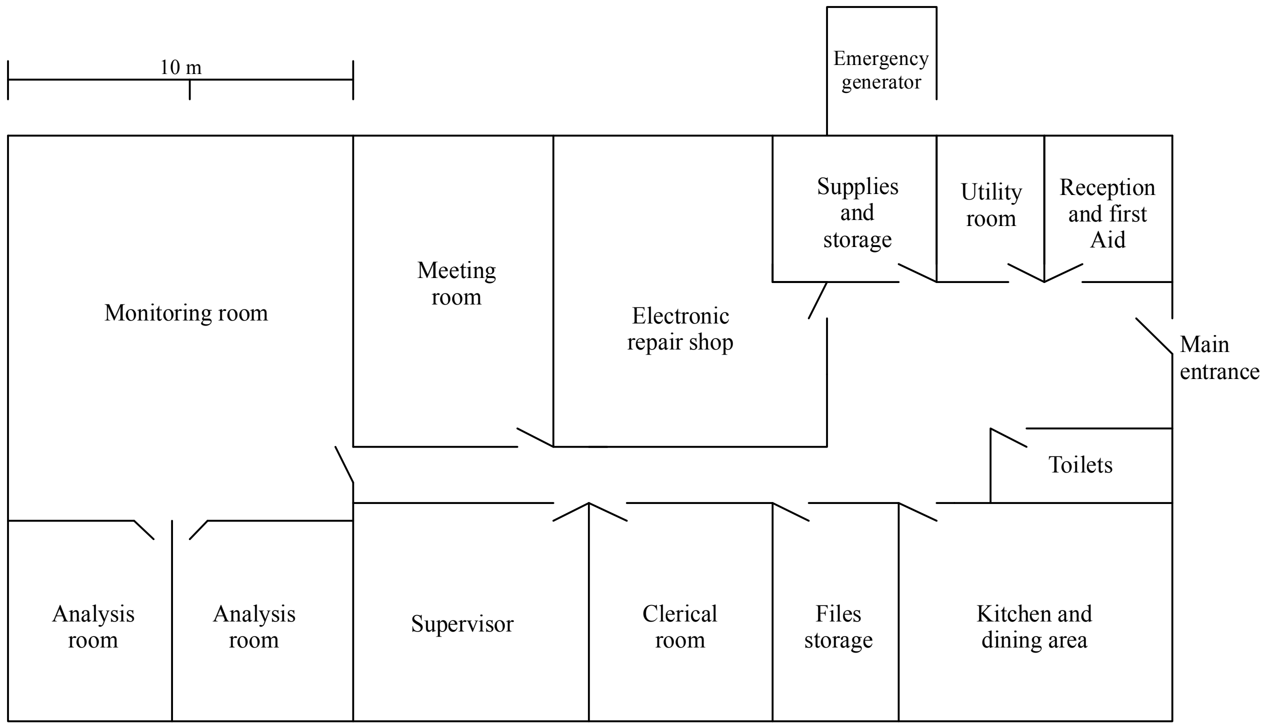
This example represents a monitoring building for a staff of twenty or less which includes space for combined supervisory, monitoring and office personnel. The building consists of a main monitoring room with two small special project rooms adjoining. Offices are provided for a supervisor and also for administrative/clerical personnel. Additional space is provided for an electronic repair shop, kitchen, meeting room and utility, sanitary and storage facilities. An outline drawing of such a building is found in Fig. 2.6-1, showing how such space can be allocated. Example dimensions are found in Table 2.6-2.

Example B

The building which is presented in example B could be used where more space is needed for a larger staff or multiple monitoring positions. The area dimensions given in Table 2.6-2 may give an impression of the size of such a building, which could support a larger monitoring staff with more functions. Such a building could accommodate about 35-40 persons of the radio monitoring service as well as additional staff for the radio inspection service and other sections. It should be mentioned that typically a fraction of the 35-40 persons mentioned work in the building at the same time (others are mobile, off shift, on holiday, etc).

FIGURE 2.6-1

Example of a floor plan for a monitoring station building showing how workspaces could be allocated (not all building details are shown)



Spectrum-2.6-01

TABLE 2.6-2

Example of space allocation for monitoring station buildings

Purpose	Example A Approximately Area (m^2)	Example B Approximately Area (m^2)	Remarks
Main monitoring room	100	190	
Electronic repair shop	50	60	
Mechanical repair shop (if separate)	–	25	
Meeting room	50	50	Small meeting space may alternately be in supervisor office
Office accommodation	15-40	15-40	In some cases offices (e.g. administrative) may be occupied by more than 1 person
Copy machine and file storage	(part of clerical office)	24	In some cases additional rooms for file storage could be located in the basement
Server and telecommunication equipment	10	31	Utility room or basement

TABLE 2.6-2 (*end*)

Purpose	**Example A Approximately Area (m^2)**	**Example B Approximately Area (m^2)**	**Remarks**
WC	10-15	25	May be multiple rooms and room sizes and facilities may be dictated by local building codes
Dressing room	–	6	
Kitchen	50 (including dining area)	6 (kitchen only)	Dining area may be part of kitchen or shared with meeting space
Cleaning equipment	–	6	
Equipment and antenna storage	10 (may be more space in outbuildings)	100	May be partly be in basement or outbuildings
Caretakers storage	–	30	
Heating	5-10	36	Basement or utility room
Emergency power plant	(outbuilding or external)	36	Basement
Uninterruptible power system	10	10	Basement
Power transformer	(external)	10	Basement
Garage (if monitoring vehicles at site)	100	300	

2.6.2.1.3 Acoustic treatment

Acoustic tiles or other acoustic treatment of the ceiling (and perhaps the walls also) should be provided in the main monitoring room and special project rooms. Acoustic treatment of some other rooms may, in some instances, also be desirable.

2.6.2.1.4 Shielded rooms

If extensive use is to be made, either in the special purpose rooms or in the electronic repair shop, of high-output signal generators or other sources of radio-frequency energy which might cause interference to monitoring operations, consideration might be given to shielding such space by means of appropriate continuous screening in the walls, ceiling and floor. Shielding is not normally required if the signal generating equipment is typical of that used for normal equipment maintenance and testing procedures.

Accommodation of the server and the private branch exchange in shielded rooms is also recommended if accommodation is not possible in the basement.

2.6.2.1.5 Cable ducts

The extensive RF, IF, audio, power and control cable connections required for interconnecting various components within the monitoring building and for cable circuits from antennas and other external facilities, make it common practice to incorporate cable ducts into the floor of the building. These ducts should be provided with frequent access openings to simplify installation and replacement of the various cables. Two types of floor duct are commonly used:

– an open-top duct with suitable removable continuous covers which, when installed, lie flush with the surface of the floor;

– enclosed ducts with screw-in caps at frequent intervals for access to the ducts.

The compatibility of materials has to be taken into account when ducts are constructed, as from a metallurgical point of view, aluminium ductwork or cable tubes should, under no circumstances, be in direct contact with concrete.

It is suggested that incoming signal and control cables from antennas, DFs, and the transmitter building be routed to a terminal board at the point where the cables enter the building, with all incoming cables terminated at this board using appropriate connectors. This arrangement permits more rapid isolation of cable faults than is possible when the various cables are run directly to the equipment racks within the building. Also it is not good engineering practice to run RF or audio cables in the same ductwork as power cables.

2.6.2.1.6 Building or room for emergency power plant

If the capacity of the emergency power plant is greater than a few kW, it should be installed on a floating base, which was cast separately from the surrounding floor to minimize the transmission of vibrations to the floor and the building itself. For larger plants, an underground fuel tank is desirable; it should be installed several metres away from the building to minimize fire hazards.

Depending on national safety regulations it can be mandatory or at least more cost effective to house the emergency power plant in a separate building. In both cases adequate fire protection arrangements have to be made.

2.6.2.1.7 Machine shop, vehicle storage building

The requirement for this building will depend upon local conditions and the number and size of the vehicles. If petrol is to be stored for use in the vehicles, it is desirable that the fuel tank and pump be outside and separate from the building, to avoid undue fire hazards. Fire or excessive temperature-rise alarms should also be considered for this building.

2.6.2.2 Protective enclosures for remote, unattended monitoring operation

Protective enclosures, also known as equipment shelters, can be used to house radio monitoring and DF equipment for transportable stations and/or for remote, unattended operation. Such buildings should include the minimum space and power needed to support the equipment and casual local operation and maintenance activities. While protective enclosures are available in a variety of size and shapes, two types of typical enclosures are described here.

Type 1: Type 1 enclosures have the dimensions of a typical 19-inch equipment rack. They are constructed of sturdy, watertight materials, and include doors in front and rear for access to equipment. They include a cable entry panel. They typically have heating and air conditioning, placed on the ground next to the equipment, to provide cooling for the equipment.

Type 2: Type 2 enclosures have the dimensions of a small shelter. They are constructed of sturdy, watertight materials. They include an access door, and have room for a maintenance person to access the front and back of equipment rack(s). They include an operator work area inside the shelter, consisting of a desk or table and storage cabinet. They typically have heating and air conditioning, mounted on the shelter, to provide cooling for the equipment.

Both types of protective enclosures should have a uninterruptible power supply (UPS) with battery backup. They should include an automatic over-temperature shut-off, so the equipment is not damaged by excessive heating should the environmental control units fail. They should include remote status and alarm for power failure, ECU failure, or condition of over/under temperature.

2.6.2.3 Utilities, power supplies and other installations

2.6.2.3.1 Electrical power

Where reliable and adequate electrical power is available from power sources external to the monitoring facility, it is usually preferable to obtain power for normal operations from such sources rather than to depend entirely on power generated in the station. If adequate power is not available from outside sources, and if uninterrupted operation of the monitoring station is required, two separate power plants of adequate capacity to handle the peak station load and with good voltage and frequency stability should be installed.

Where an external source of power is used, a single emergency power plant will normally be sufficient to bridge the time gap when the external power supply is not available.

It is desirable to install all power distribution cables underground, to minimize the introduction of radio-frequency noise into the station. This is particularly important when high voltage transmission lines provide service to industrial or residential areas, since noise may be introduced into the local distribution lines from machinery connected to the outside line. By running the circuits underground within the confines of the monitoring station property, radiation from the lines will be negligible, and the capacitance between the lines and ground will tend to by-pass radio-frequency energy existing on the external lines. The routes of all underground power, communication and control cables should be carefully plotted and recorded, to avoid the likelihood of damage when excavations are made for antenna poles and structures.

Modern emergency power plants allow automatic switching between main and emergency power. With automatic switching, it is desirable to provide a time delay of a few seconds between disconnection of main power and activation of the emergency source to avoid repeated starting, stopping and switching arising from very short power failures.

2.6.2.3.2 Uninterruptible power system

Besides an emergency power plant, it is necessary to have an uninterruptible power system (UPS) in the monitoring station to support the computer system during the changeover intervals between normal power mains failure and starting the emergency generator. UPS systems convert DC to AC and normally operate from a dry cell or storage battery supply.

The UPS should have appropriate technical specifications (e.g. time delay for starting better than 5 ms, effective noise and surge features, and having the capability of running for a sufficiently long interval, i.e. more than 10 min) to prevent computer systems from losing information and having to be reset. This operating interval allows operators to save information and data that would otherwise be lost, and to manually start the emergency power generator in case of failure of the automatic start and changeover from power mains.

In the design phase of the UPS it must be decided which equipment will be powered by the UPS. The cost very much depends on the maximum power. Nevertheless, a reasonable reserve should be calculated.

2.6.2.3.3 Emergency lighting

It is necessary that the monitoring building and the emergency power plant building be provided with battery-operated emergency lights, which are automatically activated when the normal power supply to lighting circuits is interrupted. With this emergency lighting, station personnel can rapidly locate the emergency power plant controls and manually start the emergency generator, if needed.

The emergency lighting can be operated either by dry-cell batteries, which require periodic testing and replacement, or by wet cells which float on the normal electrical circuit and which are constantly charging.

2.6.2.3.4 Telephone and data circuits

There is a constantly growing importance of properly working telecommunication connections with availability near to 100% for a modern radio monitoring service. The private branch exchange and servers should be installed in separate rooms with restricted access. This Handbook is not able to summarise the experience of operators and computer companies in this permanently developing field adequately. Therefore the only advice given here is to dimension the communication architecture sufficiently to meet future requirements. Sections 2.5 and 2.6.3 should also be considered.

2.6.2.3.5 Heating and air conditioning

Heating and air conditioning requirements will depend upon the local climate. It may be well to consider providing exhaust fans, together with air ducts extending from the tops of the monitoring equipment racks to the outside of the building. During cold weather the heat discharged from the monitoring equipment may be exhausted within the building to effect economies by reducing the demand on the normal heating system.

2.6.2.3.6 Fire warning and extinguishing systems

It is necessary for every monitoring station to be equipped with alarms and smoke detectors along with fire extinguishers appropriate for electrical fire, and a water sprinkler system throughout the building.

Large buildings typically require standpipes for connection to hoses by fire fighters.

2.6.2.4 Lightning protection

The purpose of lightning protection is to protect a vulnerable part of the spectrum monitoring station with minimum damage.

The lightning rod has been the front line of defence against the direct lightning strike.

For induced lightning, the total lightning protection plan for grounding, interconnection or bonding, shielding and surge suppression shall be implemented.

2.6.2.4.1 Lightning effect

Lightning is the result of separation of charges in thunderclouds.

The maximum dumped current (power) of flash can amount to almost 400 KVA.

However, from the statistics, the majority of dumped currents are less than 100 KVA, and about 50% of them are between 20 and 25 KVA; the range when the end of leader launches lightning stroke toward ground (stroke range) is between 30 m and 70 m for 20 KVA and between 70 m to 150 m for 50 KVA.

There are two categories of lightning effects known as:

a) Direct lightning strike that causes enormous damage due to a huge amount of lightning strike current. Normally conductor elements, e.g. building and antennas are exposed to this kind of effect.

b) Induced lightning effect caused by an intense electromagnetic field results in transient voltage and current surge in equipment, and can effect actual strike up to several kilometres away.

2.6.2.4.2 Protection against direct lightning strike

This kind of protection is mainly for outdoor objects such as sheaths of buildings, antennas and power supplies.

The method for this process is to catch the main portion of lightning power and lead it into the ground.

To accomplish this, three main elements are important:

a) Lightning rod (air-termination): this is the first and front line of defence against the direct lightning strikes, which is intended to intercept a lightning stroke.

b) Down-conductor: an electrical conductor connecting the lightning rod to an Earth-termination. According to the existing standards, the most conductive metals (e.g. copper or aluminium) should be used for the down conductor.

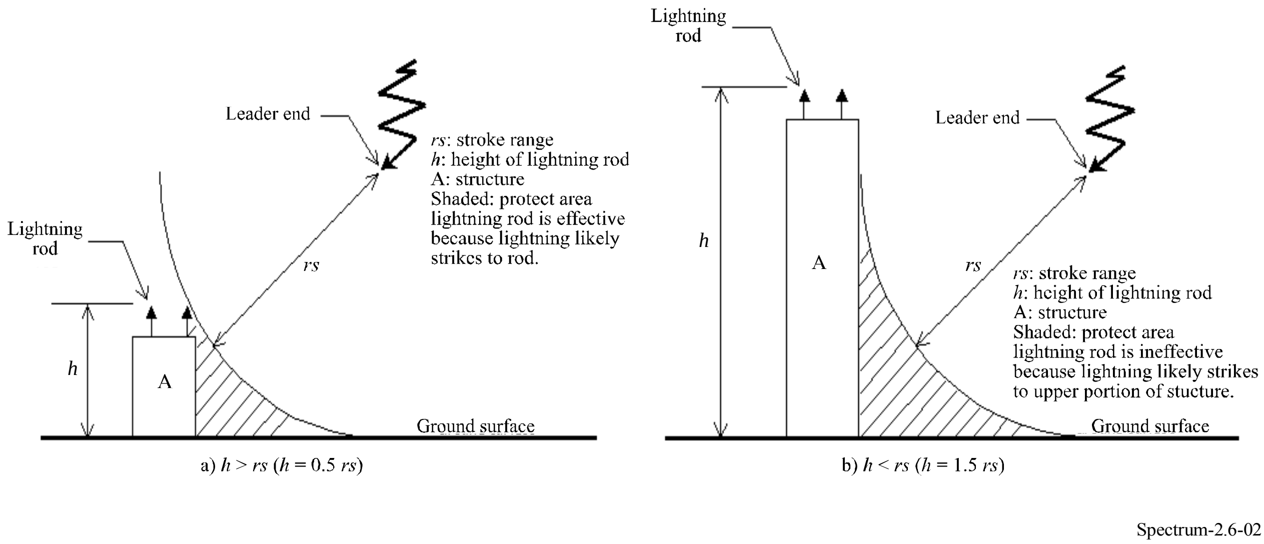
c) Earth-termination: a system of earth-electrodes (usually buried) intended to disperse lightning current into the earth.

As shown in Fig. 2.6-2, the extent of the protected area for a structure largely relies on the magnitude of stroke current (see § 2.6.2.4.1) and the height of the lightning rod.

When the height of the lightning rod is bigger than the stroke range ($h > rs$) as shown in Fig. 2.6-2b), the lightning rod is ineffective in attracting the lightning; hence the lightning may strike the upper portion of the structure.

FIGURE 2.6-2

Protection area



Because the stroke range relies on the stroke current, IEC 1024-1 (Basic principal of structure protection) defines the protection level of a structure as listed below.

Protection level	Stroke range (m)	Probability of lightning (%) strike to lightning rod
Level I	20	98
Level II	30	95
Level III	45	90
Level IV	60	80

The lightning protection system with a lightning rod is not the complete system for protection against lightning strike. It is important to determine to what extent the spectrum monitoring station shall be protected.

2.6.2.4.3 Protection against induced lightning

This kind of protection is mainly for indoor equipment, e.g. receivers, a.c. power supplies, including protection against direct lightning strokes. This protection could only be achieved by a careful investigation of the spectrum monitoring station to identify all sensitive equipment and all possible paths for the transient voltage and surge current. These should be followed by the design, specification, installation and maintenance of the protection system.

For designing the protection system, there are four engineering concepts of grounding, bonding, shielding and surge suppression.

– Proper grounding and bonding provides additional paths for lightning current that leads lightning current to the ground, thereby minimising surges. These include interconnecting equipment cabinets, individual components, grounding wires and may include interconnecting of adjacent conductors such as structural steel and conduit.

– Shielding of cables reduces surge by providing a preferential path for lightning current rather than the actual circuit. To be most effective, shielding must be completely continuous, and grounded or terminated.

– Surge suppression device provides a function to suppress transient voltage and surge current resulting in damage to the equipment interconnected by cables over long distance. It shall be so selected that it can handle the voltage and current expected from severe induced lightning.

Effective protection includes the protection of all interfaces of the installation using one protection concept.

2.6.2.4.4 Protection process

Using a lightning rod for outdoor objects is necessary as the first step for protection of the building, but it is also necessary to limit the overvoltages on power source, antenna and data lines, before arriving at the electronic equipment.

All the lines (power and communication) and antenna feeders should enter the building at the same place.

In the entry point, all the lines should be connected to the equipotential network, so the cables, shields and other metal elements that do not carry signal or power are connected to the equipotential bonding bar directly.

Power and signal lines (from receiving antennas, direction finders or communication/computer lines) that carry signal or power are connected to the above mentioned bar through their own special arresters. In such a case, the potential of all lines will increase equally and simultaneously and therefore the difference of potential (between signal lines and shields) trends to zero during the lightning period.

The residual voltages or the overvoltages resulting from the length of the conductor (from entry point to the equipment location) induced by electromagnetic signals should be omitted by inserting a finer protector at the point nearest to the equipment.

It is noteworthy that a protector device by itself cannot provide full protection; the most suitable protective devices should be used in several phases, according to the specifications of the equipment.

2.6.2.4.5 Earthing and screening

Effective and secure earthing is an essential factor for lightning protection procedure and shall comply with IEC 1024-1.

It is recommended that suitable measures be taken already in the planning phase. All metal parts of significant dimensions associated with the structure shall be bonded together and to the lightning protection system, e.g. metal reinforcements of concrete or metal skin roofs and metal facades.

Bonding shall be carried out for all external conductive parts entering the structure. In larger structures like monitoring centres, the connection to copper internal ring conductors is a good solution. Adequate bonding of cable shields is an essential part of the lightning protection zone concept. Basically, all shields shall be bonded at both ends – at the patch panel as well as at the terminal/socket – directly or indirectly via surge protection devices. It is beneficial to have many parallel paths to reduce the injected currents in the cables and shields. A meshed earthing system fulfils this requirement.

Bonding shall be provided and installed at the boundary of lightning protection zones (LPZs) for metal parts and systems crossing boundaries, all by an equipotential bonding bar that should be connected to the electrodes of the earthing system.

The contact and bedding resistance of the ground can be reduced by appropriate measures, termed “earthing improvement”, such as increasing the soil conductivity by injection high-conducting solutions and thereby reducing the contact and bedding resistance. One example is hygroscopic emulsion that has been developed for this purpose.

The earthing network should be clean with a minimum resistance of 4-10 Ω or better. Metallic parts must be anti-corrosive with high conductivity. According to the climate conditions, soil composition, humidity and quality of materials applied in, the earthing system should be tested and improved at regular periods of time. The ground connection itself should be short and include buried plates to minimise the impedance.

2.6.2.4.6 Antenna protections

Besides earthing and outdoor protection measures the following also should be considered:

– The antenna system/array should be brought within the 45° protection area, and/or rolling sphere protection radius of the lightning rod.

– The lightning rod should be mounted vertically above the antenna system/array or, if not possible, it may be mounted in the vicinity of the system so as to make a proper protection area around the system.

– The air-termination and down-conductor should be mounted in such a way to retain the antenna array symmetry.

– In regions with a high rate of lightning, it is preferred that the antenna be disconnected from the equipment, if a prediction of the lightning time is possible.

– To cover the antenna surface by proper insulations (e.g. fibreglass materials).

– For active antennas, appropriate arresters should be used to allow DC voltage to pass, due to normal operation of the antenna systems.

– Antenna masts/towers must be earthed to the best advantage.

– Shields of RF and coaxial cables should be earthed properly and in the case of high mounted antennas, these shields should be bonded to the antenna mast at the top and bottom ends.

2.6.2.4.7 Maintenance of lightning protection system

Maintenance of the lightning protection system is sometimes disregarded because lightning protection systems are not counted among the main equipment. Scheduled maintenance is indispensable to the lightning protection in order to limit damages when the lightning strikes. In particular, the lightning rod and the down conductor installed outside the structure should be well maintained to avoid chipping due to lightning and rust. The grounding resistance should also be kept continuously under watch.

2.6.3 Sources of interference affecting the operation of monitoring stations

2.6.3.1 General principles

As far as possible transmitters of any kind should be excluded from a monitoring site. If, however, it is necessary to accommodate such equipment for good reasons, e.g. communication purposes, care should be taken at the planning and installation stage to avoid or minimise interference.

More commonly, interference arises from equipment radiating RF energy unintentionally. There are basically two main interference mechanisms: radiation and conduction. Radiation can occur either directly (due to insufficient or faulty screening of the source) or via connecting cables. Interference can arise also via an antenna if the frequency of the radiated signal falls within the operational band(s) in use at the station.

However, if the source of interfering radiation is outside the casing of a piece of monitoring equipment, interference may or may not occur depending upon the effectiveness of the equipment screening. Similarly, radiation in or outside a cable run may or may not cause interference depending upon the effectiveness of the screening of the cable run and the manner in which it is laid.

Conduction of interference from an offending source can either be mains-borne or by control and signal cables used for inter-connection purposes.

2.6.3.2 Sources of interference

These are as follows:

– PCs and servers, including their peripheral devices (monitors, printers, scanners, cabling, etc.) used for office applications and device control;

– telephone exchanges, modern telephone terminals, cordless telephones, fax machines;

– fluorescent lamps;

– halogen lamp power supplies;

– solid-state switches used in power supplies, heating/air-conditioning and other control equipment;
– electric motors used for fans and ventilators (kitchen, offices), vacuum cleaners and antenna rotors;
– vehicles and lawnmowers with spark ignited engines;
– ISM equipment (microwave oven);
– cable TV and similar cable distribution systems.

2.6.3.3 Remedial action

All metallic services entering the sensitive areas should be separately earthed in a manner that also complies with local electrical safety regulations. The merits of non-metallic barriers can be considered but if metal is used inside the sensitive area it must again be suitably earthed.

RF cabling should be separate from all other cables in the console and securely earthed. Interference caused by telephone and intercom cables may often sufficiently be reduced, e.g. by passing the cables e.g. 5 times through 4 rings.

PCs are ubiquitous and cannot be excluded from the operations room. Therefore low radiation types should be procured. Some caution should be exercised in relation to tempest specified devices since they only guarantee that the radiation does not contain any information rather than low radiation.

LANS and similar interconnections should be based on fibre-optic cabling rather than copper. This will avoid any radiation and also avoid unintentional earth loops. The signals of the station frequency standard should also be distributed to the consoles using fibre-optic cables for the same reasons.

If the proximity of data cables and RF or audio cables is unavoidable, double screened cables should be used. Audio cables should be tightly twisted and screened or double screened.

Normally radio-monitoring equipment has adequate radiation properties. Some care may be required however, if radio amateur equipment is used.

Purely data processing devices, which do not need to be manned by the operator, should be in a separate, adjacent cabinet if possible.

Effective and secure earthing and screening is essential not only for lightning protection but also for the reduction of RF interference. For more details about earthing refer to § 2.6.2.4.5.

These precautions are relatively simple if considered at the installation phase. Subsequent identification and elimination of discovered problems can be protracted and costly.

2.6.4 Site survey

Before installing the spectrum monitoring system a comprehensive evaluation of the operational tasks, the required geographical coverage, the radio conditions and other limitations shall be made. The priority of all relevant items should be clear and written in a document.

Following this, a site survey has to be undertaken using a checklist adapted to the requirements. Normally the site evaluation will show that most of the surveyed sites will not meet all requirements and compromises cannot be avoided.

The results of the evaluation shall be summarised in a comprehensive report. The report and the attached checklist shall be kept as reference for the future.

The example of a site survey checklist and a comprehensive evaluation report form is contained in Annexes 1 and 2.

ANNEX 1

TO SECTION 2.6

Site survey checklist

<table>
<tr><td colspan="2">Ref. No.:</td><td colspan="3">Prepared by:</td><td>Date: / /</td></tr>
<tr><td>0</td><td>Site name</td><td colspan="4">□ New □ Existing</td></tr>
<tr><td>1</td><td>Site address</td><td></td><td colspan="3"></td></tr>
<tr><td>2</td><td>Proprietor</td><td colspan="4"></td></tr>
<tr><td rowspan="3">3</td><td rowspan="3">Consent of proprietor for installation</td><td colspan="4">□ Agreed with no requirements</td></tr>
<tr><td colspan="4">□ Agreed under condition of:</td></tr>
<tr><td colspan="4">□ Disagreed with refusal of site survey</td></tr>
<tr><td>3</td><td>Address</td><td colspan="4"></td></tr>
<tr><td>4</td><td>TEL/FAX/mail address</td><td colspan="4">/</td></tr>
<tr><td rowspan="5">5</td><td rowspan="5">Building
(With pictures)</td><td colspan="2">Form</td><td colspan="2">Height from ground surface</td><td>Elevation of ground surface from MSL</td></tr>
<tr><td colspan="2">□ Building
□ Tower ( )
□ Others ( )</td><td colspan="2"></td><td></td></tr>
<tr><td rowspan="3"></td><td rowspan="3"></td><td>Frequency:</td><td colspan="2"></td></tr>
<tr><td>Distance:</td><td colspan="2"></td></tr>
<tr><td>Remarks</td><td colspan="2"></td></tr>
<tr><td>7</td><td>Surrounding area
(with pictures)</td><td colspan="4"></td></tr>
<tr><td rowspan="13">8</td><td rowspan="13">Geographical position</td><td>Latitude
(degrees, min, s)</td><td colspan="3">°N ’’’</td></tr>
<tr><td>Longitude
(degrees, min, s)</td><td colspan="3">°E ’’’</td></tr>
<tr><td>UTM
(zone, North, East)</td><td colspan="3"></td></tr>
<tr><td>Datum used</td><td colspan="3"></td></tr>
<tr><td>Method and Source</td><td colspan="3">□ GPS / □ Map</td></tr>
<tr><td>Elevation AMSL (m)</td><td colspan="3">“x” m</td></tr>
<tr><td>Accuracy of determination X,Y,Z:</td><td colspan="3">“x” m</td></tr>
<tr><td>Positioning on map (file or paper)</td><td colspan="3"></td></tr>
<tr><td>Map reference</td><td colspan="3">map code:</td></tr>
<tr><td>Projection system on map</td><td colspan="3">Cylindrical, Lambert conical, polyconical, gnomonic: xxx</td></tr>
<tr><td>Site sketch</td><td colspan="3">See attachment No. x</td></tr>
<tr><td rowspan="2">Photographs</td><td colspan="3">□ Yes, see attachment No.</td></tr>
<tr><td colspan="3">□ No</td></tr>
</table>

9	Site environment	Temperature range (°C):	Minimum	Maximum	
		Deforestation required:	□ Yes	□ No	
		Moisture content (%):			
		Storm water	□ Yes	□ No	
		Snow (cm)	Minimum	Maximum	
		Seismic risk:	□ No	□ Yes, value (Richter range):	
		Remarks:			
10	Antenna location	Location	See attachment No.		
		Coordinate	See attachment No.		
		Elevation against surrounding obstruction	□ highest (with picture)		
			□ not highest but good enough (with picture)		
			□ lower (with picture)		
		Elevation	From ground surface:		
		Other antenna	□ No		
			□ Yes	Classification:	
				Polarisation:	
				Distance:	
		Overhead line	□ No		
			□ Yes	Classification:	
				Distance:	
		Resonant object	□ No		
			□ Yes	Classification:	
				Distance:	
		RF field strength	Frequency:		
			Field strength:	See attached sheet 3	
11	HFDF Antenna	Land available for array diameter plus guy wire extension area	□ Yes	□ No	
		Flatness of the land; 3° gradual slope for the site is acceptable from one side of the antenna to the other			
		The vertical clearance is better than 3° for TOA			
		Soil bearing for the antenna support			
		Identify potential scatters such as tall buildings, big trees, high voltage transmission lines, radio towers, etc.			
		Potential scatters need to be at least as far away as specified in Table 2.6-1 from any antenna element			

11	HFDF Antenna (*cont.*)	Scattering free environment for inside the antenna array				
		High voltage power lines need to be away from the antenna array, see Table 2.6-1				
		Equipment needed; camera, theodolite with magnetic compass, 100 or 300 foot tape measure, 12-foot tape measure, GPS binoculars, spectrum analyzer and field strength meter; obtain site contour map if possible	Should be prepared before site survey			
		Corrosive or wet environment conditions	□ Good	□ Not good		
		Ground conductivity should be measured	□ Good	□ Not good		
			Ω			
12	Radio technical aspects	Coverage area	See attachment No:			
		Existence of nearby radio station including planned	□ Yes	□ No	Name:	
					Frequency:	
					Field strength:	
					Distance:	
					Remarks:	
		Nearby high power unwanted emitters	Transmitter name			
			Transmitter service			
			Frequency (MHz)			
			Field strength (dBµV/m)			
			Saturation or **i**nterference			
			Distance (km)			
		Natural/man-made noise sources	Threshold	µV/m, mV/m, dBµV/m		
			Acceptable noise level to determined	□ Yes	□ No	
		Measurements of wanted emitters and controlled emissions	See attachment No:			
13	Structural strength for antenna installation	□ Sufficient (provided with structural strength calculation)				
		□ Structural strength calculation required				
14	Receiver equipment room	□ Existing	See attachment No.			
		□ None	Room proposed			
			Remarks			
15	Structural strength for receiver installation	□ Sufficient (provided with structural strength calculation)				
		□ Structural strength calculation required				

16	AC power	□ Provided		
		□ Not provided	□ Alternative power source available:	
			□ No power source available	
17	Data communication media	□ Provided	Classification:	
			Cable route:	See attachment No.
		□ Not provided	Alteration:	
18	Required materials for installation	Antenna system		
		Receiver system		
		Removal of any		
		Grounding system		
		Obstruction height		
		Lightning protection		
		Special requirements if any		
19	Accessibility	Vehicle	□ Yes	□ No
		Heavy duty vehicle	□ Yes	□ No
		Parking lot		
20	Foundation work		□ Yes	□ No
21	Working environment	Working hours	□ No restriction	
			□ Restricted	
		Transporting equipment	□ No restriction	
			□ Restricted	
		Noise	□ No restriction	
			□ Restricted	
		Lighting	□ Not required	
			□ Required	
		Materials keeping space	□ Not available	
			□ Available	
		Working space	□ Not available	
			□ Available	
		Special condition		
22	Special requirements of proprietor	For installation		
		For installation work		

ANNEX 2

TO SECTION 2.6

Comprehensive evaluation report

Prepared by:	Date: / /
Site name	
Reference number of site survey checklist	
Result of evaluation	□ Good □ Good with condition □ Cancelled
Background of evaluation	□ Installation cancelled by proprietor’s refusal □ Inappropriate siting because of: □ Others
Remarks	

2.7 Maintenance, calibration and repair

This section proposes methods to enhance the readiness and availability of the monitoring station (and the overall monitoring system), it discusses the required support activities and needed tools for a long term reliable operation of the monitoring system. Modern computer controlled monitoring station based on digital equipments, and specifically digital receivers, is basically a reliable unit with much less measurement drifts and inaccuracy problems that were typical in the previous generation of monitoring equipments.

The verification and enhancement of station operability will be based on the following:

– Periodic and operator initiated use of a built in test (BIT) to detect failures of the station elements.

– Scheduled maintenance- tests and maintenance activities to be done at defined intervals (i.e. monthly and yearly), to verify and enhance the station long term operability.

– Calibration, if needed, may be considered as a specific repair activity.

– Repair – when a failure is detected and should be rectified.

Other important issues are discussed at the end of this section including: spare parts stock that should be available to the administration for a quick repair of a failure, software maintenance, and management of the system maintenance

2.7.1 General considerations

Information on measurement accuracy depends on knowledge of the measurement uncertainties in the methods applied. The required measurement accuracy is based on national and international standards and/or specified by the Administrations responsible. Measuring equipment is exposed during its use to a large number of factors that influence its specified technical parameters and change them over time. Regular examination, maintenance and calibration of the measuring equipment used are therefore essential. If the equipment is not regularly maintained, the probability of erroneous measurements and outages increases. If the values measured fall outside the permissible tolerances, the measuring equipment is to be promptly taken out of service and repaired.

When an item of equipment is brought into use a file should be established immediately comprising any papers relating to its purchase, guarantee, maintenance, calibration and repair. This equipment file should be linked to the equipment using a unique reference such as the serial or inventory number. Records of all repairs and calibrations for each item of equipment should be kept in the files, to create a life history for each item. Labels should be attached to the equipment clearly stating its unique reference, and also the date of calibration, calibration certificate number and next calibration date.

In order to ensure quality and compliance by measuring equipment with the accuracy requirements, a multi-stage system comprising the following checks is proposed:

– basic functional test before and after each measurement;
– enhanced functional test at regular intervals;
– maintenance at regular intervals by specially trained staff;
– calibration also at fixed intervals.

Test schedules and testing intervals to be laid down for each individual stage are essential for such a quality system. These schedules contain details of the measuring equipment data, the technical parameters to be tested, together with their nominal values and tolerances, and a checklist with instructions for carrying out the tests. The test schedule and instructions, list of components in measuring systems and test reports form part of the test manual belonging to each measuring equipment or system. The test date and tester's name are to be displayed clearly.

For the purposes of quality assurance, a staff member should be designated as having responsibility for quality whose tasks comprise in particular:

– maintaining a manual in which the procedures for maintenance and calibration are defined;
– ensuring that the test and maintenance schedules for each item of measuring equipment are drawn up and made available on time;
– monitoring compliance with the deadlines for testing, maintenance and calibration activities.

2.7.2 Functional tests

2.7.2.1 Basics

The basic functional test is directly related to each specific measurement task and is carried out by the measurement staff themselves at the beginning and end of each measurement or series of measurements. Only those technical parameters that are relevant to the measurement task are checked. For instance, before a field strength measurement the functionality of the equipment used to detect and display the measurement values is to be checked in respect of the frequency to be measured. The functional test documentation forms part of the measurement report (see § 2.2.5).

2.7.2.2 Built In Test capability

A built in test (BIT) capability that is based on system resources will verify the proper operation of the station; this BIT will be a central element in assuring the station operability.

The BIT activation may include three methods:

– Automatic BIT performance on Power ON.
– Automatic Periodic operation- every several hours, 24 h for example.
– Operator initiated (including possibility of remote execution initiation).

BIT results (of the automatic and operator initiated) may be available to the operator locally and remotely in the control station.

2.7.3 Enhanced functional tests

The enhanced functional test is carried out at fixed intervals by the measurement staff. It is not directly related to specific measurement tasks. The typical testing interval is between one and three months. The basis for the enhanced functional test is again a test schedule comprising details of the nominal values and permissible tolerances as well as instructions for carrying out the test itself. In contrast to the simple test, the enhanced functional test covers the entire operational range of the measuring equipment or system.

As far as possible, several items of measuring equipment should be grouped to form a system and tested collectively. The enhanced functional tests can thus cover the equipment at an entire test site or in a monitoring vehicle. The checks are to be documented in a test report that contains details of the nominal value, permissible tolerance and measured (actual) value for each parameter to be tested.

2.7.4 Scheduled maintenance

Normally a technical department supporting the monitoring service takes care for the maintenance of the (measuring) equipment. These activities are usually carried out in a dedicated workshop and not at the test site or in the vehicle.

The maintenance work differs from the functional tests in that it is considerably more thorough and comprehensive. The content of the maintenance schedules generally corresponds to the manufacturer's measuring equipment specifications.

A maintenance schedule is required for each measuring equipment or system, setting out the technical parameters to be checked, together with their nominal values and tolerances, as well as the maintenance instructions and intervals. The maintenance work carried out is documented in a relevant report.

The scheduled maintenance activities consists of more elaborated manually administered tests (relative to the BIT), that may use external test equipments and mechanical related preserving activities (such as lubrication of moving elements, cleaning and protection from dust and moisture, protection from corrosion and erosion).

The scheduled maintenance activities is usually done according to the relevant manufacturer instructions, by the manufacturer itself or his authorized local support agent under a comprehensive maintenance and support agreement.

2.7.5 Calibration

In order to be able to continuously ensure the absolute accuracy of the technical parameters of antennas and measuring equipment according to their specifications, recalibration of the equipment at regular intervals is necessary. Calibrated equipment guarantees that a value as measured is within the specified measurement uncertainty of the actual value. Measurement uncertainty can be provisionally defined as that part of the qualitative expression of the result of a measurement that states the range of values within which the true value is estimated to lie. The range limits should be associated with a specified probability. For example, the result of a field strength measurement might be expressed as 30 dB(μV/m) ± 2.5 dB (with 95% confidence), which means that one can be 95% confident that the true value of the field strength lies between 27.5 and 32.5 dB(μV/m).

In contrast to the functional tests and maintenance, calibration traces the technical parameters such as frequency and signal level, with a defined absolute accuracy to national or international standards through an unbroken chain of comparisons.

Reference standards may only be used for calibrations. National or international calibration authorities or their subordinate organizations calibrate them preferably. Where this is not possible, the calibration laboratory tasked must state in writing its procedure for achieving traceability. Approved mathematical/physical procedures must apply to standards that are not directly traceable to national or international standards. Traceability works because there is a fixed relation between every standard within the calibration hierarchy and the national standard. Each working standard is regularly compared with the reference standard of the same level, and the latter is in turn compared with a reference standard of the next higher level. This leads to an uninterrupted calibration chain, which has a decisive advantage.

Monitoring stations use a relatively large number of specialized equipment in order to carry out the various measurement tasks. The parameters most frequently measured include frequency and field strength, using antennas, receivers and spectrum analyzers. Hence the focus should also be on the calibration of the frequency, signal level and antenna gain; measurements where these values are of legal significance should be carried out only with calibrated antennas, receivers and spectrum analyzers. The reverse conclusion is that there are, however, also measurements that can be carried out with uncalibrated equipment. It is therefore necessary to determine which equipment must be calibrated in the first place.

It is not possible in all cases to calibrate measuring equipment. This applies in particular to a large number of antennas. In such cases, it is of particular importance to record reference values when putting the measuring equipment into operation, since the measurement uncertainty is at its lowest at this point in time and can serve as a reference in the functional tests and maintenance work.

It is not possible to calibrate DF systems in a laboratory. However, to maintain the accuracy of the DF regular, bearings of known transmitters in various frequency bands should be taken. Substantial deviations from prior results are an indication of possible defects.

In the case of measuring systems, it is often only possible to calibrate individual components such as receivers. Possible errors owing to other components in a measurement set-up, such as antenna feeds and antennas, must also be taken into account when assessing the measurement uncertainty.

Each calibration is to be documented in a detailed calibration report to accompany each item of equipment. The calibration report contains full documentation of the measurements made, including the values measured. Each item of equipment must therefore be reliably and permanently marked or labelled, etc. to indicate its calibration status. The calibration reports are incorporated in the equipment file when the equipment is put back into service.

It is not possible to specify a standard calibration interval. Intervals of one year are common. There is, however, no generally applicable period. The calibration interval should be chosen from a technical viewpoint by assessing the varying measuring equipment characteristics.

Calibration places high demands on the technical equipment used. This equipment cannot generally be provided by a monitoring station’s normal workshop. The expense of installing and maintaining a calibration laboratory within the authority can be justified only in large organizations, since only they have larger numbers of equipment that continuously enable full utilisation of the calibration laboratory’s capacity.

In many cases it makes more economic sense to outsource calibration of the equipment to either the manufacturer or an external calibration laboratory. This eliminates the need to set aside resources for premises, equipment and trained staff.

Some manufacturers of spectrum monitoring equipment who market and sell their products worldwide also operate regional service and support centres at various locations around the globe. These centres are equipped with, amongst other things, portable calibration sets and standards. A calibration team is paid to check and calibrate the radio monitoring equipment at regular intervals. Calibration issues related to specific systems (such as radio direction-finders) are discussed in more detail in other sections of the Handbook covering those systems.

2.7.6 Repairs

Measuring equipment outages owing to technical defects or deviation from the permissible tolerances cannot be prevented. In order to ensure smooth measurement an operation, a repair service is to be organized that is able to react quickly and provide replacements. Technical staff responsible for installing and maintaining equipment forms a vital part of every monitoring service. Constructing minor electronic or mechanical devices and locating faults is also part of their job. Setting up an internal workshop guarantees short routes and rapid response times, and largely reduce the need for replacements spare parts to be kept.

However, it is often not worth smaller monitoring stations having their own workshop with comprehensive repair facilities. In this case, a central workshop serving several monitoring stations or contracts with manufacturers[(1)] or authorized specialists are better and more economic alternatives. Central and external repair services generally mean that more replacements spare parts are needed to be kept in order to ensure smooth operations.

NOTE 1 – In some occasions, in addition to repairs, suppliers of the equipment may also maintain it.

2.7.7 Spare parts

In order to ensure the continuous operation of monitoring stations, it is proposed to keep a stock of essential spare parts recommended by the equipment manufacturer. Due to cost considerations, spare parts lifetime and for the small administrations, it is not advisable to maintain a whole lot of spare parts.

2.7.8 Software maintenance

Software modification and repair of a complex package as needed for the implementation of a Spectrum Monitoring System calls for professional support, hence it is recommended to use software maintenance service from the supplier/manufacturer of the system.

System administration, namely setup and changes of various operational parameters and management of saved data (such as measurement results) should be supported locally by the administration IT (Information Technology), personnel or authorized local support agent of the supplier/manufacturer of the system.

Management of the system maintenance

It is recommended to keep track of maintenance activities by a dedicated logging of relevant information.

The maintenance log may include:

– Status of the spare parts (ready in stock or faulty in a repair process).

– Follow up and register of scheduled maintenance activities.

– Failure detection reports and follow up of the corrective actions (for hardware and for software).

– For each equipment item the Administration will keep a history file with relevant maintenance activity and repairs. The data in this file will enable statistical analysis of the equipment operation and reliability.

As a rough estimation, the scope of the overall yearly maintenance (spare parts, repairs, schedule maintenance) and support to a monitoring system is on the order of 10% of the cost of the establishment of said system.

2.8 Personnel

2.8.1 General

In spite of the automation of measurements as made possible by processors, the most important – and in many countries most expensive – resource remains personnel. Careful planning is needed in order to guarantee the continued availability of an adequate number of properly qualified staff.

The number of staff and the qualifications required depend on a variety of factors, including the tasks of the monitoring service, the degree of automation of the technical facilities, and the number of sites and vehicles.

The age structure of the personnel should provide older staff with long-standing experience in the field of radiocommunications and younger staff with up-to-date IT knowledge. With only older, experienced workers, the monitoring service would risk losing its expertise within a short period of time owing to staff retirement. Equally, it would make little sense to have only young workers with up-to-date IT know-how but no experience in the field of radiocommunications and wave propagation. In addition, a mixed age structure has an advantage in that staffs have opportunities for promotion.

2.8.2 Categories of personnel

The personnel of a monitoring service can be categorised as follows:

– management;

– operators;

– technical/maintenance service;

– clerical staff.

2.8.2.1 Management

The personnel with managerial tasks include monitoring station managers and staff responsible for fundamental decisions relating to the organization and facilities of the monitoring service. The management staff needs skills in the following areas:

– structure and procedures within the administration;

– operational procedures and technical knowledge in the monitoring stations and equipment;
– Radio Frequency technology;
– economic interrelationships;
– law.

Station managers should have preferably worked as operators or technical staff at monitoring stations.

2.8.2.2 Operators

Operators perform the monitoring tasks and need to be familiar with the administrative regulations for radiocommunication services as well as the technical equipment. In view of the increasing use of automated monitoring systems and software, they also need IT know-how. Both engineers and technicians are therefore suitably qualified to work as operators, gaining specialized knowledge of the radiocommunication sector mainly through on-the-job training.

2.8.2.3 Technical/maintenance service

Appropriately qualified operators may occasionally perform technical tasks, including installing and maintaining equipment, in the smaller stations and vehicles. However, it is more practical to have separate staff so that operators can focus on their monitoring tasks. Staff that is only responsible for maintenance do not need any special knowledge of the individual radiocommunication services.

2.8.2.3 Technical/maintenance service

Appropriately qualified operators may occasionally perform technical tasks, including installing and maintaining equipment, in the smaller stations and vehicles. However, it is more practical to have separate staff so that operators can focus on their monitoring tasks.

2.8.2.4 Clerical staff

Clerical staff must be familiar with standard PC software, including word processing and spreadsheet programmes.

2.8.3 Training

2.8.3.1 Introduction

Quality can only be created by staff who are properly trained and motivated. Training is therefore essential to prepare staff for their duties. It widens their knowledge, complements their skills and refreshes their background.

The technology of radiocommunication systems and hence of spectrum monitoring equipment is evolving rapidly. Considering that the issues at stake are also changing rapidly, it is necessary to take into account the changes in national and international regulations, too; these changes strongly affect, directly or indirectly, spectrum monitoring activities. Training must therefore be understood as a continuous, open-ended process.

2.8.3.2.1 Identifying requirements and planning the course

Training requirements can be defined as the difference between the target and the actual qualifications that the staffs possess. Before identification can take place it is therefore important to clearly define the workplace requirements, to make an objective assessment of actual qualifications, taking account of future requirements as well. In one-to-one talks with staff, managers should find out what training requests/wishes exist and establish the requirements accordingly. Training is a management function.

As far as planning is concerned, it is important to pinpoint the deficit and to define the knowledge and skills that the course is to impart. Only when this is done can “training tourism”, bad investment and poor motivation be avoided.

Afterwards the following questions must be answered:

– What are the aims and content of the course, what knowledge and skills are desired to be imparted?

- What qualifications do the participants already have in this field? (Among the spectrum monitoring staff a wide range of educational degrees can be found.)
- Is the course intended to start from scratch, to provide retraining, to be a refresher course or to lead to a special qualification?
- Is it to be a technical, an IT, a foreign language, an administrative or a management course?
- Does the organization have suitable staff of its own to hold courses, or should this be done by private companies, consultants or manufacturers?
- What media/teaching aids (paper, videos, simulators, exercises, interactive software, etc.) are to be used?
- Are syllabuses and course material available?
- What is the maximum number of participants for training to be effective?
- Does the course need to be held in a particular place?

Once these questions have been answered it can be decided whether in-house or external training is appropriate, how long the course should last, what the timetable should be and who will compile the course material. Often it is not possible, however, to provide training on the scale required because of, budget constraints. In this case priorities must be set, whereby a consensus should be sought with all concerned.

As soon as the planning has been finalised, instructors and instructees should be given timely notification in order to make their preparations.

2.8.3.2.2 Review and evaluation

The review and evaluation is a very important step in the process. The importance of this step is sometimes underestimated. At the end of the course it should be checked whether the course was carried out as planned and whether the goals were achieved. For this purpose participants should complete a questionnaire assessing the training received. The following questions, for instance, could be asked:

- Was the course helpful for your day-to-day activities?
- How do you rate the material provided?
- How do you rate the instructors?
- How do you rate the technical/specialist content?
- Was the course well organized?
- How do you rate the venue?
- How do you rate the course overall?
- If you had to prepare and hold the course yourself, what would you do better?

The evaluation could also include a poll of participants after about three months, inquiring whether they had been able to use what they had learnt, whether they had passed on to their colleagues what they had learnt and whether they considered the course aims had been achieved.

2.8.3.2.3 Correction measures

The assessment input provided by the participants and their superiors, too, feeds into the planning of further courses. This closes the circle.

2.8.3.3 Training methods and implementations

There are different possibilities how to implement the training. Some Administrations do the training by themselves with their own facilities and staff. Others prefer to hire private companies, consultants or manufactures to perform the training.

Besides attending theoretical and practical courses, including the use of simulators and interactive software, it is essential for the personnel to read books, articles, documentation and ITU-R Handbooks, Reports and

Recommendations; exchange information and experience with other colleagues, both national and from other Administrations, is important

As part of the overall training strategy on the job training is the most effective and frequently used form of training for new staff. It is a key method to preserve the know-how of the department. Yet it is not enough simply to assign new members of staff to an experienced colleague and trust that all will be well. It is the responsibility of the manager to plan on the job training and to monitor progress.

2.8.3.4 Skills required of the spectrum monitoring staff

The radio monitoring service has to cope with a wide range of radio services, systems and administrative procedures. This includes the need for updated knowledge (e.g. digital modulation schemes) and the preservation of already existing knowledge (e.g. analogue modulations). There are differences between countries in respect of their legal systems, administrative structures, educational systems and frequency management systems, for instance. Also, the skills required of the spectrum monitoring staff depend on their specific tasks. Hence it is not possible to specify a common, comprehensive syllabus for the skills required.

For this reason, the items listed in Annex 1 are only suggested theoretical and practical items for inclusion in training programmes and courses directly relevant to spectrum monitoring staff. A theoretical basic knowledge of mathematics, physics and language, along with a fluent ability in calculations in logarithmic units is assumed.

2.8.3.5 Worldwide available training facilities for radio monitoring

Training is very much connected to the actual type of equipment, which can be significantly specialized; however, it is worth mentioning here below some institutions and industrial facilities that offer training in the field of radio monitoring.

As a means of promoting and developing monitoring systems, the Administrations of Australia, France, Germany, Italy, Japan, Portugal, the United Kingdom and the United States of America have offered in Resolution ITU-R 23 (Note 1) to receive monitoring officials from other Administrations. South Korea is also inviting monitoring officials from other administrations. Initial contact to arrange such training may be made to the appropriate Central Office as defined by RR Article 16 and as shown in List VIII (List of Monitoring Stations) published periodically by the ITU.

Manufacturers such as Rohde & Schwarz (Germany); THALES (France); TCI, an SPX Company (United States of America); Tadiran Electronic Systems (Israel); and Agilent Technologies (United States of America) also provide training.

2.8.3.5.1 Training facilities in the United States of America

Within the United States of America, the United States Telecommunications Training Institute (USTTI) has been offering training opportunities in radio monitoring and related spectrum management activities since 1983, after the Institute was launched at the ITU Plenipotentiary Conference in Nairobi, Kenya. Each year the USTTI offers a number of courses related to radio monitoring, radio spectrum management, or radio measurements:

– Radio frequency spectrum management (each spring).
– Spectrum management in the civil sector (each spring).
– Radio spectrum monitoring and measuring (each spring).
– Practical applications of spectrum management and spectrum monitoring (each spring).
– Radio spectrum monitoring techniques and procedures (twice a year, once each spring and once again in the summer).
– Laboratory techniques in support of equipment authorisation programmes (each fall).

In addition to these opportunities, as described below, U.S. companies sponsor USTTI wireless radiocommunication courses, which may contain elements of spectrum management. Details of these are available in the USTTI course catalogue, published yearly. Training under the aegis of the USTTI is tuition-free.

USTTI course on radio frequency spectrum management: this course, lasting two weeks, is intended to help develop trained spectrum management technical staff that is able to carry out daily and longer-term activities in implementing new systems and technologies.

USTTI course on spectrum management in the civil sector: this course, lasting two weeks, is intended to provide information and material for the national civilian telecommunications spectrum manager to enable logical, spectrum-related decisions that are well grounded in basic technical procedure.

USTTI course on radio spectrum monitoring and measuring: this course, lasting one week, is specifically designed as a follow-up instruction to the course on Spectrum Management in the Civil Sector, a prerequisite for this course. It is for those with particular interest in radio monitoring and measuring techniques.

USTTI course on practical applications of spectrum management and spectrum monitoring: this one-week course focuses on the practical application of ITU-compliant spectrum management and monitoring techniques, including licence processing, engineering analysis tools, radio direction finding and signal measurements, and emphasising automatic violation detection and other benefits that accrue from the use of an integrated and automated management and monitoring system. The course also covers the objectives of and international organization for spectrum management and monitoring. More information on this course can be obtained from its sponsor, TCI, an SPX Company.

USTTI course on radio spectrum monitoring techniques and procedures: this course provides basic, practical instruction in the procedures of off-the-air technical measurements and radio direction-finding for frequencies in the 30 MHz to 3 GHz range. USTTI course on laboratory techniques in support of equipment authorisation programmes: this one-week course is intended to give participants hands-on training and experience in a functioning laboratory environment in making technical measurements, and in the testing and calibration of telecommunications equipment.

2.8.3.5.2 International training programme for spectrum monitoring in Japan

The Ministry of Public Management, Home Affairs, Posts and Telecommunications (MPHPT) has international training schemes for spectrum monitoring.

This international training programme is executed by JICA (Japan International Cooperation Agency) for the developing countries in cooperation with MPHPT every year. This programme is operated by ODA (Official Development Assistance) of Japan. More detailed information can be obtained from MPHPT or JICA.

2.8.3.5.3 International training programs of radio monitoring in Korea

Korea Communications Commission (KCC) has been providing the developing country with international training programs to facilitate development of radio monitoring theories and techniques. International training programs are structured by KISA (Korea Internet and Security Agency). The programs include items in the radio monitoring and spectrum management. This training has been mainly planned for government officials and technicians in the developing countries.

Korea Internet & Security Agency (KISA) radio monitoring program

The course on Radio Wave Management Policy is composed of spectrum management policy and monitoring technologies. This course is designed to introduce new technologies on radio monitoring. Most items are theories and techniques of new RF systems, such as intelligent radio monitoring system in Korea and direction finding theories and systems.

The course on Radio Monitoring Management instructs radio monitoring techniques. The course introduces new RF technologies, overviews radio monitoring technologies, details radio spectrum measurements and describes trends of radio monitoring technologies. This course contributes RF knowledge and techniques to human resources. To promote advanced technology in the radio monitoring CRMO (Central Radio Management Office), under KCC, supports the training program with lecturing, introducing the radio monitoring facility and discussing the radio monitoring issues in the site.

The program schedules and participant application requirements are published on the Web sites, (www.Koalp.org) and notified to administrations prior to arrangement. The proposed courses are free of charge.

ANNEX 1

TO SECTION 2.8

Aspects of spectrum monitoring training

Organizational and general

– Structure, functions and common procedures.

– Structure, functions and procedures of the national organizations relevant to frequency management and monitoring (e.g. aeronautical authority, maritime authority, police).

– Structure, functions and procedures of the relevant regional and international organizations.

Regulatory Frameworks

– Laws applicable.

– Ordinances.

– Agreements.

– Regulation and standards.

Spectrum management

– Spectrum allocation tables, national, regional and ITU Radio Regulations.

– Frequency assignment and licensing procedures.

– Designation of emissions.

– International Frequency List (IFL).

– Call signs.

– Frequency re-use concept.

Basic radio theory

– Radio services, systems, and applications.

– Propagation of electromagnetic waves, free space loss, effects of multipath propagation, link budget calculations.

– Antennas: theory, types and techniques in each frequency range, antennas for monitoring stations.

– RF Transmitters including unwanted emissions.

– Receivers: spectrum monitoring receivers, noise factor and signal to noise ratio, noise temperature; sensitivity and immunity, intercept points.

– Modulation techniques, necessary bandwidth.

– e.i.r.p. calculations and computer programs comparing measured to calculated levels.

– Fourier Transform and Fast Fourier Transform (FFT).

– Filtering and shielding.

Measurement procedures

– Frequency, frequency offset, frequency deviation.

– Occupied bandwidth, spurious and out of band domains.

– Field strength and power flux density (PFD).

– Radio direction finding, quality of triangulation.

– Identification of stations.

– Selection of measurement points.

– Registration, analysis, decoding.

Practical aspects

- Reporting and data presentation including the production of reports of infringement and harmful interference, in compliance with the RR.
- Procedures to identify TV interference sources, distinguishing between a faulty or wrongly tuned TV set, a spoiled amplifier power supply, a damaged cable or antenna joining, a damaged or saturated antenna amplifier, a multipath antenna orientation, an AM interfering emission, an FM interfering emission, industrial, scientific or medical apparatus in the vicinity, Short Range Devices, other electronic devices, etc.
- Procedures to identify possible elements where an intermodulation product is generated, as a faulty contact, etc.
- Procedures to monitor various radio services.
- Selection of measurement points for mobile monitoring stations.
- Recognising and reducing RF interference; main measures to be taken against harmful interference.
- Aural identification of signals.
- Finger print measurements.
- Recognition of spread spectrum systems such as Frequency Hoppers and Direct Sequence.
- Use of spectrum analyzers.

CHAPTER 3

MONITORING EQUIPMENT AND AUTOMATION OF MONITORING OPERATIONS

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3.1 Introduction

3.1.1 General considerations

The equipment available at a radio monitoring station should be suitable to perform the measurements required at that station. The measurements are derived from the tasks that the station has been assigned. These tasks in turn depend on the purpose and goals of radio monitoring within the country as covered in §§ 1.3 and 2.3. The nature and quality of the measurements will determine which types of equipment are necessary.

A monitoring station that will take part in the international monitoring system must be able to carry out the measurements with an accuracy that complies with the technical standards for monitoring stations contained within the relevant ITU-R Recommendations. Where applicable, these Recommendations are mentioned in §§ 3.3 to 3.5. Other characteristics of the equipment should meet the minimum criteria as stated in the relevant parts of §§ 3.3 to 3.5. Particular attention should be paid to provide recommended linearity for measurement receivers and active antennas as discussed in § 3.1.2 and to take into account the effect of the environment, such as surrounding metallic structures.

For a monitoring station, a minimum set of equipment would be a receiver and an antenna system for the frequency range of interest. A rotatable directional antenna can provide coarse bearing information. Basic frequency and field-strength measurement capability is also required and may be provided by using a calibrated receiver and antenna.

This system could then be supplemented by the addition of a process controller to provide automation of some basic measurement tasks and direction-finding (DF) equipment for azimuth bearing information. Most monitoring stations use automation to relieve the operators from performing time-consuming, long-term measurements such as conducting spectrum occupancy measurements.

The most sophisticated monitoring systems consist of a hierarchy of national, regional, remote and mobile monitoring stations networked together in real-time to provide integrated control of multiple stations from a single operation console. This type of system is computer-and network-based, using sophisticated software to relieve the operators of tedious tasks and greatly increase measurement speed. It also increases equipment utilization by allowing background tasks, such as searching for unlicensed transmitters, to be automatically executed when the equipment is not required for other purposes.

A block diagram of a modern, integrated monitoring station with minimum equipment is shown in Fig. 3.1-1. The station uses receivers covering frequencies from 9 kHz to 3 000 MHz or higher to provide basic measurement functionality for frequency, field strength, modulation analysis and DF. The control unit allows measurements such as spectrum occupancy to be made over time. A database containing licensing and technical information or a direct interface to a spectrum management system database is provided. This technical database includes technical information on licensed stations and their parameters, which allows an integrated station to identify frequencies on which there are transmitters that are not included in the database and therefore are presumably unlicensed, and to identify transmitters that are not operating within their licensed parameters.

It should be noted that the overall accuracy of radio monitoring systems depends not only on specifications of individual components such as receivers and antennas. Relevant parameters such as linearity, sensitivity, azimuth accuracy and field strength accuracy may also be influenced by the type and length of the cables between the system components as, well as by environmental conditions.

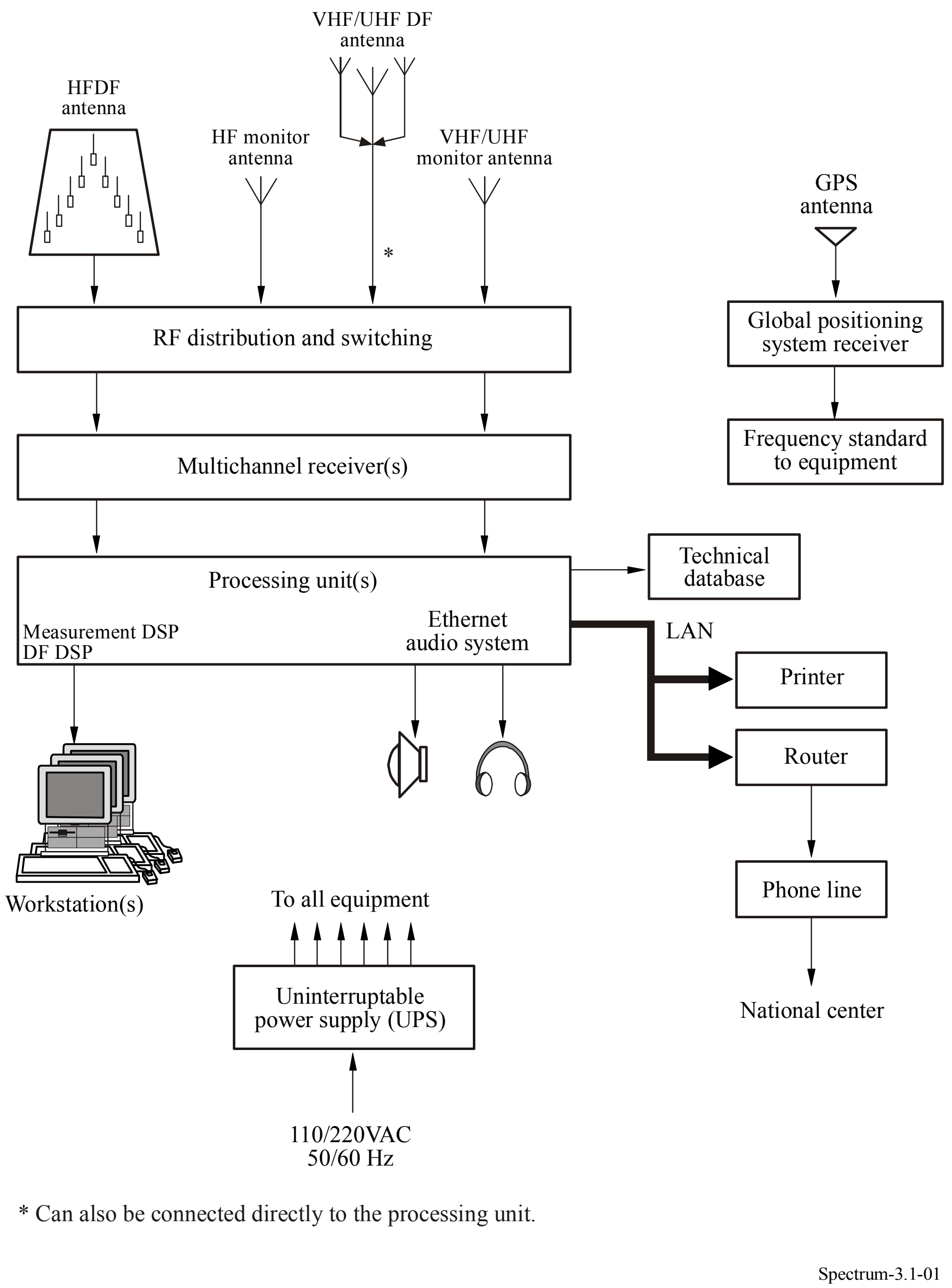
3.1.2 Influence of interference environment

Ideally, monitoring stations should be placed at sites where monitoring is not interfered with by transmitters close by, or by high-voltage lines or microwave links passing across the site. Further, once a site is selected, or more importantly, once monitoring operations have started, the site should be protected by means such as frequency planning.

Since the aforementioned principle cannot always be observed, the antennas and receivers of spectrum monitoring stations generally operate under interference conditions that are generally far more rigorous than those experienced by ordinary communication-receiving antennas and receivers. The working frequency, location, antenna height and azimuth, etc., of a fixed-service receiver are specially selected at the frequency assignment stage such that the receiver in question is adequately protected (by providing an appropriate frequency and a geographical separation between radio stations based, in particular, on the given parameters of the antenna and receiver) from the effects of interference from transmitters of other radio links. Every effort is made therefore to maintain such protection *vis-à-vis* all new frequency assignments.

FIGURE 3.1-1

Block diagram of an integrated monitoring station



Spectrum monitoring station antennas should ideally be set up on a raised point surrounded by open space to ensure that signals are received from the greatest possible number of monitored transmitters within a wide service area and for all azimuths. It often happens that monitoring stations are located in cities close to powerful transmitters – including those used for sound and television broadcasting – with high antennas, or that such power transmitters are installed close to existing monitoring stations. In such cases, little or no attention is ever paid to the question of observing the frequency and geographical separation requirements that are a fundamental feature of frequency planning for communication radio facilities. As a result, monitoring station antennas and receivers generally have to operate under far more rigorous interference conditions than other radio facilities. This imposes special requirements in terms of the parameters characterizing the intrinsic protection of receivers and active antennas against the effects of potential interference.

These requirements concern parameters such as receiver selectivity and linearity (second-and third-order intercept points), IF and image frequency rejection, receiver dynamic range and linearity (second-and third-order intercept points) of active antennas and their protection from interference (damage threshold). The above, to a large extent, determines the ability of the spectrum monitoring station equipment as a whole to perform measurements and DF under arduous uncontrolled interference conditions. If, as a result of insufficient protection due to a failure to observe the requirements indicated in §§ 3.2 and 3.3, the antenna and/or receiver is affected by interference, both the measurement of certain (or all) transmitter emission parameters and DF operations can be subject to significant errors; in other words, the data will be unreliable or may simply be unobtainable. Therefore, when antennas and receivers with inadequate characteristics are used, the large sums spent on setting up the spectrum monitoring stations and networks may have been wasted. The influence of interfering signals usually appears as intermodulation and/or blocking. The mechanisms of these phenomena are considered in § 3.3.2.

In the light of the foregoing, it is recommended to avoid the use for spectrum monitoring purposes of standard receivers that do not satisfy the full set of requirements laid down in §§ 3.2 and 3.3.

Results of measurements and DF at the site are also greatly influenced by other antennas and surrounding metallic structures; this subject is discussed in § 3.2.5.

3.1.3 Man-machine interface

Manual operation of equipment, including receivers and maintenance equipment, and the interactive operation of systems, is often required to conduct monitoring station tasks. Also, for the operation of automated spectrum monitoring systems described in § 3.6, certain guidelines concerning man-machine interface should be observed.

General guidance is given by IEC 447/4.93: Man-machine interface (MMI) – Actuating principles.

3.1.3.1 Basic principles

The application of actuating principles, disposition and sequence of actuators should be applied in an unambiguous manner, especially for monitoring stations where operators have to carry out various tasks with equipment of different origin. It should take into account the working speed required, ergonomic aspects and the required level of prevention of unintended operation.

Actuators shall be unambiguously identifiable, it shall be possible to execute a command only through the intended operation of an actuator (this limits the application of double-function actuators), the method of dialogue used should take into account ergonomic aspects relevant to the task.

To avoid operator errors, the application of the following measures is recommended:

– defined command priority;

– simplification of actuator operating sequence (e.g., through automation).

The arrangement of actuators shall be logically grouped according to their operational or functional correlation. One or more of the following grouping principles can be used:

– by function or interrelationship;

– by sequence of use;

– by frequency of use;

– by priority.

3.1.3.2 Actions and effects

As far as possible, the necessary action of the actuator should be correlated to the required final effects, according to the operating direction or to the relative location of an actuator. Final effects can be classified into increasing effects and decreasing effects.

Principally, there are two different methods to perform opposite actions by using:

– one actuator with two operating directions (e.g., a hand wheel or tuning knob);

– a set of, e.g., two actuators (e.g., push-buttons), each with only one operating direction.

Some operators prefer, especially for the setting of the frequency of a receiver and for volume control, to use tuning knobs. Thus, the correction of the frequency while listening to the audio signal with volume setting at the same time can be done in an easy way. Sufficient separation between the two knobs is required for two-hand operation.

3.1.3.3 Actuator identification and feedback requirements

Visual, audible or tactile information/feedback will help to improve the man-machine interface. The reaction/effect of the actuator action should be immediate, any delay might cause erroneous actions by the user. Examples are:

– A light-emitting diode (LED) may be used to indicate that a switch has been set to ON (LED colour preferably amber or green).

– Each change of a setting (e.g. frequency, bandwidth, attenuation) should be indicated immediately on a display.

– Displays should be easily readable both in sunlight and in a dimmed room.

– In most cases, an audible feedback other than the one coming from the loudspeaker is inadequate, since it may interfere with the audio signal.

– A loudspeaker should preferably be mounted on the front panel of a receiver, since the phone jack may switch it off.

– A panoramic spectrum display helps for frequency tuning and for orientation when interfering effects disturb the reception. Ideally the display should be of the real-time type with the possibility of digital storage for maximum hold. When a minimum hold is added, intermittent signals can easily be discovered among continuous emissions.

– When tuning of the frequency is done in discrete steps using a tuning knob, it has proven to be very useful to have a tuning knob with magnetic locking, which gives a tactile feeling for each step while preventing unintentional detuning caused by e.g., vibrations. On the other hand, magnetic locking combined with a flywheel permits fast tuning.

– Digital processing of the information step should provide acceleration with increasing tuning speed. A combination with a set of keys allows quasi-continuous tuning with the tuning knob and tuning from channel to channel, this by using a combination with two actuators as described above.

– It is advantageous to have an analogue reaction with manual tuning by e.g., a level and a tuning meter, especially when no panoramic spectrum display is available. An analogue meter helps e.g., to direct an antenna to the direction of maximum reception.

3.1.3.4 Computer interface

Instead of each instrument having its own individual user interface, a user interface can be created using computers, software and remote-controlled equipment as discussed further in § 3.6. This user interface allows access to the controls of each instrument in a similar way, reducing operator training. Examples of such user interface, use menus and dialogue boxes, or graphical representation such as icons and symbols. This technique is particularly powerful when the operator for practical tasks can customize it, allowing flexibility in addressing mission and processing methods.

3.2 Monitoring and measurement antennas

3.2.1 General considerations

The purpose of receiving antennas is to extract the maximum possible signal from the environment and to apply this signal to the input of the receiver, while at the same time minimizing the pick-up of noise and interfering signals. The specific characteristics of a monitoring antenna will be determined largely by each particular application. When a monitoring antenna is chosen, consideration must be given to such factors as the properties of the desired signal, the parameters intended for observation, the characteristics of the installation site and any interference that may be present.

For the best reception results, antennas should have a polarization corresponding to the polarization of the arriving signal wavefront and should provide matching of the impedance of the transmission line and receiver input circuits, so as to ensure the maximum transfer of power. Omnidirectional reception patterns have proved useful for general monitoring or for radio-frequency spectrum determinations. For the observation of a particular signal on shared frequencies, it may be desirable to use a directional antenna, which either nulls one or more of the interfering signals, or maximizes the desired signal. A mobile unit is also useful in separating shared frequencies by driving closer to the antenna radiating the signal of interest. For some types of observations, such as studies of field strength, it is considered necessary that the properties of the antenna used be accurately predictable with respect to frequency response and be invariant with time. A mobile unit with calibrated antennas is able to provide a measure of average field strength in a given area. Since no one type of antenna has all the properties necessary for efficient reception of all types of signals, a number of different antennas will generally be required at monitoring stations.

Descriptions of the various types of antennas for specific applications are given in the following paragraphs, categorized by frequency band.

3.2.2 Suitable antenna configurations

The properties of electromagnetic waves, including wavelength, resonance, and signal and noise propagation, help determine choice of antennas in relation to:

− Directivity and gain, which are the main technical parameters of antennas. Antennas may be divided into two groups: omnidirectional antennas (where the azimuth radiation pattern is essentially circular) and directional antennas. Omnidirectional antennas may be used for general tasks of monitoring when the transmitter position is not known (occupancy rates, scanning), while directional antennas may be used for specific tasks (technical measurements) when better sensitivity is needed.

− VLF, LF, HF, VHF, UHF or SHF frequency bands.

− Size and weight may be considered when choosing an antenna, depending on the type of monitoring station: fixed, mobile, transportable or portable.

3.2.2.1 Monitoring tasks associated with omnidirectional antennas

Omnidirectional antennas are suited for the following monitoring tasks:

– unknown transmitter search;
– spectrum occupancy;
– band or frequency scanning;
– DF;
– automatic missions.

Omnidirectional antennas are also well suited for:

– technical measurements (field strength, bandwidth and frequency measurements), when the antenna factor is known;
– monitoring of a moving transmitter;
– identification and analysis of mobile or cellular networks services.

3.2.2.1.1 VLF/LF/MF/HF bands

For these frequency bands, the wavelength is very long and it is not practical to have antennas of a size of the order of a quarter wavelength, which would give maximum antenna sensitivity. Active antennas could be used, but they have lower linearity due to intermodulation.

Fixed stations:

Fixed radio monitoring equipment has fewer size and weight limitations and therefore can employ higher performance antennas. Fixed monitoring stations should be installed in rural areas away from cities and where adequate land areas are available to accommodate all of the antennas needed.

Fixed VLF/LF/MF/HF monitoring stations are very important for long distance signal analysis and high power transmitter analysis, including monitoring near borders or in large countries, DF, and single station location (SSL), where a single station can measure elevation and azimuth angles and use ionospheric information to locate a transmitter.

Suitable omnidirectional antennas at such stations include:

– An antenna system that will provide omnidirectional vertically-polarized reception over the short-wave frequency range (2 to 30 MHz). This system could consist of one large antenna such as a wideband inverted conical antenna, several conical monopole type antennas that overlap in frequency, or an active antenna.

– At least one omnidirectional active antenna system providing both vertical and horizontal polarization or the possibility of polarization diversity reception and covering the frequency range between 9 kHz and 30 MHz, especially if space and/or economics are limiting factors.

– One long-range, wide-aperture DF array that could be from 50 to 300 m in size, to provide directional bearings. Antennas could be either omnidirectional or directional. Other monitoring stations can provide additional bearings and the transmitter location can be determined by triangulation. (Frequency range from several 100 kHz up to about 30 MHz.)

Mobile stations:

Antenna size is the principal limitation for VLF/LF/MF/HF mobile monitoring stations. Such stations allow for:

– Measurement results when moving near the transmitter. For example, whereas a fixed monitoring station may not be able to perform an accurate measurement because the S/N is too low, a mobile monitoring station can be driven near the transmitter to increase the S/N.

– An additional line-of-bearing (LoB), in association with a fixed monitoring station, to increase location accuracy.

Size limits considerably the choice of such antennas:

– Short monopole (whip antennas).

– Dipole (centre-fed).

– Magnetic loops.

– Active antennas.

3.2.2.1.2 VHF/UHF bands

Antenna size is less critical in these bands (except for the lower VHF band where the dimensions of the antenna have a direct impact on the sensitivity). Fixed and mobile antennas have similar characteristics; the main difference is the position of the antenna and the ability to put it on the top of a mast.

The types of omnidirectional antenna encountered in these bands include dipole, conical or biconical antennas. Directional antennas may also be used, such as those for DF systems.

Fixed stations:

A main advantage of a fixed monitoring station is the possibility to raise the antenna to the top of a high fixed mast in order to increase line-of-sight (LoS) for more distant transmitters than it would be possible from a mobile station. In the use of such antennas in cities, it is important to try to minimize multipath due to building reflections.

Omnidirectional antennas are useful for general monitoring near the fixed station and for coverage of large areas, especially for automatic tasks. Physically larger omnidirectional antennas are also required for a better sensitivity in the lower part of the VHF band.

If a fixed station is located in or near a metropolitan area, one vertically and one horizontally polarized medium gain omnidirectional general purpose monitoring antenna system can be used. A small improvement in sensitivity can be achieved by using a rotating high-gain log-periodic cross-polarization (vertical and horizontal) antenna system for the frequency range(s) required. It is generally more cost effective to increase the height of an omnidirectional antenna because VHF/UHF propagation is LoS.

Mobile stations:

In the VHF/UHF bands, omnidirectional, conical or biconical antennas are well suited for mobile use:

– Low size and weight, associated with good performance, means they are a good compromise for installation on a vehicle.
– Antennas that allow for monitoring and DF homing while driving.
– Their low weight allows them to be placed on top of an erectable mast, improving coverage area and minimizing influence of low obstacles.
– They can perform monitoring in cooperation with fixed monitoring stations. For example, when fixed monitoring stations intercept a signal with low S/N, the mobile monitoring station may give better results by moving near the transmitter.
– They allow monitoring where fixed monitoring stations cannot be deployed. Since propagation for the UHF band is more LoS, coverage with fixed monitoring stations is often impossible.

These monitoring stations are useful for cellular network monitoring:

– small size of cells favours the use of mobile monitoring stations;
– received signal levels do not require high sensitivity antennas.

Portable/transportable stations:

The advantages of such monitoring stations are the same as for mobile monitoring stations. Portable and transportable antennas may also be used in the following tasks:

– monitoring from the top of buildings. Mobile monitoring stations are often disturbed by multipath and portable monitoring stations may provide a solution to lower the effect of multipath;
– monitoring from the countryside, to put the monitoring station at a high level or at a remote point which a mobile vehicle cannot reach;
– for measurement from a specific point or from a building (school, hospital).

3.2.2.1.3 SHF band

In the SHF band, some omnidirectional antennas have very poor gain and the propagation loss requires high gain antennas; so that, in this band, monitoring antennas are usually very directional; omnidirectional antennas and fixed antennas need to be in the main beam of the signal to be useful.

Mobile omnidirectional antennas are usually used only for the lower frequencies of the SHF band (e.g., frequencies up to about 6 GHz), where they are often used for the following tasks:

– to intercept and analyse and perform measurements of the direct beam stream of a microwave link with the monitoring antenna near the transmitter;
– to analyze cellular networks.

3.2.2.2 Monitoring tasks associated with directional antennas

Directional antennas are useful for the following tasks:

– for known transmitter measurements, to allow better gain in the direction of the signal and then to improve monitoring of low level signal or to get better *S/N*;

– for technical measurements, where directivity is required, to get better measurements by improving *S/N* and lowering multipath or interference;

– for SHF monitoring, where propagation requires high gain antennas.

Rotators for directional antennas must be very accurate for SHF antenna. The rotation of the antenna requires time to steer the antenna to the direction of arrival. Therefore, directional antennas are not adapted to fast scanning and for occupation rate measurement.

3.2.2.2.1 VLF/LF/HF bands

Large size directional antennas are required in these bands and are only useful at fixed sites where large installation areas are available.

Fixed stations:

A main objective of directional antenna in these bands is to increase either the sensitivity or the received *S/N*. The principal use is to monitor international or national signals.

Suitable directional antennas at such stations include:

– An antenna system that will provide highly directional, vertically-polarized reception in sectors around all points of the compass over the short-wave frequency range. Alternatives include a single log-periodic star-shaped curtain array with six curtains, or a spoke pattern of bidirectional end fire loop arrays.

– An antenna system that will provide highly directional, horizontally-polarized reception at all azimuths over the short-wave frequency range. Alternatives include a large rotatable, wire-strung horizontally-polarized log-periodic array, which has the disadvantage of requiring up to 60 s or more to rotate in azimuth, or an array of six horizontal curtains that provide 360° azimuth coverage on six 60° beams.

– One long-range, wide aperture DF array that can be from 50 to 300 m in size, to provide directional bearings. Antennas can be either omnidirectional or directional.

3.2.2.2.2 VHF/UHF bands

Directional antennas may improve technical measurement by reducing noise and interference and provide increased coverage and *S/N* for general monitoring and DF tasks. Individual directional antennas may be on a rotator, or may use fixed arrays of directional antennas covering all directions, such as an outward looking circularly disposed antenna array. Fixed arrays with directional or omnidirectional elements are suitable for a VHF/UHF DF system.

Fixed stations:

In a fixed monitoring station, size and weight is less important than in a mobile monitoring station, and directional antennas are a good complement to omnidirectional antennas.

Mobile stations:

Directional antennas on a mobile monitoring station have the same advantage than those of a fixed monitoring station, but have the disadvantage that they need the installation and maintainance of a rotating antenna in a mobile environment. An omnidirectional antenna on a mast which can be raised to improve reception provides an excellent alternative to a rotating antenna. Also, higher sensitivity is not required on a vehicle, which can move to increase *S/N* and improve reception.

3.2.2.2.3 SHF band

Due to propagation loss at these frequencies, directional antennas are well suited for SHF bands, because of their high gain. Their main disadvantage is the directivity of the incidence signal, which means that the measurement must be performed on the main beam of the signals.

Fixed stations:

Fixed monitoring stations have only specific tasks when monitoring SHF signals. They are useless for microwave links, uplink satellite and cellular networks. Fixed monitoring stations are required only for satellite downlink monitoring. Use of large directional antennas in a fixed monitoring station is required when monitoring downlink satellite signals. These antennas may be 10 m diameter dishes, which offer a high level of sensitivity.

Mobile, transportable and portable stations:

Measurements above 3 GHz usually require mobile operation in order to deploy the antenna into or near the antenna beam. Mobile, transportable and portable monitoring stations allows the use of small antennas, with diameters up to 1 m.

Their goal is to:

- intercept and analyze microwave links (direct path or secondary lobs of emission antennas);
- analyze uplink satellites links by moving the monitoring station close to the transmitter antenna;
- DF signals with the directivity of the antenna. On the SHF band, the measurement may give accurate results with a dish antenna.

Two main types of antennas, horn or dish, are used in these bands for mobile monitoring stations:

- Horn antennas have lower gain and as a result, lower sensitivity. However, horn antennas have less directivity, which may be more suitable for unknown signals.
- Dish antennas have the best gain and thus offer better sensitivity. However, the high directivity of such antennas requires that the direction to the transmitter or the source of the signal be well known, or that automated scanning be implemented to localize the source. In conclusion, horn antennas are well suited for general monitoring in the low frequencies of the SHF band (f < 18 GHz). Only dish antennas are suitable for upper frequencies where path loss is high.

3.2.2.3 Antenna selection summary

The selection of antennas should allow for new emerging digital processing techniques, such as smart antennas, which allow omnidirectional antennas to take on directive properties. Table 3.2-1 gives general guidelines for the selection of antennas for the various monitoring tasks.

3.2.3 Antennas for VLF, LF, MF and HF

3.2.3.1 VLF/LF/MF omnidirectional types

In view of the extremely long wavelengths at VLF, LF and MF (e.g., 10 000 m for a frequency of 30 kHz), antennas for these frequencies are necessarily limited to those that are small compared to the wavelength. Since signals in these bands are primarily vertically polarized, vertical antennas are generally used for reception. A simple upright antenna, which represents only a small percentage of a quarter wavelength, has an impedance which is largely reactive and of large magnitude. Such an antenna can generally be made tall enough to provide required sensitivity above atmospheric noise levels.

TABLE 3.2-1

Antenna selection according to monitoring task and frequency band

Antenna	VLF/MF/HF bands					
	Monitoring applications				DF applications	
	Omnidirectional antennas		Directional antennas			
	Fixed	Mobile/ transportable	Fixed	Mobile/ transportable	Fixed	Mobile/ transportable
Loop	X	X	X(1)		X	X
Monopole	X	X	X(1)		X	X(2)
Dipole	X	X	X(1)		X	X
Conical/biconical	X					
Log-periodic by sector	X					
Log-periodic			X			
	VHF/UHF bands					
	Monitoring applications				DF applications	
	Omnidirectional antennas		Directional antennas			
	Fixed	Mobile/ transportable	Fixed	Mobile/ transportable	Fixed	Mobile/ transportable
Monopole	X	X	X(1)	X(1)	X	X
Dipole	X	X	X(1)	X(1)	X	X
Conical/biconical	X	X	X(1)	X(1)	X	X
Fan			X	X	X	X
Log-periodic			X	X(3)		
	SHF bands					
	Monitoring applications				DF applications	
	Omnidirectional antennas		Directional antennas			
	Fixed	Mobile/ transportable	Fixed	Mobile/ transportable	Fixed	Mobile/ transportable
Dish			X	X		
Horn			X	X		
Log-periodic			X	X	X	X
Slant	X(4)	X				
Dipole					X	X

X(1): Used as an array with analogue or digital beamforming.

X(2): In the MF/HF band only.

X(3): Antenna height is more important than directivity; it is easier to lift higher a smaller omni antenna than a directional antenna, so a transportable log-periodic application is more practical than a mobile one.

X(4): With limited coverage since it is a fixed station.

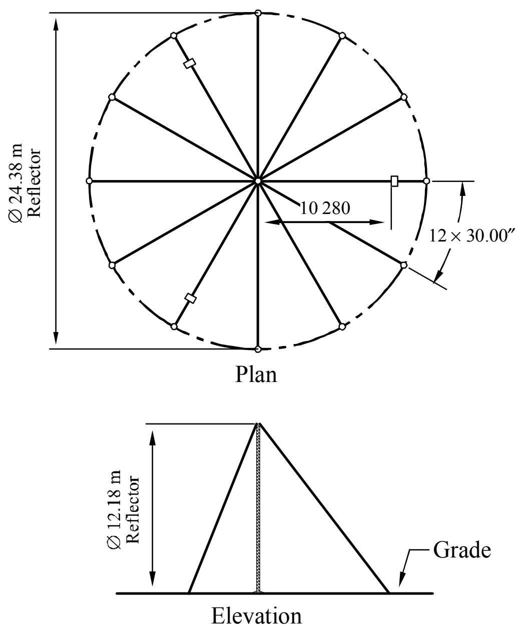
When the size of the antenna element is limited physically to a small part of a wavelength, such as occurs at VLF and LF, an active antenna will generally provide a much greater *S/N* than that obtained by connecting the antenna directly to the receiver without the use of an active device for impedance matching. In order to avoid intermodulation and cross modulation in the active circuits, attention should be paid to the following technical data:

Antenna factor 20 log(E/V) should lie between:	15 dB and 25 dB
Second-order intercept point (antenna output) should be not less than:	50 dBm
Third-order intercept point (antenna output) should be not less than:	25 dBm
Permissible field strength for 10 dB cross modulation should be not less than:	10 V/m
Maximum permissible r.m.s value of the interfering field strength (lightning protection damage threshold) should not be less than:	20 kV/m at 100 kHz and 200 kV/m at 10 kHz

State-of-the-art active antennas fulfilling the above given specifications are offered by several manufacturers. In high local field strengths, which are common in medium wave as well as FM and TV bands, even the above specifications for active antenna are not adequate and one should resort to a passive antenna such as a 12 m tall monopole shown in Fig. 3.2-1.

FIGURE 3.2-1

Typical passive receive antenna for VLF/LF/MF/HF, 9 kHz – 30 MHz

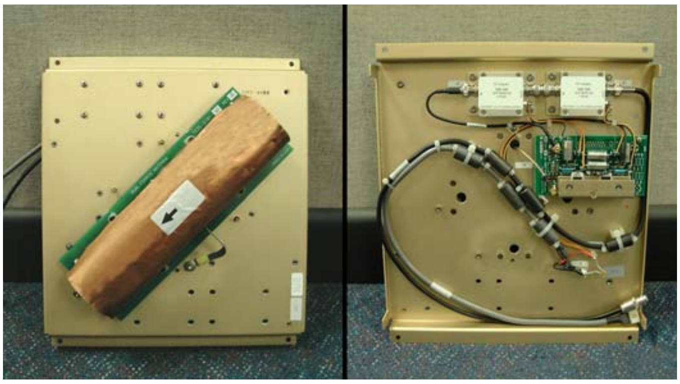


Spectrum-3.2-01

One example of a compact active antenna, which is useful for both monitoring and DF purposes, is a pair of small active magnetic loops; top and bottom views of one of the pair of loops are illustrated in Fig. 3.2-2. This antenna can be quite small (box with sides approximately 0.3 × 0.3 m and 0.1 m high) to cover 300 kHz to 30 MHz, but has the sensitivity and azimuth DF accuracy of a much larger antenna (such as an array of 3 m-tall whips).

FIGURE 3.2-2

Compact active antenna



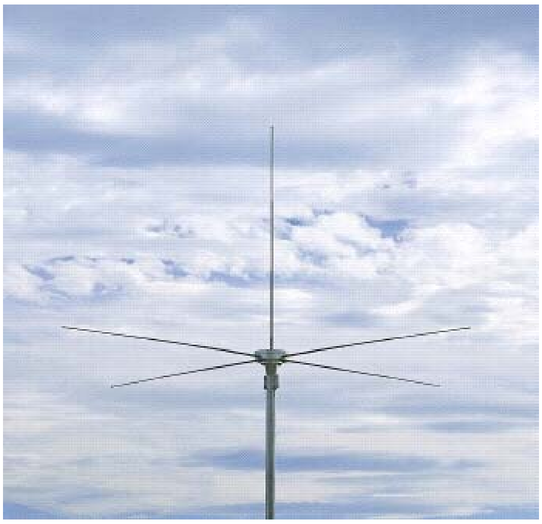
Spectrum-3.2-02

Each loop consists of a high permeability ferrite rod wound with a multiple turn coil. The coil is shielded with an electrostatic shield and the outlet is connected to a transformer –to make the antenna less sensitive to local e-field disturbances and thereby improve DF accuracy. The transformer provides impedance matching, common mode rejection, and balance to unbalance transformation.

Active antennas covering VLF/LF/MF/HF frequencies (9 kHz to 30 MHz) can also be built for horizontal polarization as well as for vertical polarization, as shown in Fig. 3.2-3. The antenna provides two output connectors, one for vertical polarization and one for horizontal polarization. It covers 9 kHz to 80 MHz vertically polarized and 600 kHz to 40 MHz horizontally polarized.

FIGURE 3.2-3

Active antenna for vertical and horizontal polarization



Spectrum-3.2-03

3.2.3.2 General considerations for HF antennas

At HF, the radio waves reflect off the ionospheric layers that exist from 100 to 300 km above the Earth. The antenna must direct maximum radiation at these ionospheric reflecting layers at the desired elevation and azimuth angles, such that coverage to desired locations will be achieved.

For instance, if a transmitter location is 350 km from a monitoring station, maximum radiation from the antenna should occur at an elevation angle near 60° for reflection off the 300 km-high ionospheric layer. In this case-the ray path from the monitoring station to the ionosphere and then to the transmitter forms an approximate equilateral triangle, including a direct line between the monitoring station and the transmitter; this simple one-reflection path is called a one-hop path.

As the distance increases, the elevation angle or take-off-angle for the one-hop path decreases; the take-off-angle of the one-hop ray can get as low as about 3° for the longest paths. Three degrees is typically a minimum take-off-angle, being limited by nearby hills, other obstructions and antenna radiation pattern undercutting at the very low elevation angles. In general, the path to the receiver may consist of several hops; for instance, a two-hop path occurs where there is a ground reflection midway between the transmitter location and the monitoring station and there are two reflections from the ionospheric layer. The one and two hops may exist singly or simultaneously. When two or more paths occur at the same time, this is known as multipath propagation.

A highly efficient receive antenna is generally not needed because of the moderately high levels of man-made and atmospheric radio noise at HF. For instance, one might wish to use a vertically-polarized antenna for reasons of radiation pattern coverage and accept a few dB of antenna loss because this antenna loss usually will not have a significant effect on the receive system sensitivity.

For receiving, it is much more important to use antennas with a high directive gain so that the signal level picked by the antenna is enhanced relative to the noise. Under the assumption that equal noise power density is being received from all directions, which is usually the case, the total noise power received by the antenna is independent of the antenna directivity. Thus, the received S/N is increased by increasing receive antenna directivity.

A given monitoring station may be able to use several antennas to provide required short- to long-range coverage. Antenna selections may include a short-range omnidirectional high take-off angle antenna combined with several moderate- to long-range directive antennas. Also, a monitoring station may have limited land area available and may need to use a small number of antennas of a single type that provide the best service to all ranges. Several ground station antenna types are presented in this section that may be chosen for use by a monitoring site. All HF-high power transmitters (>1 kW) should be located at least 5 to 10 km from the monitoring station in order to provide high isolation between HF transmitters and HF receivers and to allow a lower radio noise environment at the receive site. Antennas for HF should cover the 2 to 30 MHz frequency band.

3.2.3.3 HF antenna types

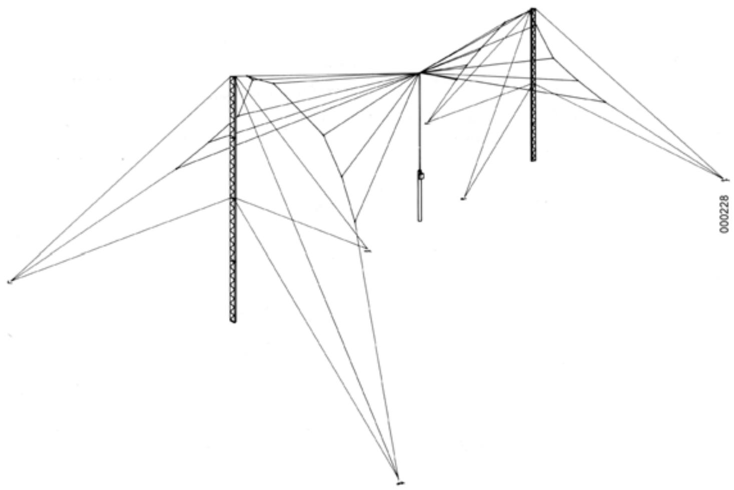
Horizontal broadband dipole (see Fig. 3.2-4)

The best antenna types for short to moderate range HF coverage are horizontally- or circularly-polarized antennas that have peak radiation near the zenith. The ground wave radiated by a vertically-polarized HF antenna is attenuated by ground losses and generally not received farther than about 100 km over ground and about 300 km over ocean water. All vertically-polarized antennas have a null overhead and are not suitable for very short-range skywave monitoring at HF.

The horizontal wideband dipole is an example of an antenna that can provide short-range coverage, from approximately 3 to 12 MHz, with a fairly omnidirectional radiation pattern. These antennas are relatively small; an example of such a horizontally-polarized dipole is mounted on two towers, 22 m tall and requires 66 m x 38 m of land area; this is a good antenna to use on a limited receive or transmit site. The gain of this antenna is typically 5 dBi or higher. For significant higher gain values, horizontally-polarized log-periodic antennas can be designed to provide short range coverage with a fairly omnidirectional radiation pattern for low frequencies changing to more moderate- to long-range coverage and directional behaviour for higher frequencies.

FIGURE 3.2-4

Broadband horizontal dipole – short to moderate range



Spectrum-3.2-04

Horizontally-polarized rotatable log-periodic antenna

Using horizontally-polarized log-periodic dipoles mounted upon masts one can achieve even higher gain values (up to 12 dBi-depending on the height of the mast).

These directional antennas have a half-power beamwidth of typically 60° to 70°. With the use of a rotator, the antenna can be turned to cover all azimuth angles (see Fig. 3.2-5).

FIGURE 3.2-5

Example of horizontally-polarized antenna with rotator for monitoring 2 to 30 MHz

Spectrum-3.2-05

Log-periodic star-shaped curtain array

A log-periodic star-shaped curtain array can provide directive beams of either vertical polarization or horizontal polarization, or both polarizations.

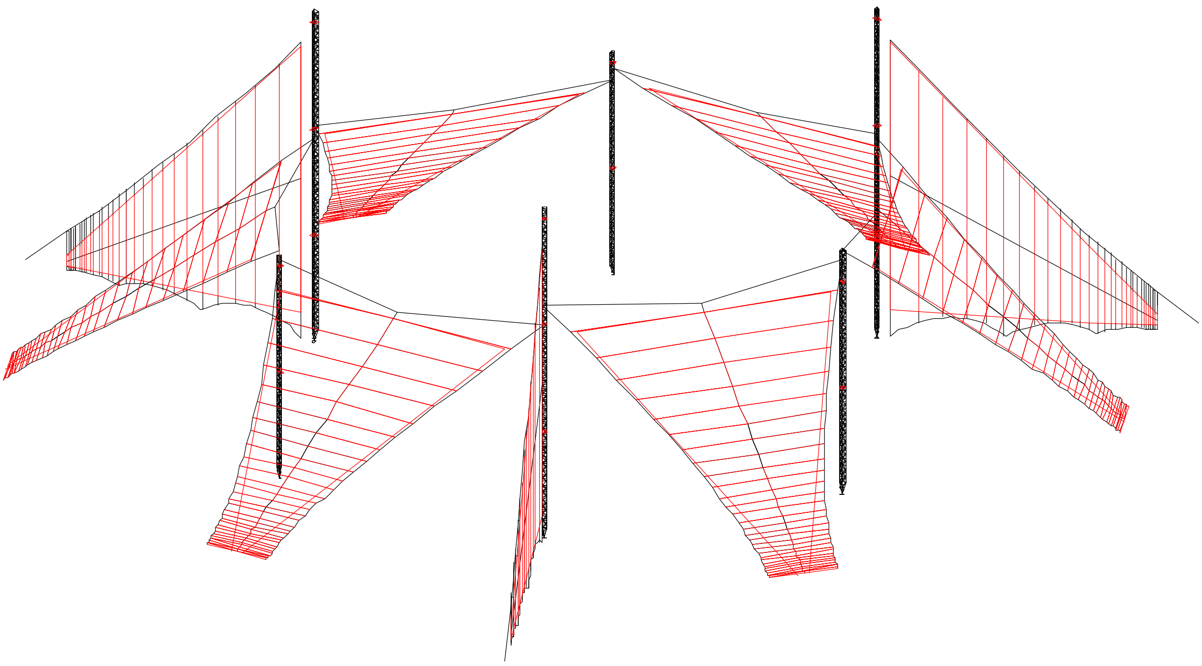
A vertically polarized array can have six curtains each with a half-power beamwidth of about 60° and each spaced at 60° intervals around a central support mast (up to 60 m high).

A horizontally-polarized array can have six horizontal curtains that share six support masts, which would also provide 360° azimuth coverage on six 60° beams.

An array that provides both polarizations is illustrated in Fig. 3.2-6; this particular example includes six horizontally polarized antennas and three vertically polarized antennas.

FIGURE 3.2-6

Example of log-periodic star-shaped curtain array



Spectrum-3.2-06

Omnidirectional circularly-polarized LPA (see Fig. 3.2-7)

An antenna type that provides omnidirectional coverage over the entire HF band is a circularly-polarized log-periodic antenna (CPLPA).

This antenna has the advantage of providing short- to moderate-range communications from one structure.

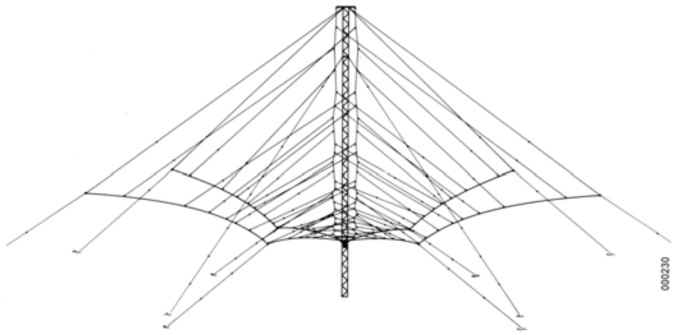
At the lower frequencies the antenna radiates at the higher elevation angles for shorter-range coverage and at the higher HF frequencies the take-off angle is lower for reception from longer ranges.

This antenna is supported by one tower and has two sets of orthogonal log-periodic dipole arrays, each dipole being a centre-fed inverted Vee connected to feedlines supported along the sides of the tower.

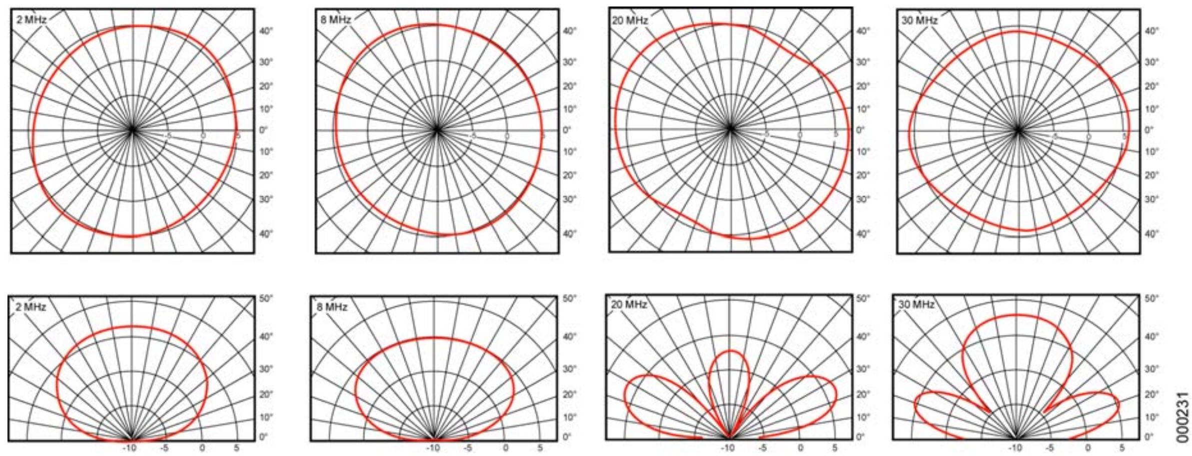
Tower height is 28 m and requires an area of 94 m x 94 m. The gain of this antenna is 5 dBi.

FIGURE 3.2-7

**Circularly-polarized log-periodic omnidirectional antenna
(short to moderate range)**



Azimuth patterns at elevation angle of beam maximum (gain (dBi))



Spectrum-3.2-07

Vertically-polarized broadband monopole omnidirectional antenna

This antenna is a broadband omnidirectional antenna that can be used to receive short-range ground wave and moderate- to long-range skywave.

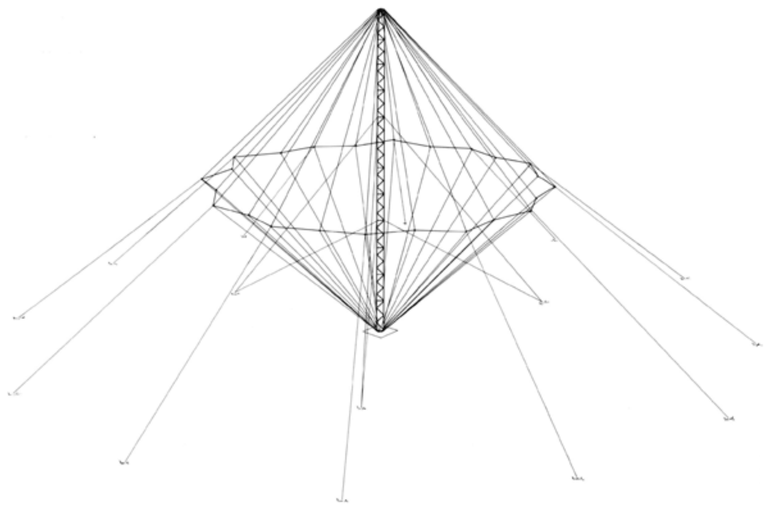
A typical vertically-polarized broadband monopole is shown in Fig. 3.2-8.

This antenna for the 3 to 30 MHz frequency range is 25 m high with a diameter of 52 m.

The vertically-polarized broadband monopole and CPLPA have nearly equal gain at low frequencies at the lower take-off angles; however, the CPLPA is superior at the higher frequencies.

FIGURE 3.2-8

Broad and vertical omnidirectinal antenna – moderate to long range



Spectrum-3.2-08

Loop arrays

Electrically small, inefficient antennas such as loop antennas can be used to advantage in a wide range of receiving applications in the HF frequency range. Noise caused by antenna inefficiency has the same effect as other sources of noise on the *S*/*N*. When external noise is greater than the noise from antenna inefficiency (and internal electronics, if present), an antenna is said to be "externally noise limited". The internal noise of an externally noise-limited antenna is relatively insignificant, since the greater external noise source determines the system's *S*/*N*. When external noise is relatively high, small receiving antennas work as well as the full-size fully, efficient antennas.

The basic loop is a large low-inductance aluminium tube. It is fed at the upper mid-point via a broadband, passive matching network. One advantage of loops over dipoles is their lower input impedance. The loop's performance is comparatively unaffected by nearby conducting bodies such as trees, buildings and snow. Moreover, since the radiation resistance of electrically small antennas is low, mutual effects are generally insignificant, enabling loops to be configured in various arrays that tailor their performance to particular receiving requirements.

The azimuthal pattern of a single loop is a figure eight at the horizon, increasingly omnidirectional at higher angles of arrival, and virtually independent of azimuth at angles of arrival above 50°. Signals from multiple loops can be combined in phase, or "beam formed". The resulting pattern is directional, with a bearing corresponding to one of the array directions. The directional pattern has its maximum gain at some angle below the zenith. Increasing the number of loop elements, increases gain and directivity. While this directional pattern is useful for monitoring, if an array of loop elements is used for DF, the elements should not be combined, so that the response of each element may be separately measured.

Beam forming is accomplished by bringing the feed cables from each element in an array to a delay/combiner unit, or beam-former, located at the array's physical centre. In unidirectional beam forming, signals from each element are delayed by means of appropriate lengths of coaxial cable, or delay lines, then summed in a combiner. In bidirectional beam forming, the signals are split and fed into two separate sets of delay lines, then summed in two separate combiners.

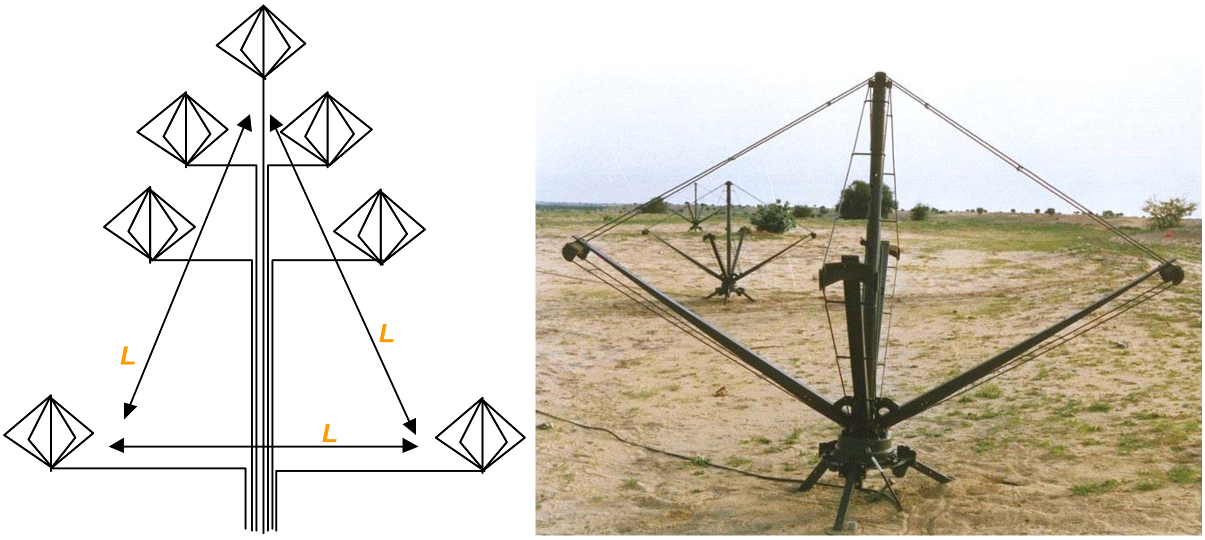
Multiple small arrays are often combined in rosette configurations. One common rosette consists of three bidirectional arms equally spaced in azimuth with a common centre. Each arm consists of eight loops. This three-arm, 24-element loop configuration can produce six beams, one for each 60° of azimuth.

Cross loop antenna

Another type of loop antenna consists of two perpendicular active frames, perhaps 2 m in height. This cross loop antenna may be used as a stand-alone or in an antenna array, with a switch commutation device and DF based on the interferometry principle. The array consists of seven or nine antenna elements, including a reference antenna, installed on the two sides of an equilateral triangle or in a circular configuration with approximately 200 m of aperture. Reducing the aperture reduces the DF accuracy. An antenna array is shown in Fig. 3.2-9.

FIGURE 3.2-9

1-30 MHz cross loop antenna array



Spectrum-3.2-09

Unlike a monopole antenna, this antenna is able to receive all polarizations. A switch inside the antenna allows the selection of one or the other of the two ports of the cross loop, depending on the chosen polarization. These antennas, along with the interferometry DF principle, can perform DF on sky waves and line-of-site propagation, and outperform U-Adcock type antennas that are limited to only vertical polarization and grazing incidence, a major disadvantage at HF because all polarizations are present in this frequency range. The interferometry DF principle allows single station location (SSL) measurements, whereas with the Watson Watt principle, the elevation angle cannot be measured and SSL is therefore not possible.

3.2.4 Antennas for VHF, UHF and SHF

The propagation conditions encountered in the VHF and UHF bands generally restrict reception to near LoS distances. In order to increase the reception area coverage, the VHF and UHF antennas are usually mounted at the top of a tower positioned near the monitoring building. In this manner, coaxial line losses, which can become high at these frequencies, are kept to a minimum.

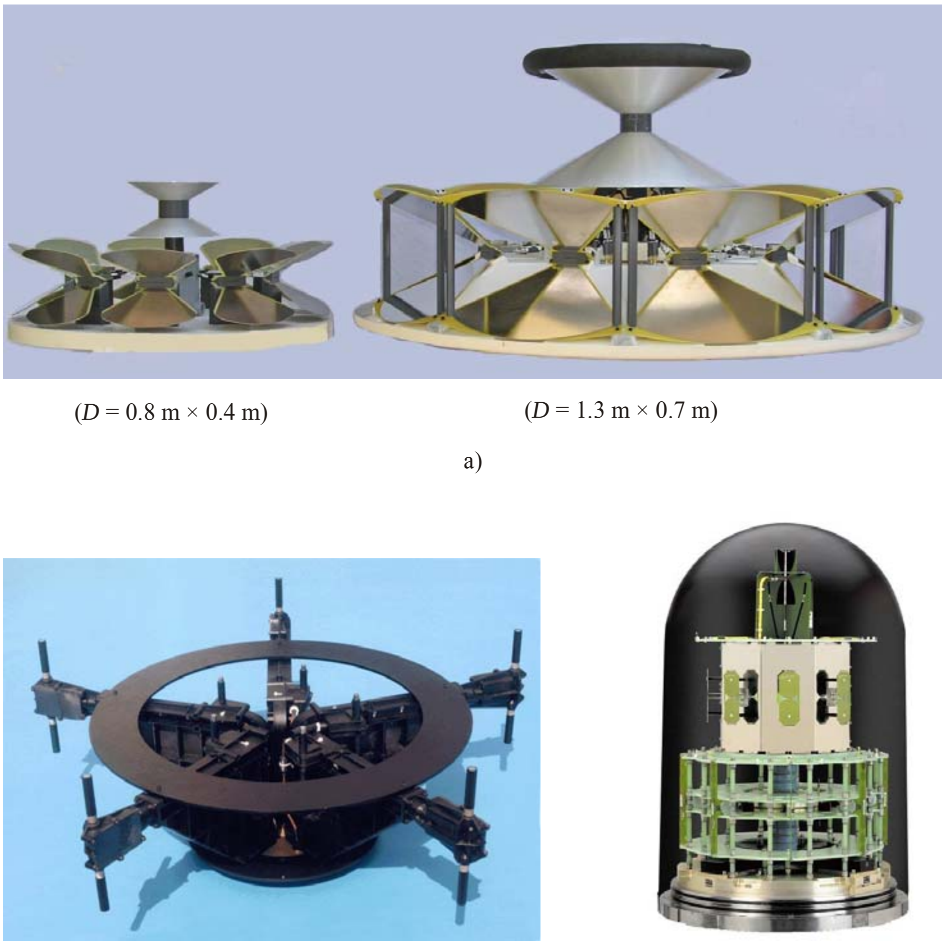
3.2.4.1 VHF and UHF omnidirectional types

One example of an antenna used in the VHF/UHF range is the broadband omnidirectional biconical antenna illustrated in Fig. 3.2-10a). This antenna may be supplied along with a nine-element fan array, also illustrated in the figure, to provide DF coverage. Two size configurations of the antenna are illustrated. The smaller configuration on the left is compact and light weight enough to be used in a portable configuration, or it can be placed on the roof rack of a standard passenger automobile in what looks like a piece of luggage to provide an inconspicuous mobile monitoring station. The larger configuration on the right is available in either vertically-polarized or dual-polarized versions (vertically polarized is illustrated); the dual-polarized version has separate outputs for vertical and horizontal polarization. Both configurations provide very good coverage over a 150:1 frequency range of 20 to 3 000 MHz, the smaller one with somewhat reduced sensitivity at frequencies below 100 MHz.

The combination of the biconical antenna and the nine-element fan may be used for monitoring and DF over the entire VHF/UHF range in both fixed and mobile applications; however, for improved sensitivity and accuracy at fixed sites, the larger antenna in Fig. 3.2-10a) and an additional, physically larger array, consisting of a five-element VHF vertical dipole array illustrated in Fig. 3.2-11a) may be used.

FIGURE 3.2-10

Examples of VHF/UHF antenna elements (enclosures removed)



(*D* = 0.8 m × 0.4 m) (*D* = 1.3 m × 0.7 m)

a)

(*D* = 1.1 m × 0.44 m) (Height: approximately 0.8 m)

b) c)

Spectrum-3.2-10

Figures 3.2-10b), 3.2-10c), 3.2-11b) and 3.2-11c) illustrate other antennas used for monitoring and DF in the VHF/UHF range. Figure 3.2-11c) includes a nine-element VHF vertical dipole array.

For optimum performance in applications requiring high dynamic range (good sensitivity and low distortion), the antenna should use passive antenna elements followed by active RF switching and preamplifiers. Use of passive antenna elements ensures that the antenna will be free of parasitic responses, has well behaved patterns and gain/phase response for DF accuracy, and does not produce distortion (IM or harmonic), a common problem in active element antennas. An example of such an antenna is given in Fig. 3.2-11b); three independent sets of dipoles are arranged in a pentagonal structure and allow coverage of the 20-3 000 MHz frequency range with vertical polarization.

This antenna type is designed to provide the best resistance against bad weather and lightning. Lightning protection is of utmost importance for a VHF/UHF DF antenna that, by its nature, should be installed at the highest possible location of the area to be monitored, thus directly exposing it to lighting. The antenna shown in Fig. 3.2-11b) includes one resistant metal box containing the monitoring and DF equipment, thus protecting it from lightning. The structural tubing of this antenna provides grounding for the electrical charges picked up by the lightning arrester installed at the top of the antenna.

One should consider that active antennas might present parasitic responses, producing distortions such as IM and harmonics, lower MTBF and varying performance with aging, although they also present benefits such as broader range and larger antenna gain for a smaller size and lower weight. One should also consider the intended use and the local of installation such as the benefits and drawbacks of each technology is properly considered.

For some applications it may be desirable to have the benefits of both active and passive antenna elements. The DF antennas shown in Fig. 3.2-11 have antenna elements that can be switched between active and passive operation by mouse click. Since active operation offers better sensitivity this is the default setting. In case very strong signals appear in the spectrum, the antenna can be switched to passive mode to minimize intermodulation problems.

FIGURE 3.2-11

Examples of VHF/UHF (20-3 000 MHz) antenna arrays

a) b) c)

Spectrum-3.2-11

As an example, one could consider the installation of a monitoring station in urban areas with large spectrum use. Such installation might be desirable to monitor low-level transmissions that might not be detectable from even very sensitive stations and theoretically perfect sites located outside the urban centre. Due to high RF levels on urban centres, active antennas and broadband switching devices used in monitoring stations might have their performance and effectiveness strongly affected on this sites, pushing the demand for passive use of passive antennas and/or even filters and more band selective systems, such as to avoid interference.

However, passive element antennas suffer from poor sensitivity unless they are physically large and are built in multiple bands that are optimized for relatively narrow frequency ranges. This could result in a complex antenna structure that is difficult to install and maintain. Rather, if very high dynamic range RF preamplifiers and RF switching circuitry follow the passive elements, the antenna can both cover a wide frequency range and provide good sensitivity. This is possible if both the passive antenna elements and the active RF amplification operate at the same impedance, where it is possible to build the preamplifiers and switches with very high dynamic range and broadband response.

The high dynamic range RF switching and pre-amplification circuits should be physically mounted in the antenna, to eliminate the need for phase-matched RF cabling between the antenna and the rest of the system when used for DF, and to provide line amplification near the signal source to overcome cable losses that would otherwise increase the system noise figure and thereby degrade sensitivity. The RF preamplifier used in the antenna should have RF performance characteristics that substantially exceed that of the receiver to which it is connected, because the RF preamplifier must handle the entire VHF/UHF spectrum while the receiver typically has pre-selector filters that limit the amount of RF signal energy that the receiver RF front-end circuitry must handle.

Another useful antenna is illustrated in Fig. 3.2-12, which shows a VHF/UHF coaxial broadband dipole with optimum performance in the frequency range 80 to 2 000 MHz. In the lower frequency range the vertically-polarized antenna works in the coaxial mode, while in the upper range it works in the omnidirectional waveguide mode.

As noted above, active antenna systems can minimize the size of antennas for VHF/UHF. Figure 3.2-13 shows an active broadband antenna system using active dipoles as basic elements with wide dynamic range and high sensitivity. The vertical antenna is a centre-fed active dipole for the frequency range 20 to 1 300 MHz. The horizontal antenna covers the 20 to 500 MHz range and is built up as a turnstile type, consisting of two active broadband dipoles combined via a hybrid in order to provide a nearly omnidirectional radiation pattern. These small active antennas are highly suitable for broadband monitoring systems, including signal distribution to many receivers, because the distribution system will be more straightforward with only one antenna for the complete frequency range.

FIGURE 3.2-12

VHF/UHF broadband dipole

Spectrum-3.2-12

FIGURE 3.2-13

Active VHF/UHF antenna system

Spectrum-3.2-13

Another effective technical solution for improving characteristics of omnidirectional VHF/UHF monitoring antennas is mounting converters of radio signals on intermediate frequency in antennas (intermediate frequency (IF) converters) rather than amplifiers [Ashikhmin *et al.*, 2006]; [Rembovsky *et al.*, 2006].

Improvement of antenna characteristics in this case is reached by high-frequency cable length reduction to a minimal value, considering that this cable is the main source of noise in transferring received signals from antenna elements to a radio receiver. The placement of IF converters in the immediate proximity of antenna elements allows for the elimination of the effect of a cable on the antenna (which, in this case, transfers IF signal) and also to transmit IF signal to distances up to several hundred meters. It results in increasing sensitivity and dynamic range of a system.

3.2.4.2 VHF and UHF directional types

In VHF and UHF bands, the need for antennas that have low-voltage standing wave ratio (VSWR) and uniform patterns has led to the development of arrays with a series of elements whose characteristics repeat according to the logarithm of frequency (log-periodic). These arrays can be made to achieve a moderate gain (10 dBi typical) with good directivity (a front-to-back ratio of 14 dB is typical), and a pattern that remains uniform over a frequency range of up to approximately 10:1. The radiation pattern is typically broad, approaching that of a dipole reflector-director antenna for most frequencies. The uniform gain, pattern and impedance characteristics of the antenna make it suitable for combining together to form a broadband array, for use where highly directional antennas are desired. In particular, the log-periodic antenna serves well as the illuminator for parabolic reflectors at UHF, where very narrow beamwidths are desired.

This antenna is generally constructed of a series of radiating elements, which are fed by, and positioned along, a central transmission line. The individual dipole pair elements are each designed to have the required antenna properties over a narrow part of the entire operating frequency band, and to maintain their characteristics as uniformly as possible over their active frequency range. The individual elements are repeated at intervals, which are constant with the logarithm of frequency. The number of intervals depends on the required gain and VSWR of the completed antenna design.

The overlapping of the characteristics of the individual elements of the array produces an active zone consisting of several adjacent elements, which progresses smoothly along the structure as the frequency is varied. The VSWR of the antenna is directly dependent upon the number of elements in the active zone of the antenna at a particular frequency and their efficiency in coupling energy between the electromagnetic wave and the transmission line.

Complete log-periodic antennas are available from a number of manufacturers for both wideband use and for narrow-band special services. Detailed design information is available in publications listed in the Bibliography and in other sources.

3.2.4.3 Antennas for frequencies above 3 000 MHz

To achieve the necessary high antenna gain for monitoring over long distances, primarily "dish and feed" antennas are used. The gain depends on the relation between dish diameter and wavelength, and on the aperture efficiency of the antenna. A principal alternative to the use of "dish and feed" antennas is the frequency extension of some VHF/UHF antennas to provide coverage of the lower portion of the SHF band.

For an optimized antenna system in the SHF range, several parameters have to be taken into consideration: narrow-band, broadband application and general monitoring or surveillance of signals.

For narrow-band applications, a horn or waveguide feeder, dipole or crossed dipole can be placed exactly in the focus of a parabolic reflector. The relation focus length/diameter can be optimized with respect to the high efficiency achieved by minimizing losses caused by either insufficient illumination or side radiation. The result will be an antenna gain as high as possible.

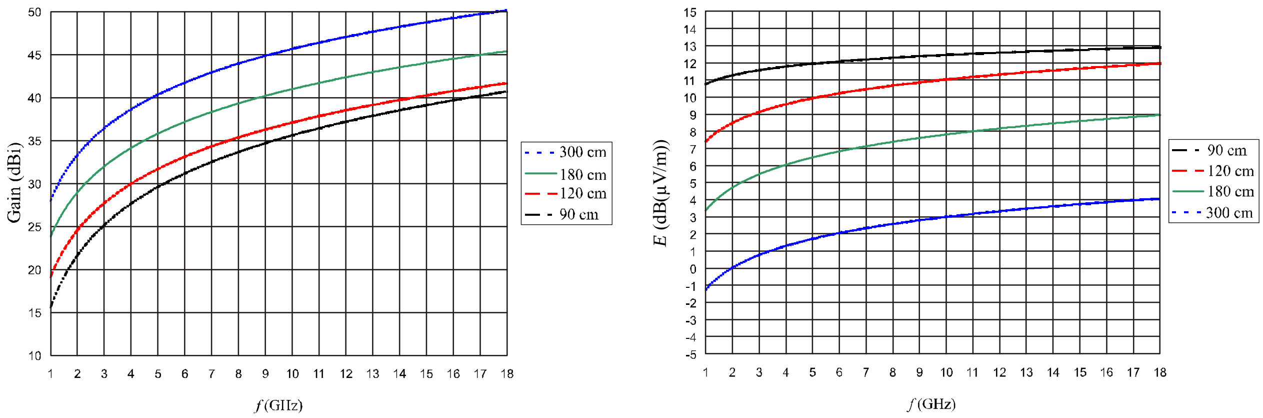
For monitoring and surveillance, high gain and a broad beamwidth for picking up the signal is required. In this case, a common method is focusing or defocusing the antenna feed by means of a motor-driven mechanical equipment. Variation of the beamwidth between 1:4 and 1:10 is possible.

For broadband applications, either linearly, dual linearly log-periodic antennas, conical spiral or cavity backed antennas may be used, the latter primarily for circular polarization. The broadband feeds, based on the log-periodic principle, do not have a constant phase centre. The phase centre moves from the shortest to the longest radiator of the structure, depending on the frequency. If the structure is positioned in the reflector for a certain frequency, defocusing will occur for the others. Optimization based on the calculation of additional parameters (e.g., length/diameter) allows to minimize losses caused by defocusing. To avoid these losses mechanical focusing, as described above, may be used.

Another solution is to use a special contour for the reflector, which is not perfectly parabolic. In this case, the antenna gain will increase and the beamwidth will decrease up to a certain frequency, then both will be nearly constant (see Fig. 3.2-14).

FIGURE 3.2-14

Gain and lowest measurable field strength for reflectors with different diameters and linear feed



Spectrum-3.2-14

Microwave antennas are mounted stationary on a tripod or tower for surveillance of signals coming from a certain direction. In this case manually, adjustable equipment is provided to adjust the antenna system exactly to the desired direction. Beamwidth of the antennas may vary between 20° and 0.05°, depending on diameter/wavelength.

For general monitoring, the antenna systems are installed on high-accuracy mono- or bi-axial positioners. Depending on the diameter of the antenna reflector, dimensions and costs may be highly different if operation and survival for high wind speeds is required. For terrestrial monitoring, mono-axial positioners with rotary joints or with cable twist equipment are used. The latter is limited by the azimuth rotating range (e.g., 360°). The elevation can be adjusted manually or remotely controlled within ±10°.

For satellite monitoring, bi-axial positioners allow additional movement between –10° and more than +90°.

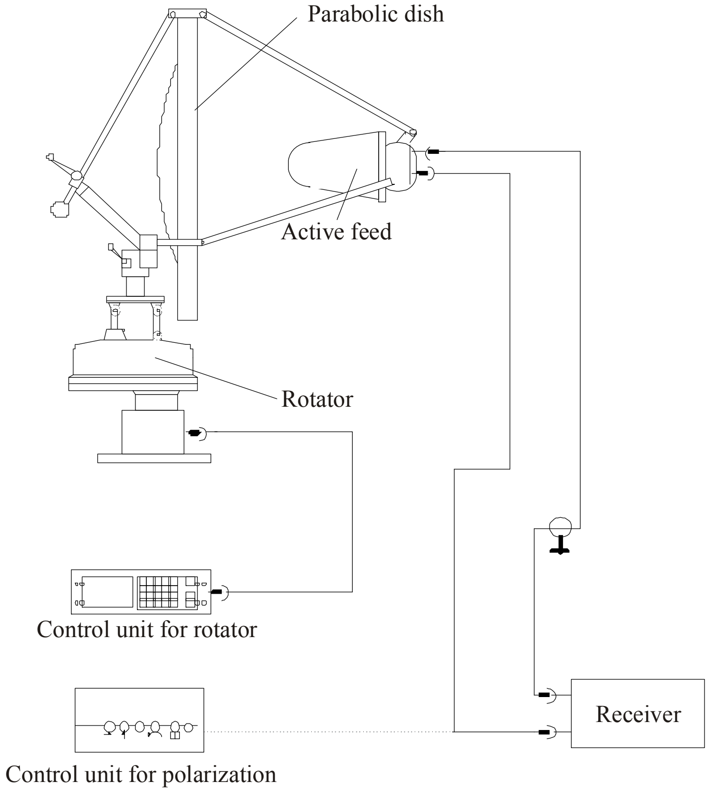
The motor-driven positioners are remotely controlled via control units with different possible operation modes, e.g., variable speed, presetting of positions, scanning and antenna selection. Parallel and serial computer interfaces are provided for system integration.

Figure 3.2-15 shows a typical block diagram. It is highly recommended to install low-noise amplifiers (LNAs) close to the feeder to avoid additional attenuation and noise caused by cables. These combinations are available as so-called “Active Feeds”, either with broadband preamplifiers (e.g., 1 to 18 GHz) or with amplifier units switchable in frequency ranges of 1 octave. An example of these feeds is shown in Fig. 3.2-16.

Therefore control units for remotely controllable polarization and frequency range are provided too. Additional features are switchable bypass, attenuators and built-in limiters. It is also recommended to install converters of the receiving system close to the antenna to achieve best system performance.

FIGURE 3.2-15

Block diagram of steerable microwave antenna 1-18 GHz



Spectrum-3.2-15

FIGURE 3.2-16

Example of a feed for a reflector antenna system 1-18 GHz
(cross-section of the radome)

Spectrum-3.2-16

For large antenna reflectors, the feeder is not located at the focus of the dish but at its apex. An hyperbolic subreflector diverts the radiation. The reflector can also be fed in the "offset mode", where the antenna feeder is located in a tilt position out of the secondary radiation of the reflector.

For special applications, dual-shaped reflectors such as cylinder parabolic or cosecant may be used. In this case, the beamwidth in azimuth and elevation is different, depending on the application.

For mobile applications where roof space is limited, omnidirectional antennas can be used. Slant-linear-polarized omnidirectional antennas receive all polarizations including vertical polarization, horizontal polarization, right- and left-hand circular polarization-and cover many frequency bands. Typical ranges covered include: 1-4 GHz, 4-18 GHz, 1-18 GHz and 12-40 GHz.

Thus with three relatively small (300 mm maximum dimension) antennas, the entire band can be covered. It is very important that these antennas be mounted very close (within about 3 m) to the receiver in order to keep attenuation loss small in the connecting coaxial cables.

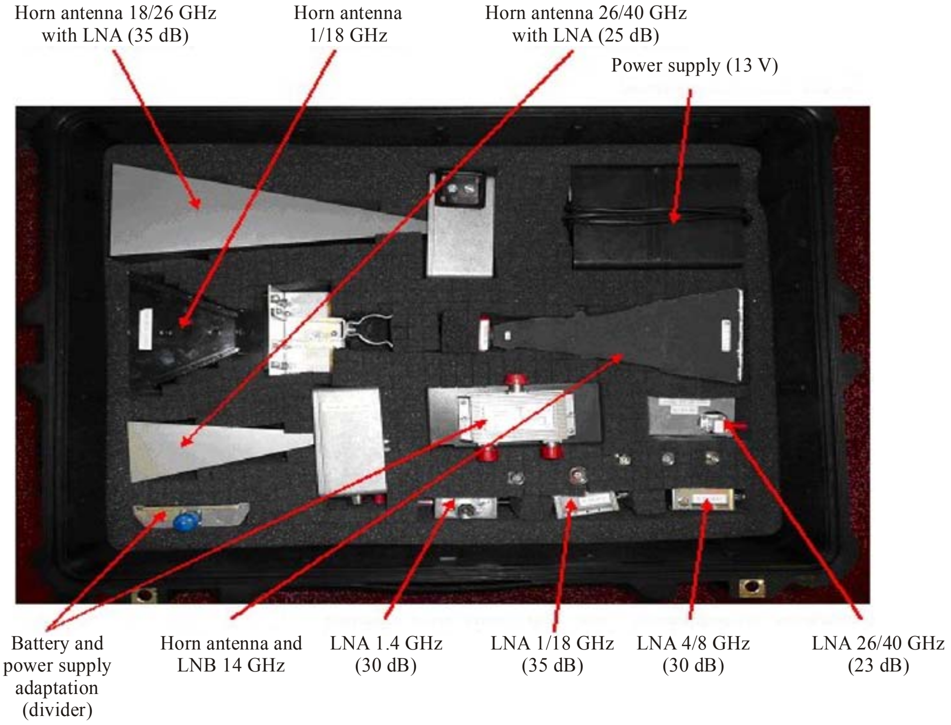
A compact solution to measure the SHF band from 1 to 40 GHz and above, consisting of several horns and a single tripod, is described as follows:

In the 1 to 18 GHz band, to avoid a large contribution of noise, selective filters should be used and the LNA gain should be limited (less than 20 dB). In the band 18 to 40 GHz and above, measurements results could be improved by the use of waveguides. As waveguides are by definition band-pass filters, higher gain amplifiers could be used.

Taking into account these considerations, a typical example of a handheld system is illustrated in Fig. 3.2-17. It consists in a hand-held suitcase that contains a pack of horn antennas with amplifiers, filters, power supply, batteries and cables to carry out measurements from 1 to 40 GHz. In addition, several cables and adapters could be added in the suitcase. The size of the suitcase is 600 x 500 x 230 mm, and its fully loaded weight is just 16 kg.

FIGURE 3.2-17

Typical compact solution to carry out SHF measurements



Spectrum-3.2-17

3.2.5 Siting of antennas

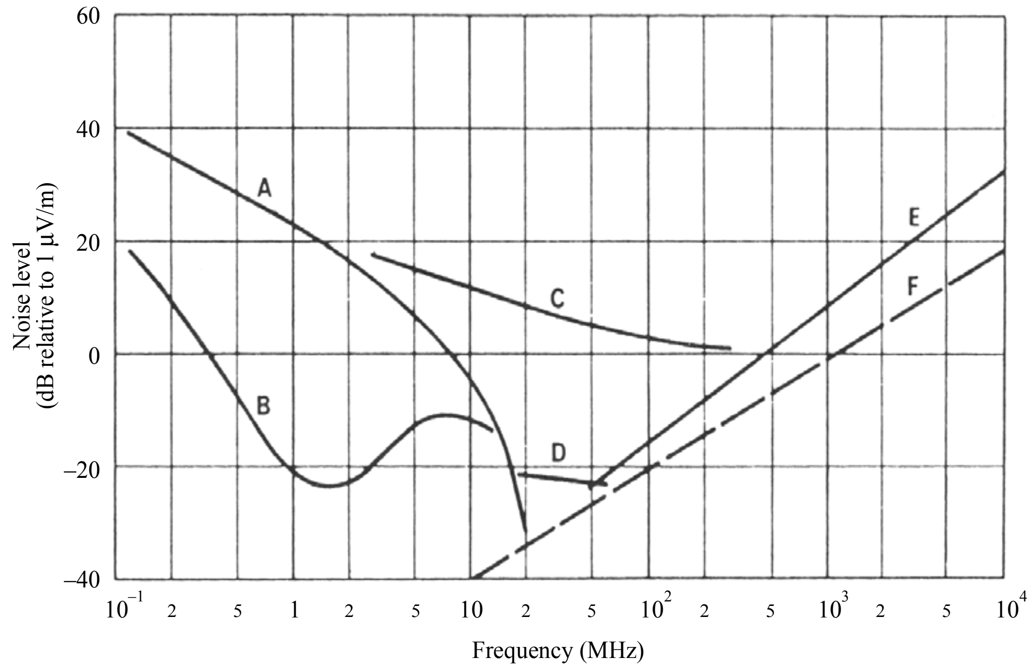
There are three primary considerations that must be examined when a site for monitoring station antennas is being chosen: the interfering noise level, the effects of terrain on the performance of the antennas, and the influence of other antennas and metallic structures or objects nearby. These factors must all be considered before a suitable antenna location and layout are established. Influence of nearby metallic structures such as antenna masts and mast guys should be considered during the design of the antenna structure. Other factors, such as economic and political considerations, will influence the location and layout of the monitoring station itself.

Noise that interferes with the reception of radio waves may be divided into two general categories: natural and man-made.

Natural noise is that produced by the various mechanisms of nature, both on the Earth itself and in neighbouring celestial systems. The major component of natural noise generated on the Earth is the static discharges resulting from the many storm centres, which are almost continuously active on the globe. Storms are most active in the equatorial regions and their noise is radiated toward the poles, resulting in atmospheric noise components that are largest at the equator and smallest at the poles. High-energy, galactic noise sources exist in the sky (in particular the constellations of Sagittarius and Cassiopeia) and may constitute a considerable portion of the noise picked up by antennas, which are located in an environment where the atmospheric noise levels are low, e.g., at higher latitudes. As shown in Fig. 3.2-18, cosmic noise is for most frequencies generally masked by other sources, but it can be significant in some cases, particularly if the receiving antenna happens to have a lobe oriented in the direction of a strong source.

FIGURE 3.2-18

Typical average noise level in a 6 kHz bandwidth (frequency range, 100 kHz to 10 GHz)



Curves A: atmospheric static noise, night
B: noon
C: large city ignition noise
D: cosmic noise
E: typical set noise
F: thermal noise

Spectrum-3.2-18

Interference to reception from man-made sources may take many forms (see also §§ 2.6 and 4.3). One of the most important sources to avoid when choosing an antenna site is a nearby broadcasting station. Even though the operating frequency of the station may be very different from the proposed monitoring frequencies, there can be significant interference caused by radiation of spurious emissions and harmonics of the principal frequency, and production of intermodulation or other responses caused by the overloading of the receiver's radio-frequency, intermediate-frequency and audio-frequency circuits. Receiver desensitization may also occur, even if spurious response is not noted.

Other man-made noise sources such as X-ray and diathermy machines, high-voltage power generation and distribution facilities, welding and heavy industrial fabrication processes, street lighting, heavy concentrations of vehicular traffic, and even large areas of residential buildings may create significant levels that may override wanted radio-frequency signals. In addition to direct radiation, noise from these sources may be conducted over power distribution lines to cause interference to areas at considerably greater distances than those affected by direct radiation.

Once a suitable location has been chosen from the standpoint of noise interference criteria, the influence of the terrain on reception must be examined. This is particularly important since the monitoring antennas are usually co-sited with a DF antenna. For the latter, it is important that the terrain be flat, free of discontinuities, and have an uninterrupted view in all directions in order to avoid errors in the azimuth of arrival of the radio waves. The siting of monitoring stations, and of DFs, is dealt with in §§ 2.6 and 4.7. However, it is true that except for limited, special, monitoring purposes, a good DF site is also a good location for monitoring antennas.

An effect which must be considered when choosing a site at which a number of different antennas are to be installed at the same location, is the interaction which will occur between them and with other nearby metallic structures such as antenna masts, mast guys, fences, metallic tubes, stairs and other metallic structures.

The interaction among multiple antennas at a site will be most significant for similar types of antennas either designed for the same frequency range or which attain near-resonance at the same frequency. For instance, it is recommended that two rhombic antennas should not be closer than about 10 wavelengths when one is in the lobe of the other at the receiving frequencies in use.

For minimum interference between antennas of different types, it is recommended that maximum differences be provided in at least two of the general categories of space, frequency and polarization.

In addition to other antennas, surrounding metallic structures situated at distances less than several wavelengths from an antenna may unacceptably deform antenna characteristics such as elevation, azimuth antenna patterns and matching with feeders, relative to those in isolated conditions.

Errors in the measurement of emission parameters, arising from such influence, can considerably exceed specified error tolerances indicated in Chapter 4.

The quantitative determination of the influence of other antennas and metallic structures can be calculated with computer software [Kharchenko and Fomintsev, 2001], [Tanner and Andreasen, 1967], [Harrington, 1968] and [Thiele, 1973].

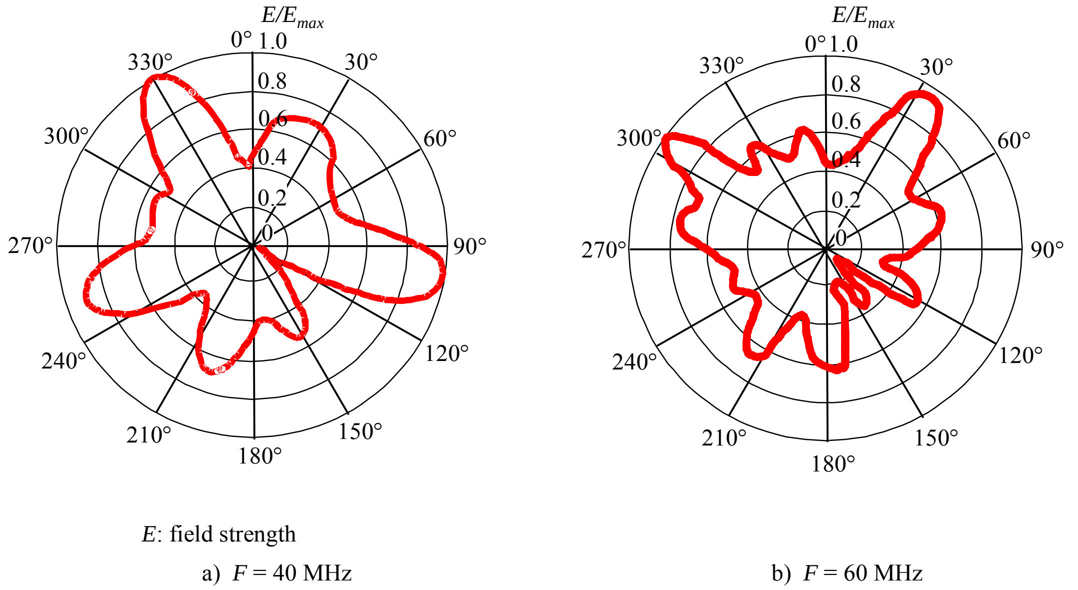
Metallic structures and other antennas within several wavelengths (usually from 4 to 8 wavelengths) from an antenna under consideration are modelled by wire structures, preserving the geometrical proportions of the structures.

Then with the help of a method of moments computer program, the distribution of currents within all elements of wire structures are calculated; this electrodynamics model of the antenna and its surroundings allows the true characteristics of the antenna to be determined in the presence of scattering, reradiation and resonances produced by nearby metallic structures.

As an example [Kharchenko and Fomintsev, 2001] of the use of the given technique, Fig. 3.2-19 shows the calculated azimuth pattern of a 30-80 MHz omnidirectional disk-cone umbrella-type antenna in the presence of significant surrounding metallic structures. These structures include other similar antennas for the same frequency range and two disk-cone umbrella-type antennas for the range 80-100 MHz. There are also several rod communication antennas, a metal fence and some other metallic objects.

FIGURE 3.2-19

Actual azimuth pattern of omnidirectional 30-80 MHz antenna



As is clearly seen from Fig. 3.2-19, surrounding antennas and other metallic structures convert an omnidirectional pattern such as illustrated in Fig. 3.2-7 to a directional one. Moreover, the variations in the patterns vary considerably with frequency, reaching differences of 20 dB due to non-linearity. This variation highly complicates the ability to obtain correct measurements from the antenna.

Some specific recommendations on the placement of antennas relative to the monitoring buildings and to one another are for:

HF loop antenna arrays

These should be at least 100 m from the array-receiving building to prevent distortion of radiation patterns by the receiving building.

MF/HF wideband arrays

These should not be located too far from the building (≈100 to 200 m). Enough spacing should be obtained to prevent shadowing of the antenna by buildings, but not so great as to introduce significant losses in the feed line. Coaxial line is recommended, since these antennas are wideband units with closely controlled impedance characteristics and somewhat lower gain than resonant types.

Transmitting and receiving antennas

Maximum separation should be maintained between antennas that are used for transmission and antennas used for reception, so as to minimize the overloading of receivers by signals generated by local transmitters. Care should be taken to locate transmitting antennas so that their main lobe and side-lobes do not directly illuminate antennas used only for receiving purposes.

DF antennas

If DF equipment is to be installed at the monitoring station, the possible effect of reradiated components from the receiving antennas should be considered in regard to their effect in introducing errors in the DF equipment (see §§ 2.7 and 4.7).

Active antennas

Since mutual coupling between active antennas, as well as mutual coupling between them and other structures, is reduced to a minimum, active antennas may be installed closer together than passive antennas. Active antennas can be disturbed by high-power radio transmitters, and this needs to be taken into account when siting those antennas.

VHF/UHF antennas (above 30 MHz)

These should be located high on towers near the receiving building to minimize losses in the coaxial cable, to maximize LoS coverage area. For a 20 km LoS radius, a 24 m tower is required. A 48 m tower would provide LoS coverage out to about 30 km.

Antennas for frequencies (above 1 000 MHz)

These should be located where a clear LoS is guaranteed (e.g., on a building, tower or mountain), especially for terrestrial monitoring. The receiving systems should be installed close to the antenna to avoid high losses in the coaxial cable.

3.2.6 Antennas for mobile monitoring stations

A mobile monitoring station offers the same functions as a fixed station in a mobile vehicle that can be driven from one location to another. This configuration provides measurement resources which can be easily moved to respond to a specific complaint or other monitoring need, and which can be located on the LoS propagation path of a signal of interest.

The chief limitation on antennas for mobile monitoring stations is their size. Owing to the inevitable lack of space, antennas must be small. Therefore, antenna size in the case of the lowest frequencies represents only a very small fraction of a wavelength. Loop antennas covering the frequency range 9 kHz to 30 MHz are available with or without ferrite material, and by reason of their clearly defined electrical characteristics, are particularly suitable for field-strength measurements and DF of ground wave signals. For frequencies between 30 MHz and 3 GHz, wideband omnidirectional antennas are available for receiving vertically or horizontally-polarized waves. Typical frequency ranges are 20 to 1 000 MHz, 200 to 3 000 MHz, or 30 MHz to 3 GHz.

A wide variety of directional and DF antennas are available for frequencies above 30 MHz, including wideband or narrow-band Yagi antennas, tunable dipoles, folded dipoles, biconical antennas and log periodic antennas. These antennas can cover fairly wide frequency bands and are capable of meeting all the requirements of a mobile monitoring station. A representative antenna is described at the beginning of § 3.2.4.1.

Most antennas for mobile stations are mounted on the vehicle. However, reflector antennas for frequencies above 1 000 MHz are usually not permanently installed on a vehicle, but carried along and erected when needed while the vehicle is stopped, as shown in Fig. 3.2-20. In all frequency ranges, active antennas may be used considering their technical data and their limitations, which are given in the discussion above dealing with omnidirectional antennas. Hand carried active antennas (see Fig. 3.2-21) may be used for the purpose of monitoring, field strength measurement, or even DF.

Typical mobile monitoring stations are shown in Fig. 3.2-22, each with a roof-top antenna mounted on a pneumatic mast.

Mobile stations are particularly important for monitoring at microwave frequencies. Microwave communication signals usually propagate in very narrow, well-defined beams designed for point-to-point, or point-to-multipoint communication.

Therefore, it would be very unlikely for a fixed station to be located close enough to a microwave path, so as to be able to intercept a microwave communication signal. Because of its high cost and very limited benefit, it is not recommended to install microwave intercept at a fixed station; instead, this equipment should be in a mobile vehicle or portable configuration. For a dedicated vehicle, a complete system could be implemented to carry out measurements from 1 to 40 GHz and above.

FIGURE 3.2-20

Transportable microwave antenna

Spectrum-3.2-20

FIGURE 3.2-21

Hand-held directional antenna

Spectrum-3.2-21

FIGURE 3.2-22

Examples of mobile monitoring stations

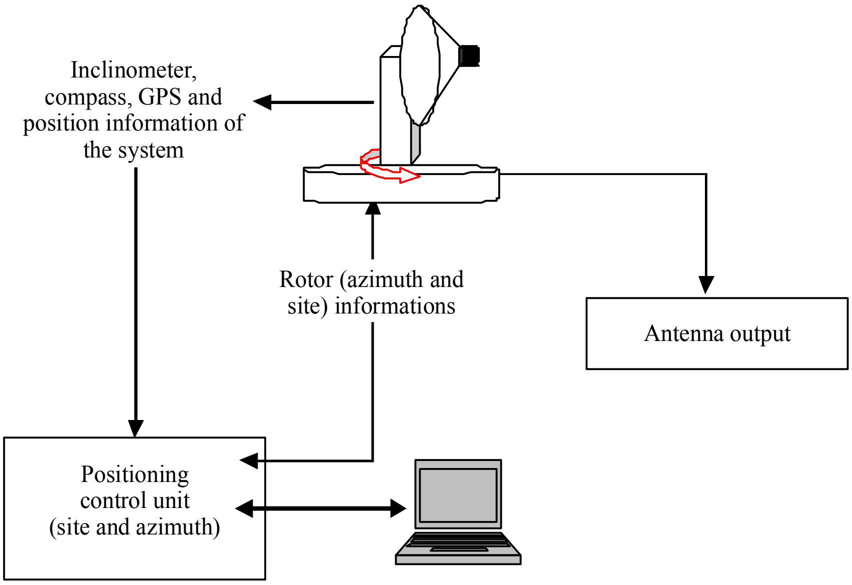
Spectrum-3.2-22

In this case, illustrated in a typical block diagram (see Fig. 3.2-23), the antenna system consists of the following elements:

– Antenna system.
– Automatic positioning system.
– Antenna monitoring unit.
– Output antenna table.
– Azimuth and elevation control unit.

FIGURE 3.2.23

Example of a SHF monitoring system



Spectrum-3.2-23

The antenna system could consist of several antennas to monitor the full band, as illustrated in Fig. 3.2-24. Moreover, to ensure flexibility in SHF measurements, taking into account different measurement situations and the low level of SHF signals, it is useful to include, close to the antenna system, some accessories like LNAs and YIG filters.

A PC provides the interface between the antenna system and the user.

The positioning control unit is the supervisor. It sends data to monitor the positioning system and receives information from different sensors to provide the status of the system and geographical referencing data.

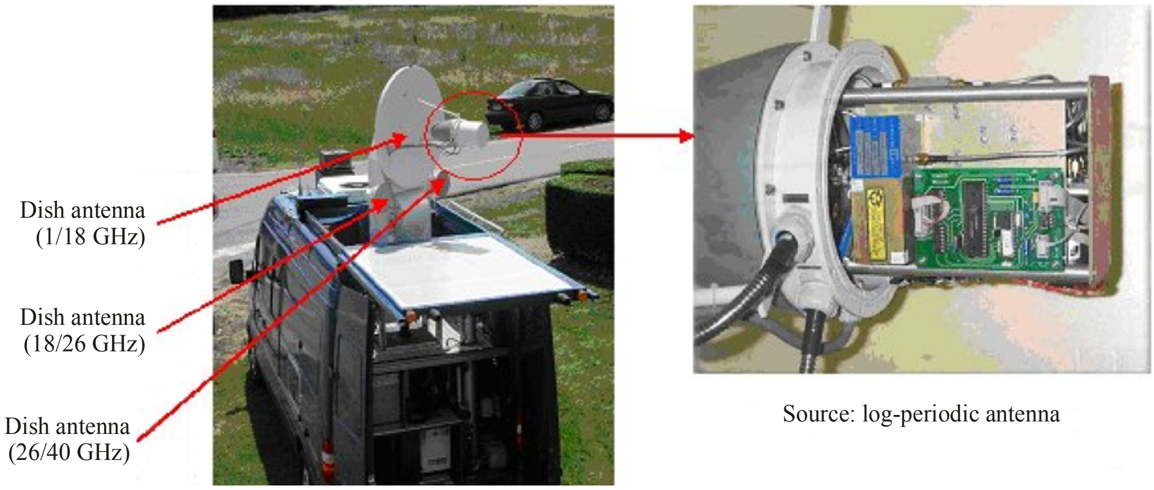
An antenna output panel is available to the user to connect different measurement equipment with all available outputs (with or without LNA, filters and so on). Figure 3.2-25 gives a typical SHF measurement chain block diagram.

3.2.7 Antennas for transportable and portable stations

Transportable and portable antennas are designed for minimum weight and size. The antenna shown in Fig. 3.2-10a) (left) is used for mobile or transportable uses. The antenna is easily transported in a packing case. The transportable antenna may be fixed at the top of a small telescopic mast, to minimize set up time. It can also be mounted on vehicles for semi-fixed stations.

FIGURE 3.2-24

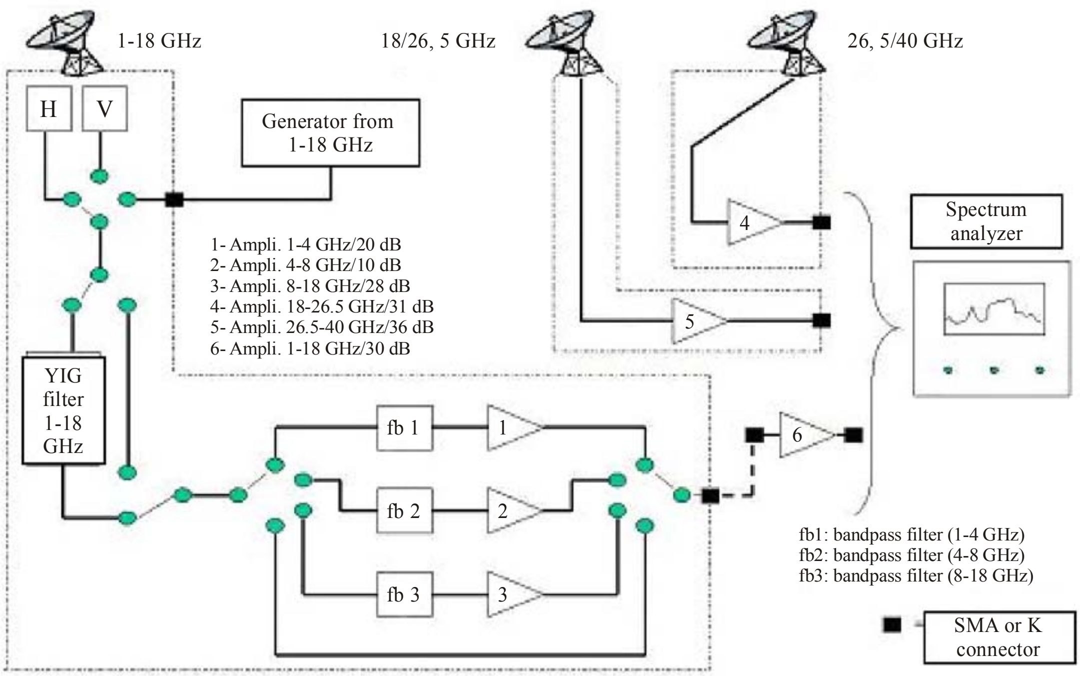
Overview of the antenna system



Spectrum-3.2-24

FIGURE 3.2-25

Block diagram of the receiving chain



Spectrum-3.2-25

Improvements in technology and integration allow transportable antennas to offer similar functionality and performance as antennas for fixed and mobile stations. These antennas associated with an integrated receiver allow a station to become transportable or portable, which is especially useful for in-town or difficult access areas for monitoring tasks. The spectrum is very dense in city areas, and monitoring measurements on the streets are not always relevant; only measurements from the top of dedicated sites, generally buildings in town, deliver reliable results. For this monitoring operation, compact and low-height/weight portable antennas and stations are needed. The transportable or portable configuration provides measurement resources that can be easily moved to locate on the LoS propagation path of the signal.

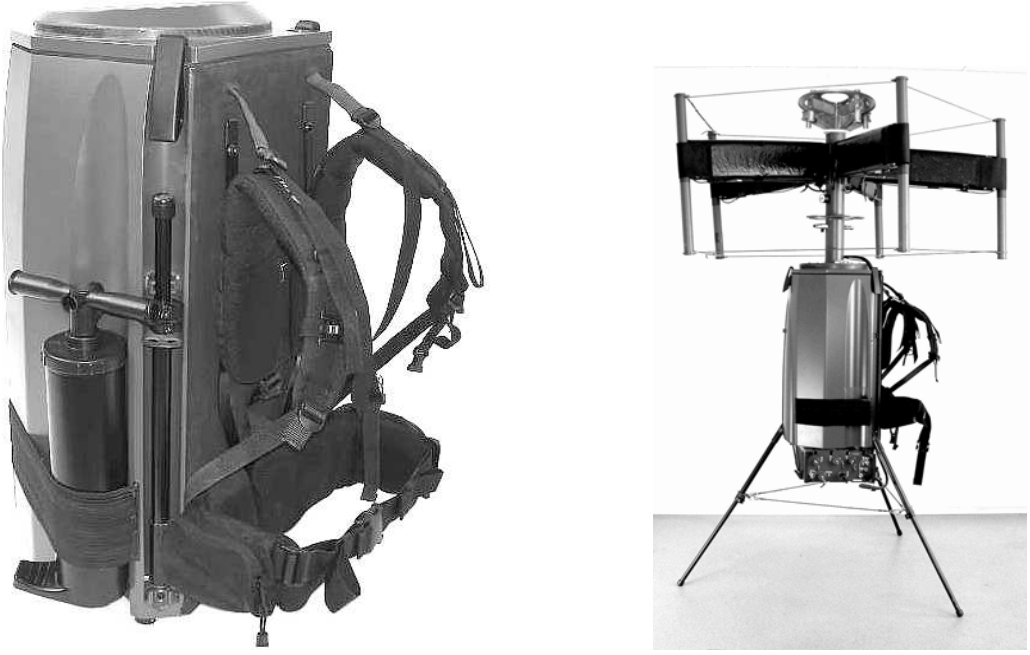
Three examples of portable antenna/stations are as follows:

Type 1: The first type of portable antenna/station requires deployment. The equipment is carried on a person's back to a dedicated measurement site. Figure 3.2-26 is an example of such a DF antenna, which enables fast deployment (a few minutes). The antenna and monitoring station is completely integrated, including receiver, cable switching unit and antenna, and carried on the back. The antenna structure is completely enclosed in a plastic box.

Type 2: The second type of portable antenna does not require deployment. The entire station (antenna and receiver) is integrated in a man-pack, which operates while the operator moves. The MMI is either integrated on a PDA allowing the operator freedom of movement, or on a laptop computer. A built-in DF antenna is integrated on the side of the receiver. The monitoring tasks are performed by a single person, with hands free for man-portable applications. A DF antenna for upper frequency bands could be provided.

FIGURE 3.2-26

Example of a portable VHF/UHF antenna



a) The antenna is enclosed in its box ready to be carried

b) A 20-3 000 MHz antenna in deployed configuration where a compact receiver and DF is installed

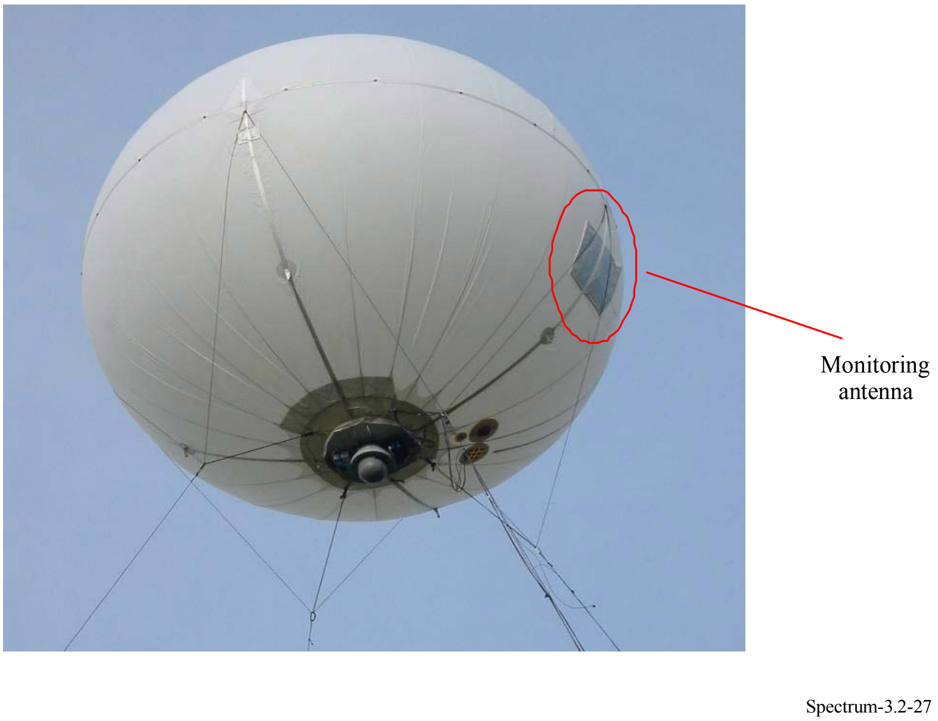
Spectrum-3.2-26

Type 3: A third type of portable antenna is a very compact solution. A hand-held directional antenna serves as monitoring and DF antenna and is connected to a hand-held receiver that allows for front panel operation without the need of an additional PC/PDA. The monitoring tasks are performed by a single person.

Another antenna type that may be required for specific use is shown in Fig. 3.2-27. This is a flexible monitoring antenna mounted on the envelope of a balloon which may be very useful for short-duration events, for example, to monitor special events such as state visits and sporting events.

FIGURE 3.2-27

Example of a balloon support for a flexible VHF/UHF antenna



An antenna altitude of up to 100 m allowed by such a balloon may detect and measure a maximum number of signals of interest. It is also better than terrestrial stations for intercepting a maximum number of signals without disturbance from buildings, forest and other high obstacles, and the presence of multipath.

The balloon is associated with a compact receiver (installed on the ground), is deployed quickly and easily, and can rapidly monitor the VHF/UHF frequency bands including unlicensed users and interference.

To avoid excessive cable loss due to the balloon height, two configurations are used:

− A monitoring receiver and processing unit may be located below the balloon. In this case, two cables (supply and data transmission) run to the ground station.

− A down-conversion unit may be used to convert the RF signal into an FI baseband. With analogue conversion, a RF cable may be used if the balloon is at a low height. For digital conversion, an optical or a data link may be used to transfer data to the ground station.

3.2.8 Transmission lines and distribution systems

3.2.8.1 Transmission lines

Transmission lines at monitoring stations conduct the received power from the antenna to the receiver.

Among the various types of transmission lines the preferred solution at monitoring stations is the coaxial transmission line. Its impedance is uniform provided the dimensions of the various parts including the connectors are adequately controlled. Signals on good coaxial cables are not severely affected by the presence of other objects. Coaxial cables are manufactured in a wide variety of sizes and materials. Properties of the available coaxial cables are many and varied, and cover a wide price range. There are a number of manuals available, particularly from cable manufacturers, which list individual coaxial cable properties. It is important to use double-shield braid or solid outer conductor type coaxial cable.

A 3 dB total attenuation may be quite acceptable for a receiving transmission line. The use of an integrated receiver at the antenna base avoids long cable runs, reduces insertion loss and eliminates any need for an LNA in a switching unit.

3.2.8.2 Distribution systems

Once the energy received by a particular antenna has been conducted to a point inside the monitoring building, there is usually a requirement to distribute this energy to a variety of receiving positions. The distribution system should take into account the final use that is to be made of each output so that the optimization of results can be obtained. In general, the level of the signal should be maintained as high as possible, so that undue sensitivity is not required of receiving equipment. Also, the quality of the signal (S/N) should be maintained, or the degradation kept as low as possible, so that the advantages of high gain antennas and low-loss distribution cables are not compromised.

Receivers which are simply connected in parallel across a transmission line will degrade the monitoring system performance because of e.g., standing waves, undefined power splitting and local oscillator reradiation. This method is not recommended. Instead, matching and signal splitting should be used.

As technology evolves, the number of antennas in a radio monitoring station is increasing; this results in complex receiving systems and distribution systems. It is sometimes necessary to receive signals from different frequency band antennas with different receivers. Distribution systems have benefited from computer and software technology and have evolved from mechanical to digital equipment modules.

3.2.8.2.1 Principle

Distribution systems generally include an antenna switch and antenna duplexer. State-of-the-art technology is used to combine the two to achieve remote control via network.

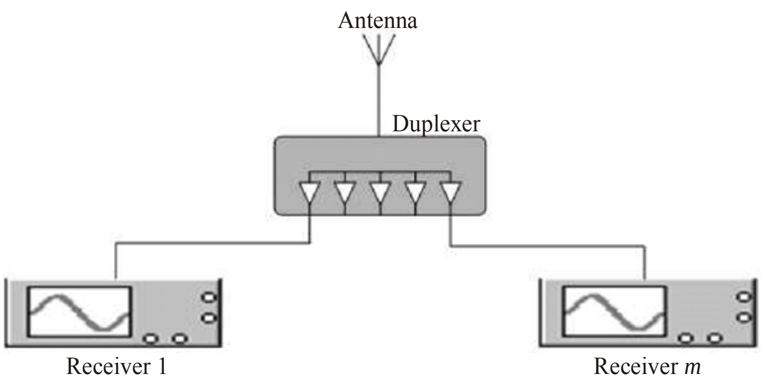
3.2.8.2.1.1 Antenna duplexer

In a receiving system, the equipment which distributes a signal from one antenna to a multi-channel receiver or multiple receivers is known as a duplexer. A duplexer is the first component of the receiving system and it should have good linearity to minimize intermodulation.

Figure 3.2-28 shows the connectivity of antenna, distribution system and analysing equipment.

FIGURE 3.2-28

Example of distribution system



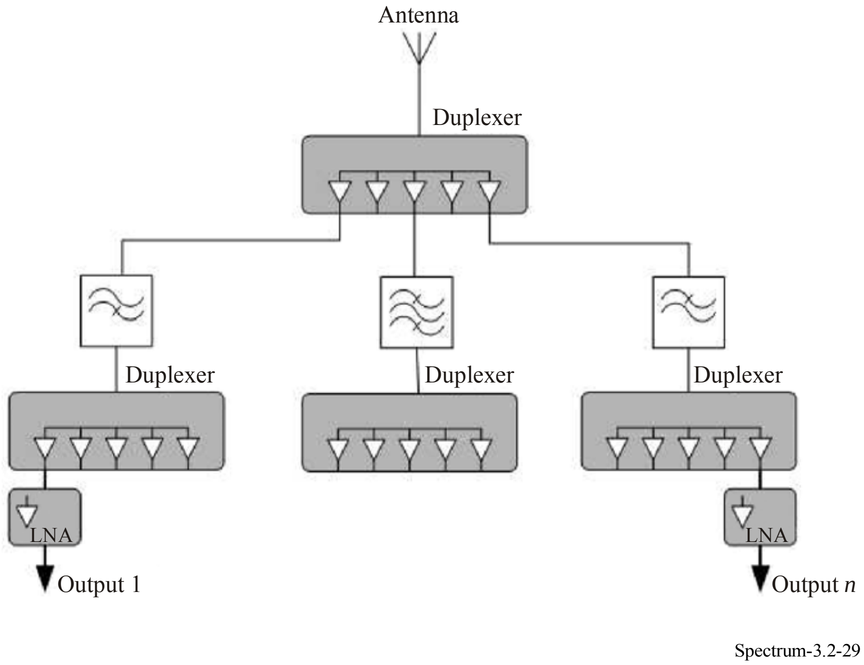
Spectrum-3.2-28

An antenna duplexer may be comprised of multiple duplexers and may include single filters that isolate different signal paths; an LNA is used to compensate for the attenuation and the controlling circuit.

A block diagram of a multipath duplexer is shown in Fig. 3.2-29.

FIGURE 3.2-29

Typical block diagram of a multipath duplexer



Because of the non-linearity of some of the components, the degradation of the noise figure is inevitable in the case of a multi-level duplexer for connection. Therefore, to maintain its performance, 2-level and 3-level duplexers are widely used. In general, noise figure and linearity degrade as the number of outputs increases.

3.2.8.2.1.2 Antenna switch

An antenna switch selects from several antenna inputs a wanted input signal for one receiver. An RF antenna switch is shown in Fig. 3.2-30.

Like antenna duplexers, an antenna switch consists of different components for different frequency bands because of the frequency limitation of individual components; insulation design is necessary between these components.

LNA are sometimes used to compensate for the attenuation of components.

3.2.8.2.1.3 Distribution system

An RF signal distribution system is used to distribute signals from different antennas to different receivers.

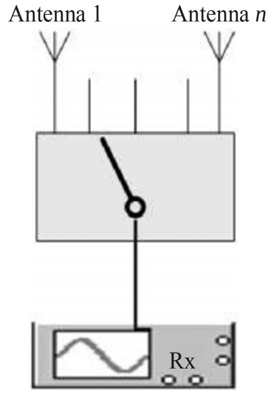
Signals from any antenna are available to any one of the receivers; any input signal can be delivered to any output of the distribution system.

There are two types of distribution systems. One is similar to what we see in a switching system, and is known as a blocking system. In such a system, only one antenna is connected to the receiver, and any new attempts to connect will be blocked. A typical blocking distribution system is shown in Fig. 3.2-31.

The other type, which utilizes newer technology, allows the connection to be established between multiple antennas and any of the antennas, or one antenna and multiple receivers.

FIGURE 3.2-30

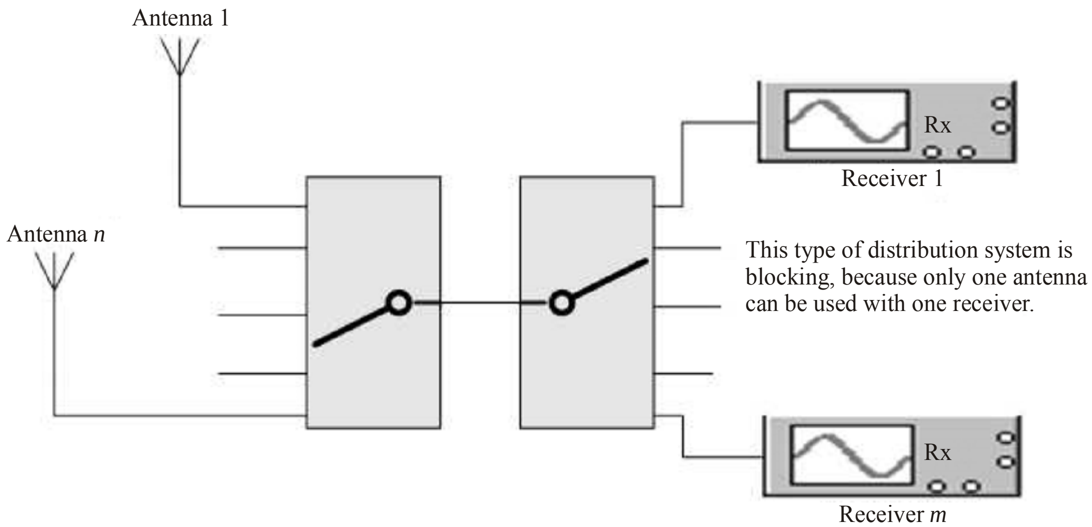
Typical antenna switch



Spectrum-3.2-30

FIGURE 3.2-31

Typical distribution blocking system



Spectrum-3.2-31

In fact, an ideal M ×N matrix is composed of an M duplexer and an N antenna switch. Each antenna provides the n paths duplexer with its outputs, while the n paths outputs of the duplexer are connected to the inputs of the n antenna switch. Each antenna switch will provided the n receivers with its outputs. The principle of a non-blocking antenna matrix is shown in Fig. 3.2-32.

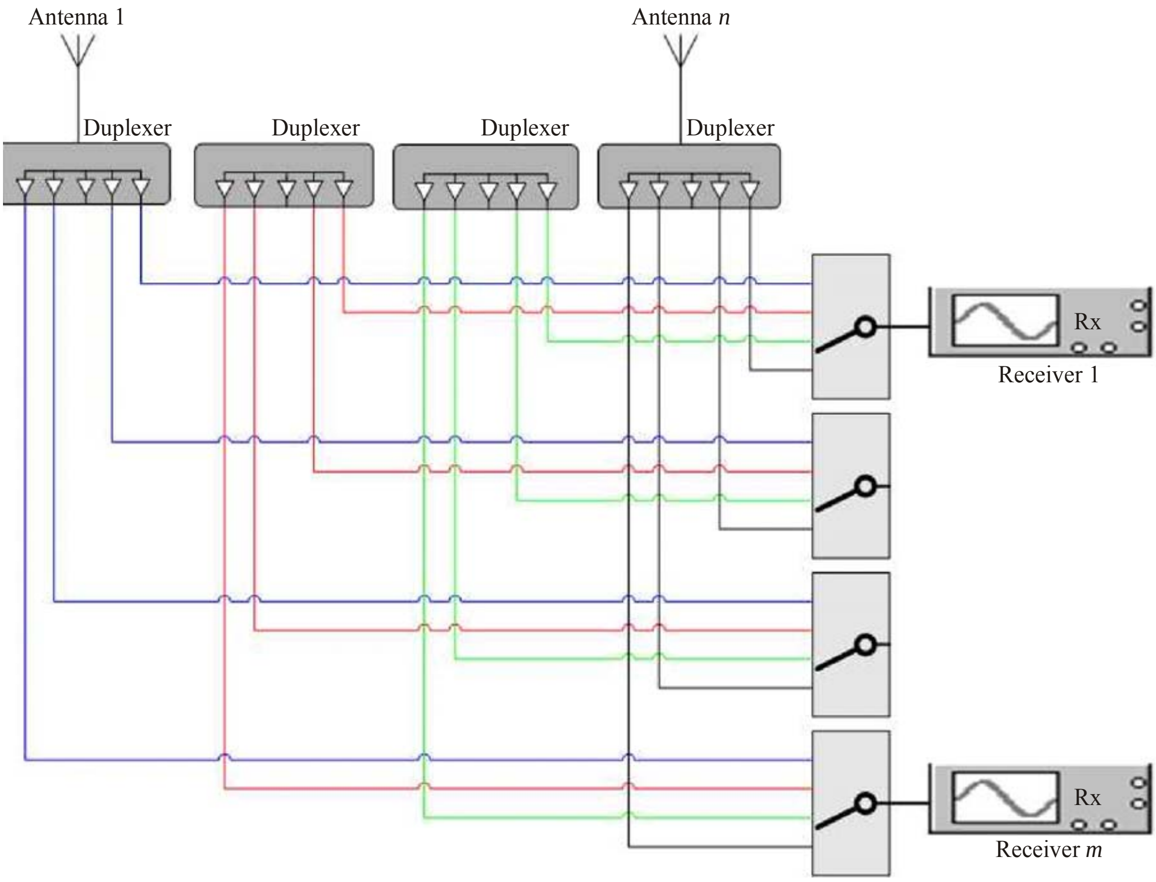
For example, if an x receiver has to be connected to a y antenna, the signal of this antenna will be split into m outputs by the y duplexer and switched to the x receiver by the x antenna switch.

where:

- *n*: maximum number of antennas with duplexer
- *m*: maximum number of receivers
- *x*: selected receiver
- *y*: selected antenna.

FIGURE 3.2-32

Typical non-blocking distribution system



Spectrum-3.2-32

3.2.8.2.2 Performance

Despite the burgeoning development of digital signal processing technology in signal detection, demodulation and DF, analogue technologies are still necessary in signal distribution.

A good distribution system should be optimized for performance in such areas as sensitivity, dynamic range, switch of RF signal, capability of distribution, and isolation between channels.

Specifications of a distribution system should include the following major parameters:

- Frequency range.
- Insertion loss.
- Isolation.
- Dynamic range.
- Third order intermodulation product (IP3).
- Noise figure.

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ITU-R Recommendations:

NOTE – In every case the latest edition of all the referred Recommendations is encouraged to be used.

Recommendation ITU-R F.162 – Use of directional transmitting antennas in the fixed service operating in bands below about 30 MHz.

Recommendation ITU-R BS.705 – HF transmitting and receiving antennas characteristics and diagrams.

3.3 Monitoring receivers

3.3.1 General considerations

The performance of a monitoring station is directly related to the quality of the station equipment, including the antennas, receivers, radio DF and processors. Antennas, DF and processing equipment are discussed in §§ 3.2, 3.4 and 3.6.2. An in-depth study of receivers would require a dedicated book, so only an overview of the composition of receivers, definition of the main features and operating precautions is provided here.

The function of a receiver is to select a radio signal from all the signals intercepted by the antenna to which it is connected, and to reproduce at the receiver output the information transmitted by the radio signal or its characteristics. In the past, most receivers have used entirely analogue circuitry, but most modern receivers are digital, using digital signal processing (DSP) techniques to implement many receiver functions, from simply digitizing the detector output to digitizing the full base band, including digital demodulation, such as performed by "software-defined radio" systems. Both types of receivers, analogue and digital, are discussed below.

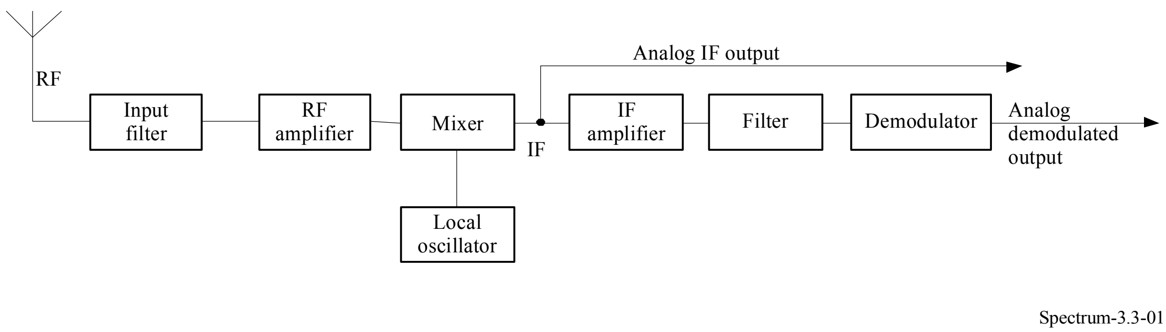
Due to technological improvements, modern receivers are becoming more and more compact. Miniaturization of high stability oscillators allows the analogue portion of a receiver to become smaller. For digital receivers, the digital part is becoming more powerful and compact, due to improvements in analogue to digital converters, memory and processors. Interfaces are now fully digital.

3.3.2 Analogue receivers

The block diagram in Fig. 3.3-1 shows the main stages of an analogue receiver. The input filter, which is typically a bank of suboctave preselector or tracking filters, allows for the reception of the desired signals and eliminates those which are out-of-band, in order to preclude intermodulations in the high-frequency amplifier. This filter should include the centre frequency of the transmission to be received, and have a passband wide enough to receive the entirety of the desired transmitted spectrum.

FIGURE 3.3-1

Typical block diagram of an analogue receiver



The designer of a monitoring station must then pay attention to the power of transmissions likely to be received within the passband of this input filter; signals other than the desired one are likely to generate spurious signals by intermodulation in the RF amplifier and/or to result in sensitivity degradation of the RF amplifier due to its blocking. To eliminate these effects, it is necessary to have sufficient RF amplifier linearity.

The purpose of the input filter is also to attenuate reception of the image frequency.

The RF amplifier, by its gain, partly determines the receiver sensitivity. But it also has another very important purpose: with the input filter, it prevents the local oscillator signal from being conducted to the antenna, which would radiate it, thus generating a spurious radio signal.

The intermodulation between two signals occurs when such signals go through a non-linear circuit as described in § 6.5. Intermodulation signals can be superimposed on usable signals, and interfere with them.

The quality of a receiver, from the intermodulation point of view, is characterized by the value of its third-order intercept point, which should be as high as possible.

Receiver sensitivity is limited by the noise generated by its input circuits, in particular by the RF amplifier and the mixer. The sensitivity is also expressed by the noise figure in Table 3.3-1, which should be as low as possible. The relationship between sensitivity and noise factor, for the same receiver, involves the receiver passband.

When a receiver is connected to an antenna, in addition to its own internally generated noise, natural noises of external origin are added, such as atmospheric, galactic and solar noise, as well as artificial noises such as industrial interference, radiation from electronic equipment and radiation by transmitters generally. The designer of a monitoring station has, therefore, to select the receiver from the standpoint of its sensitivity, according to the noise levels measured.

It should be noted that a receiver with very high sensitivity would have poor performance as regards linearity, i.e. intermodulation and blocking. Blocking characterizes degradation of receiver sensitivity and can be caused by only one unwanted signal situated in the vicinity of the wanted carrier and outside the receiver IF passband.

Due to this fact, monitoring receivers usually contain switchable or programmable-gain preamplifiers. This allows the receiver to operate either in high sensitivity mode (with the preamplifier in the “on” mode) or high linearity/low distortion mode (with the preamplifier in the “off” mode).

Other characteristics should also be specified or investigated, such as:

– bandwidths of intermediate frequency filters;
– types of demodulation needed;
– effectiveness of the automatic gain control;
– effectiveness of the automatic tuning system;
– frequency response of the circuits processing the demodulated signals;
– precision and legibility of displays; and
– variations in characteristics depending on the temperature.

Normally two types of receivers are used to cover the frequency range from 9 kHz to 3 000 MHz, one for frequencies up to 30 MHz and the other for 20 MHz-3 000 MHz. The frequency range of some 20 MHz-3 000 MHz receivers may be extended to provide coverage of the lower portion of the SHF band. If an extended frequency range (e.g. up to 40 GHz) is to be covered, additional equipment may be required. In selecting the receivers, the various types of modulation to be monitored e.g., AM, CW, SSB, ISB, FSK and FM, should be taken into account and provision made for the reception of these emissions.

All the qualities expected of receivers for use at a main receiving station are required of monitoring receivers, with the addition of good frequency setting accuracy (better than or equal to 1 Hz), rapid tuning and a minimum of waveband switching.

Provision should also be made for the connection of additional units, i.e., radio teleprinter keying units, oscilloscopes, panoramic adapters, etc. The intermediate frequency output of the receivers should be provided at low impedance via buffer stages. To obtain long-term high-frequency stability, it is useful to have an input for an external frequency standard (see § 3.3.4). It is also necessary to provide for the insertion of an attenuator at the receiver input to eliminate spurious frequencies caused by high-level signals overloading the receiver input stages. Interfaces for remote control and data output should also be provided.

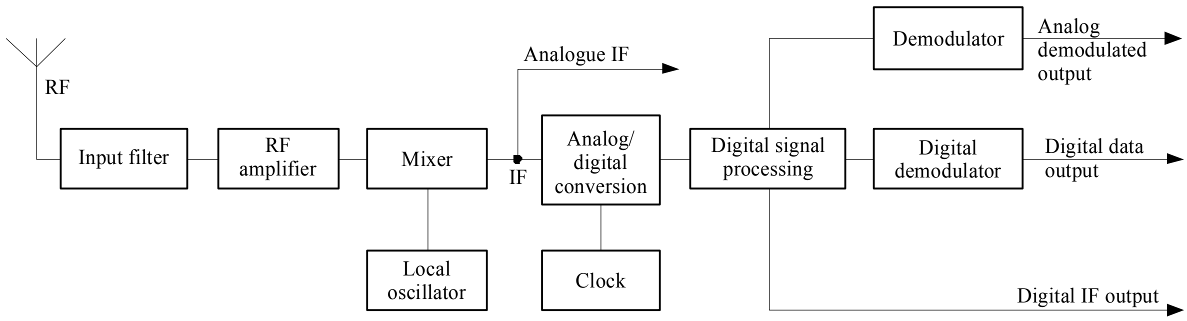
3.3.3 Digital receivers

The advent of high-speed, low-cost digital signal processing (DSP) chips and high dynamic range analogue to digital (A/D) converters has made possible the design of high performance receivers that use digital circuitry to replace analogue circuitry. These “digital receivers” provide improved performance in frequency conversion; filtering and demodulation, which leads to increased selectivity, stability and automatic, gain control. Additionally, functions such as adaptive interference cancellation, and speech enhancement and recognition not found in analogue receivers may be available in digital receivers. These functions are very important when attempting to sort and identify specific signals in a congested signal environment. The performance of these receivers, because of the use of digital circuitry and associated software algorithms, does not vary with regard to time and temperature. One of the most significant features of digital receivers is improved flexibility, an example of which is the ability of the digital receiver to accommodate complex modulation formats commonly used in cellular and high performance control links. Additional IF bandwidth, demodulation modes, or other functions can be made in a DSP-based circuit by software change versus costly equipment replacement of analogue receivers. Filters can be synthesized by digital processing to provide extremely sharp filter shape factors, while maintaining very flat amplitude and linear phase response over the desired pass band. This process minimizes signal distortion usually introduced by analogue filters. It is also possible to generate very narrow (less than 50 Hz) filters allowing direct measurement of transmitter carrier spurious components such as power line related hum.

The basic elements of a digital receiver: the RF tuner, IF digitizer, signal processor, and analogue signal reconstruction modules, are shown in Fig. 3.3-2.

FIGURE 3.3-2

Typical block diagram of a digital receiver



Spectrum-3.3-02

The first major processing step in a digital receiver is the conversion of the desired RF signal to digital form. This process is performed by the combination of the RF tuner and the IF digitizer. The RF tuner, including analogue preselection, translates the desired portion of the RF spectrum to a wideband, or pre-IF, for processing by the IF digitizer. The IF digitizer utilizes an A/D converter and other circuitry to digitize the IF from the RF tuner. The resulting digitized signal is used by the signal processor to perform such functions as filtering, fine tuning and demodulation. Digital output from the module is then made available for further processing and/or recording. The analogue signal reconstruction module converts the digital outputs to analogue for operator monitoring or further processing.

The receiver characteristics listed in § 3.3.2 apply also to digital receivers. Receivers for the execution of spectrum monitoring tasks according to ITU-R Recommendations should provide the following functions:

– scan of predefined frequency ranges;

– memory scan of several hundred channels;

– audio monitoring of FM, AM, CW, SSB, ISB, ASK, FSK, PSK, IQ and pulse transmissions;

– identification;

– storage of measured values for a later use or download.

Processing these different functions for the various signals available, with optimum S/N, requires a large number of IF bandwidths.

Modern digital monitoring receivers include a display and control unit, either a separate PC with computer software that provides a “Virtual Control Panel” or a built-in control unit. The receiver has a remote interface, including LAN (Ethernet) that provides for both local and remote control operation. Also, the operational concept of a monitoring receiver should meet all the demands made on a receiver for measurement of frequency and frequency offset, field strength, modulation, bandwidth and spectrum occupancy. For the spectrum occupancy the receiver has to scan the frequency range of interest with digital control and has to display the associated spectrum.

Digital receivers may be packaged separately, but are often integrated into the measurement and processing system as described in § 3.6.2. The receivers include a number of interfaces, such as: Digital IF output, I/Q-based output for DF, wideband IF output for external panoramic display, output for external loudspeaker, and headphone socket.

With the help of a digital down converter (DDC) a selected signal is mixed down to baseband for further processing (demodulation, decoding, identification, measurement of modulation-parameters). By using a bank of DDCs in parallel (implemented e.g. in FPGA, DSP or ASIC technology) many signals can be mixed down and processed in parallel. Every DDC can be tuned in the frequency range covered by the wideband IF and works as a virtual receiver. This technology is especially useful for processing signals that were recorded within a digital wideband IF by replaying the digital IF back to the wideband receiver and using the DDCs to select the signals of interest for processing.

This processing technique makes it possible to detect and analyze short-duration transmissions such as frequency hopping signals. The bursts of hopper transmitters are received with the wideband receiver (live or replayed) and detected with an automatic burst detection algorithm. By using DDCs the hops are mixed down to baseband and analyzed (exact length, bandwidth, modulation-parameters). An evaluation process investigating the measured information of all detected bursts determines the different types of bursts, the different hop rates und hop-sets (frequency-sets) of the received transmitters. This statistical analysis provides information about hopper scenarios like the number of active hopper transmitters and the types of communication methods used.

3.3.4 Frequency synthesizers for receivers

One of the most essential components of the receiver is the frequency synthesizer. The main purpose of the frequency synthesizer is to provide a standard source of RF energy of which the frequency, power level and modulation characteristics are known exactly. The accuracy required for a frequency used for controlling and checking modern receiving systems is becoming more and more stringent and is the reason why the synthesizer must have the highest possible precision and stability. Consequently most monitoring stations have a frequency synthesizer which covers a wide frequency range with very high precision.

3.3.5 Typical specifications for monitoring receivers

A monitoring receiver should generally meet the specifications for VLF/LF/HF and VHF/UHF receivers that are given in Table 3.3-1. This table applies to both analogue and digital receivers. One should also consider these specifications as a general guideline to select equipment that is able to provide a good performance and reliability for the tasks required by a monitoring system. For certain applications it is possible to find on the market simpler equipment that might be sufficiently suitable when considering the desired application.

Certain receiver parameters given in Table 3.3-1, such as third order intercept, noise figure, and filter parameters, are so important and have such a direct influence on the suitability of a receiver for certain monitoring tasks, that their specification and measurement procedures are defined by ITU-R Recommendations. Measurement results strongly depend on the test procedures used, and standardized test procedures allow easier and more objective comparison of products from manufacturers. Scanning speed, discussed in Recommendation ITU-R SM.1839, required for different measurements is very dependent on the intent and application of the measurement; for example, the required receiver scanning speed to detect the presence of a single-event signal burst is much faster than receiver scanning to measure some parameter or characteristic of the signal.

The specifications given Table 3.3-1 represent the performance of a good quality commercial monitoring receiver. The table describes “typical” specifications, not “minimum” nor “best achievable”. Administrations should consider their own specific needs when specifying equipment performance, using the table as a guide. The performance of a receiver intended for a different purpose than a general purpose monitoring receiver may emphasize improvement in some specifications and relaxation in other specifications, depending on the purpose.

TABLE 3.3-1

Typical specifications for general purpose monitoring receivers

Function	VLF/LF/HF	VHF/UHF
Frequency range	9 kHz to 30 MHz	20 MHz to 3 000 MHz
Tuning resolution	≤ 1 Hz	≤ 10 Hz
Tuning error	≤ 1 ppm, or ≤ 0.01 ppm using global positioning by satellite(1) for external reference	≤ 0.1 ppm, or ≤ 0.001 ppm using global positioning by satellite(1) for external reference
Synthesizer settling time	≤ 10 ms	≤ 5 ms
Input (antenna input) VSWR	50 Ω, nominal ≤ 3	50 Ω, nominal ≤ 2.5
Preselection (highly linear receivers may meet intermodulation specifications without preselection)	Set of suboctave band filters or tracking filter	Set of suboctave band filters or tracking filter
3rd order intercept	≥ 20 dBm (> 3 MHz)(1)	≥ 10 dBm(1)
2nd order intercept	≥ 60 dBm (> 3 MHz)	≥ 40 dBm
Noise figure	≤ 15 dB (> 2 MHz)(2)	≤ 12 dB(2)
LO-phase noise	See below	See below
IF rejection	≥ 80 dB	≥ 80 dB
Image rejection	≥ 80 dB	≥ 80 dB
IF bandwidths (–6 dB)	Internal or external filters, preferably digital, from 0.1 to at least 10 kHz(3)	Internal or external filters, preferably digital, from 1 kHz to at least 300 kHz(3)
Selectivity 60 to 6 dB (shape factor)	2:1(3)	2:1(3)
Detection modes (in digital receivers, demodulation may be done in internal or external DSP)	AM, FM, CW, LSB, USB	AM, FM, CW, LSB, USB
AGC range (for digital receivers, may be partly implemented in internal or external DSP)	≥ 120 dB	≥ 120 dB
Outputs – IF	Digital IF output	Digital IF output
Audio	0 dBm, 600 Ω or digital streaming audio and ear-phone jack	0 dBm, 600 Ω or digital streaming audio and ear-phone jack
IF monitor	For external IF monitor, or digital data stream	For external IF monitor, or digital data stream
Remote control	Ethernet LAN, or GPIB, or RS-232	Ethernet LAN, or GPIB, or RS-232
IF spectrum (may be done in DSP)	Built-in or external, FFT processing; refresh ≥ 10/s	Built-in or external, FFT processing; refresh ≥ 10/s
RF spectrum (may be done in DSP)	Built-in or external; refresh ≥ 10/s	Built-in or external; refresh ≥ 10/s
RF and IF spectrum display	Via local or remote control	Via local or remote control
Electromagnetic compatibility	IEC 61000-4-2, -3, -4 CISPR 11, group 1, class B	IEC 61000-4-2, -3, -4 CISPR 11, group 1, class B
Operating temperature range	0° to 45° C	0° to 45° C
Relative humidity	95% non-condensing	95% non-condensing
Vibration	IEC 68-2-6	IEC 68-2-6

(1) Measurement procedures according to Recommendation ITU-R SM.1837.

(2) Measurement procedures according to Recommendation ITU-R SM.1838.

(3) Measurement procedures according to Recommendation ITU-R SM.1836.

Phase noise

The phase noise performance of a receiver directly impacts the ability to resolve closely spaced signals of different amplitudes. It can also prevent accurate demodulation. Phase noise in a receiver phase modulates received signals increasing their bandwidth. Two adjacent signals that may not have overlapping spectrums at the input to the receiver may interfere with each other in the receiver once modulated by receiver phase noise.

Phase noise is multiplicative and therefore is specified as a noise density relative to a carrier (dBc/Hz), the larger the signal, the greater the phase noise power. The greatest impact of phase noise is on closely spaced signals of unequal power.

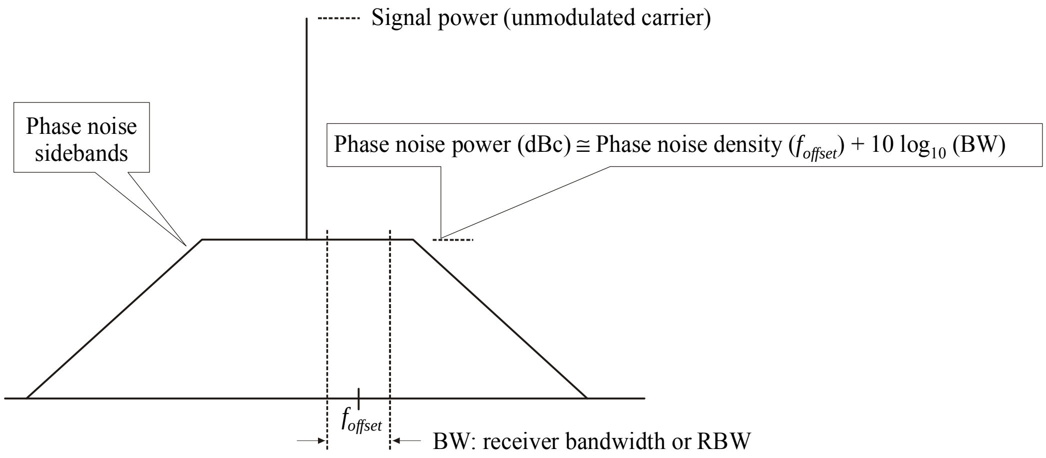
The larger signal will have greater power in the phase noise sidebands and therefore have greater impact on the detection or demodulation of the weaker adjacent signal than the other way around. For large signals, phase noise limits the receiver's dynamic range.

Phase noise density is usually specified at fixed frequency offsets such as 10 kHz or 100 kHz. The phase noise density is generally greatest at small frequency offsets. For this reason the phase noise requirement is largely determined by the types of signals that are to be monitored. Phase noise requirements will be much greater with narrowband signals than with wideband signals, so receiver specifications will be driven primarily by the narrowest carrier (or subcarrier) to be monitored.

With the assumption that the phase noise spectrum is relatively flat across the bandwidth (BW), the dynamic range near a large signal can be estimated as illustrated in Fig. 3.3-3.

FIGURE 3.3-3

Estimation of dynamic range and phase noise power



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Example of application of the equation in Fig. 3.3-3.

Bandwidth or RBW	Phase noise	foffset	Phase noise power
1 kHz	–100 dBc/Hz	10 kHz	–70 dBc

The frequency offset and required bandwidths affect the phase noise power. HF applications may have narrower bandwidth requirements whereas UHF applications may have wider bandwidth requirements.

References

ITU-R Recommendations and Reports

NOTE – In every case the latest edition of all the referred Recommendations is encouraged to be used.

Recommendation ITU-R SM.331 – Noise and sensitivity of receivers.

Recommendation ITU-R SM.332 – Selectivity of receivers.

Recommendation ITU-R SM.1836 – Test procedure for measuring the properties of the IF filter of radio monitoring receivers.

Recommendation ITU-R SM.1837 – Test procedure for measuring the 3rd order intercept point (IP3) level of radio monitoring receivers.

Recommendation ITU-R SM.1838 – Test procedure for measuring the noise figure of radio monitoring receivers.

Recommendation ITU-R SM.1839 – Test procedure for measuring the scanning speed of radio monitoring receivers.

Recommendation ITU-R SM.1840 – Test procedure for measuring the sensitivity of radio monitoring receivers using analogue-modulated signals.

Report ITU-R SM.2125 – Parameters of and measurement procedure on HF/VHF/UHV monitoring receivers and stations.

3.4 Direction-finding

3.4.1 General considerations

Identification of an unknown transmitting station can be facilitated if the location of the transmitter can be determined by triangulation or SSL using Direction-finding (DF) equipment. A more accurate determination of the transmitter location requires bearings to be taken by several DF stations established at suitable geographical locations. Ideally, a "cross bearing" or a "fix" (i.e., the point where the bearing lines intersect) can be obtained when a minimum of two DF stations, which need not necessarily be in the same country, work in unison. A monitoring station that has the possibility of taking bearings can provide an experienced operator with information, which will enable him to identify transmissions with a higher degree of confidence.

The complexity of the DF equipment depends upon the required accuracy and the local conditions and is discussed in more detail in § 4.7. Since the DF antenna must be set up at a place clear of any buildings, antennas, power and telephone lines and other prominences, it should generally be installed at some distance from the rest of the monitoring station, or perhaps at a separate location, where it is operated under remote control.

The accuracy of the bearings depends upon the following factors (not in order of importance):

– antenna aperture, as described in § 3.4.2;
– antenna configuration, including number of antenna elements, their organization into frequency bands, element directivity and other factors;
– type of DF equipment;
– number of receiver channels;
– nature of site;
– signal strength and S/N;
– integration time;
– propagation conditions;
– amount of interference.

In the frequency range where skywave propagation is present, typically 1-30 MHz, an SSL system allows determining the geographical position of a transmitter with a single radio DF that measures elevation as well as azimuth angle of arrival. Processing data supplied by the radio DF (azimuth, elevation, position), associated with ionospheric predictions or preferably real-time ionospheric measurements from a sounder, allows estimating the transmitter distance. The SSL concept thus allows performing the location mission when, for geographical, timing, availability reasons, a complete triangulation radio DF location system could not be installed, or the signal of interest could not be received at multiple stations.

For further information see Recommendations ITU-R SM.854 – Direction finding and location determination at monitoring stations, and § 4.7.

3.4.2 Antennas

The DF antenna is one of the most important components of DF equipment because it largely defines the DF accuracy. The aperture of the antenna array (D/λ; D: diameter of the antenna array, λ: wavelength of the received signal) plays a most important role in determining the bearing accuracy. DF antennas with $D/\lambda > 1$, so-called wide-aperture antennas, overcome multi-path problems and other propagation effects, noise, interference, site irregularities and other sources of error, providing higher *S/N*, smaller DF errors, higher immunity to reflections, higher sensitivity, and shorter integration times for a given level of accuracy than narrow-aperture antennas ($D/\lambda < 0.5$). Not all DF methods allow the use of wide-aperture antennas, but where they may be used, they provide the most accurate DF results.

Each DF antenna consists of a number of antenna elements (minimum three). Depending on the DF method various configurations of the DF antenna array are possible. Wider aperture DF antennas tend to have more antenna elements to fill the aperture and avoid ambiguities; the probability error introduced by random noise tends to reduce by the reciprocal of the square root of the number of elements. In the HF range circular and "L"- or "X"-shaped linear arrays are common, in the VHF/UHF range mainly circular arrays are in use. The DF method has also an influence on whether a wide frequency range can be covered by only one antenna array or whether the range has to be divided into a number of arrays for different sub-ranges.

Generally one has to discriminate between DF antennas for fixed and mobile application. The type of antenna elements depends on the frequency range and application: in the HF range, arrays of monopoles or crossed-loop elements are used for fixed systems, whereas mobile systems use antenna arrays consisting of either loops or ferrite elements (see § 3.2.3.1). For the VHF/UHF range, mostly arrays of dipoles or fans are in use (see § 3.2.4.1).

3.4.3 Equipment

DF equipment may be integrated in with the measurement equipment at a monitoring station as described in § 3.6.2, or may consist of separate units. For portable units, see § 3.2.7. The frequency range of DF equipment is not only determined by the DF antenna but also by the receivers, which form part of the equipment. In practice, there is MF/HF DF equipment (e.g., 0.3-30 MHz) and VHF/UHF DF equipment (e.g., 20-3 000 MHz). In some cases VHF/UHF DF equipment may provide coverage of the lower portion of the SHF band.

The number of receivers may vary from 1 to n, where n is the number of elements that form a DF antenna array and it depends also on the DF method. Multiple receiver systems require less integration time and/or less *S/N* for a given accuracy and therefore provide faster response time than single channel systems. If more than one receiver is used, all receivers have to be tuned by one common oscillator. In modern receivers, the IF is processed in digital form. A very important feature for DF receivers is the selectivity of the receiver to avoid a mutual interaction of two adjacent signals. At least one of the DF receivers should offer the possibility to demodulate the modulation of the received signal.

Some DF methods require a calibration of the receivers, RF distribution and antennas at certain time intervals. For this purpose, a defined signal will be injected in parallel into the receiving paths, and after measuring amplitude and phase for each path, corrective steps are taken to restore identical characteristics for each channel, if necessary. A very important feature is the possibility to remote control the equipment over any distance. Interfaces for RS-232, ISDN, LAN WAN and cellular telephone links are common.

3.4.4 Number of receivers

This section compares DF systems with varying numbers of receiver channels, considering the advantages and disadvantages of each. A DF system may have a single-channel receiver, dual-channel receiver, triple-channel receiver, or a receiver with up to as many channels as there are antenna elements. Systems with at least two receiver channels, but less channels than the number of antennas, are termed multi-channel systems. Systems with the number of receiver channels equal to the number of antennas are termed N-channel systems, where N is the number of receiver channels and antennas.

3.4.4.1 Single-channel systems

Advantages	Disadvantages
– Only one receiver channel required – Less cabling from DF antenna to equipment – No phase matching/calibration required – For interferometer single-channel DF using multiplexing circuits, accurate phase measurement is possible	– Amount of switching and associated sampling time require substantially more measurement time than DF systems with more than one channel – Sensitive to rapid signal phase variations, which can result in bad data and/or long integration times – If multiplexing circuits are used, antenna switch is complex

Single-channel DF systems can be divided into two groups:

– simple single-channel DF systems, where each antenna element is sampled sequentially with one receiver channel; and

– interferometer or multiplexed single-channel systems, where the reference antenna element is sampled together with each other antenna element and both signals are combined and routed to one receiver channel.

In either case, after each switch, the IF filter in the receiver must be allowed to settle before the voltage can be sampled. The total sampling time depends on the settling time of the filter, which is tied to its bandwidth, and the number of antenna elements. This sampling time is substantially longer in single channel systems than in systems with more than one receiver channel.

During the sampling period in a single-channel system, the wave state of the signal could change due to changes in the internal modulation of the signal or effects of the propagation medium such as fading, multi-path and reflections that arise during the sequential sampling of the elements of the array. These wave-state changes during the sequential switching process can introduce errors in single-channel systems, because they may be indistinguishable from changes in the signal that arise from sequentially sampling antennas with different patterns or orientations of their main beam. The single-channel system can only deal with errors introduced by this mechanism through measurement of the signal over periods of time long enough to average out such effects. In cases where sufficient averaging time can not be applied, such as in the case of short duration signals, single-channel systems can be confused. However, single-channel DF systems can be built that fulfil the requirement of 10 ms response time.

3.4.4.1.1 Simple single-channel DF systems

Simple single-channel DF systems sequentially sample each antenna element. In contrast to interferometer single-channel DF systems using multiplexing circuits, only amplitude is measured and processed. Phase is not measured. Systems that do not make use of phase information in the arriving wave are inherently less accurate than systems that use all of the available information in the arriving wave.

3.4.4.1.2 Interferometer or multiplexed single-channel DF systems

Interferometer single-channel DF systems use a quadrature-multiplexing technique. This allows the measurement of amplitude and phase, since the phase-reference element is always measured together with all other antenna elements.

During the measurement process, in which all antenna elements are sampled one after the other, the amplitude of the signal could change due to changes in the internal modulation of the signal or effects of the propagation medium such as fading, multi-path and reflections. To avoid a decrease in accuracy, additional averaging is required. Furthermore, the amplitude difference between two antenna elements cannot be simultaneously measured and can only be obtained by averaging over time, losing information that would be useful in systems where directional antenna elements are employed.

After each switch between antenna elements and in the quadrature-multiplexer, the IF filter in the receiver must be allowed to settle before the voltage can be sampled. The total sampling time depends on the settling time of the filter, which is tied to its bandwidth, and the number of antenna elements. This sampling time is substantially longer in interferometer single-channel systems than in simple single-channel systems.

3.4.4.2 Multi-channel systems (one reference channel and one or more switched sampling channels)

Advantages	Disadvantages
– Requires less time to obtain a result than a one-channel DF, i.e. shorter response time – Accurately handles changes in wave state due to propagation or modulation conditions – Phase and/or amplitude matching are easily accomplished by calibration or double averaging method – Simultaneously measures amplitude difference between channels	– Two or more receiver channels needed; cabling is more complex – Amount of switching and associated sampling time require more measurement time than DF systems with as many receiver channels as antennas – Regular calibration needed to match both receiver channels or, for dual-channel systems, double averaging method may be used

Multi-channel systems have more than one receiver channel, but less receiver channels than the number of antennas; they have one reference channel and one or more switched sampling channels. They have only one local oscillator, since all channels are driven from the same oscillator source. The channels do not have to be identically matched with filters which have exactly the same filter shape; rather, unmatched receivers may be used which are driven from the same oscillator. These receivers provide coherent detection of the signals in the two channels, and are calibrated over the entire RF path from antennas to A/D converters as to any phase delays, differences in the filter shape, etc., taking into account feed line differences between DF elements and the sampling circuits. This calibration is also the backbone of built-in test and diagnostics for such a system.

To avoid matching elements and/or calibration source and to simplify the measurement, but without the end-to-end calibration and built-in test, a double averaging method may be used in the case of two receiver channels, where a measurement of amplitude and phase difference between the two channels is made, and then the switching reverses the antenna connections and another amplitude and phase measurement is made, and the results are averaged, canceling out any amplitude and phase mismatch without separate calibration. A disadvantage of this double averaging method is increased measurement time.

Since systems discussed here have a reference antenna and receiver channel that can serve as a reference for phase, the difference in phase between the sampled and reference channels can be precisely measured to an accuracy of one-tenth of a degree or better. The difference in amplitude between the sampled and reference channels can also be precisely and simultaneously measured, allowing the system to distinguish amplitude changes arising from any differences in directivity of the antennas, which single-channel systems cannot do without averaging over long periods to average out effects of modulation and propagation.

The measurement of voltage on each sampled antenna is compared with the voltage on the reference antenna measured at precisely the same time. Measurements on the sampled channel are normalized by the reference channel; the voltage on the sampled channel is divided by the voltage on the reference channe/l.

This normalization divides out the effects of propagation and modulation changes that introduce error as discussed above in connection with single-channel systems, since modulation and propagation factors affect each antenna equally, under plane wave reception conditions (usually assumed case). This normalization eliminates all external factors that may affect phase and amplitude measurement accuracy.

3.4.4.3 *N*-channel systems (*N* = number receiver channels = number antennas)

Advantages	Disadvantages
– Faster DF measurements than other methods – No antenna switching is needed	– Multiple receiver channels needed; cabling is more complex – Need for phase and amplitude calibration increases complexity of the system

N-channel systems with one receiver channel for each antenna are the fastest and highest performance systems, because the arriving wave can be sampled simultaneously on all antenna elements, rather than sampling the antennas sequentially as is done in systems with less receiver channels. All receiver channels are driven from one common local oscillator.

These systems are more costly than systems with less receiver channels, as a function of the number of receiver channels and the need to either phase match the channels, or to provide real-time calibration among them. The channels do not need to be precisely matched, but rather may be simply calibrated in real time.

N-channel systems measure voltages and phases on each element relative to one of the elements which is chosen as a reference, so they have all the advantages of systems discussed in the previous subsection in terms of being able to measure both phase and amplitude information relative to the reference element.

3.4.5 Bearing processing

Bearing processing can be based on different DF methods. Each principle has its advantages and disadvantages, depending on the application. The primary methods used are the following:

– Rotating antenna.

– Doppler and pseudo-Doppler.

– Adcock/Watson-Watt.

– Phase interferometer.

– Correlative interferometer.

– Advanced resolution.

DF equipment produces a bearing with more or less accuracy and will also indicate the receiving level of the signal to which the system is tuned. Some DF equipment produces for each bearing a quality value that can be used to suppress “wild” bearings. Phase-sensitive DF equipment for the HF range indicates also the elevation angle of the received signal if it arrives as a skywave.

One very important feature of modern DF equipment is the ability to operate in a “DF scan” mode. With this feature, it is possible to scan through defined frequency ranges performing spectrum occupancy and simultaneously calculating the associated bearings of any signals above a threshold. This DF scan function is performed with DSP where Fast Fourier Transform (FFT) techniques are applied to subdivide the receiver bandwidth into many individual channels or FFT bins. Occupancy information and voltage information for a DF processing technique are computed by the FFT for each individual channel.

This processing technique makes it possible to intercept short-duration transmissions such as frequency hopping and burst emissions. DF scan is discussed and illustrated near the end of § 3.6.2.

3.4.6 Typical specifications for DF systems

A direction finding system should generally meet the specifications for MF/HF and VHF/UHF DF systems that are given in Tables 3.4-1 and 3.4-2. One should consider these specifications as a general guideline to select equipment that is able to provide good performance and reliability for the tasks required by a DF system. Chapter 3 of Report ITU-R SM.2125 provides information on testing of specifications for DF station IP2, IP3, sensitivity, angular accuracy, scanning speed and minimum signal duration.Some of the specifications may vary, or may not even be applicable, depending on the types of emissions to be encountered and/or the application for the direction finder. For example, a direction finder to support fast scanning of the radio spectrum should have the DF interception scanning speed as given in the table.

However, a direction finder that is used only for DF homing in a mobile environment would not need to have a fast scanning speed.

As another example, a short minimum signal duration (response time) may be required where short duration signals are encountered or in cases of rapid scanning of the spectrum, but a longer minimum signal duration may be acceptable in cases such as homing on a particular emitter.

It should also be noted that shorter signal collection times help with propagation-related effects such as multipath that can change rapidly and help mitigate interference, and it is more accurate to take lots of "snapshots" of a signal, each over a short enough period that the propagation and interference effects will not have changed, and average the results, than it is to take a few snapshots of the signal, each over a longer data-collection period.

TABLE 3.4-1

Typical specifications for MF/HF DF Fixed and Mobile Stations

Function/Performance (non exhaustive list of parameters)	Fixed Station (300 kHz-30 MHz)	Mobile Station (1-30 MHz)
DF bearing accuracy of the system (tested on open-air test facility in reflection-free environment, as per Report ITU-R SM.2125)	1° r.m.s. ($f > 1$ MHz), groundwave; 2°/cos(elevation) r.m.s., skywave	5° r.m.s. ($f > 1$ MHz); 2° r.m.s. ($f > 10$ MHz), groundwave, system installed in vehicle, test in reflection-free environment
Single Site Location (SSL)	Optional (needs ionospheric data, see § 4.7)	N/A[(1)]
DF interception scanning speed (refer to definition in § 3.3.2 of Report ITU-R SM.2125; applicable to scanning DF systems)	50 MHz/s, 5 kHz channel BW and 50% channel occupancy	50 MHz/s, 5 kHz channel BW and 50% channel occupancy
DF modulations	All	
DF instantaneous bandwidth	≥ 500 kHz	
DF Sensitivity	2 μV/m ($f > 1$ MHz) referred to 250 Hz DF bandwidth, 1 s integration time and 2° r.m.s. accuracy	30 μV/m ($f > 1$ MHz) referred to 250 Hz DF bandwidth, 1 s integration time and 2° r.m.s. accuracy
Minimum signal duration (refer to definition in § 3.3.3 of Report ITU-R SM.2125)	5 ms to 10 ms	

(1) N/A: Not applicable.

NOTES – Specifications for frequency tuning error, receiver noise figure, 3rd order intercept (IP3), IF bandwidth, operating and storage temperatures and power supply are given in Table 3.3-1.

The bearing accuracy specification for skywave signals is dependent on the cosine of the elevation angle of arrival because as the elevation angle becomes higher, the great circle arc covered by an azimuth degree becomes smaller in accordance with cos (elevation), and in fact at 90° elevation, the great circle arc covered by an azimuth degree goes to zero.

TABLE 3.4-2

Typical specifications for VHF/UHF DF Fixed and Mobile Stations

Function/Performance (non exhaustive list of parameters)	Fixed Station (20-3 000 MHz)	Mobile Station (20-3 000 MHz)
DF bearing accuracy of the system, (tested on open-air test facility in reflection-free environment, as per Report ITU-R SM.2125)	1° r.m.s.	3° r.m.s., system installed in vehicle, test in reflection-free environment, DF antenna on roof, not extended
DF interception scanning speed (refer to definition in § 3.3.2. of Report ITU-R SM.2125; applicable to scanning DF systems)	1 GHz/s, 25 kHz channels, 50% channel occupancy	
DF modulations	All	
DF instantaneous bandwidth	20 MHz	
DF Sensitivity	10 μV/m referred to 1 kHz DF bandwidth, 1s integration time and 2° accuracy parameters as per Report ITU-R SM.2125	20 μV/m referred to 1 kHz DF bandwidth, 1s integration time and 2° accuracy parameters as per Report ITU-R SM.2125
Minimum signal duration (refer to definition in § 3.3.3. of Report ITU-R SM.2125)	1 ms	

NOTES – Specifications for frequency tuning error, receiver noise figure, 3rd order intercept (IP3), IF bandwidth, operating and storage temperatures and power supply are given in Table 3.3-1.

DF accuracy measurement procedures use signals of signal to noise ratio > 20 dB as discussed in § 4.7.

3.5 Additional and separate equipment

Most spectrum monitoring stations use automated, integrated systems described in § 3.6. These systems make the ITU-recommended measurements of frequency, field strength, bandwidth, and modulation, as well as spectrum occupancy and DF measurements, with integrated measurement equipment. However, instead of or complementary to these automated, integrated systems, additional and separate equipment is also available to perform these measurements and to assist in identification. Some of this equipment is discussed below.

3.5.1 Frequency measuring equipment

3.5.1.1 General

Frequency is the most important emission characteristic that needs to be measured by a radio monitoring service. The required accuracy is quite dependent on the purpose of the measurement. When the purpose is to quickly check the use of the proper channel of narrowband FM voice radios at major events, it may be sufficient to use simple handheld frequency meters with accuracy of about 10 Hz. In contrast, when compliance of emissions with ITU-R Recommendations or national provisions is to be verified the required accuracy may be very high.

Frequency-measuring instruments are generally provided with a crystal standard. The output frequency of the crystal stage depends upon the ambient temperature and the operating voltage. Even after the warm-up period, a crystal oscillator shows a steady variation of the output frequency. At present, the order of magnitude of these variations ranges is 10^{-8}. For good instruments, the steady variation of the crystal frequency is between 10^{-10} and 10^{-9} per day after a continuous warming-up time of several weeks.

Consequently, instrument crystal stages must be frequently compared with a frequency standard or must be controlled by a standard frequency emission. An alternative to periodic comparison is to permanently lock the crystal to a reference standard (i.e., Rubidium oscillator or GPS-disciplined oscillator) and in this way, combine the short-term stability of the crystal oscillator with the long-term stability of the atomic standard.

3.5.1.2 Frequency standards

Caesium is one of the most stable frequency generators under laboratory conditions. The Caesium oscillator is used as the primary standard for time and frequency. According to the International System of Units, a second is defined as the duration of 9, 192, 631, 770 cycles of microwave light absorbed or emitted by the hyper-fine transition of Caesium-133 atoms in their ground state undisturbed by external fields. Commercially available Caesium standards are quite expensive and are therefore not generally used in monitoring stations.

Rubidium is a secondary standard for time and frequency, and is calibrated using the Caesium primary standard. Commercially available Rubidium standards are less expensive than Caesium standards. Both Caesium and Rubidium are atomic standards and exhibit extremely high accuracy and ageing characteristics.

Crystal standards are comparatively inexpensive, and available in various forms depending on the accuracy level required. As a result, crystal standards are widely used in test and measurement equipment, and telecommunication. Quartz is primarily used for making crystal oscillator standards.

Typical characteristics of some frequency standards are given in Table 3.5-1.

TABLE 3.5-1

Typical characteristics of some frequency standards

	TCXO*	**OCXO****	**GPS*****	**Rubidium**	**Caesium**
Short-term instability	$< 1 \times 10^{-9}$	$< 1 \times 10^{-12}$	$< 5 \times 10^{-12}$	$< 2 \times 10^{-12}$	$< 5 \times 10^{-14}$
Long-term instability	$< 2 \times 10^{-6}$	< 1 x 10–8	$< 1 \times 10^{-12}$	$< 1 \times 10^{-11}$	$< 5 \times 10^{-12}$

* TCXO = temperature compensated crystal oscillator

** OCXO = oven controlled crystal oscillator

*** GPS = GPS controlled crystal oscillator

3.5.1.3 GPS disciplined time and frequency standards

Each Global Positioning System (GPS) satellite carries two caesium clocks on board that are synchronized by their master station. If used for time and frequency comparison the time error is much lower than 1 µs, usually the average error value is about 10 ns. A time error of 1 µs/day corresponds to a frequency error of 10^{-11}. For spectrum monitoring, it is recommended to control a local crystal oscillator or atomic standard by an appropriate GPS receiver.

A typical frequency accuracy of 5×10^{-12} (10 MHz output) can be achieved by using a GPS-disciplined Rubidium standard, while not affecting the short-term stability of the local oscillator. Additional information on frequency and timing signals provided by satellite can be found in the ITU Handbook on Satellite Time and Frequency Transfer and Dissemination.

3.5.2 RF level and field-strength measuring equipment

Measurement of field intensity or field strength is mainly based on the determination of the response of a receiving antenna to the electric or magnetic fields that impinge upon it. A receiver connected to the antenna detects this antenna response. The response to the electromagnetic field must be analyzed with regard to the behaviour of both the antenna and the field. Measurement of field strength is accomplished through the use of a combination of the following elements:

– a calibrated antenna;

– a coupling network and/or transmission line;

– a measuring receiver or spectrum analyzer with:
  i) attenuating and preselecting circuits;
  ii) amplifying circuits in front of the main mixer and (switchable) IF filter, filters with a low 60/6 dB-bandwidth ratio are preferred;
  iii) a detecting and an indicating device, such as an analogue or digital meter, or A/D converter with computing and displaying device;
– a calibration source (e.g., a CW standard signal- or tracking-generator, an impulse generator or a random noise generator), which may also be a part of the measuring receiver or spectrum analyzer.

These elements may be combined in a single instrument, or in a number of separate instruments, each performing one or more of the required functions. For use in applications such as measurement of antenna patterns or station service areas, it is common practice to use a single portable field-strength meter containing all the above-listed elements except the antenna, and in some cases even the antenna is an integral part of the field-strength meter. In mobile or fixed installations where weight and power consumption are not so important, a wide choice of combinations is available, from a standard field-strength meter to separate units consisting of a receiver, meter, standard signal-generator or other calibrating device and an appropriate antenna system. Microprocessor systems are commonly used for controlling the receiver, calibrator, printers and/or plotters and are able to indicate and to store measurement results – all parts often being built into a single unit.

Field-strength measuring sets should have the following properties:

– high stability; it should be possible to measure over a fairly long period without the necessity of frequent recalibration;
– good relative precision; in practice, measurements of a constant field, carried out separately by two operators, should yield the same results;
– a wide range of measurement (ranging from several microvolts per metre (μV/m) to several volts per metre (V/m));
– the indication of the measuring instrument should be proportional to the r.m.s., peak or average value of the field strength, depending on the type of measurement.

Knowledge of the bandwidth, detector statistics function (i.e. linear average, log-average, peak, quasi-peak, root-mean-square function) and time constant of the meter, such as measuring time per measured value in the equipment used in the measurement of RF level and field strength is of considerable importance when modulated emissions are observed. This information generally is readily available for commercially manufactured instruments.

The bandwidth should be wide enough to receive the signal including the essential parts of the modulation spectrum. The type of detector should ensure that the signal carrier is measured, if applicable.

Examples of state-of-the-art equipment:

Microprocessor controlled automatic measuring receivers/field strength meters developed, are available on the market as compact units either for the 9 kHz to 3.0 GHz frequency range or with reduced frequency ranges. Built-in calibration generators, precision attenuators, automatic calibration and range setting can establish input voltage measurement errors of less than 1 dB over the full input voltage range and a wide temperature range. Together with an achievable ± 1 dB antenna factor accuracy, the overall accuracy of a complete, automatic field strength measurement system can be within ± 2 dB over the whole frequency range, but may be limited by various factors such as inaccuracies in the knowledge of antenna pattern. Individual tables of cable attenuation and antenna factors of any calibrated antenna can be entered into the measuring receiver for direct indication of the field strength. The receivers are well shielded so that measurement accuracy is not affected due to stray-pickup at low or high field strength values.

In selecting measuring receivers to be used, account should be taken of the need for adequate sensitivity, high overload capability (i.e. high second and third order intercept points) and for frequency and gain stability including self-calibration. The better grade-measuring receivers of the type normally used for regular monitoring operations are usually satisfactory for this purpose. Measurement bandwidth should be the minimum required for satisfactory reception of the signal to be measured, while at the same time excessive bandwidth should be minimized to avoid adjacent-channel interference. For field-strength measurements measuring receivers shall be equipped with the necessary calibration and detector functions.

Modern, fast measurement equipment makes use of digital recording media, especially where more than one channel is measured automatically. Measurement results are secured on mass storage devices and graphic representations of measured data may be obtained at any time.

For further details of field strength measurement techniques, see §§ 4.3 and 4.4 and Recommendation ITU-R SM.378.

3.5.3 Spectrum analysing and bandwidth measuring equipment

Although the equipment described above will perform many of the monitoring functions, certain additional instruments will permit more effective operation of a monitoring station and will expand its capabilities.

Recent technological advances in the capabilities of spectrum analyzers and vector signal analyzers, having large dynamic ranges of displayed signal amplitude, have resulted in an increased importance for visual monitoring operations. Spectrum analysis provides a means for rapidly recognizing and classifying various types of complex emissions. Visual monitoring can increase efficiency of monitoring operations by defining areas of current activity worthy of further examination. Service to users of the radio spectrum is speeded by the use of visual display techniques to synchronize the occurrence of interference with the activity of the emissions causing the interference.

Nowadays, computers and process controllers are used more and more in monitoring stations to generate reports and/or to control the monitoring equipment.

Three broad classes of equipment provide analysis of the radio spectrum in the frequency domain:

– wideband analyzers are available which can display selected portions of the spectrum with a definition of between 10 Hz/div. and more than 100 MHz/div.;
– panoramic display modules, connected to receiver IF outputs, are available which show a limited portion of spectrum surrounding the tuned receiver frequency. This usually does not exceed about 40% of the IF frequency for common receiver types.

Panoramic receivers are also available which can display the entire range of the selected tuning module or smaller portions of it (sometimes simultaneously), using both FFT and IFM methods.

Apparatus is available for automatic comparison and control of a frequency source relative to a standard frequency transmission.

See § 4.5 for further information on bandwidth measurements.

A spectrum analyzer can be used for the following purposes:

– complete signal analysis (amplitude-modulation, frequency-modulation or pulse) as a function of time and frequency;
– waveform monitoring;
– detection and identification of spurious amplitude-modulation and frequency-modulation signals;
– measurement of pulse rise time, pulse width and pulse repetition rates;
– measurement of spectral characteristics of pulse modulation signals;
– application as a sensitive pulse and CW receiver in propagation studies, plotting of antenna patterns, etc.

The quality of the bandwidth measurements depends upon the following technical characteristics of the bandwidth measuring set or the spectrum analyzer:

– detector and averaging;
– sweep width;
– filter bandwidth;

– relative amplitude accuracy;

– amplitude dynamic range.

The performance of all types of instrument used for bandwidth measurements is limited by fading and interference, especially for observations on long-distance transmissions. With a spectrum analyzer it is possible, by superimposing the results of several successive sweeps, to obtain very useful information on the spectrum occupancy of the frequency bands received at the monitoring station.

For further information on bandwidth measurements, see § 4.5 and Recommendations ITU-R SM.328 and ITU-R SM.443.

3.5.4 Equipment for automatic monitoring of spectrum occupancy

Spectrum occupancy is one of the most important measurements required for spectrum monitoring. The goal of occupancy measurements is to determine how bands may be allocated and how the spectrum may be shared.

The equipment needed for such measurement may be as follow:

Antennas: For general occupancy rate measurement, omnidirectional antennas are required. The goal of the measurement is to measure the whole spectrum in one region.

For a particular measurement, and for example to determine the time occupancy for a dedicated transmitter, a directive antenna may also be used.

Receivers: For the occupancy rate, the wider the analogue bandwidth, the more information will be simultaneously available. With a narrowband receiver, the analogue bandwidth must switch frequency by frequency.

For occupancy rate and automatic monitoring, high accuracy measurements – including precise frequency and level – are not required. The main parameter is the overall scanning speed and the maximum instantaneous bandwidth:

– the shorter the synthesizer settling time, the quicker the occupancy is measured. A settling time shorter than 5ms in the VHF/UHF and 10 ms in the HF band is preferred;

– a wideband instantaneous bandwidth makes possible a wide FFT, allowing less synthesizer switching. An instantaneous bandwidth on the order of 20 MHz in the VHF/UHF band and 2 MHz in the HF band may be used.

Digital treatment: FFT techniques are well suited to performing occupancy measurements, and have many advantages:

− FFT methods allow the instantaneous analysis of the whole IF bandwidth. Associated with a wideband receiver, FFT methods allow the computation of all signals falling in the bandwidth.

− New frequency modulations may be taken into account with high speed scanning receivers associated to FFT method. Modulations such as TDMA may not be seen with a swept spectrum analyzer because the band of interest may need more time to be scanned. Moreover, FFT techniques are better able to measure time-varying (gated, pulsed or transient) signals and complex modulated dynamic signals by processing all frequencies of the measured spectrum simultaneously.

− FFT methods allow other measurements to be made in parallel. While an occupancy measurement is applied to the whole bandwidth, a digital down-converter may select a specific signal in the bandwidth and then determine frequency or bandwidth.

− Occupancy measurement is supported by statistical computation. It implies that a large number of samples are required, depending on the occupancy rate and independent and dependent samples. FFT method, thanks to its rapid revisit time, allows a high confidence level to be reached in a short time.

− Occupancy measurements using FFT techniques offer advantages over conventional methods in terms of frequency accuracy, speed, digital storage of spectrum data, reproducibility of results, discrimination of closely spaced carriers and noisy environments.

Examples of occupancy data are shown in Figs 3.5-1 and 3.5-2. Whereas the FFT is a modern and effective method of performing occupancy measurements, other methods are still possible.

3.5.5 Recording equipment

It is useful to record spectrum monitoring system data that contains radio spectrum and audio information. The recorded data can be reproduced and verified later and can be used for evidence against an illegal radio station. Cost-effective, unattended spectrum monitoring system operation, can also be realized by recording data results.

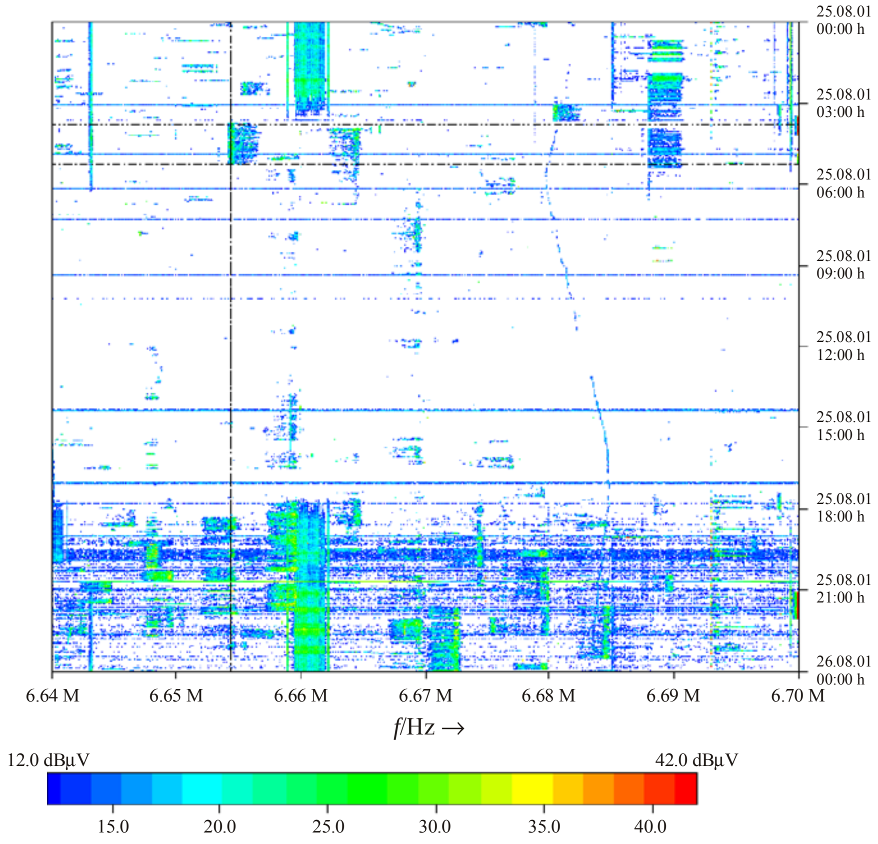
In addition to recording audio that is received at the spectrum monitoring station, information on time of detection, frequency, modulation, bandwidth, direction, field strength and ID should be recorded or logged.

3.5.5.1 Recording media

Solid state and disk-based data recorders are a preferred alternative to conventional tape recorders. Recording media should provide a significant continuous recording capacity and should be capable of random access to allow rapid replay of data. It is desirable for the equipment to provide for data recording, reproduction and editing.

FIGURE 3.5-1

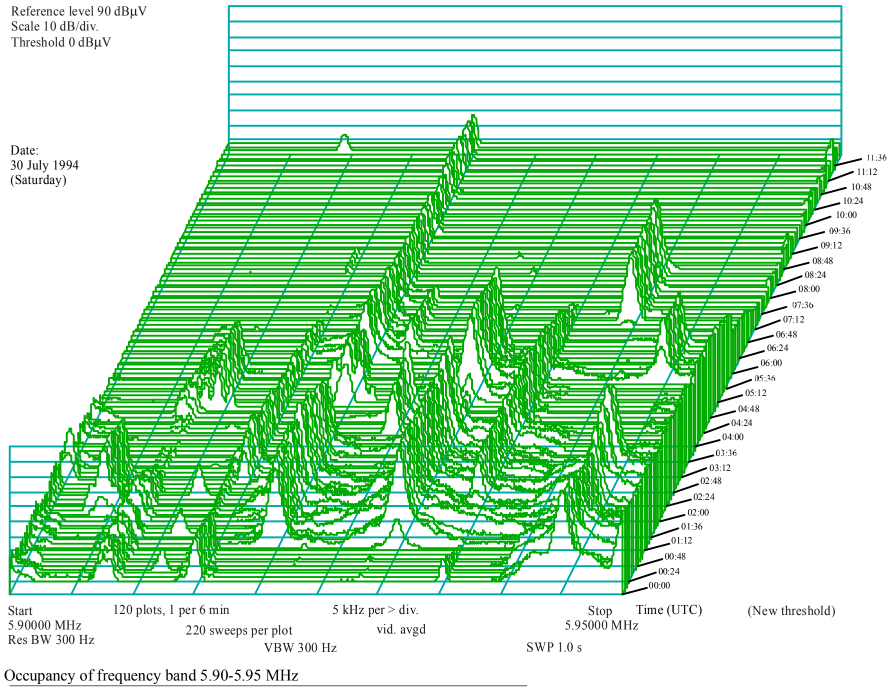
Example of a spectrogram representation



Spectrum-3.5-01

FIGURE 3.5-2

Example of a waterfall representation



Spectrum-3.5-02

Data recording for a period of at least 72 h of continuous recording time is preferred. Such long recording time allows long periods of unattended operation. The recording function should start when monitored data is received, to provide prompt capture of unexpected signals, and should stop when monitored data is not received. Formatting of recording media shall be carefully considered for easy reproduction of specific data. The operator should be able to insert a "mark" in a stream of monitored data, and the "mark" should be easily located, when desired, during replay.

Data reproduction functions should reproduce exactly the same monitored data based on the recorded data. The radio spectrum information and sound information should be synchronized during reproduction. Data reproduction functions should also have a "mark" seeking function, fast forward, fast rewind, and header seeking function.

The data editing function should be capable of extracting and copying designated data from the recorded data. An operator should be able to easily designate a desired data selection for extraction and copying.

3.5.5.2 Wideband recording equipment

This section deals with the needs of digital data storage capacities in monitoring stations. This section gives no technical specifications but outlines how to determine the needed storage capacities. Indeed, technical evolution is so fast that today, specifications will be obsolete in a few years.

3.5.5.2.1 Recording data and format

With modern stations, there are five types of recording data and their associated files:

Type 1: Digital data, representing the in-phase and quadrature (I/Q) components of a continuous stream or block mode samples of the baseband or IF output is a common format. This raw data may be subsequently fed into a receiver to analyze the recorded signals. This is especially useful for mobile signal recording where the analysis equipment of the fixed monitoring station is not always available. Application examples include the analysis of short duration signals and signals captured during unattended recording.

Type 2: Spectrum data resulting from the FFT of time domain measurements. Modern monitoring stations may output several hundred FFT per second associated with wider bandwidth measurements. Text file is the standard file format.

Type 3: Demodulated and decoded data where the output format is text files.

Type 4: Audio digital data in wav, mp3 or other audio format files.

Type 5: Raw measurement data in text files.

The digital data storage in I/Q format typically requires high capacity storage and high recording bandwidth because of associated high data rates. Other types of recordings have lower requirements.

3.5.5.2.2 Digital data recording

Since the interfaces are either A/D converters or digital down-converters, an important consideration is the length of recording, data type (bytes per sample) and signal bandwidth. Large storage capacities are available today and technology research will continue to develop larger capacity systems. Digital receivers can directly interface to the recorder, given that a suitable digital input/output is available on the receiver and recorder.

3.5.5.2.3 Recording equipment bandwidth

The bandwidth of the signal to be recorded impacts requirements for not only recording capacity, but also the recording bandwidth of the system. The recording receiver may be local to the storage equipment or may use wide area network interconnects. Wider bandwidth signals (for example, > 5 MHz) require very fast storage system access due to high data rates. Care should be taken when selecting network interconnects and recording equipment that have a high sustained data rate throughput greater than that required for the maximum signal bandwidth to be recorded, without placing high (> 30% in a packet-switched environment) loading on the interconnect capacity.

3.5.5.2.4 Recording equipment performance requirements

Storage capacity and data rate requirements may be computed as follows:

$$C \text{ (Mbytes)} = F_s \times N_b\_\text{Bytes\_Per\_Samples x Rec\_time}$$

where:

Fs:	sampling frequency of the ADC or DDC (MHz)
Nb_Bytes_Per_Samples:	generally 4 bytes for I/Q samples of 16 bits
Rec_time:	recording time (s).

For example, a signal bandwidth of 10 MHz requires a sampling rate of F_s = 25 MHz baseband or 12.5 MHz I/Q. A baseband signal with 16 bits per sample and recording time of 1 min leads to:

– Data rate: 25 (MHz) × 2 (bytes/sample) => 50 Mbyte/s.

– Storage capacity/recording: 50 (Mbyte/s) × 60 (s) => Storage capacities = 3 Gbytes.

3.5.6 Modulation measuring equipment

Standard ITU-recommended modulation measurements are described in § 4.6. Wideband receivers and processing capabilities of modern stations allow modulation measurement, including digital modulation measurements. When using narrowband receivers with IF outputs, specialized measurement equipment may be desirable. A vector signal analyzer (VSA), an external spectrum analyzer with vector analysis capability, or the monitoring station itself with appropriate software is useful for measuring digital modulation.

The necessary receivers for demodulation and measurement of n-PSK, QAM and other vector-type schemes described in § 4.6 are characterized by high performance down-converters whose IF amplitude and group delay response will not degrade the measured signal. The down-converter or receiver is followed by a VSA for digital modulation analysis [Blue *et al.*, 1993]. A VSA implements the final IF bandwidths using DSP in order to achieve IF passband responses that are stable and high performance. Additionally, by changing the

DSP coefficients, a range of receiver filters can be synthesized for versatile coverage of a variety of modulation types.

If the optional RF down-converter of the VSA is used and it does not contain an RF preselector, an external preselector or banded filter must be used in dense signal conditions. The corrections for the preselector's passband response may have to be included in the correction procedure for the IF filter's passband response for the highest performance.

After setting the desired carrier frequency, modulation type and symbol rate, the DSP in the VSA or spectrum analyzer accomplishes the demodulation. In addition to displaying the modulated signal, the analyzer also provides digital modulation error measurements. This is accomplished by demodulating the signal and generating an ideal reference. The two are compared to generate the error measurement results.

For over-the-air monitoring of modulation quality, the transmission path may be the dominant factor when measuring the modulation quality factors. Multipath or other co-channel interference may render the modulation quality measurements highly questionable or useless. Therefore, detailed modulation measurements are only appropriate at the transmitter site, preferably with a direct connection to the transmitter. Such measurements include: error vector magnitude, phase and amplitude errors, carrier feed through, I/Q gain imbalance, amplitude droop and carrier frequency error.

General measurements that provide an indication of overall modulation quality and can be made at the transmitter site, or off-the-air some distance away, include: error vector spectrum (to highlight interference), adjacent channel power ratio, occupied bandwidth, spectrum emission mask, complementary cumulative distribution function, carrier frequency and code domain measurements (power, timing and phase).

The channel impulse response (CIR) measurement [Riedel; 1991; Bues and Riedel, 1993] is not a modulation measurement, but is a measurement of the propagation channel multipath. This multipath greatly affects the modulation quality at the receiving site. Another indirect measure of the modulation quality at the receiving site is measurement of the BER. These quality measurements are described in more detail in §§ 5.3.6.2 and 5.3.6.3.

3.5.7 Identification equipment

Identification of radio signals is one of the most difficult monitoring tasks. This difficulty is partly due to the infrequent emission of call signs, partly to the use of abbreviated or unregistered call signs and to a considerable extent to the difficulty in decoding signals due to the growing use of complex transmission systems, i.e., frequency shift, frequency division and/or time division multiplex. In addition, there are machine telegraph systems using a variety of codes other than Morse, facsimile systems, single and independent sideband systems and privacy devices.

Digital processing techniques and microcomputers have now made it possible to design multipurpose identification equipment, able to demodulate and decode most signals and to be programmed to respond to new transmission schemes. This subject is discussed in Recommendation ITU-R SM.1600 – Technical identification of digital signals.

A monitoring station must, in consequence, have equipment for the reception and/or identification of several types of analogue and digital modulations.

See § 4.8 for further information on signal identification.

References

BLUE, K. et al. [December 1993] Vector Signal Analyzers for Difficult Measurements on Time-Varying and Complex Modulated Signals. *Hewlett-Packard J.*, Vol. 44, p. 6-47.

BUES, D. and RIEDEL, P. [1993] Planning digital radio networks using Impulse Response Analyzer PCS and test transmitter system. *News from Rohde & Schwarz*, **141**, p. 26-27.

RIEDEL, P. [1991] TS 9955 measures channel impulse response in GSM radio networks. *News from Rohde & Schwarz*, **137**, p. 12-14.

YANG Xuhai, Zhai Huisheng, Hu Yonghui, Li Zhigang, Li Xiaohui, Study on GPS Disciplined Rb Clock Based on New Frequency Accuracy Measurement Algorithm, National Natural Science Foundation of China (60172031), Chinese Journal of Scientific Instrument, 2005 Vol. 26-1.

ITU Handbook [2010] on Satellite Time and Frequency Transfer and Dissemination, available at: http://www.itu.int/publ/R-HDB-55.

ITU-R Recommendations

NOTE – In every case, the latest edition of all the referred Recommendations is encouraged to be used.

Recommendation ITU-R SM.182 – Automatic monitoring of occupancy of the radio-frequency spectrum.

Recommendation ITU-R SM.328 – Spectra and bandwidth of emissions.

Recommendation ITU-R SM.377 – Accuracy of frequency measurements at stations for international monitoring.

Recommendation ITU-R SM.378 – Field-strength measurements at monitoring stations.

Recommendation ITU-R SM.443 – Bandwidth measurement at monitoring stations.

Recommendation ITU-R SM.854 – Direction finding and location determination at monitoring stations.

Recommendation ITU-R SM.1600 – Technical identification of digital signals.

3.6 Automation of monitoring

3.6.1 Introduction

Automation, through the use of computers, modern client/server architectures and remote communications, simplifies many of the duties and responsibilities of the monitoring service. Computerized equipment provides a means to perform mundane repetitive measurement tasks rapidly and accurately, freeing service personnel for more demanding tasks.

The use of databases and computer modeling streamlines spectrum management functions and can help prevent interference.

Coupling of spectrum management and spectrum monitoring makes possible an integrated system, which can automatically use measured data from the monitoring system and license information from the management database to detect unlicensed transmissions and other licensing violations.

The integrated monitoring and management system may have a central management facility, in which overall management of radio monitoring system is performed and statistical analysis of stored measurement data in the monitoring system database are available.

These analyzed results are utilized for spectrum management planning (for example, frequency withdrawal and reassignment).

A typical integrated system diagram is presented in Fig. 3.6-1 and described further in Recommendation ITU-R SM.1537.

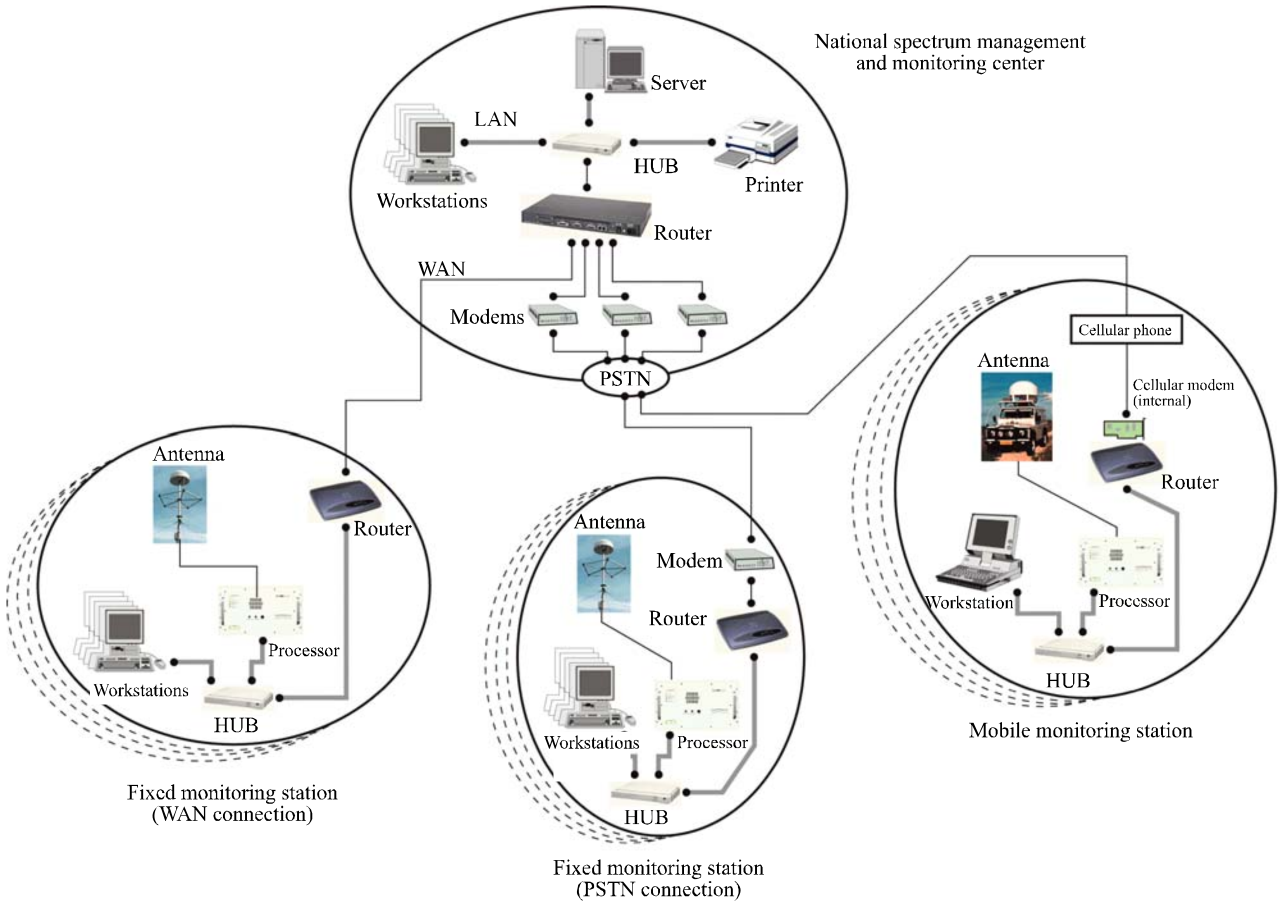
The configuration (number of workstations at each station, number of stations, etc.), methods of communication (TCP or other protocol; use of PSTN, radio or satellite) and other details will vary according to the application.

An alternate system configuration includes the addition of a monitoring centre, which is connected directly to the monitoring stations and in turn to the management centre.

A large monitoring service may have regional monitoring centers in addition to a main or national monitoring center to distribute control of monitoring operations.

FIGURE 3.6-1

Example of a monitoring system integrated with a management system



Spectrum-3.6-01

3.6.2 Automation of monitoring operations

Automated stations generally perform the functions of a fixed monitoring station, as described in § 2.4. All routine monitoring measurements are repetitive tasks that lend themselves easily to automation:

– *Occupancy measurements*: Fine-resolution scanning of the frequency bands with computer-generated displays and storage capacity of channel occupancy over several days is well suited to automation.

– *Frequency measurements*: These can be made automatically when the *S*/*N* is sufficient and for transmissions with carrier frequency. At HF, channels are usually very closely spaced; thus sharp frequency selectivity must be provided in the case where several frequencies are present in the same channel.

– Level and, if applicable, field strength measurements.

– Bandwidth measurements.

– Modulation parameter measurements. Advancements in DSP hardware and algorithms have led to the development of modulation recognition systems which identify modulation types in real-time. These systems may be implemented in stand-alone instruments, computer add-in cards and associated software, or may be integrated into other instruments (such as receivers or analyzers). These systems can be used to recognize various modulation formats (both digital and analogue), measure common technical parameters, and demodulate or decode the signals.

– *Signal analysis*: however, not all aspects of signal analysis can be done automatically.

- *DF*.
- *Station identification*: through location, message content information, or automatic signal analysis (code recognition, number of elements, transmission rate).

All of these measurements can generally be made automatically, but some measurements, such as bandwidth and modulation, require signals with good *S*/*N* to achieve sufficient accuracies. These measurement tasks yield technical measurement data that can be compared to the technical parameters recorded in spectrum management databases or to data desired therefrom. The technical parameters recorded for a transmitter in such a database include:

- Assigned frequency.
- Calculated field-strength.
- Emission class.
- Assigned bandwidth.
- Emission bandwidth.
- Call-sign.

Each monitoring station usually has a list of transmitters and the operators match the listed transmitter parameters against the observations recorded by the automated equipment. Integrated automated systems may automate this comparison task in addition to collection of the data, which is an example of automatic violation detection discussed below. Either way, the comparison must be made using tolerances in measured parameters that are consistent with ITU-recommended measurement accuracies, to minimize false alarm rate. The goal is to confirm the compliance with established procedures and with the technical data listed in their database file. When discrepancies or anomalies are detected, they typically include:

- Illegal or unlicensed transmitters or frequencies.
- Unauthorized operating periods or locations.
- Illegal emission classes or poor modulation quality.
- Excessive frequency offset.
- No call-sign or incomplete call-sign.
- Excessive bandwidth.
- Excessive power (excessive field-strength).

3.6.2.1 Levels of automation

Automation can occur at many levels within monitoring operations. A single workstation may conduct an automated occupancy survey using pre-programmed parameters. Several workstations at a site may be tied to a single set of measurement equipment to share those measurement resources. An entire station, or network of stations, may be automated, possibly because of their remote location, and the results of their monitoring may be retransmitted to a more centralized station. Individual positions at several sites may be linked together in such a manner that one position automatically tunes positions at other sites to obtain multiple simultaneous measurements on signals of interest. Computer-controlled equipment may be programmed to identify frequencies on which there are transmitters which are not included among a database of licensed transmitters and to identify transmitters which are not operating within their licensed parameters.

Automation can help reduce the time to locate and identify a signal, reduce the personnel needed to operate stations and make these personnel available for higher priority functions such as assisting a mobile station in DF operations or performing data analysis, and increase the portion of the radio-frequency spectrum that a service can effectively monitor. On the other hand, the absence of an operator or technician at a remote site may result in long equipment down times-should there be an equipment failure. Also, automated equipment may not give the sensitivity for tuning difficult to receive signals that an operator can achieve through manual tuning, which may often be the case in the HF environment. In any case, when automating a position or station, a service should incorporate the option to revert the position or station to manual operation, either locally or remotely. Automation of older equipment usually requires a separate computer, and often the older equipment needs to be replaced.

3.6.2.2 Station automation

Modern DSP techniques allow economical automation of entire stations. An automated station consists of:

– a small group of sophisticated measurement equipment modules, including digital receivers operated by a computer, which is often referred to as a measurement server;

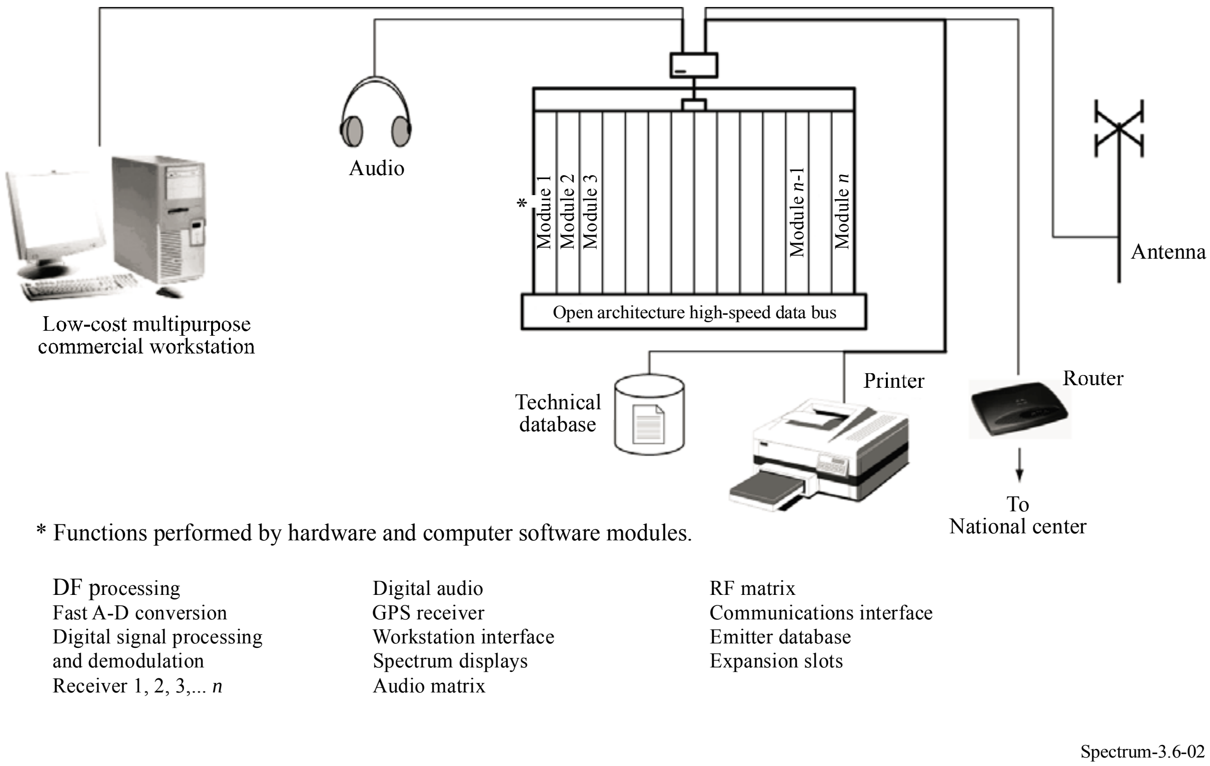
– operator workstations, often referred to as clients, which are used for operator interface and which contain computer software that make the system easy to use and easy to maintain.

The station can be operated either locally or be remotely controlled from a more convenient location. The links between the measurement stations and control stations can be radio or terrestrial. Essentially, the station becomes a node on a wide area network administered at the control station.

A fully automated station typically has the architecture illustrated in Fig. 3.6-2. This station consists of antennas, a compact measurement server which is a modular, high-speed bus unit including processors, receivers and other electronics, one or more low-cost commercial workstation clients, and various peripheral equipment including printers, phones, and modems. An alternate but related station architecture includes separate but highly integrated units including digital receivers, direction-finders and processors; in this case, the portion of Fig. 3.6-2 containing the open architecture high-speed bus with various modules is replaced by separate units, including a digital receiver, a digital direction-finder and a processor. An automatic built in test equipment (BITE) can provide the current status of all devices and can give alarm in case a device shows a fault.

FIGURE 3.6-2

Typical modern integrated radio spectrum monitoring station



The functions of an automated monitoring station include:

– monitoring, demodulation and decoding;

– audio recording;

- technical measurement and analysis including frequency and frequency offset, level/field strength, modulation parameters including AM modulation depth and FM frequency deviation, bandwidth, and spectrum analysis;
- spectrum occupancy;
- DF;
- automatic real time comparison with licence parameters;
- automatic alert generation on abnormal or unknown transmissions.

3.6.2.2.1 Typical automated station modes of operation

Automated monitoring stations typically have three modes of operation which are used to perform these tasks:

Mode 1: Interactive or real time operational.

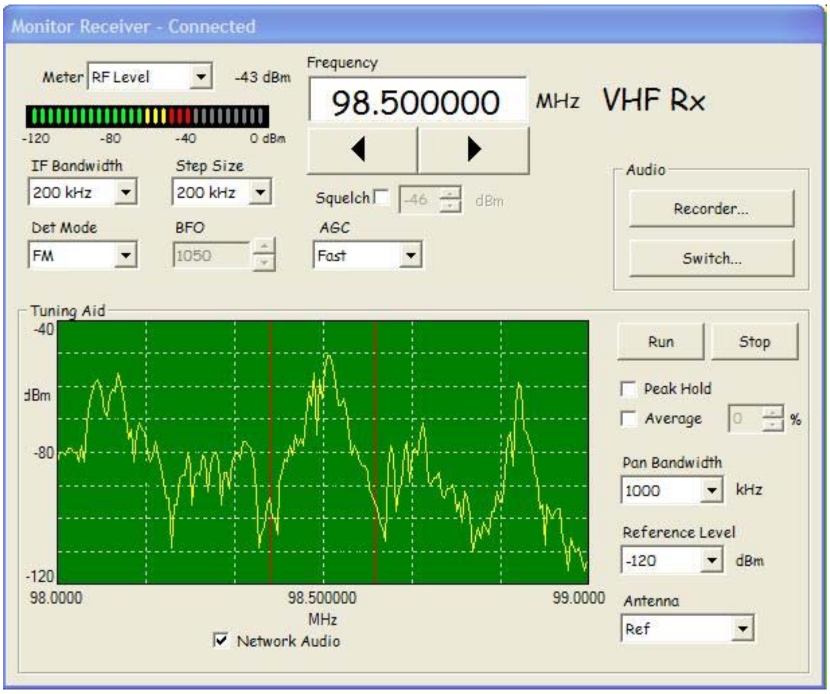
Mode 2: Automatic or scheduled.

Mode 3: Background.

Interactive mode allows direct interaction with various functions that provide instantaneous feedback such as monitoring receiver tuning, demodulation selection, and pan-display selection. An interactive mode is necessary even in an automated system to allow operator intervention when necessary, so that equipment can be remotely controlled by operators as well as by the automated system software. Interactive functions are controlled from "virtual control panels" on the client workstation, using screens such as is illustrated in Fig. 3.6-3. Synthetic panoramic and spectrum displays are created on the operator workstation, and include waterfall displays (three dimensional displays of signal amplitude, versus frequency, versus time) and spectrogram displays (two dimensional displays of signal frequency versus time, with signal amplitude indicated by colour).

FIGURE 3.6-3

Example of a virtual control panel for monitoring receivers



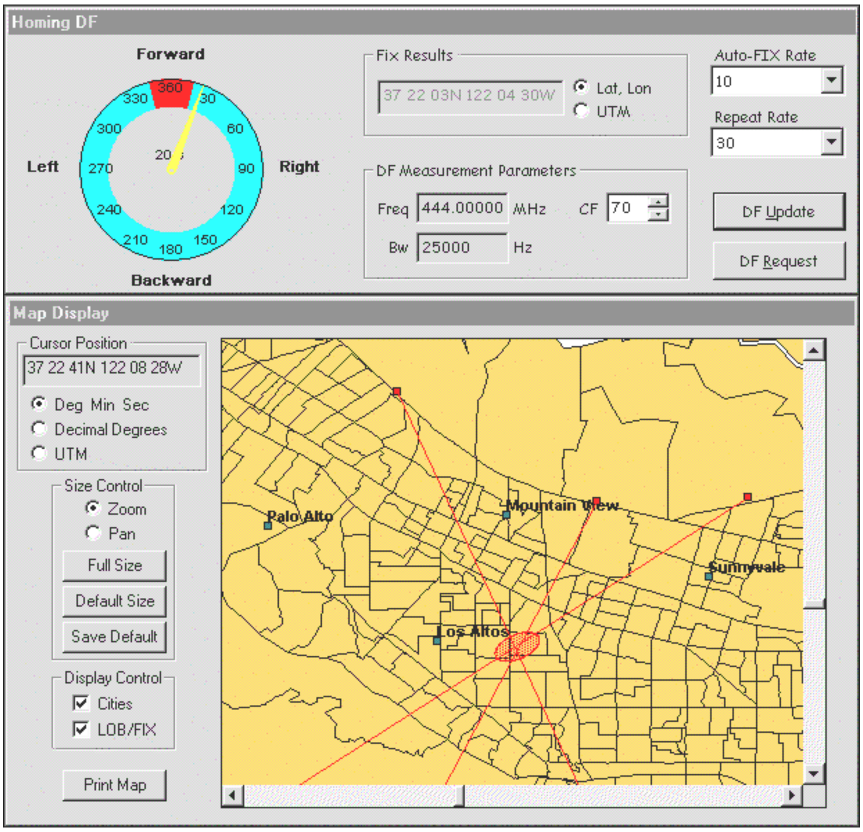
Spectrum-3.6-03

DF homing is an important example of interactive operation. DF may be commanded in a mobile unit as the unit is in motion. DF results are presented with respect to the front of the vehicle, as illustrated in Fig. 3.6-4, and allow the driver to decide which direction to drive to approach the desired signal transmitter. DF results from different locations are also displayed on a geographic map, allowing triangulation by the system to locate the signal transmitter. A high precision GPS receiver continuously updates the exact location of the mobile unit, and an electronic compass measures the orientation of the vehicle with respect to North.

Automatic or scheduled mode may schedule tasks to be executed immediately or to be executed at specified times in the future. Functions that are performed under the scheduled mode include technical measurement and analysis, and DF. Measurement parameters, such as measurement and averaging methods, and measurement time (or times, in the case of measurements which are to be repeated) may be specified, or default values provided by the system may be used. The operator may use a screen containing a calendar with days of the week and multiple intervals within each hour of the day to schedule these functions. The client requests time slots for the desired measurements from the measurement server. The time slot assignment approach allows multiple clients to connect to a single server. In order to handle scheduling attempts of multiple measurements in the same time slot, the server should support a "convenient" mode of scheduling. When the requested time slot is already reserved, the client's request for a server time slot is moved to the first available time slot. The server can look for the available time slot within a specified time window that is typically a few minutes. The measurement server performs the requested measurements, using appropriate scheduling and priority algorithms to resolve any scheduling conflicts, and retains the measured results until the client requests them. For some measurement types, the server may have the capacity to record signal audio along with those requested measurements.

FIGURE 3.6-4

Example of DF homing display and geographic map



Spectrum-3.6-04

Background mode is used for performing tasks such as spectrum occupancy and automatic violation detection – tasks where it is desirable to collect data over long periods of time. Wideband scanning for occupancy, or DF combined with occupancy (termed "DF scan"), may be specified, and the system may be scheduled to perform an automatic scan over particular frequencies or ranges of frequencies, and upon detecting a signal, initiate operator specified activity, such as DF or technical measurement.

Background mode operates on a lower priority than scheduled mode, so specific scheduled measurements will interrupt the background mode to use the measurement server.

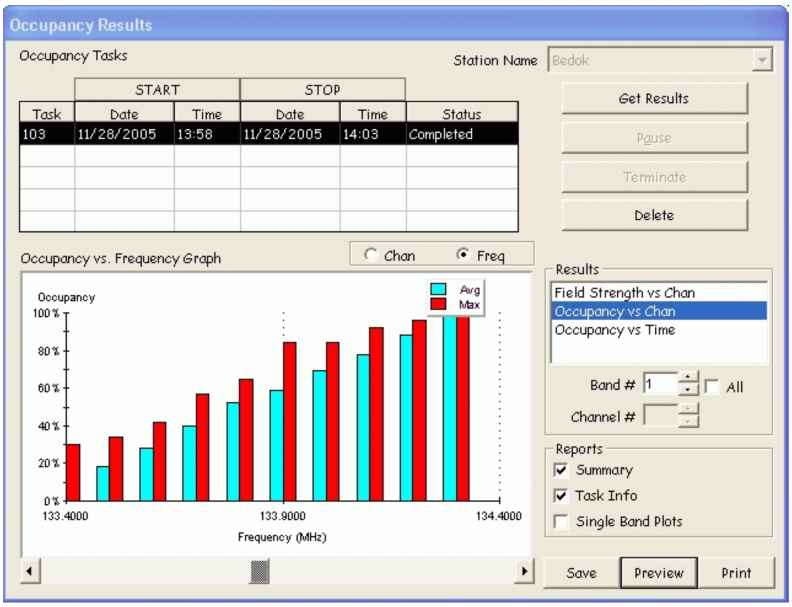
After the scheduled measurements are completed, control returns to any background mode measurements that were in process.

When the client requests the results of measurements, the client may see them displayed in convenient formats.

Much of the information is displayed graphically, in the form of occupancy histograms (see Fig. 3.6-5), field strength versus frequency plots, geographic map displays showing location results (see Fig. 3.6-4), and other graphical displays.

FIGURE 3.6-5

Example of occupancy histogram



Spectrum-3.6-05

These systems can perform DF on many frequencies simultaneously and provide azimuth versus frequency plots (see Fig. 3.6-6) which are useful for intercepting and processing modern digital modulations; DF results on such a display at the same azimuth from many different frequencies are a clear sign of the presence of a frequency hopping signal.

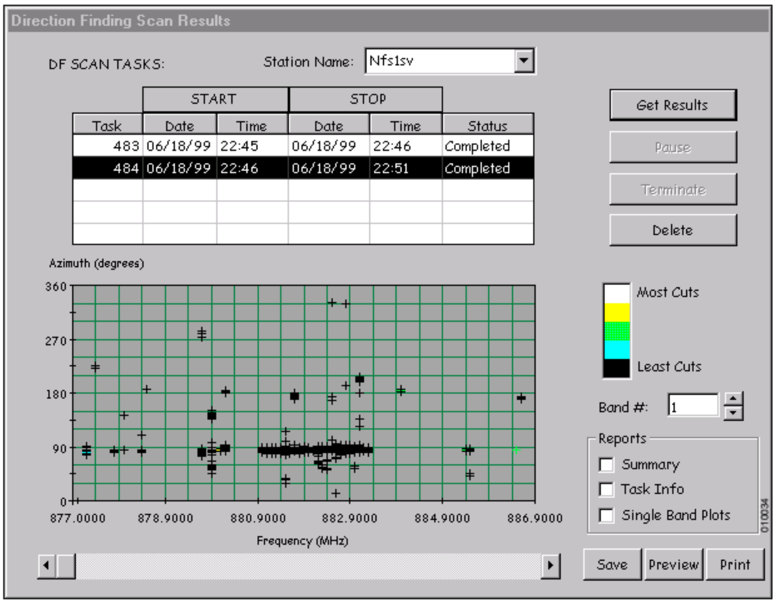
Sophisticated client/server systems can be designed to be easier to use than systems with separate or stand-alone units of equipment such as receivers and spectrum analyzers.

With task icons and toolbars on the computer screen, which the operator can access via pointing, and clicking on a computer mouse, these systems can be very intuitive and easy to learn.

For administrations with difficulty in obtaining qualified operators, simplicity of operation of a monitoring system is a very important consideration.

FIGURE 3.6-6

Example of DF scan display results



Spectrum-3.6-06

3.6.2.2.2 Examples of automated broad bandwidth displays

Modern DSP-based measurement servers are able to provide very broad instantaneous bandwidths, up to 20 MHz per Recommendation ITU-R SM.1794, along with a high dynamic range so that strong signals within this bandwidth do not prevent weak signals in the bandwidth from being received and processed.

Automated systems with very broad instantaneous bandwidths are able to scan the spectrum at very fast rates, automatically tuning the receiver and gathering occupancy data, allowing very frequent revisits and refresh of data displays to give the operator a better understanding of the radio spectrum.

They are able to effectively acquire and measure intermittent, broadband and frequency agile signals that may appear to be noise when monitored with a narrow bandwidth system.

To provide the highest performance when narrower measurement bandwidths are desired, a smaller instantaneous bandwidth, which reduces noise and improves *S/N*, can be selected automatically instead of the broader bandwidth.

Operators can view a very broad bandwidth panoramic display, improving their ability to locate interferers and identify the kinds of signals and interference being monitored.

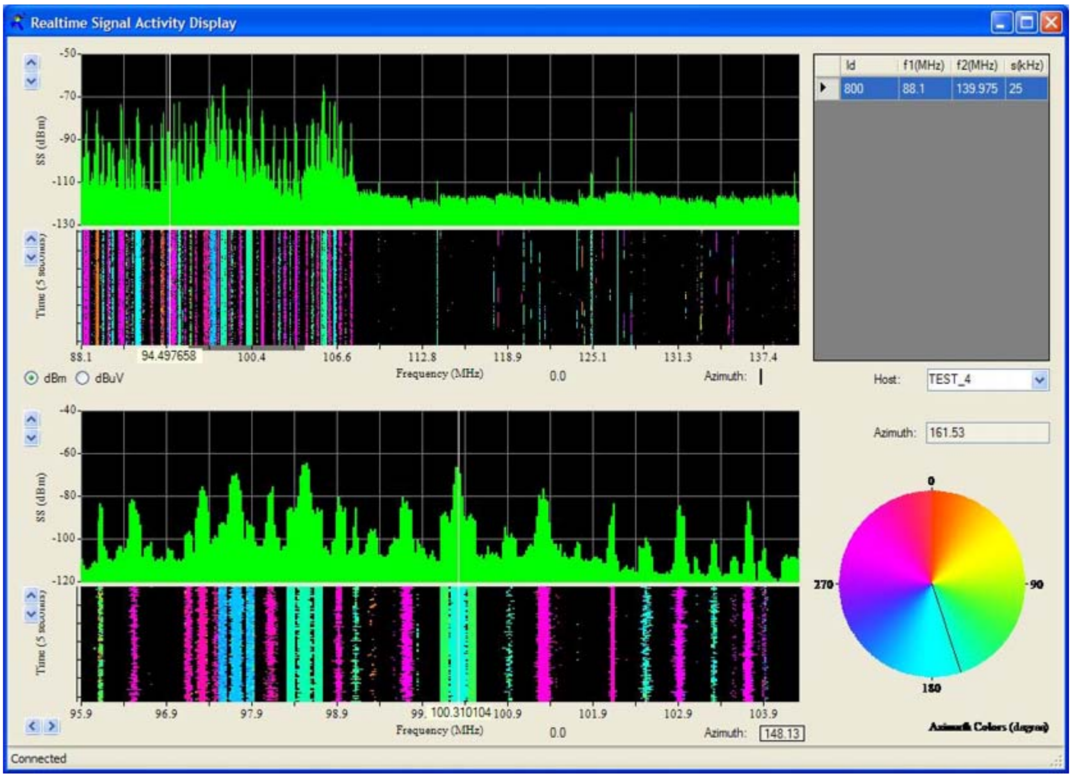
A typical display is illustrated in Fig. 3.6-7. This particular display covers over 50 MHz of the spectrum, with a panoramic display across the top of the screen, below which is a spectrogram display showing signal activity over the past 5 s, with signals colour-coded as to their direction of arrival. The colour-coded direction of arrival display can be changed to a colour-coded display of signal strength upon operator command.

The bottom portion of the display provides a magnified panoramic display and spectrogram display where the operator can simply click on the upper display to indicate the frequency region to be magnified, and the system automatically produces a magnified display; in the illustration, an 8.5 MHz portion of the upper displays has been magnified to fill the horizontal region available for display.

The display is continuously updated in real time, with the spectrogram display continually advancing in time to show current signal activity with directions of arrival.

FIGURE 3.6-7

Typical display of very broad bandwidth measurements

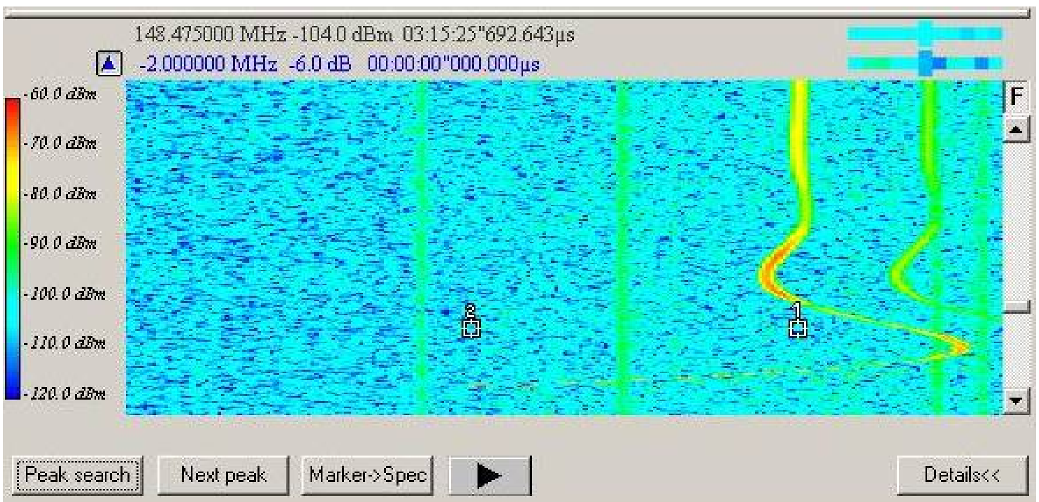


Spectrum-3.6-07

The display in Fig. 3.6-8 shows a transmitter signal without stabilization. Only a wideband receiver can detect such signals that disturb adjacent channel signals. A narrowband receiver is either too slow to detect these signals or too narrow to see the fluctuation of the signals.

FIGURE 3.6-8

Typical display of a very fast fluctuation wideband signal detected by a wideband receiver

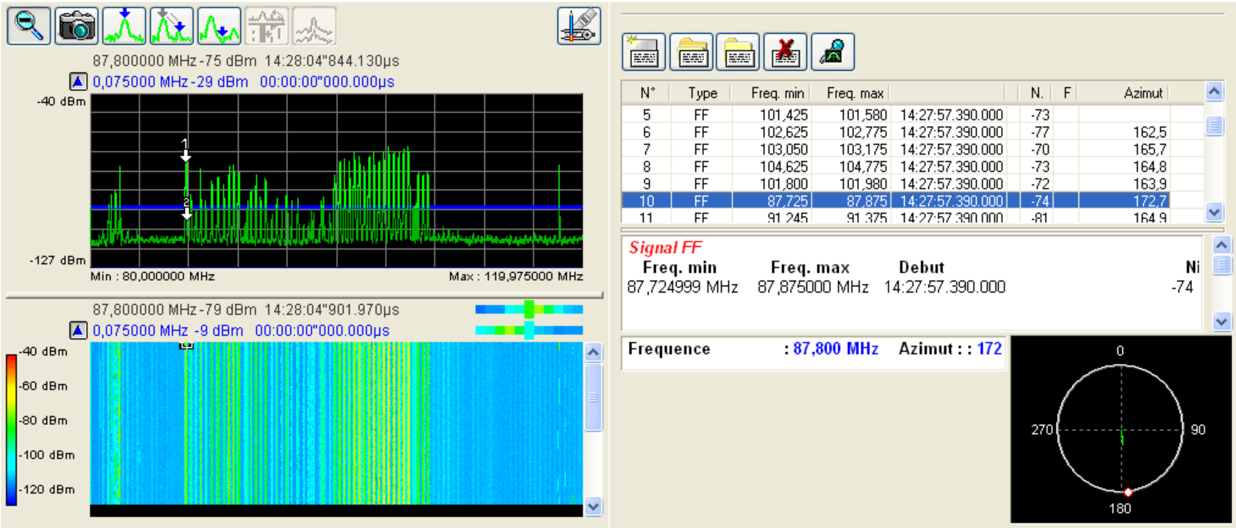


Spectrum-3.6-08

Operators can view a very broad bandwidth panoramic display, improving their ability to locate interferers and identify the kinds of signals and interference being monitored. Such a display is illustrated in Fig. 3.6-9, showing a real-time instantaneous 40 MHz bandwidth without any scanning. The wide instantaneous bandwidth allows the detection of very short duration signals in several microseconds.

FIGURE 3.6-9

Typical display of very broad bandwidth measurements



Spectrum-3.6-09

DSP allows great flexibility in adding capability to a monitoring system in the future. Should new signal types appear that require special processing, or new bandwidths be desired, they can be added to a DSP-based system simply by changing the monitoring system computer software.

3.6.2.2.3 Examples of measured results analysis

Automated monitoring stations could have a measured results analysis mode of operation. This mode is used for analyzing the measured results from the measurement equipments under various conditions. The analysis can be performed in a spectrum management centre.

The radio quality measurement results are displayed graphically, in the form of graphs of measured values (field strength, frequency offset, frequency deviation, occupancy bandwidth) versus time, distribution plots of deviation, or accumulated distribution plots of deviation and spectrogram. A typical spectrogram display is illustrated in Fig. 3.6-10. While graphs of measured value versus time are most useful for an analysis over short periods of time, distribution plots of deviation or accumulated distribution plots of deviation are useful in analysis over longer periods.

Band occupancy measured results may be displayed in a time versus frequency plot; field strength is displayed graphically with color. A typical display is illustrated in Fig. 3.6-11.

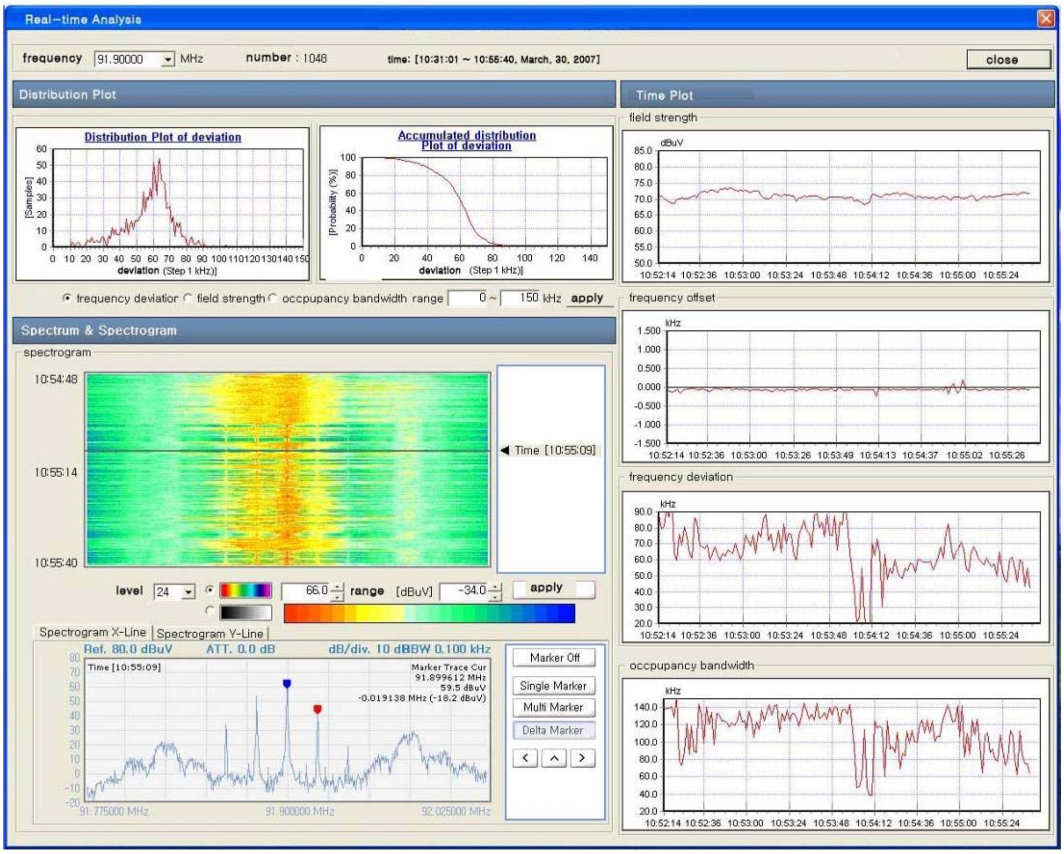
The band occupancy histogram with signal spectrogram shows signal appearance rate, spectrum occupancy rate and field strength.

Spectrum analysis can be performed through various functions using rapidly-produced spectrum measurement results. The spectrum band is compared with a frequency distribution chart and signal frequency is displayed according to marker indication.

A typical display is illustrated in Fig. 3.6-12. Measured and analyzed results are used for predicting the possibility of interference and detecting the arriving radio wave.

FIGURE 3.6-10

Typical graph for real-time analysis of measured results



Spectrum-3.6-10

3.6.2.2.4 Real-time operation with fast spectrum scanning, instantaneous DF and operator alerts

There are certain frequency bands in which maintaining real-time control of radio transmission activity at all times is an essential requirement. This includes rapid identification and location of legal transmitters and rapid identification, location and elimination of interferers. Examples of frequency bands that require such protection are the aeronautical band, the maritime band, and various emergency channels that are essential for search and rescue operations. This type of spectrum protection requires a radio monitoring system capable of operation in real-time, with fast scanning of the spectrum and instantaneous DF measurements on all active signals. When detecting signal activity on any of the emergency channels, the system needs to be able to issue real-time alerts to local or remote operators.

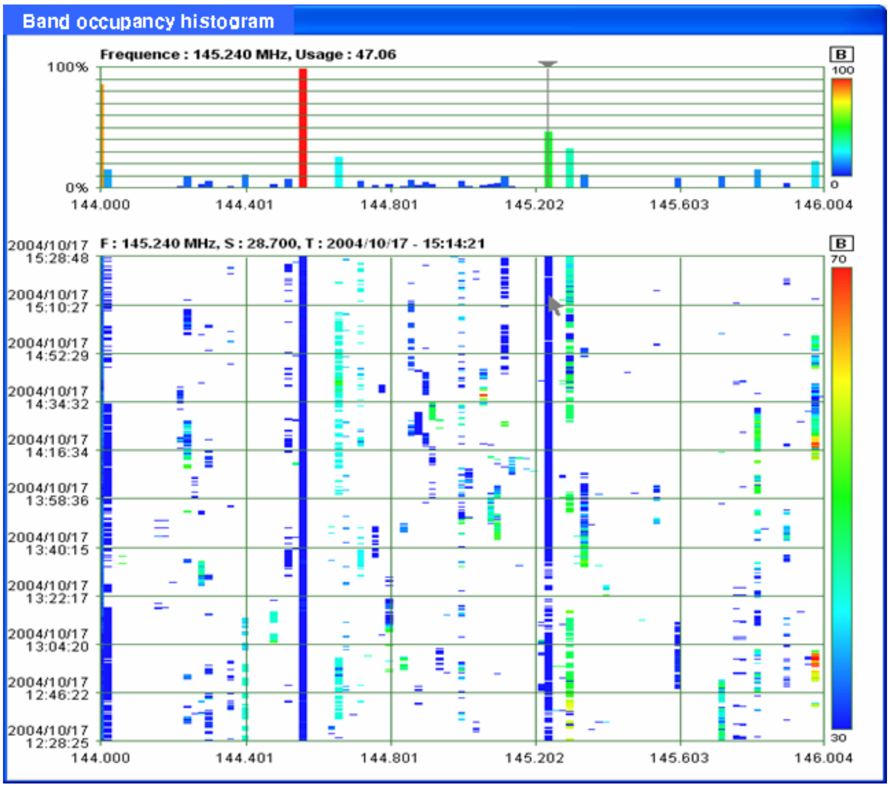
Integrated signal search, DF and monitoring functions into one single processor allows fast scanning of the spectrum with simultaneous DF measurements on all detected signals. Typical systems can revisit up to several dozen maritime mobile and emergency channels at least ten times each second, and can detect and measure signals as short as 10 ms.

DF results are measured simultaneously for up to several dozen channels, and presented on the operator display in real-time. LoB for selected channels are displayed on a large digital map and on a polar histogram. If two or more monitoring stations operate in a netted configuration (as discussed in § 3.6.3), then the system would display on the operator's workstation not only the LoB but also the resulting triangulation fix of the corresponding transmitter.

This operation would be performed automatically by the system with no operator intervention, and the location estimate would be displayed on the operator screen within a fraction of a second after the start of transmission.

FIGURE 3.6-11

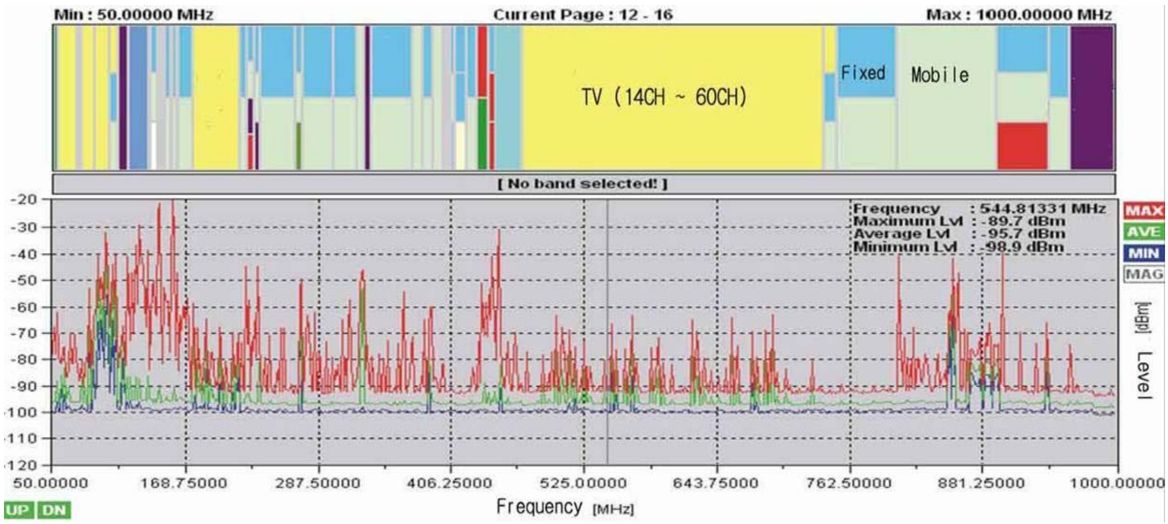
Band occupancy histogram with signal spectrogram



Spectrum-3.6-11

FIGURE 3.6-12

Spectrum band compared with frequency distribution chart



Spectrum-3.6-12

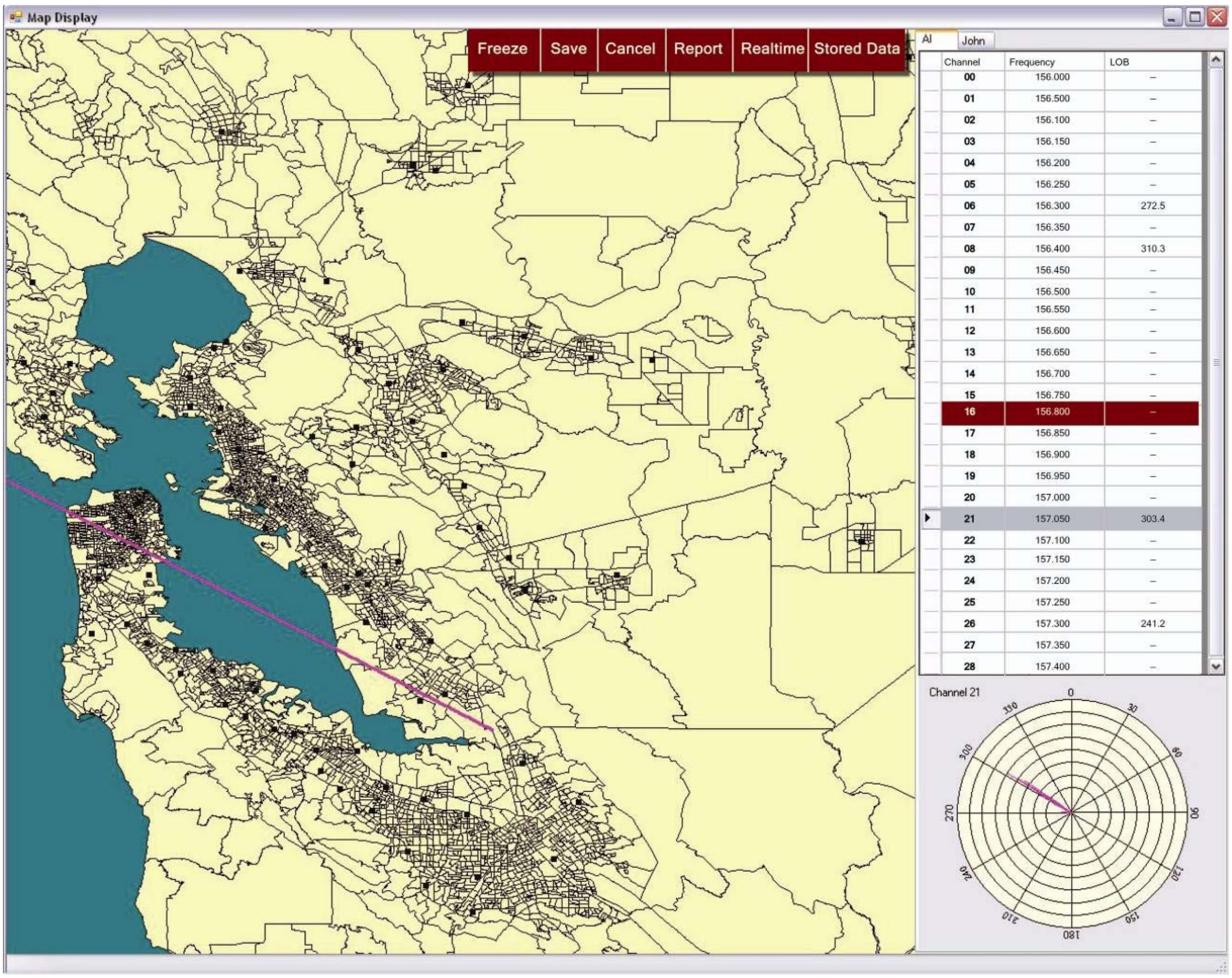
All DF measurements may be automatically stored in a local database on the operator workstation, and retained there for a reasonable period of time such as 48 h. The operator may perform a variety of functions from his workstation computer, including:

− Monitor continuously signal activity, LoB and fixes in all his assigned channels.
− Freeze the DF results and create a transmitter location report that is automatically stored in his local database.
− Review and play back DF results and fixes stored on his computer.
− Review DF results stored on his computer and create signals activity lists.

An example of real-time operation in the maritime band with fast spectrum scanning and instantaneous DF is illustrated in Fig. 3.6-13. LoB are measured simultaneously for up to 29 channels in real-time and are displayed in numerical form on the screen (upper right).

FIGURE 3.6-13

DF results measured simultaneously for many channels refreshed in real time (upper right); LoBs for selected channels display on map (left) and polar histogram (lower right)



Spectrum-3.6-13

LoB for selected channels are displayed on the map (left) and on polar histogram (lower right). In this example, the operator has selected Channel 21 for monitoring, so this is the LoB shown on the map and on the polar plot. The special function keys available to the operator are shown at the top of the screen.

Figure 3.6-14 illustrates the case when a signal is measured by more than one radio station. In this example, there are two radio stations. The system automatically calculates the fix and displays the results on the map in real-time.

The software may allow the operator to define several “high priority” channels. If any signal activity is detected on any of the high-priority channels, the software automatically alerts the operator on the screen, it issues an audible alarm at the workstation, and it can be scheduled to send a message to an external e-mail address or cell phone number.

FIGURE 3.6-14

Automatic calculation and display for a fix in real time, for a signal measured by more than one station

Spectrum-3.6-14

3.6.2.2.5 Example of DF homing automation

Advanced monitoring automation software [Rembovsky *et al.*, 2006] also provides statistical processing with continuously obtained bearings at mobile monitoring stations to simplify operator′s activities related to searching for signal transmitters.

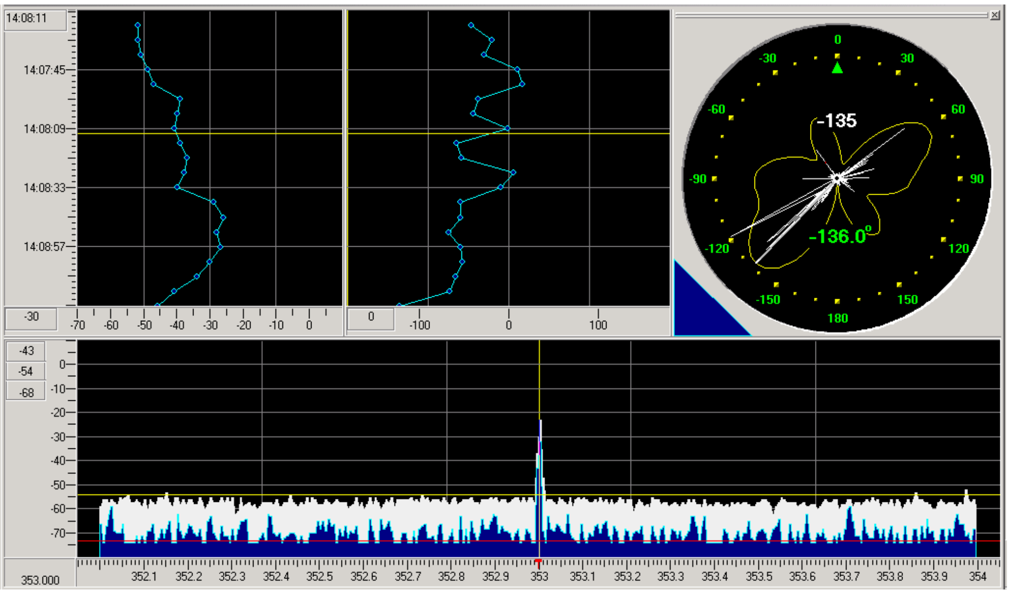
A typical display window of the equipment control software working on one signal of interest is shown in Fig. 3.6-15. It contains the graph of the amplitude history (located at the left top corner of Fig. 3.6-15) and the graph of the bearing history (located in the middle). Both graphs have the common time ordinate. Abscissa of the amplitude history is the level of the bearing signal (dB), and abscissa of bearing history is the angle of bearings (degrees).

The history graphs allow tracking in time the change of signal amplitude and bearing. In addition, the circular limb at the right top of the window simultaneously indicates instantaneous bearing values and the curve of the bearing direction distribution density (the bearing histogram) whose maximum corresponds to the most probable bearing direction of arrival. Change of direction of the bearing distribution curve maximum is reflected on the bearing history graph. In conditions of strong interference, the angular value of a maximum shows a preferred direction of the direction finder movement.

The history graphs of amplitudes and bearings in Fig. 3.6-15 provide very useful information for real time homing. In this example, gradual increase of the signal amplitude from −50 dB(mV) up to −30 dB(mV) and bearing values at the beginning of the graphs confirm that, during this period (from 14:07:45 to about 14:08:45 in Fig. 3.6-15), the mobile monitoring station moved closer to the signal transmitter. Then (from about 14:08:45 in Fig. 3.6-15), the signal transmitter is situated left of the vehicle because bearings have systematically shifted to the left and signal amplitudes start to systematically decrease. For locating the signal transmitter, the mobile monitoring station should turn 180º, return back and search for the transmitter at the right side of the station.

FIGURE 3.6-15

A window of the programme in the homing mode



Spectrum-3.6-15

Advantages of homing with amplitude and bearing history graphs include increased reliability, shorter search time, and reduction of the effect of errors caused by surrounding objects because the mobile monitoring station is in continuous movement, and the most probable direction to the signal transmitter is determined by a statistical processing of continuously obtained bearing data.

3.6.2.2.6 Automated site search for sources of electromagnetic emissions

Mobile station fitted out with a high-speed correlation/interferometry DF system capable of providing DF information (azimuth and elevation) can be used for locating a transmitting set, HF consumer or medical equipment, and other sources of radio interference [Ashikhmin *et al.*, 2003]; [Rembovsky *et al.*, 2006]. The mobile station should also be fitted with a video camera and customized software.

An investigation session for a particular frequency range consists of three steps:

Step 1: Compilation of frames of raw data.

Step 2: Analysis of frames and determination of frequencies to be studied more closely.

Step 3: Analysis of the frequencies in the list and precise determination of source locations.

The mobile station is positioned at several points in the near vicinity of the site under investigation, and others that are at a relatively great distance (see Fig. 3.6-16). For each position, one “frame” of raw data is collected.

The data are as follows:

– spectra and bearing panorama (frequency, level, azimuth, and elevation);

– digital camera imagery of the site that describes angular boundaries of the site, as seen from the station's position.

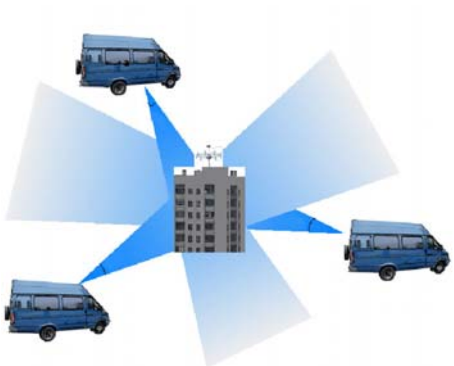
Under urban conditions, bearing analysis relies on probabilistic methods, due to the effects of multipath propagation and other local effects. Ideally, the position should be chosen so that the site being surveyed is within LoS, and there are no high buildings or large metallic structures near the mobile station. The more the frames obtained from different positions are used, the greater will be the positioning accuracy.

During *Step* 2, collected raw data are used to obtain a list of frequencies that shall be studied based on the following criteria: azimuth and elevation measured on a frequency shall be within the site angular boundaries for two or more frames; signal level measured from a distant position is much weaker that from a near position. Figure 3.6-17 shows software screens in cases when the frequency list is obtained based on three frames for distant and three frames for near positions. The programme shows the digital images of the site obtained in the immediate proximity of the site. Analysis led to the identification of a signal transmitted at 300.25 MHz, present in all six frames, with an angle of arrival from inside the site's angular boundaries. The most probable transmitter location is on the first floor (fourth or fifth window of the building from the left).

During *Step* 3, the frequency list is analyzed based on DF from near positions. DF data are superimposed on the video image of the site in real time, the signal is listened to by the operator. In order to increase reliability, the station can be positioned at several locations.

FIGURE 3.6-16

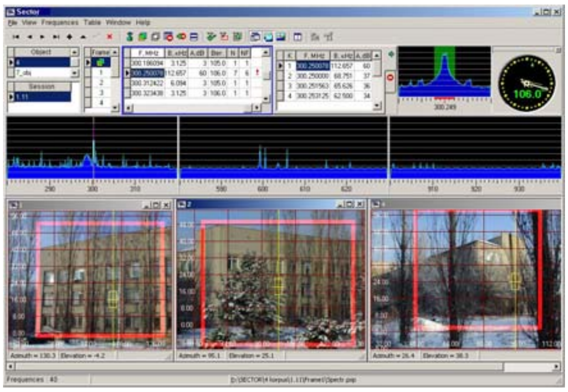
One operational session of the mobile station corresponds to several "frames"



Spectrum-3.6-16

FIGURE 3.6-17

View of the analysis module screen after the second step



Spectrum-3.6-17

3.6.2.2.7 Visualization of coverage areas of VHF/UHF spectrum monitoring stations

Prediction software allows spectrum monitoring stations to determine their coverage areas, a feature that is particularly useful for mobile stations. Practice shows [Bondarenko et al., 2008] that the methodology [Kogan and Pavlyuk, 2004] and relevant software (see "Case study 9" in Chapter 5 of the Handbook on Computer-Aided Techniques for Spectrum Management (CAT), Edition of 2005) for planning and design of spectrum monitoring networks can be successfully used for automation of visualization of VHF/UHF fixed and especially mobile monitoring station coverage areas in the course of their operations. This tool also allows determining interaction conditions of fixed and mobile monitoring stations in performing various monitoring functions that increase the operational efficiency of the stations.

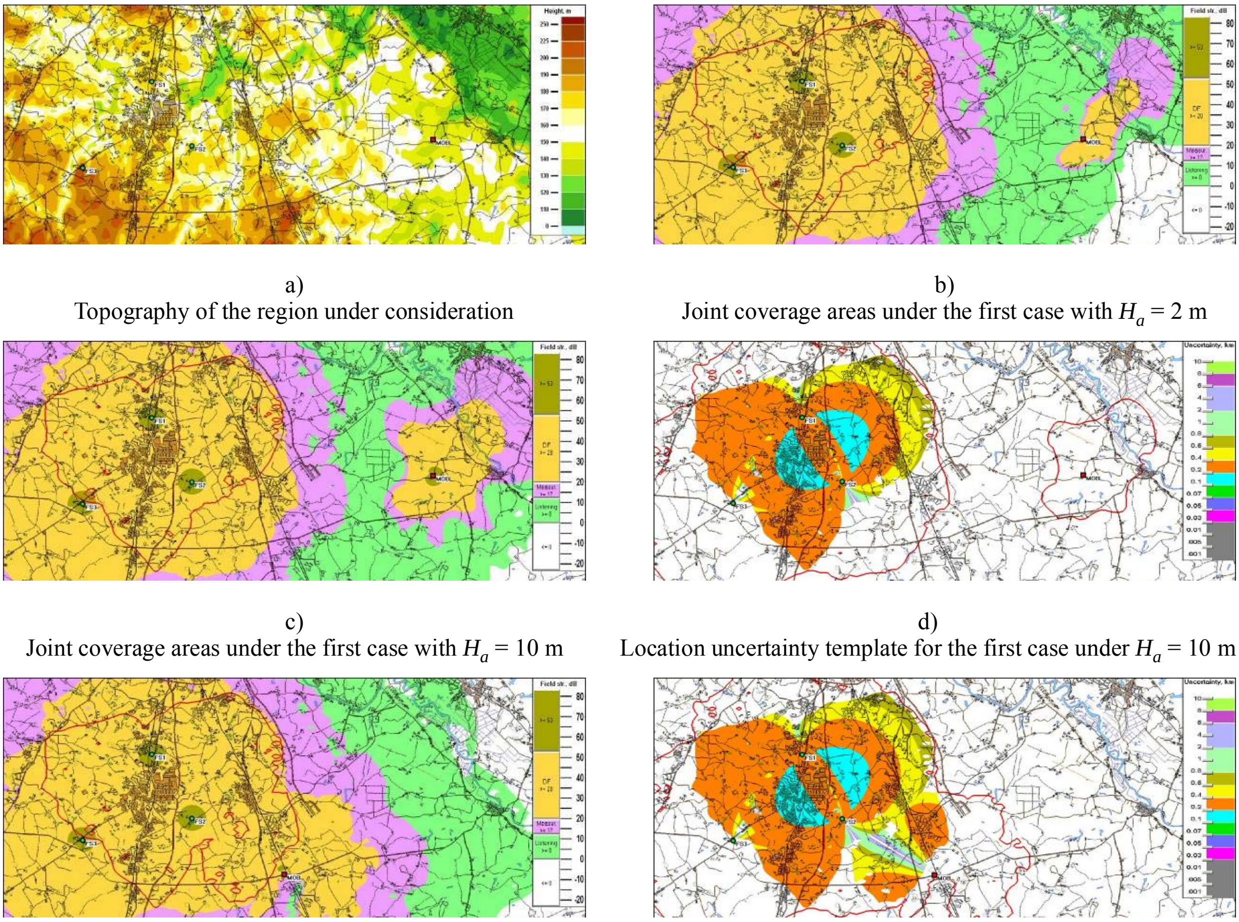
An example presented in Fig. 3.6-18 illustrates these functions. Calculations were made using a set of incoming parameters presented in [Kogan and Pavlyuk, 2004].

Figure 3.6-18a) shows the topography of the region under consideration. It contains some hills with height differences of up to 120 m. Let us suppose that there are three fixed monitoring/DF stations around a city

(FS1, FS2 and FS3) with DF uncertainties of 1o r.m.s., and one mobile station (MOB) with a DF uncertainty 2o r.m.s. that is, in the first case, initially situated rather far from the group of fixed stations.

FIGURE 3.6-18

Example of coverage area visualisation



a)
Topography of the region under consideration

b)
Joint coverage areas under the first case with H_a = 2 m

c)
Joint coverage areas under the first case with H_a = 10 m

d)
Location uncertainty template for the first case under H_a = 10 m

e)
Joint coverage areas under the second case with H_a = 2 m

f)
Location uncertainty template for the second case under H_a = 2 m

Spectrum-3.6-18

Figures 3.6-18b) and 3.6-18c) present coverage areas of all stations when the mobile station one stays rather far away from the group of fixed stations. Figure 3.6-18b) corresponds to the mobile station antenna height, Ha = 2 m (installed on the roof of the car) and Figure 3.6-18c) with Ha = 10 m (erected antenna mast). A red line within the DF coverage area shows the borders of an area where location by triangulation is provided.

Figures 3.6-18b) and 3.6-18c) also show that the mobile station in this position, being connected to a joint local monitoring network with the fixed stations, can interact with them only when performing the listening function within the territory where relevant coverage areas intersect. Elevating the antenna mast up to 10 m demonstrates a significant increase in coverage of all monitoring functions with the exception of location.

Figure 3.6-18d) presents location coverage template whose outer borders correspond to the red line within DF coverage areas of Figs 3.6-18b) and 3.6-18c). Different colour zones within the template show gradations of the location uncertainty (km) as is given by the colour index at the right of the figure. The mobile station does not influence the template at all. The outer red line here corresponds to the borders of joint DF coverage areas given in Figs 3.6-18b) and 3.6-18c).

Figure 3.6-18e), which deals with the second case, presents coverage of all stations when the mobile station with an antenna height of 2 m stays at the top of a hill very close to the group of fixed stations. Calculations show that, in this situation, erecting the antenna mast to a height of 10 m does not improve significantly the situation.

In the second case, DF coverage areas of the fixed and mobile stations intersect, which means that the fixed and mobile stations can interact using the location triangulation function. This is demonstrated in Fig. 3.6-18f) that shows the extension of the template in the South-East direction. More details and explanations can be found in [Bondarenko *et al.*, 2005].

The short description above demonstrates the high potential of the monitoring coverage area visualization tool for supporting routine operations of the fixed and, especially, mobile monitoring stations. With such tools, operators of monitoring stations have "eyes" to see the actual coverage areas of individual stations or groups of stations combined in a joint local network, through different monitoring functions, as well as by the interaction of mobile stations with the nearest fixed stations during the course of their mission. Today, it is possible to determine quickly the gain that a mobile station can achieve by the deployment of a high semi-stationary antenna and, through this, determine not to spend time on such an action if the gain at a particular site is negligible. Thus, the operators for the first time are able to be fully informed of the situation they are dealing with. This technique also provides the capacity to survey a future route of a mobile monitoring station before an actual mission is undertaken and to choose the best observation sites along the route to optimize the mission and to shorten its duration.

3.6.3 Computerized monitoring networks

3.6.3.1 Introduction

Spectrum monitoring stations should be linked together through a computerized network, and should be networked to the administration's spectrum management system as recommended in Recommendation ITU-R SM.1537. Spectrum management and monitoring includes a set of administrative and technical activities, which can be conveniently performed within the framework of a networked, integrated system.

Spectrum management activities ultimately result in the issuing of licences or authorizations. To perform these management tasks, a computer database is essential. This database, which incorporates administrative and technical data such as assigned frequencies, licence holders, equipment characteristics, etc., forms the core of the computerized automated spectrum management system.

Spectrum monitoring allows checking that these frequencies are used in accordance with the provisions of the authorization or licence, and measures the spectrum occupancy by means of monitoring stations.

An important and indissoluble relationship exists between spectrum management and spectrum monitoring; close cooperation should be maintained between both, so that the spectrum monitoring tasks are useful for spectrum management.

The main domains of interaction between spectrum management and spectrum monitoring are as follows:

– spectrum management establishes the official list of assigned frequencies for emission monitoring;
– spectrum management provides general instructions concerning bands to be scanned and specific tasks for monitoring;
– spectrum monitoring receives requests for specific tasks from the spectrum management: e.g., complaints of interference to be monitored to solve the problem and measurement of occupancy on frequencies to be assigned;
– spectrum monitoring allows the measurement of technical parameters and checking for technical compliance of transmitters, identification of unlicensed or non-compliant transmitters and detection of specific problems.

Interaction between spectrum management and computerized spectrum monitoring systems allows operation to be optimized both for the efficiency of operation and cost of the system. The system is organized around a computerized database associated with the use of personal computers. The database is the core for all functions and associated applications: data updating, invoicing, frequency assignment, etc., as well as updating of technical parameters concerning frequencies and transmitters.

3.6.3.2 Integrated computerized national systems

A complete integrated computerized national spectrum management and monitoring system relies on one or more data servers with a network so that workstations or clients throughout the system can access the database. Management system servers include a main server and occasionally one or more servers for a database extracted from the main database and/or a database dedicated to an application or at a local command centre. Each monitoring station, whether fixed or mobile, has a measurement server and one or more workstation(s), as illustrated in Fig. 3.6-2. Each station uses a modular architecture based on server and workstation computers interconnected via Ethernet LAN.

All stations are linked over a wide area network. This fully integrated system should provide rapid access by any operator position to any of the server functions available in the system. The block diagram shown in Fig. 3.6-1 illustrates this system configuration.

The main server contains a relational database that is loaded with administrative and technical data of the region or national network, with data content as recommended by the ITU Handbook on Computer-Aided Techniques for Spectrum Management (CAT) and Recommendation ITU-R SM.1370. This server generally is a Structured Query Language (SQL)-based system, allowing the user, with appropriate access, to easily query the database. Modern databases provide redundant systems and data in conjunction with periodic backups. The database with a distributed computerized network allows for the implementation of a client/server architecture and a distributed computerized system:

– the database server centralizes data management, thus facilitating security and preserving a high integrity level; it contains data on applications, licenses, sites, equipment, invoicing, frequency assignment, etc.; portions of this database may optionally be copied to local or mobile servers for specific applications;
– the management, supervisor and data entry workstations are personal computers which allow the database to be loaded with administrative and technical parameters and which are used by management and monitoring personnel for frequency management, technical monitoring, etc.

The database software should provide for electronic data input from an existing database, should one exist, either directly or through a specially-prepared data conversion program.

3.6.3.2.1 Operation of the network of automated stations

In an integrated system, the management system should be interfaced to the monitoring stations through a wide area network (WAN) to allow remote as well as local tasking of, and reporting from, the monitoring stations. Tasking for the monitoring stations includes systematic measurements in conformity with ITU-R Recommendations such as spectrum occupancy, signal parameter, and DF measurements on a specific frequency that may follow a complaint. Measurement servers (described under § 3.6.2.2) at the stations receiving the tasking automatically execute the requested measurements. This information is made available to supervisory personnel in alphanumeric or graphical reports.

The monitoring reports may include results of measurements and geographical displays of a coverage area or region, including:

– locations of the monitoring stations;
– locations of known transmitters;
– results of the station’s DF bearings for transmitter location.

Monitoring stations may be fixed or mobile and it is useful in a computerized national system to have both types. Fixed stations are appropriate for monitoring signals over long time periods, or for HF, where requirements for antenna space is important and propagation is typically long range via skywave. Fixed stations near urban areas are also useful for monitoring VHF/UHF in urban areas.

Mobile and transportable stations are appropriate for monitoring VHF/UHF/SHF (and HF groundwave) since, with shorter-range propagation in these cases, the measurement system must generally be moved to the area of interest. They are also needed in many cases where illicit stations or the source of interference has to be located precisely.

3.6.3.2.2 Remote access to system resources

Integrated, networked, multitasking systems, with the client/server architecture described above in § 3.6.2.2, typically allow a client at any station to access the resources of any or all of the measurement servers, both those co-located with the client and those at other stations. Thus, all of the resources of a multistation network are available to any given operator, provided that the operator has the proper authorization to access all of those resources.

The monitoring stations may be controlled remotely from a workstation at a spectrum monitoring centre, the spectrum management centre, a local command centre, or locally at the station itself, and monitoring results may be reported back to that workstation. This remote control accommodates spectrum monitoring operators who may need to work from a central location rather than traveling to distant monitoring sites, provided that the situation does not require an experienced monitoring operator at the site. It is important to note that operators still need to analyse measured data and validate any data before entry into a central database.

Communication links only need to be available between stations when a client is issuing tasking to remote servers, and later when the client is requesting results of his tasking; as long as communication links are available when the tasking is issued, if they then become unavailable, measurement results are not lost, but are retained on the measurement server until requested.

3.6.3.2.3 Automatic violation detection

An integrated spectrum management and monitoring system may compare measurements from the monitoring system with licence information from the management system to perform automatic violation detection – to identify frequencies on which there are transmitters that are not included in the licence database and to identify transmitters that are not operating within their licensed parameters. Automatic violation detection allows the operator to define a monitored range by specifying the start and stop frequencies of the band(s) to be searched, and to specify search parameters, including the time period over which the search may be done.

The system should be able to perform a scan over the specified frequency range and for the specified time period. The system uses the measurements obtained from the scan and then uses information in the license database to determine which signals in the measured spectrum are not in the licence database, thus automatically providing a list of frequencies being used that are not in the database. The system should also check other signal parameters, such as bandwidth, over modulation deviation from licensed centre frequency, and issue alarms or reports where violations are found. Reports therefore alert the operator to unexpected or noncompliant signals based on either default criteria or on criteria that the operator has specified, and provides the basis for closer examination by the operator. Automatic violation detection results, including information on unlicensed or noncompliant transmitters by frequency or by channel, are displayed on a results screen. A geographic map display similar to Fig. 3.6-4 may display locations of licensed stations and indicate the locations of unlicensed or noncompliant transmitters.

In order to facilitate the automatic violation detection process and assure it is operational even in the event of unavailability of communications among stations, each client, whether at a fixed or mobile station, should maintain its own database of licensed stations in its area of operation. This database should be obtained from the management system database. With the availability of this local database, each client can continue to operate and perform automatic violation detection, even if communications are unavailable.

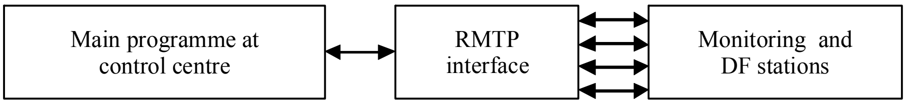
3.6.3.2.4 Example of radio monitoring transfer protocol to operate many monitoring stations from a control station

A spectrum management and monitoring system may include equipment from different manufacturers.

To achieve an integrated system with these equipments, it is desirable that a single control station, with local or remote users, operates remote fixed and mobile monitoring stations provided by these different manufacturers. Since manufacturers generally consider their communication and control protocol to be proprietary, in this example a radio monitoring transfer protocol (RMTP) used by the control centre was established. Figure 3.6-19 shows the structure of the data flow.

FIGURE 3.6-19

Monitoring network structure



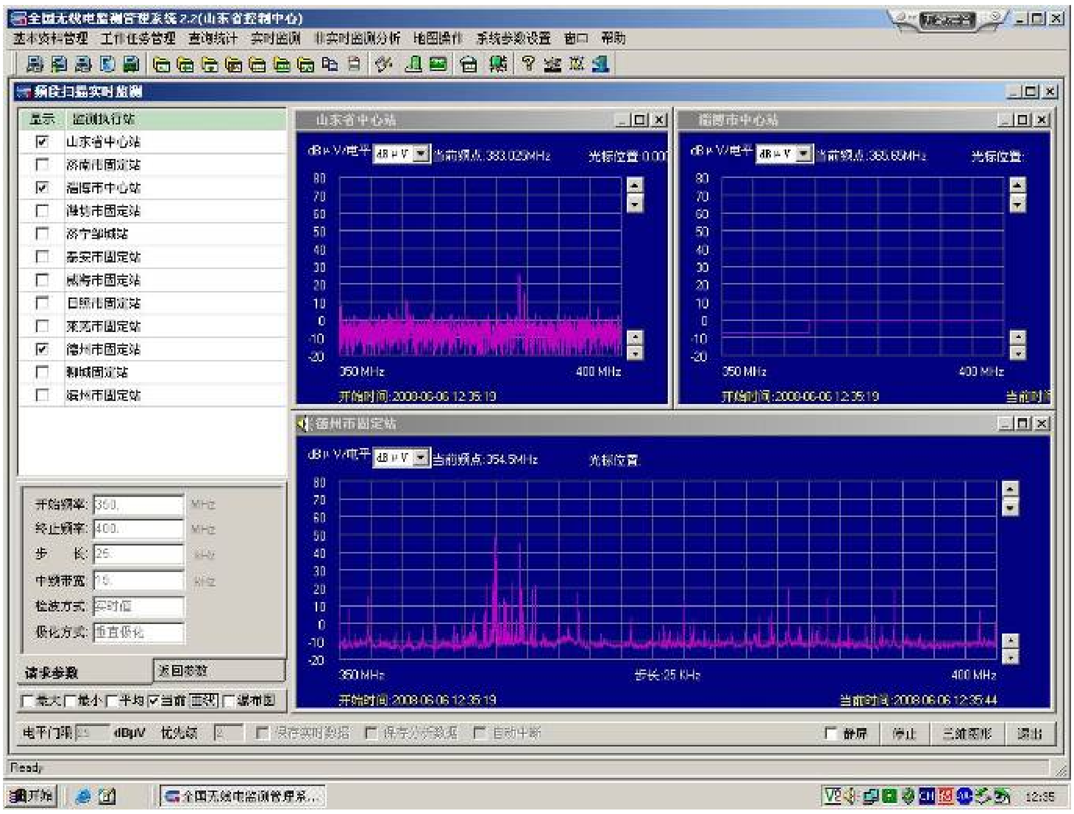
Spectrum-3.6-19

The control centre can obtain status of the various remote stations which are on line, open windows to control their receivers and set other tasking parameters for the remote stations, request technical measurements and DF measurements, perform scan over specified frequency bands using specified bandwidths, and perform other typical monitoring system functions.

The control centre can obtain measurement results, display measured DF and location information on geographic maps, view panoramic displays (provided the communication channels have sufficient bandwidth to refresh pan displays in real time), view spectrum displays, waterfall displays and other spectrum monitoring data. The control centre can compare measurements with the licence database to determine frequencies where there are likely to be unlicensed stations and to find licensed frequencies that are not being used.

FIGURE 3.6-20

Example of measured spectra from three monitoring stations



Spectrum-3.6-20

Although the monitoring data may be measured on equipment provided by different manufacturers, the data are all obtained from the remote monitoring stations using RMTP and displayed on screens at the control centre with up to nine monitoring stations on a screen. Figure 3.6-20 provides an example of a control centre screen, with spectrum displays from three different remote monitoring stations produced by receivers from different manufacturers. In some cases, the spectra are very different because some stations are far apart from the others. The upper left corner of the screen provides a list of all on-line stations that can be selected to perform some monitoring or DF task from the control centre, and the lower left corner allows parameter entry, including start, stop and step frequencies, bandwidth, polarization, demodulation, etc.

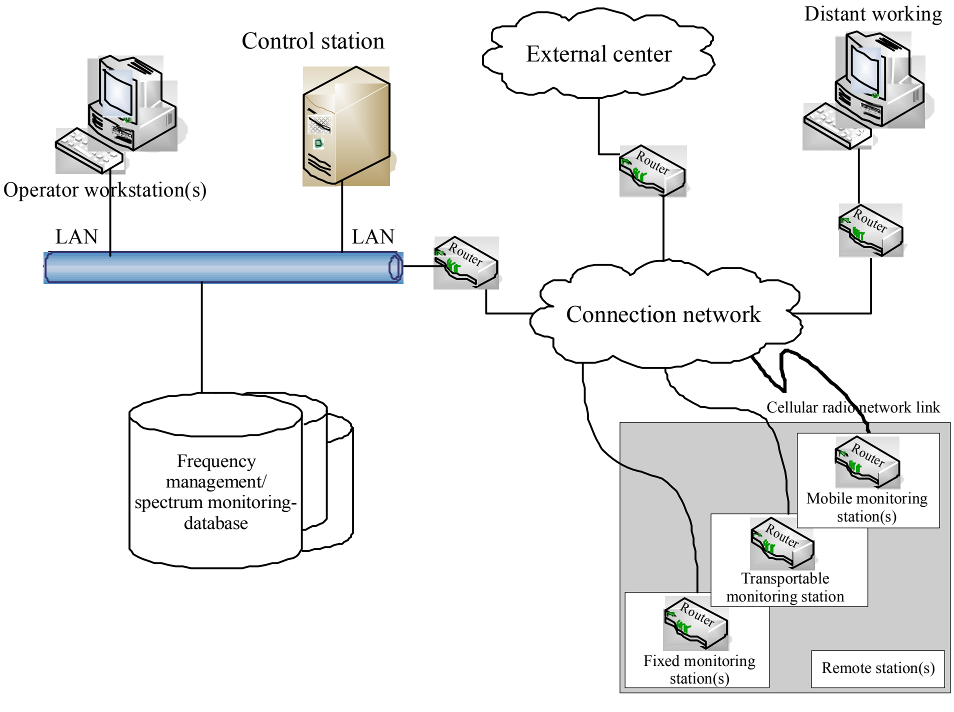
While this example is of monitoring stations within one country, the same RMTP could be used to network stations in multiple countries, so that they could be controlled from one or more control centres. This would allow administrations in different countries to share resources, for example, to use direction finders in other countries to help improve the accuracy of locating an unlicensed transmitter.

3.6.3.3 Example of a HF/VHF/UHF automated system

For spectrum monitoring in this example, there is a technical monitoring network (see Fig. 3.6-21) that consists of a number of remote stations connected to a control station via a standard communication network.

FIGURE 3.6-21

Example of HF/VHF/UHF computerized system



Spectrum-3.6-21

The various elements composing this system have the following characteristics:

a) Operator workstations are in charge of carrying out radio monitoring tasks described in Chapter 2 of this Handbook.

b) Control stations are in charge of managing and supervising the system, planning and allocating of resources, routing of messages, fault modes management and system hour management.

c) Remote stations could include different monitoring equipment to ensure a part or all monitoring tasks described in Chapter 2 of this Handbook.

Remote stations can be established as four types in various frequency bands as:

– Fixed manned or unmanned station.
– Transportable in a mobile shelter and connected to the control station via a fixed or wireless data link.
– Mobile in a vehicle and connected to the control station via a fixed or wireless data link.
– Portable in a box and connected to the control station via a fixed or wireless data link.

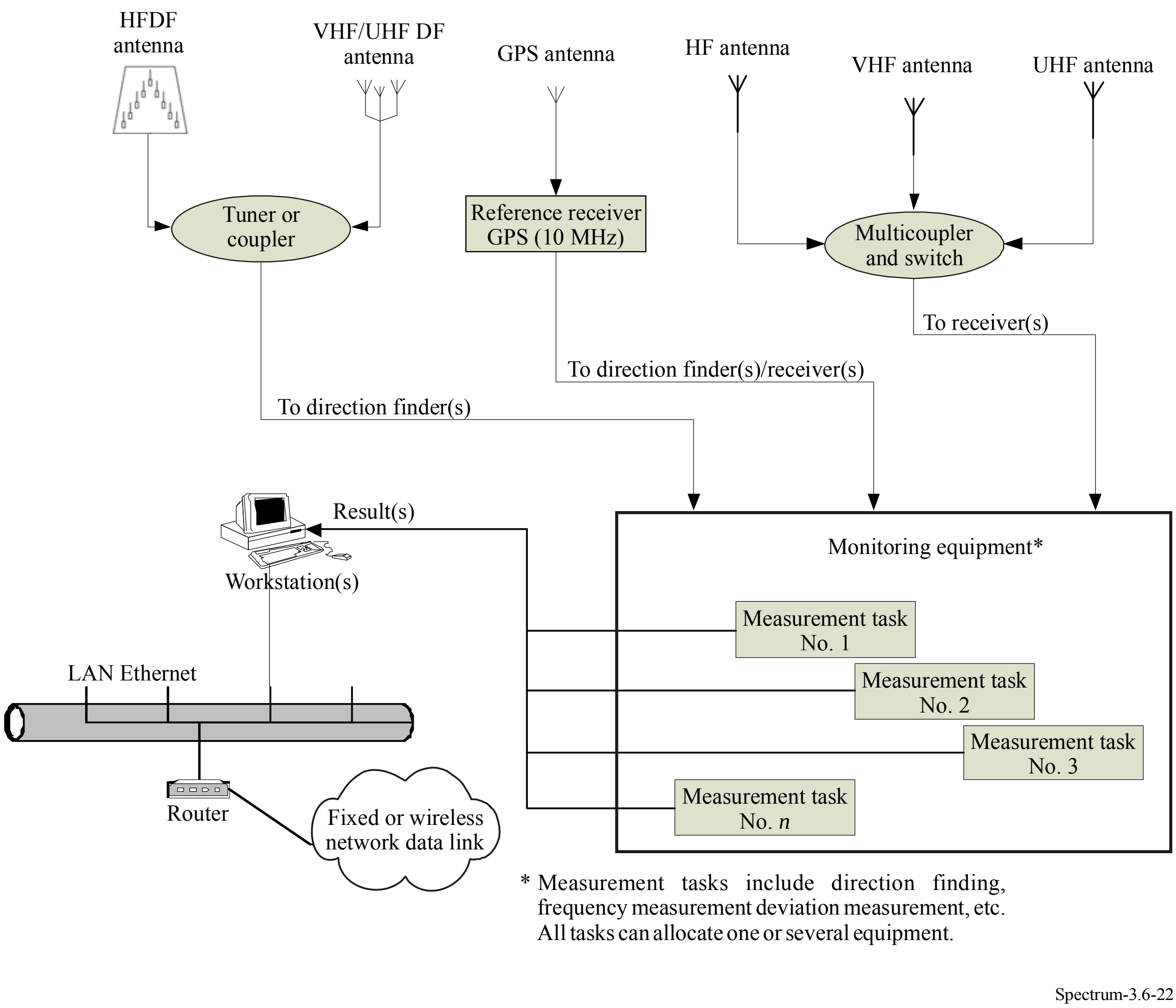
All the stations are fully automatic and supervised by an operator in the operating control centre. For each monitoring station, two different ways of working have been developed:

– First, there is on-line control of the station, making it possible for an operator to use the remote station in a similar way as if it were a local station.
– Second, the remote station is able to operate in scheduled or batch mode, thus making it possible to load a set of parameters for an automatic measurement campaign to be performed during a given period.

An example of a HF/VHF/UHF remote station is shown in Fig. 3.6-22.

FIGURE 3.6-22

Example of HF/VHF/UHF remote station



3.6.4 Reporting equipment and software in automated systems

Reports in modern spectrum monitoring systems are generated with the computer software. They are based on measurements, but can draw on different data records available in the spectrum monitoring and spectrum management databases. A large variety of reports should be available, including raw trace information, carrier analysis by date or band, channel occupancy and availability statistics, message length statistics, channel power statistics, system and alarm logs, and monitoring plan and schedule reports.

A typical computer-generated report is illustrated in Fig. 3.6-23. The system should allow adaptation or customization of reports, according to the requirements of the operator.

Reports should be produced automatically from any results screen. The operator specifies the report type of interest and the measurement data to be used; the operator activates a “Report” function to generate text reports automatically on his screen.

Graphical reports are often a preferred method of examining data, because they provide a view of data that summarizes the information and makes it easy to identify trends and exceptions. Through the use of colour, even more information is conveyed in a single graph.

A modern system should offer the same automated report capability whether one is in a mobile unit, fixed station or management system. The capability to remotely create a report based on data that is located at a different site is also part of a typical system software.

FIGURE 3.6-23

Portion of a typical computer-generated occupancy report

Occupancy vs. Channel

Task No.:	433	Storage Interval:	15 secs
Operator ID:	TRN1	Msb Length:	15 secs
Schedule Time:	05/02/2010 2:45:49 PM	Threshold Method:	Noise Riding 10 dB
Completion Time:	05/02/2010 3:15:50 PM	Duration:	Fixed: 30 mins
Site Location:	S 23 24' 47.5"	Band No.:	1
	W142 01' 56.8"	Bandwidth:	12.5 kHz
StartFreq:	152.112500 MHz		
StopFreq:	152.450000 MHz	NumChannels:	28

Channel:	Frequency:	Maximum occupancy (%):	Average occupancy (%):	Field strength (dB(μV/m)) Max.	Avg.
1	152.112500	0	0	0	0
2	152.125000	0	0	0	0
3	152.137500	53	6	5	4
4	152.150000	48	9	20	15
5	152.162500	100	100	8	7
6	152.175000	40	8	33	26
7	152.187500	37	6	28	21
8	152.200000	0	0	0	0
9	152.212500	0	0	0	0
10	152.225000	13	1	5	4
11	152.237500	20	4	39	38
12	152.250000	20	4	39	38
13	152.262500	90	71	21	17
14	152.275000	100	91	29	25
15	152.287500	0	0	0	0
16	152.300000	23	2	7	5
17	152.312500	0	0	0	0
18	152.325000	26	3	9	8

Spectrum-3.6-23

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ITU-R Recommendations:

NOTE – In every case, the latest edition of the Recommendation is encouraged to be used.

Recommendation ITU-R SM.1050 – Tasks of a monitoring service.

Recommendation ITU-R SM.1370 – Design guidelines for developing advanced automated spectrum management systems.

Recommendation ITU-R SM.1537 – Automation and integration of spectrum monitoring systems with automated spectrum management.

Recommendation ITU-R SM.1794 – Wideband instantaneous bandwidth spectrum monitoring systems.

CHAPTER 4

MEASUREMENTS

4.1 Practical considerations on measurements

4.1.1 Basic concept of measurement

The measurement is the process of assigning a value to an attribute or phenomenon. The result is, in principle, independent of the procedure used. Nevertheless, the accuracy of the measurement process is essential to obtain a reliable value.

The measurement process should define:

– Attribute or phenomenon to measure.

– Conditions of operations.

– The measurement system and parameters to use.

– Sequence of technical operations to apply.

– Result reckoning and uncertainties.

4.1.1.1 Attribute or phenomenon to measure

In the framework of the spectrum monitoring, the basic purpose of the measurement is electromagnetic fields which could be characterised as either a value of E or H fields or as characteristics of a signal (frequency, amplitude, phase, bandwidth, etc.).

Moreover, from these basic measurements, more complex measurement process may be implemented to characterise the quality and the performance of a system or a transmission such as spectrum occupancy and coverage measurements. In this case, the result is a combination of measurements of several data like time, frequency, level, etc.

4.1.1.2 Conditions of operations

Conditions of operations should be identified because of their direct influence on the outcome of a measurement. They depend on the environment, so details of all conditions have to be known to ensure the measurement is reproducible.

The advantage to proceed in a laboratory (conducted measurement or radiated measurement done in an anechoic chamber) is that all parameters are known and conditions of operations are under control.

However most of tasks assumed by a spectrum monitoring department are carried out on site with a lot of influences caused by surrounding infrastructure, weather, limitation with measuring equipment (size of antenna, embedded equipment).

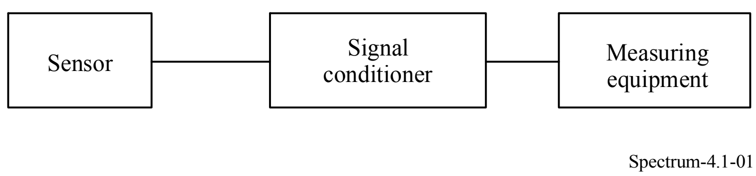
All necessary precautions should be taken to limit outside influences and conditions of operations should be specified in the measurement process to ensure reproducible measurements.

4.1.1.3 Measurement system

A measurement system comprises all equipment used to carry out measurements. Basically the measurement system may be divided into three parts:

FIGURE 4.1-1

Basic measurement system



The sensor is the device which converts the electric or magnetic field into an electrical signal. In term of spectrum monitoring, the sensor is usually a probe or an antenna.

The signal conditioner is used to arrange the signal provided by the sensor for a better measurement. It could be filters, amplifiers/attenuators, couplers, mixers, etc.

The measuring equipment is the device which processes the signal and displays or records it for exploitation. It could be spectrum analyzer or receiver for example.

In the description of the measurement process, all devices involved in the measurement should be specified to take into account all parameters in the measurement result (type of equipment, characteristics and uncertainties).

4.1.1.4 Sequence of technical operations

A general description of how to perform the measurements is provided below:

– The description of the measurement chain set up, including identification of equipments used.

– The description of preliminary measurements to carry out (e.g. measurements to ensure that there's no strong emitter at the measurement location which could lead to a wrong result).

– Measuring device settings to be used (e.g. frequency band, resolution bandwidth (RBW), span, etc.).

– Tasks to be achieved to carry out the measurement.

– Consistency of the result (e.g. checking of the result by comparison with theoretical reckoning, uncertainty calculation, etc.).

4.1.1.5 Results reckoning and uncertainties

To provide a reliable value of the measurement, post-processing is necessary to take into account uncertainties of the measurement chain to assess the uncertainty of the final result.

The final step could be, if necessary, to specify the form of publication of the results.

4.1.2 Measurement environment

Depending on the task, the measurement environment may be different.

On one hand, to test radio equipments, some measurements have to be carried out in an anechoic chamber, on the other hand, to solve interference cases measurements are performed on site. In each two cases, the measurement approach is really different.

4.1.2.1 Laboratory environment

Although such environment is not required to perform the regulatory tasks, an increasing number of activities may require such means.

The main interest of laboratory environment, in opposition to a real environment, is that it is free of any uncontrolled parameters**.**

When tests require to be performed while controlling the electromagnetic environment without being disturbed by other external radiations, two cases may be considered:

– conducted measurement;

– radiated measurement in a controlled environment.

Conducted measurements are performed mainly to test the signal from a source at the output (just before the antenna).

However, more and more system is packaged and the output or the input of the device under test may be not available. In this case, analysis of the radiated signal of a device cannot be done in conducted mode.

For radiated measurement, an electromagnetic environment under control is achieved by means of a shielded cage. Some tests require to be carried out without any multi-path and in this case, the adequate environment is an anechoic chamber.

Main activities performed under such conditions are:

– compatibility measurements between systems (e.g. a preliminary study to the introduction of a new system which should share the same frequency band with another system, or use an adjacent frequency range);
– checking specifications of measurement equipment (e.g. antenna gain);
– compliance of radiated emission of a device before commercialising (e.g. out-of-band emission, spurious, etc.).

Nevertheless, the largest proportion of monitoring measurement is carried out in the field with a real electromagnetic environment.

4.1.2.2 In-situ measurement

Main activities of a spectrum monitoring organisation are to check the emission compliance (compared to declarations), to identify interference sources, to carry out coverage measurement or QoS measurements. Such measurement must be carried out in the field.

These tasks are ensured by means of fixed monitoring station, mobile stations and mobile measuring equipments. According to the task to operate, advantages of a mobile solution is greater flexibility regarding to the choice of the measurement site. However, the advantage of a fixed monitoring station is that the measuring site may be more known regarding to the frequency spectrum occupancy.

Even if the environment is not under control, some precaution should be taken into account to limit interactions and to carry out the measurement. Among the most common precautions to consider, the followings may be highlighted:

– To ensure to be in far-field when it is required;
– To ensure a sufficient decoupling height to avoid influence of soil during the measurement;
– To choose a site with less obstacles as possible (constructions, trees, etc) to avoid reflexions and other multi path effects;
– To check there is no strong electromagnetic field in the vicinity of the measuring site.

4.1.3 Measuring principles

4.1.3.1 Time and frequency domain measurements

The signals received in a monitoring station may be characterised using the time, the frequency or the phase domain.

These three ways of looking at a problem are to some degree interchangeable. The advantage of introducing these three domains is that of a change of perspective. By leaving the perspective of the time domain, the solution to difficult problems can often become quite clear in the frequency or phase domains. After developing the concepts of each domain, we will introduce the types of instrumentation available. The merits of each generic instrument type are discussed to give the reader an appreciation of the advantages and disadvantages of each approach. Figures 4.1-2 and 4.1-3 show examples of periodic and aperiodic signals in time and frequency domains.

The frequency domain representation is especially well suited to observe channel occupancy, interference, harmonic products and spurious emission. Further, the characteristic spectrum displays of the different modulation modes sometimes allow identifying the modulation type. The time domain representation helps to understand the time dependence of signal amplitudes and to set the required measurement time (e.g. for the peak detector) for the correct measurement of signal amplitude. Especially when investigating emissions from digital systems, the time domain helps to measure parameters of time-division multiplex such as burst and idle time, number of time slots occupied and power ramping.

FIGURE 4.1-2

Some periodic signals in the time and frequency domains

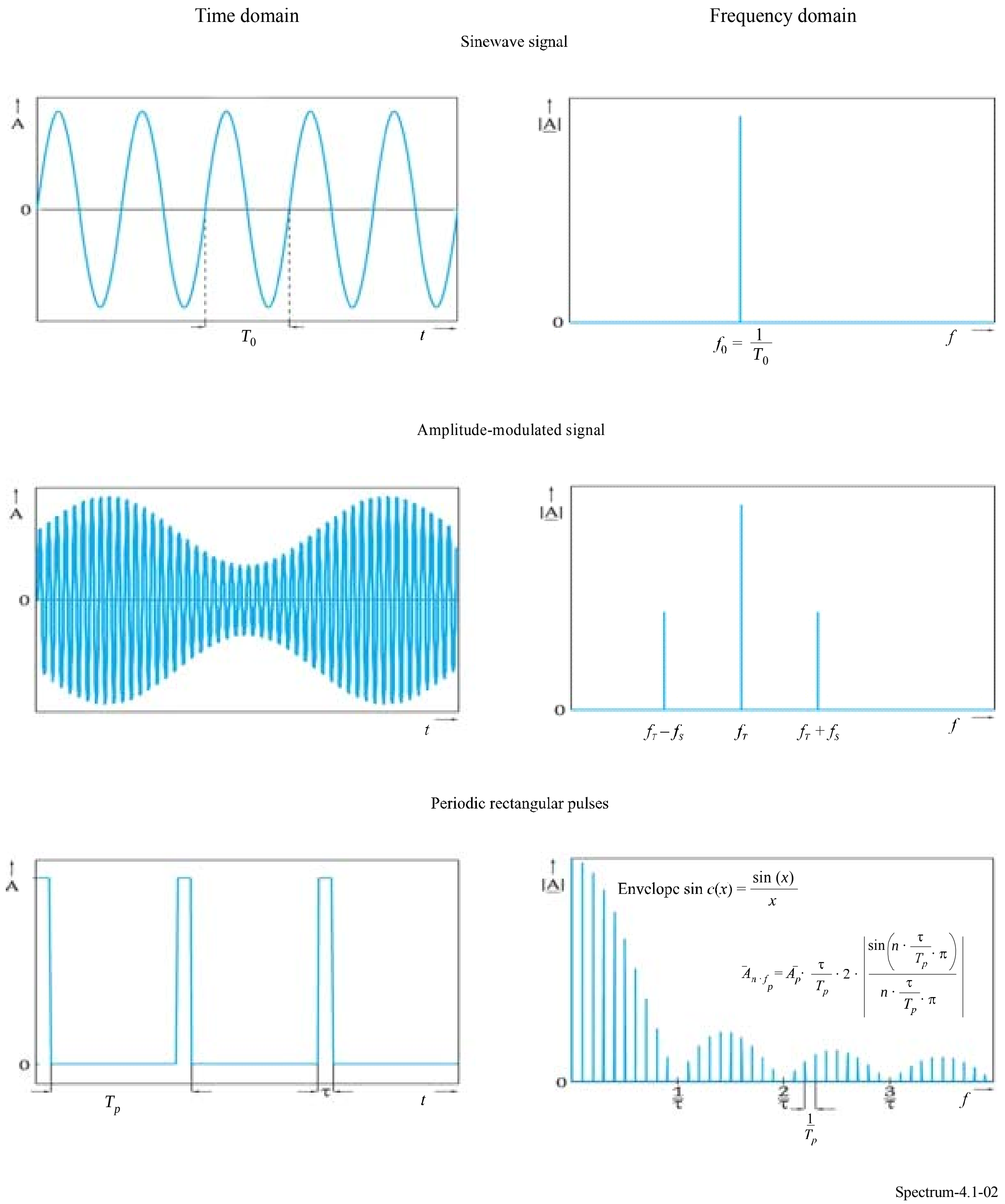
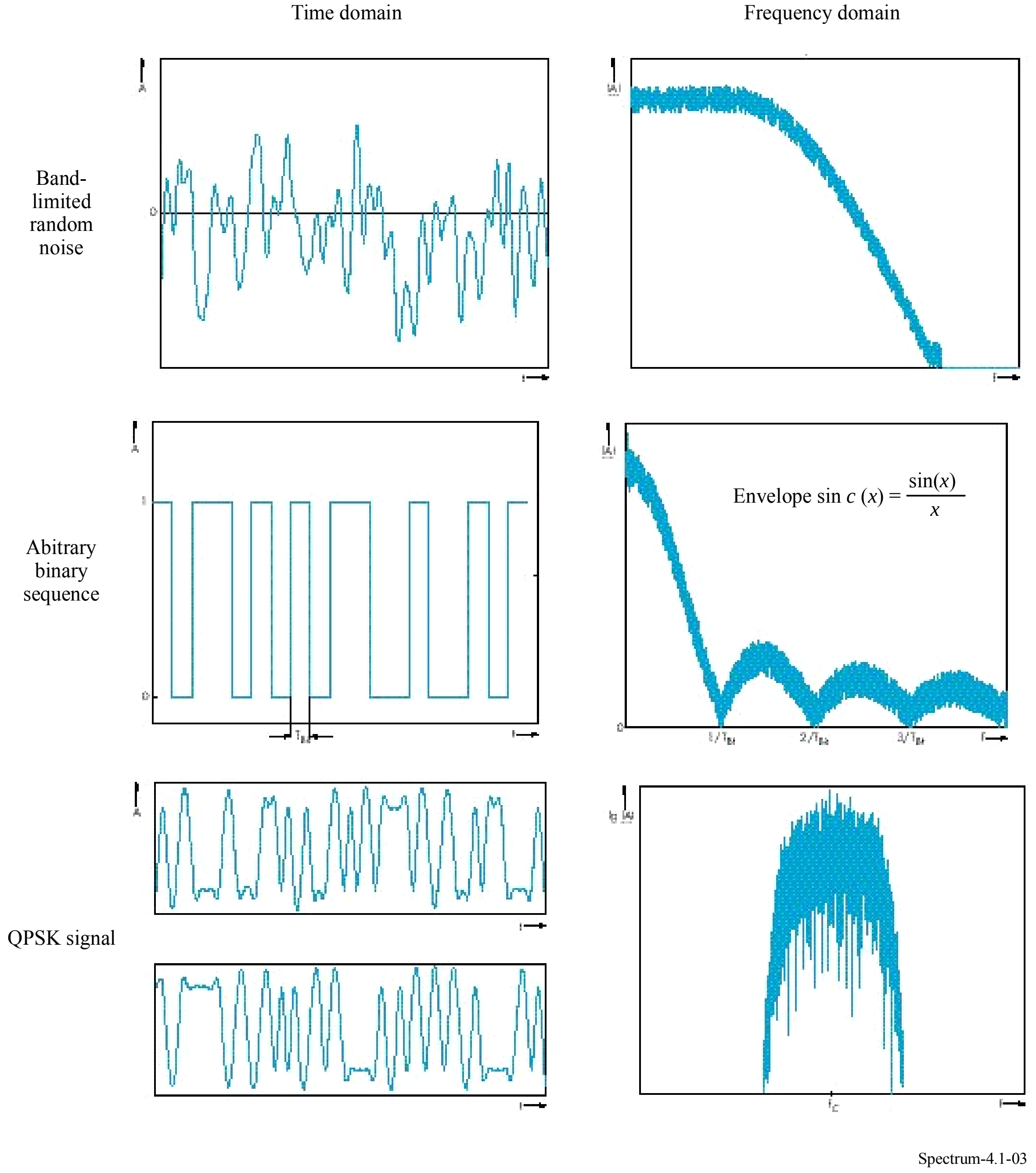


FIGURE 4.1-3

Some aperiodic signals in the time and frequency domains



The frequency domain representation is especially well suited to observe channel occupancy, interference, harmonic products and spurious emission. Further, the characteristic spectrum displays of the different modulation modes sometimes allow identifying the modulation type. The time domain representation helps to understand the time dependence of signal amplitudes and to set the required measurement time (e.g. for the peak detector) for the correct measurement of signal amplitude.

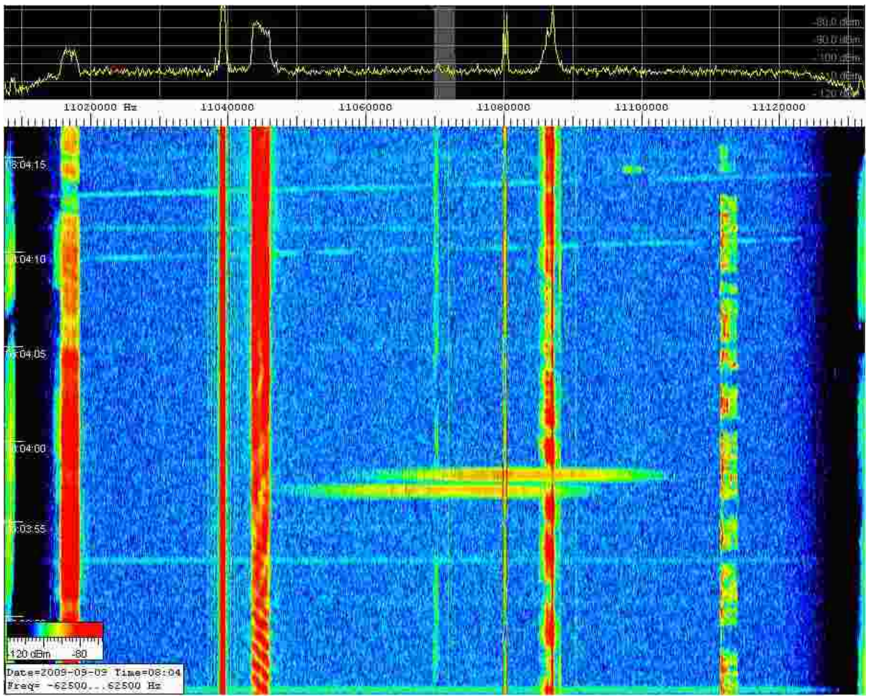
Especially when investigating emissions from digital systems, the time domain helps to measure parameters of time-division multiplex such as burst and idle time, number of time slots occupied and power ramping.

The time domain may be suitable to detect and to analyse short burst duration signals or transient effects which are not detectable with traditional spectrum analyzer.

The discussion above is about frequency versus amplitude and time versus amplitude. Another useful view for the monitoring interest is the spectrogram (see Fig. 4.1-4) to assess the frequency spectrum occupation for example. This representation is based on frequency versus time. In this view values of amplitude are provided, thanks to additional colour scale. Such representation is useful to capture broadband emission or to track an emission with a frequency drift or a frequency hopping emission.

FIGURE 4.1-4

Example of a spectrogram



Spectrum-4.1-04

4.1.3.2 Amplitude and phase domain (vector-) measurements

Most digital radiocommunication systems modulate the phase of the RF carrier (PSK, QPSK etc), or phase and amplitude together (QAM). The frequency domain, however, is not able to show phase information. To retrieve it, the emission is usually displayed in a constellation diagram. The vector length from the origin to each of the points of the constellation diagram represents the signal amplitude whereas the angle between the positive x-axis and the vector, measured counter-clockwise, represents the phase. The in-phase ("I") component of the signal is represented on the X-axis (REAL) and the quadrature ("Q") component on the Y-axis (IMAG). Vector signal analyzers are used to show the phase domain of a signal at certain defined points in time (see Fig. 4.1-5).

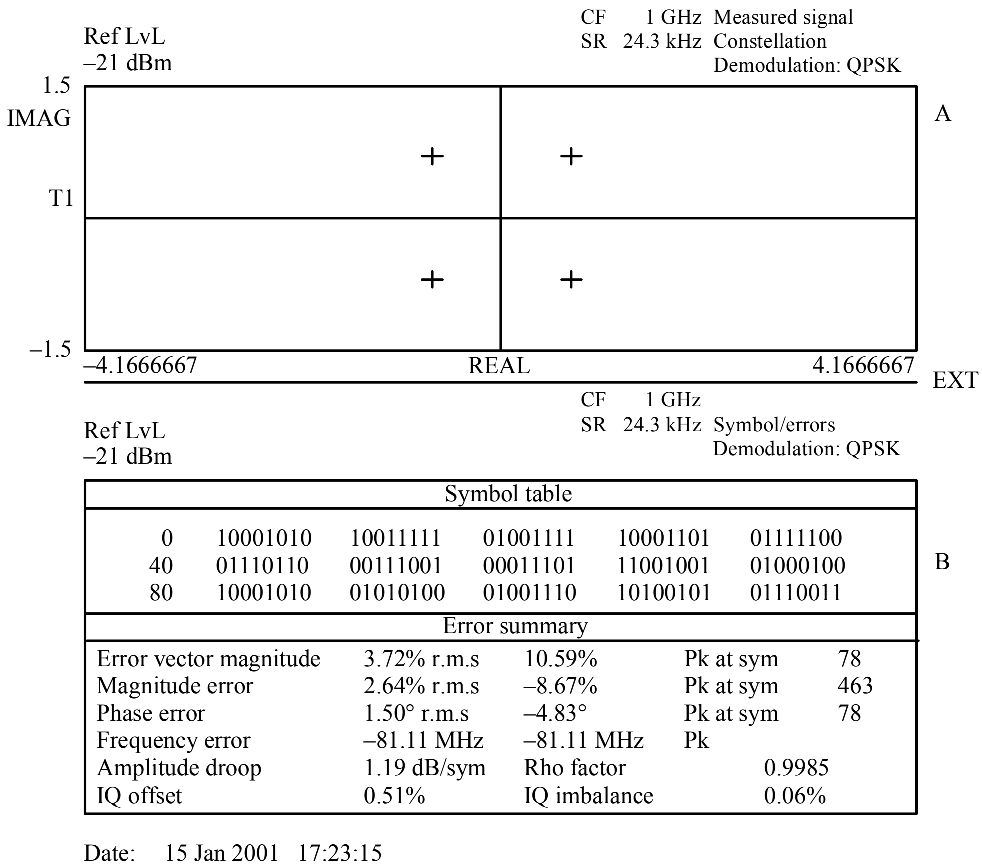
The repetition frequency of this display has to be equal to the symbol rate transmitted. In order to give a stable presentation, the analyzer has to synchronize with the signal. To facilitate this, the type of signal or at least the symbol rate has to be known.

In simple cases, when the modulation mode and the encoding scheme are known, the analysis can be done in real time. Modern vector analyzers are then able to display the binary signal sequence, or characters of decoded information.

However, in the case of a more sophisticated modulation scheme and in cases where either the modulation scheme or the encoding is unknown at receiving time, subsequent processing is necessary to get the transmitted code.

FIGURE 4.1-5

QPSK signal as constellation diagram (amplitude-phase domain)



Spectrum-4.1-05

4.1.3.3 FFT analysis

The Fast Fourier Transform (FFT) is an algorithm for transforming data from the time domain to the frequency domain. FFT technique is described in detail in § 6.7.

4.1.4 Measurement uncertainty

In order to be complete, a statement of uncertainty should accompany each measurement result. Measurement uncertainty should be determined by the monitoring station for each type of measurement and be taken into account when determining compliance or non-compliance with a regulatory limit. Regulatory measurements include the measurement of frequency, signal levels, and occupied bandwidth. In these cases regulatory limits define maximum values of frequency offset, effective radiated power (e.r.p.) and occupied bandwidth.

For more details, see § 6.9 on uncertainties calculations.

4.2 Measurement of frequency

4.2.1 General considerations

Digital signal processing (e.g. FFT, IFM…) is now generalised in measuring equipment. This has resulted in a considerable increase in the measurement accuracy, the ease of adjustment and consequently in the speed of measurement. Reference is made to Recommendation ITU-R SM.377 for frequency measurements.

Practically all frequency measurements carried out at monitoring stations are remote measurements, which have to be made with the aid of receivers. In order to obtain results that cannot be contested, the receivers should have the following properties:

– high input sensitivity;
– satisfactory image-frequency rejection;
– low cross-modulation and intermodulation;
– proper input filters (preselector) to protect the frequency band used for measurement against unwanted frequencies;
– an external frequency standard input;
– low phase noise of the internal oscillators;
– either manual or remote controlled or automatic gain control;
– transparent IF output for additional measurements.

Internal carrier(s) used at mixer(s) in the receiver must be derived from a frequency standard.

External or internal signal generators for frequency measurement should have the following features:

– the frequency must be synthesized from a frequency standard;
– the internal frequency standard should have an error of less than 10^{-7} for the frequency itself and all frequency steps;
– the smallest step should be 1 Hz or less;
– there should be an external frequency standard input for 1, 5 or 10 MHz;
– stand by operation of the internal frequency standard should be possible;
– the frequency range should cover the range of frequencies to be measured;
– harmonics should be attenuated by at least 30 dB;
– non-harmonics should be attenuated by at least 80 dB;
– low phase noise (less than –100 dBc/Hz at 10 kHz offset from the carrier);
– output voltage should be variable from 1 mV to 1 V across 50 Ω.

The influence quantities to take into account for the measurement of frequency are:

– reference oscillator;
– measurement procedure;
– resolution of reading (e.g. limited number of digits);
– stability of signal to be measured;
– measurement time in relation of signal to be measured.

The measuring procedures described below are more or less manual methods. Despite the fact that they have been partly superseded by automated methods meanwhile, they are still of importance:

– for simple and low cost measuring installations;
– for the training of monitoring operators;
– for a monitoring service at the beginning of its operation;
– and in cases where weak and/or interfered signals have to be measured because automated system often fail under these conditions.

Frequency measurement usually means a process of making comparison between an unknown frequency and a known frequency (reference frequency). Based on this comparative process, the following frequency measurement methods are applied at monitoring stations (some ad-hoc abbreviations are used for easy reference in Table 4.2-1 only):

– Conventional methods are:

  – Beat frequency (BF) method.
  – Offset frequency (OF) method.
  – Direct Lissajous (DL) method.
  – Frequency counter (FC) method.
  – Frequency discriminator (FD) method.
  – Phase recording (PR) method.
  – Swept spectrum analyzer (SSA) method.

– DSP based methods are:
  – Instantaneous frequency measurement (IFM) method.
  – FFT method.

NOTE 1 – DSP methods should be preferable on International monitoring stations.

Table 4.2-1 shows the applicable frequency measurement methods as the functions of the type of emissions.

TABLE 4.2-1

Frequency measurement methods

	BF	**OF**	**DL**	**FC**	**FD**	**PR**	**SSA**	**IFM**	**FFT**
Continuous Carrier (N0N)	X	X	X	X	X	X	X	X	X
Morse Telegraphy (A1x)	X	X	X		X		X	X	X
Morse Telegraphy (A2x; H2x)	X	X	X	X	X	X	X	X	X
Radiotelegraphy (F1B; F7B)	X	X	X		X		X	X	X
Facsimile (F1C)	X	X	X		X		X	X	X
Broadcasting and Radiotelephony (A3E)	X	X	X	X	X	X	X	X	X
Broadcasting and Radiotelephony (H3E; R3E;B3E)	X	X	X		X	X	X	X	X
Broadcasting and Radiotelephony (F3E)				X	X		X	X	X
Radiotelephony (J3E)							X		X
Digital Broadcasting (COFDM)							X		X
Analogue Television Broadcasting (C3F)	X	X	X	X	X	X	X	X	X
FDM Radio Relay (F8E)				X			X	X	X
Pulsed Radar Signals					X		X	X	X
Cordless telephone systems (F1D, F2x, F3E, G3E)							X	X	X
Point-Multipoint TDMA systems							X	X	X
Cellular telephone systems							X	X	X

The method of determining the accuracy of frequency measurements should meet the following conditions:

– Measurements should be made under optimum reception conditions, so as not to introduce new variables due to fading or interference.

– As far as possible the exact values of the frequency being measured should not be known to the operators, who might be tempted to correct the results obtained.

– To enable the above conditions to be met, known frequencies generated locally should be used rather than standard frequency emissions that have propagated.

– The method should yield the error of the method of measurement (excluding the error due to the standard) and not partial errors.

– As the error will probably be different for different classes of emission, the error has to be determined for each class.
– As the error will vary from one measurement to another for a particular class of emission and as the errors cannot be less than the discrimination of the measurement equipment, the results may be treated statistically.
– The results obtained should indicate the error or the method used for the particular class of emission. However the error due to the standard should be excluded.
– When the accuracy of the measurement system is described (frequency standard as well as measurement apparatus and method), the error should be given for each of the factors involved. The maximum error of the whole system will then be the sum of the absolute values of the errors due to the frequency standard and the method of measurement.

Like every other measurement, frequency measurements are subject to errors. The following must be considered:

– errors due to the method of measurement ($\Delta f_M / f$);
– errors due to the modulation of the signal to be measured ($\Delta f_{mod} / f$);
– errors of the reference frequency of the measuring arrangement ($\Delta f_R / f$);
– errors due to the technical characteristics of the measurement arrangement including the reading inaccuracy ($\Delta f_A / f$);
– errors on the transmission path (see below) ($\Delta f_T / f$).

The maximum error $\Delta f/f$ can be estimated from the sum of the individual errors:

$$\Delta f / f = \pm\left(\left|\Delta f_T / f\right| + \left|\Delta f_R / f\right| + \left|\Delta f_M / f\right| + \left|\Delta f_A / f\right| + \left|\Delta f_{mod} / f\right|\right) \tag{4.2-1}$$

In band 7 (HF) and, to a smaller extent even in bands 6 (MF), 5 (LF) and 4 (VLF), the accuracy of frequency measurements is not only limited by the method of measurement of the type of modulation of the transmitter, but also by frequency variations introduced by the transmission path. When making tests in band 7 (HF), departures up to $\pm$ 3 parts in 10^{12} between the incoming and the radiated frequencies have been experienced at night on a transmission path of more than 1 000 km. There is also a mean diurnal variation of the frequencies. The smallest differences are to be expected when both the transmitter and the receiver are in the daylight zone. In this case the frequency departures are mostly less than 3 parts in 10^8. Diurnal variations are also to be found with emissions in bands 5 and 4. Here the variations are as a rule of the order of 1 part in 10^9 provided the transmission distance does not exceed several hundred kilometres. However, in many cases these restrictions are of minor importance.

4.2.2 Most common conventional frequency measurement methods applied at stations for International Monitoring

4.2.2.1 Direct Lissajous method

This measurement method is applied at the receiver IF output. If a crystal-controlled frequency synthesizer sets the frequencies of the receiver oscillators, the displacement of the IF from the nominal value is equal to the displacement of the received frequency from the set frequency. For frequency measurements the receiver IF-stage output is applied to the Y amplifier and a crystal-controlled frequency (corresponding to the nominal value of the IF) is applied to the X amplifier (see Fig. 4.2-1).

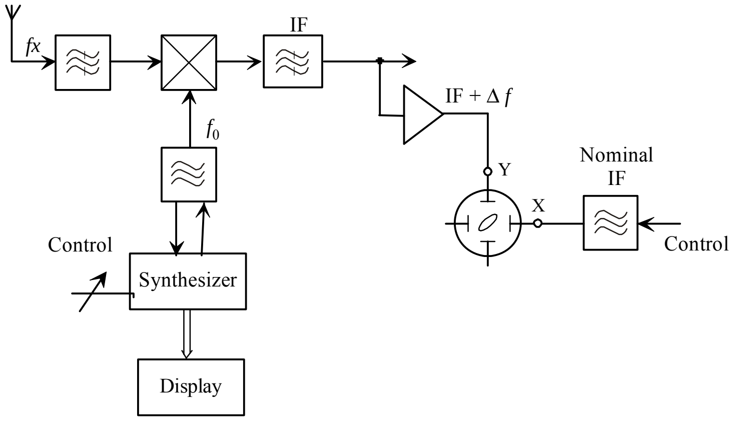
This results in an ellipse being displayed on the screen. If the frequency synthesizer is provided with an interpolation scale, it is necessary to measure while the ellipse appears to be stationary.

4.2.2.2 Frequency counter method

Apart from the intrinsic inaccuracy of the crystal standard, the accuracy of the frequency counter is restricted to a $\pm$ 1 count of the last digit. To operate correctly, frequency counters also require a clean and sufficiently high input voltage during the whole period of measurement.

FIGURE 4.2-1

Direct Lissajous method



Spectrum-4.2-01

State-of-the-art are receivers whose oscillator frequencies are synthesized and derived from an internal frequency standard. Therefore, an input frequency, which is equal to the frequency setting of the receiver, will be converted to the nominal value of the intermediate frequency (IF). Hence the IF counter whose frequency indication is corrected by the oscillator frequency (or frequencies) used will indicate the input frequency.

In view of the integrating property of the frequency counter, this method is very suitable for the measurement of FM signals, as long as the gate time of the counter remains much greater than the period of the lowest modulation frequency.

4.2.2.3 Swept spectrum analyzer method

Swept tuned spectrum analyzer method is often used at monitoring stations for measuring frequencies of received signals. A synthesized oscillator, whose output frequency is derived from an internal or external frequency standard, is applied to tune a modern spectrum analyzer.

In the case of some digital modulations, unlike to most of the analogue modulations, it is difficult to find a characteristic frequency in the spectrum of the emission (like e.g. the carrier in much analogue modulation cases). A centre frequency can be calculated in such cases from the upper and lower boundary of the occupied bandwidth (see Fig. 4.2-2).

NOTE 1 – For the measurement of the occupied bandwidth, see § 4.5.

The centre frequency is stated as:

$$f_c = (f_l + f_u)/2 \tag{4.2-2}$$

where:

f_c: the centre frequency of the spectra

f_l: the lower frequency value of the occupied bandwidth

f_u: the upper frequency value of the occupied bandwidth.

4.2.3 DSP-based frequency measurement methods applied at stations for International Monitoring

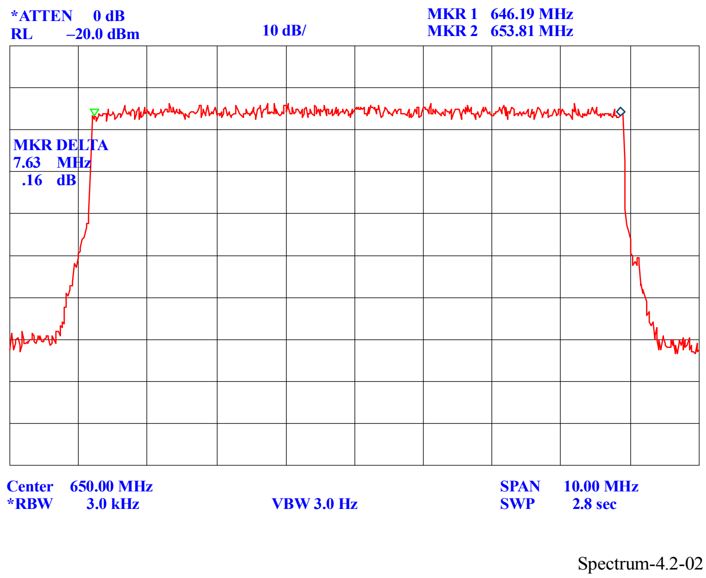
4.2.3.1 Instantaneous frequency measurement method

Due to the benefits of digital techniques in measurement, and to the progress of signal acquisition and processing technologies, it is henceforward possible to achieve, in monitoring stations, a high level of accuracy while preserving an appreciable measurement speed.

In particular, by using digital measurement receivers as sensors equipped with digital signal processing and using measurement techniques such as instantaneous frequency measurement (IFM), both the accuracy and speed performance levels can be guaranteed, while providing simultaneously several advantages: high fidelity/repeatability of measurements, averaging functions, filtering, automation of measurement, etc.

FIGURE 4.2-2

Spectra of a DVB-T signal



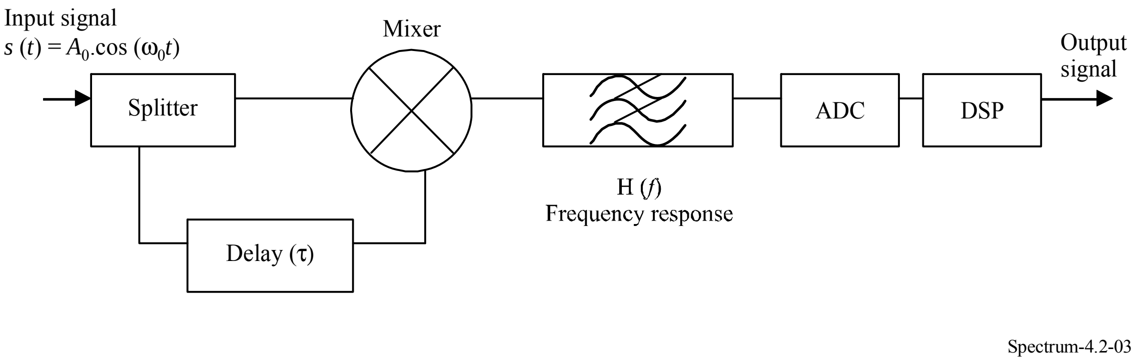
4.2.3.1.1 Principle

One principle of IFM techniques is an autocorrelation process of the captured signal. After filtering, the result of the operation is digitized and processed with a DSP to determine the exact frequency of the signal.

The basic principle could be illustrated with the following diagram:

FIGURE 4.2-3

Basic principle of IFM technique



The signal processing, in the time domain, consists in splitting the input signal in two signals.

Afterward the signal itself and the same signal delayed are mixed. This results in two mathematics terms:

$$s_{MixOUT}(t) = \left(\frac{A_0}{2}\right)^2 [\cos(\omega_0 \tau) + \cos(2\omega_0 t - \omega_0 .t.\tau)] \tag{4.2-3}$$

The first term is proportional to the frequency and the delay applied to the signal, the second term is the second harmonic of the signal which is suppressed by the low-pass filter.

After digitizing, the instantaneous frequency can de estimated by the DSP according to the following relation:

$$f_0 = \frac{1}{2\pi\tau} \arccos\left[\frac{8.s_{MixOUT}(t)}{A_0^2.H(f_0)}\right] \tag{4.2-4}$$

Another principle of the IFM could be described as an analysis of the phase of the signal.

The input signal is digitized, filtered and demodulated in I/Q.

The instantaneous phase φ of the signal is reckoned as Arctg (Q/I) for each sample. The instantaneous frequency is deducted from the following relation:

$$f_n = \frac{\varphi(n) - \varphi(n-1)}{2\pi\tau_s} \tag{4.2-5}$$

τ_s is the sample duration.

By processing the average of calculated instantaneous frequencies, the central frequency of the input signal could be calculated.

4.2.3.1.2 Performance of IFM techniques

Typically, it is possible to obtain a measurement result every second and even in less than 1 s (200 ms) while preserving an accuracy of the order of 1 Hz or even much better than 1 Hz on pure carriers or carriers of amplitude modulated signals.

These measurement times are compatible with signals the centre frequency of which drifts slowly, and also make it possible to evidence drift characteristics by consecutive measurements.

Digital signal processing techniques make it possible to perform measurements with very high accuracy and fidelity/repeatability at reasonable costs. Accuracy of the order of 10^{-10} on a pure carrier can be reached easily provided the measuring equipment is referenced to a suitable frequency standard. GPS locked frequency standards are nowadays available at a fraction of the cost that was involved in the past for rubidium standards, so that high accuracy can now be achieved without undue cost in both fixed and mobile monitoring stations. Use of a GPS frequency standard also solves problem of traceability of measurements and frequent accuracy check of receiver synthesizer accuracy.

Therefore, the accuracy of frequency measurements in modern monitoring stations can reach about 1 Hz from 9 kHz up to the higher UHF frequencies (3 GHz) on pure carriers. This performance is compatible and required if only to check one of the most stringent frequency accuracy needs described in ITU-R Recommendations, namely the frequency setting of analogue TV broadcast transmitters in high density networks (Recommendation ITU-R BT.655).

Accuracy of frequency measurements on random modulated signals depends on the statistics of the signal and the sample duration. Typically, the accuracy on a random modulated signal is one order of magnitude lower than on a pure sine wave (± 10 Hz when locked on a 10^{-10} frequency standard). However, experience and simulations show that the above recommended measurement duration values ensure that frequency measurement accuracy is at least an order of magnitude better – even on random modulated signals – than the precision required of transmitters for the various service categories defined in the RR.

In order to have a repeatable characterisation of the performance of a monitoring station, calibration and accuracy checks should be performed on pure sine wave signals.

A minimum instantaneous acquisition bandwidth should also be recommended for frequency measurement in monitoring stations, so as to be able to fit signals to be measured entirely in the measurement filter. In practice, the measurement should be done in a filter sufficiently wide to contain the emission to be measured, but also sufficiently narrow to reject contributions from adjacent emissions.

Modern receivers include a number of filters (typically 10 or more) usually sufficient to provide a good filtering of common signals; however, one should be careful to select equipment that has sufficient bandwidth to accommodate signals to be monitored. One of the most common signals to be monitored being FM broadcast which should exhibit a frequency deviation not exceeding ± 75 kHz one could require a monitoring station to have at least an instantaneous acquisition bandwidth of about ± 200 kHz to ± 300 kHz. A bandwidth of ± 300 kHz is compatible with many modern digital signals, including GSM, but not for signals such as DAB, IS95 or some high-speed point-to-point or point-to-multipoint systems such as rural telephony equipment used below 3 GHz, for which a bandwidth of 2 MHz is usually sufficient. Considering that higher bandwidth requires more costly digitisers and processors, one could recommend that instantaneous acquisition bandwidth for measurements should reach, depending on the targets of the monitoring stations:

– about ±200 kHz for a low grade monitoring station covering 9 kHz to 3 GHz;

– about ±2 MHz for high grade monitoring station covering 9 kHz to 3 GHz.

Higher instantaneous bandwidths such as ±8 to ±10 MHz might be desirable in some cases, especially when monitoring above 3 GHz or monitoring Digital Video Broadcasting or W/CDMA signals.

4.2.3.2 FFT method

The FFT is an efficient method of converting digital amplitude versus time record into amplitude versus frequency spectral display, suitable method to make it by a microprocessor.

FFT analyzers for frequency measurement should have the following features:

– ZOOM FFT capability at the IF of the applied receiver, or high frequency resolution of the receiver;

– Hann- (Hanning-) window capability;

– an external frequency standard input for 5 or 10 MHz;

– at least 16 bit resolution;

– the frequency range should cover the range of the IF frequency of the receiver to be measured;

– remote control interface;

– averaging possibilities for measuring the frequencies of the noisy signals.

Nowadays, FFT becomes commonly used in measuring equipments (receiver or spectrum analyzer). To reach better frequency accuracy, they may be driven with a frequency standard that could be done, for example, by GPS receiver embedded in the equipment. Excellent frequency resolution can be achieved by using ZOOM-FFT with Hann-weighting (windowing) function (see § 6.7).

There is a possibility to increase the resolution of the FFT-based frequency measurement by estimating that is counting the correct frequency from the power of spectrum lines around the detected peak in the power spectrum.

$$\text{Estimated frequency} = \frac{\sum_{i=j-3}^{j+3} (\text{Power}(i) \cdot i \cdot \Delta f)}{\sum_{i=j-3}^{j+3} \text{Power}(i)} \tag{4.2-6}$$

where:

j: array index of the apparent peak of the frequency of interest

$\Delta f =$ F_s/N

where:

F_s: sampling frequency,

N: number of points in the acquired time-domain signal.

The span $j \pm 3$ is reasonable because it represents a spread wider than the main lobe of the usually applied Hann-window. This calculation can reduce the measuring time significantly.

The advantages of the FFT-based measuring system are:

– very high frequency resolution and accuracy;
– the possibility of measuring frequencies of common-channel signals;
– faster speed for narrow resolution bandwidth;
– receiver sensitivity and signal resolution are improved compare to analogue receiver (with comparable condition and signal to analyze).

In a given implementation, the following additional advantages could be achieved:

– easy tuning and adjustment to the frequency bands to be monitored (via computer terminal);
– high flexibility regarding the adoption to various frequency bands;
– digital storage of the spectrum data;
– high reliability due to the reduced number of mechanical components;
– reproducibility of all system settings due to digital processing;
– possibility of transferring the data via telephone lines for further evaluation and/or processing to spectrum users, centralising offices, etc.

NOTE 1 – The position of the spectra at the IF output of the receiver must be taken into account in calculating the correct frequency.

For more detail on FFT processing, see § 6.7: "Fast Fourier Transform".

Figure 4.2-4 illustrates the frequency measurement of a stable signal even at very low frequency distances (separation).

4.2.4 Crystal-controlled stage of frequency measurement equipment against a standard frequency

All frequency-measuring instruments are provided with a crystal standard, regardless of whether the scale of a variable oscillator can be calibrated at particular points by a comparison with harmonics, or the final frequency is derived from the crystal standard, as is the case with the frequency synthesizers.

The output frequency of the crystal stage depends upon the ambient temperature and the operating voltage.

Even after the warm-up period, a crystal generator shows a steady variation of the output frequency.

At present, the order of magnitude of these variations ranges from 10^{-8} to 10^{-12}.

For good instrument, the steady variation of the crystal frequency is between 10^{-10} and 10^{-9} per day after a continuous warming-up time of several weeks.

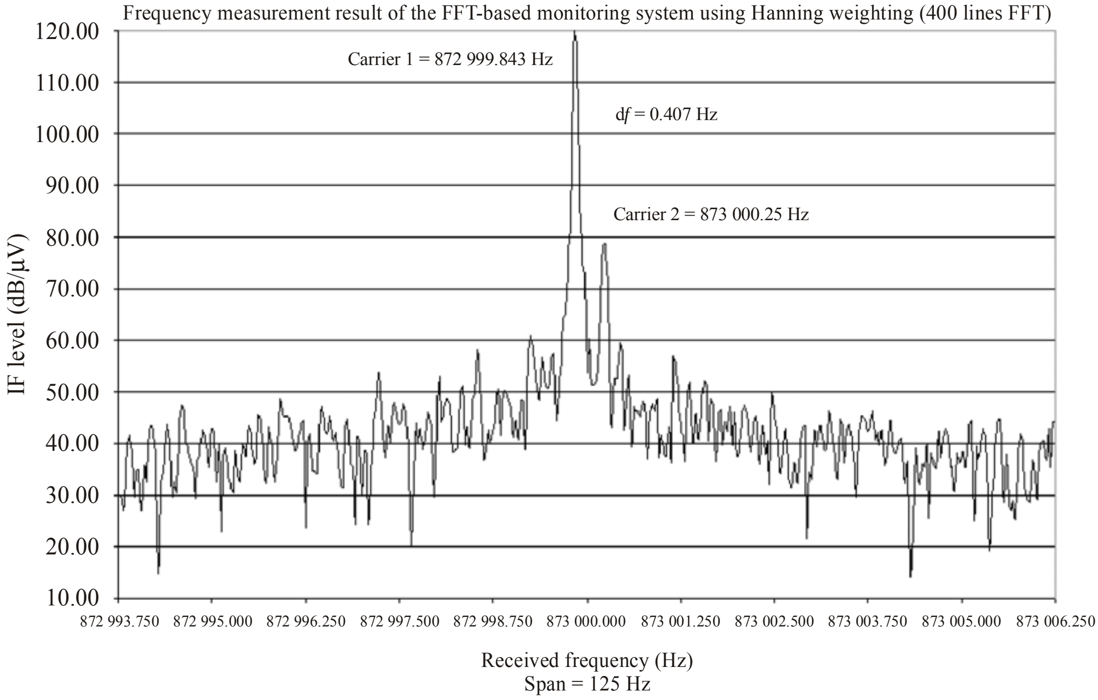
Consequently, instrument crystal stages must be frequently compared with a frequency standard or must be controlled by a standard frequency emission.

An alternative to periodic comparison is to permanently lock the crystal to an atomic standard and in this way, combine the short-term stability of the crystal oscillator with the long-term stability of the atomic standard.

In instruments with high measurement accuracy the external crystal oscillator, or at least the oven of the internal crystal oscillator, should be continuously operated so as to avoid troublesome warm-up effects and discontinuity in the rate of aging.

FIGURE 4.2-4

FFT-Spectrum of an MF-broadcasting channel
(Span = 12.5 Hz; Resolution: 400 lines)



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ITU-R Recommendations:

NOTE – In every case the latest edition of the Recommendation is encouraged to be used.

Recommendation ITU-R SM.377 – Accuracy of frequency measurements at stations for international monitoring.

Recommendation ITU-R BT.655 – Radio-frequency protection ratios for AM vestigial sideband terrestrial television systems interfered with by unwanted analogue vision signals and their associated sound signals.

Recommendation ITU-R TF.768 – Standard frequencies and time signals.

4.3 Measurement of RF level

4.3.1 Introduction

While in many cases monitoring stations require knowledge of the field strength or power flux-density (pfd) of an RF emission, the only parameter that can be measured directly is the RF level, either in terms of receiver input voltage or input power. Under certain conditions, the field strength can be calculated from the result of the level measurement.

RF level measurements of continuous emissions can be done either with a measurement receiver or a spectrum analyzer. However, certain considerations apply when the signal to be measured is modulated. Furthermore, digitally modulated signals often use time division multiple access (TDMA) and/or time division duplex (TDD). The resulting emissions are pulsed which makes the RF level measurement more complicated. Section 4.3 describes methods and equipment to be used by the monitoring service when measuring the RF level of continuous and pulsed signals.

4.3.2 Measurement detectors

Measurement receivers and spectrum analyzers are usually able to interpret or weight the RF level using different measurement detectors. While the momentary amplitude of the RF signal constantly changes, the detector looks at the momentary RF amplitude for a certain time (the measurement time) and displays one single value as a result. Following are the most important detectors:

– *Peak detector (Pk)*

  Out of all momentary RF amplitudes in the measurement time, the Pk detector selects the highest and truncated all others.

– *RMS detector (RMS)*

  From all momentary RF levels, the RMS detector calculates the average power. This is equivalent to the thermal power of the RF signal.

– *Average detector (AV)*

  From all momentary RF levels, the AV detector calculates the average input voltage.

– *Quasi peak detector (QP)*

  The QP detector integrates all momentary RF levels as a weighting network with defined rise and fall times for pulsed signals. Its characteristics are defined in CISPR-16.

– *Sample detector (SA)*

  This is often the standard detector in spectrum analyzers. For swept spectrum analyzers, the measurement time on each frequency is the time necessary to sweep from one display point to the next (*sweep time/number of display points on x axis*). From all available momentary levels during this time, only the first is selected and all others are truncated.

It is important to understand that peak and RMS detectors indicate the *effective* RF level. This means that the readout of the peak detector would indicate the root mean square value of a sinusoidal signal having the same peak level as the measured signal, i. e. $U/\sqrt{2}$.

Figure 4.3-1 shows an example of the indicated level for different detectors when measuring an RF signal that is 100% AM modulated.

4.3.3 Level definitions

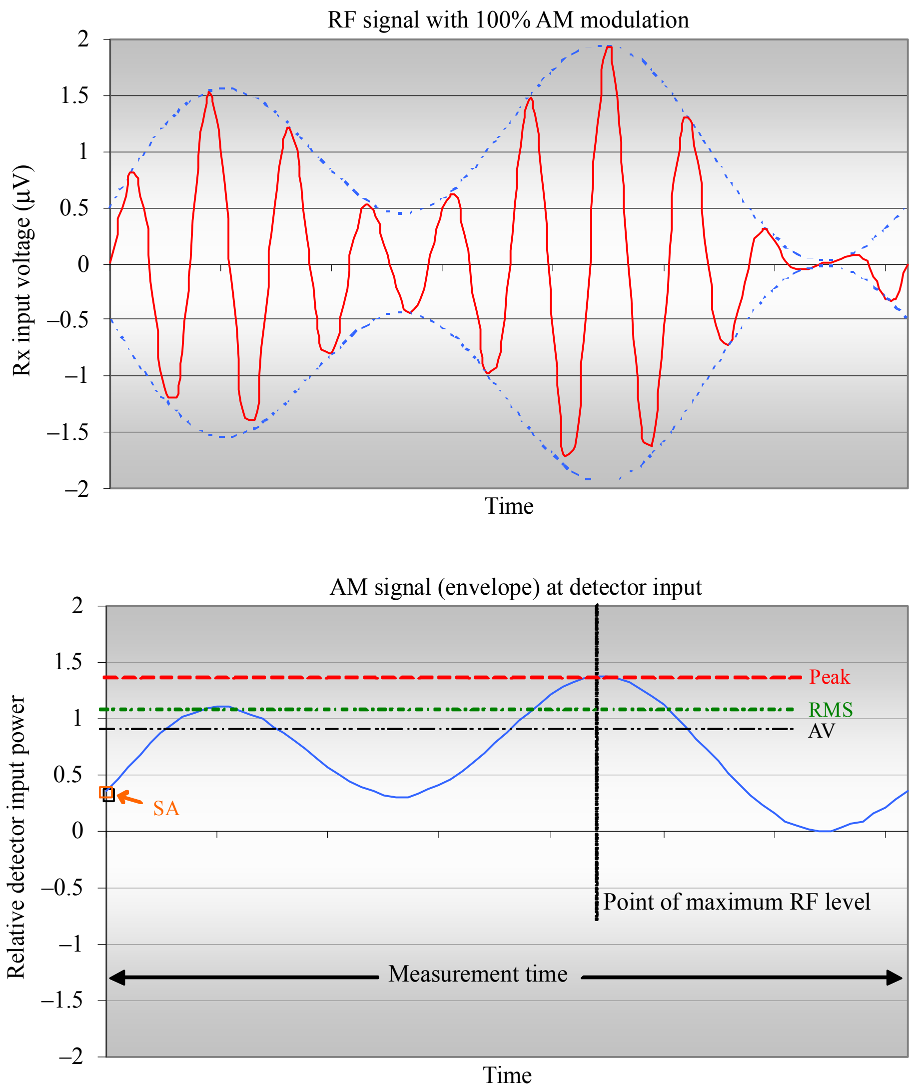
Many analogue and digital modulations such as AM, ASK, PSK, QAM and OFDM alter the amplitude of the RF signal. Therefore, when measuring these signals, the *kind* of level that should be measured needs consideration. The following levels are important:

– *Peak level:*

  This is the maximum level emitted. This level is important when the signal is regarded as an interferer, because usually the peak level determines the degree of the interference. It is measured with a peak detector and the MaxHold function (in case a spectrum analyzer is used). The measurement procedure is the same for all signals, whether they are pulsed or continuous.

FIGURE 4.3-1

Indicated RF levels when measuring a 100% AM modulated signal



Spectrum-4.3-01

– *RMS level:*

This is the average power emitted. It specifies the energy contained in the signal and therefore determines whether a receiver can decode it or not. This is the most important level for continuous signals. Unless otherwise specified, always the RMS level is meant. It is also the reference level for network planning, coordination, compatibility studies and in licences for continuous signals. The RMS level is usually equal to the so-called channel power. It is measured with an RMS detector and a long integration time.

– *Average burst level:*

This is the average power (RMS) *during a burst* when the signal is pulsed (e. g. from TDMA systems). The RMS measurement with a long integration time would normally average bursts and pauses, leading to results that depend on the timing. However, for pulsed digital signals the most important level is the RMS level measured only during the burst and sparing out the pauses. Unless otherwise specified, the average burst level is meant if the signals are pulsed. It is also the reference level for network planning, coordination, compatibility studies and in licences for pulsed signals. It is measured with an RMS detector and an integration time that is shorter than (or equal to) the burst. The measurement has to be time synchronized with the pulses of the signal.

– *QuasiPeak level:*

This level is especially used to characterize the disturbing effect of unwanted signals regardless of whether they are pulsed or continuous. The maximum QP level of electrical devices is defined in relevant standards. Due to the defined weighting characteristic of the detector, the QP level of a pulsed signal depends on the peak level during a pulse, the pulse length and its repetition frequency. It is measured with a pre-defined bandwidth (200 Hz, 9 kHz or 120 kHz depending on the frequency range) and integration time. Modern measurement receivers usually set both parameters automatically when the QP detector is deployed.

4.3.4 Influence of modulation

Some modulations alter the amplitude of the signal while others do not. This fact has great influence on the way the signal level can be measured.

For unmodulated signals and continuous signals having modulations with constant amplitude such as FM, MSK and FSK, all detectors show the same reading. In this case, Pk, RMS, AV and QP levels equal.

If the modulation alters the RF amplitude such as AM, SSB, ASK, PSK, QAM and OFDM, all detectors show different readings. In this case, it is necessary to carefully consider the level required when selecting the measurement detector, equipment and method.

The average burst measurement for systems that alter the amplitude require time synchronized measurement, making sure that pauses are spared. This function is not always available in spectrum analyzers or measurement receivers.

It is, however, easy to determine whether the modulation alters the amplitude or not. Using a spectrum analyzer in zero span mode (resolution bandwidth ≥ signal bandwidth), a certain time interval (for pulsed signals: at least one burst) is captured in ClearWrite mode. If the amplitude remains constant over time, the modulation is FM, FSK or MSK, otherwise the amplitude is modulated (AM, SSB, ASK, PSK, QAM, OFDM).

Figure 4.3-2 shows an example of a GSM/EDGE signal in the time domain (zero span). The first time slot (burst) is a standard GSM burst with GMSK modulation (constant amplitude); the second slot is an EDGE burst using 8-PSK modulation that alters the amplitude.

4.3.5 Necessary measurement bandwidth

For direct level measurements of modulated signals the measurement bandwidth has to be at least as wide as the occupied bandwidth of the signal. Depending on the type of equipment, the measurement bandwidth can be called

– IF bandwidth (in case of a conventional measurement receiver).

– Resolution bandwidth (RBW, in case of a spectrum analyzer).

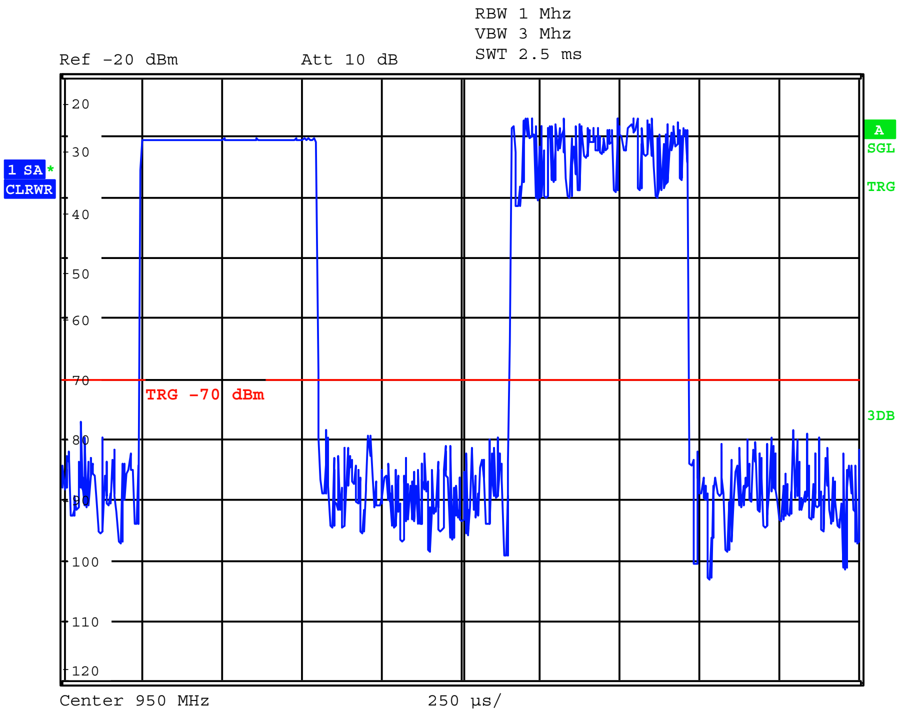
– Acquisition bandwidth (in case of an FFT analyzer).

Therefore, knowledge of the occupied bandwidth is necessary prior to measuring the level of a modulated signal. The widest available measurement bandwidth of the equipment limits the broadest signals that can be measured. One exception is the RMS level of continuous signals inside a used channel. Most modern spectrum analyzers can measure this level using smaller resolution bandwidths and integrating the spectral levels over a wide frequency range (channel power mode).

Table 4.3-1 shows necessary measurement bandwidths for some common radio systems.

FIGURE 4.3-2

Pulsed signal with and without amplitude modulation



Spectrum-4.3-02

TABLE 4.3-1

Necessary measurement bandwidths

System	Necessary measurement bandwidth	Remarks
AM double sideband	9 or 10 kHz	Narrowband (voice) transmissions
AM single sideband	2.4 kHz	Narrowband (voice) transmissions
FM narrowband with a channel spacing of: 12.5 kHz 20 or 25 kHz	 7.5 kHz 12 kHz	
FM sound broadcasting	120 kHz	Maximum occupied bandwidth is 180 kHz, but nearly all of the energy lies within 120 kHz
T-DAB, T-DMB	1.5 MHz	
Analogue TV	120 kHz	Although occupied bandwidth is higher, nearly all energy is in the vision carrier for which 120 kHz is sufficient
Digital terrestrial TV	6, 7 or 8 MHz	Equal to the channel bandwidth used
TETRA	30 kHz	
GSM	300 kHz	Although common channel spacing is 200 kHz, the occupied bandwidth of GSM signals is higher
UMTS	4 MHz	
WiMAX, LTE	3, 5, 10 or 20 MHz	Depending on system configuration (equal to maximum emission bandwidth)

4.3.6 Measurement procedure with a measurement receiver

A measurement receiver can normally measure the peak, RMS, AV and QP levels of a signal. All four levels can directly be measured using the correct measurement bandwidth (see § 4.3.5), the respective detector and a long integration time (measurement time).

When the signal is pulsed, the RMS reading only provides the "long-term" average power where pulses and pauses are averaged. When the signal is FSK or MSK modulated, the peak reading is also the average burst level. For other modulations, the average burst level can be calculated from the long-term RMS reading, provided the pulse/pause ratio remains constant over the whole measurement time:

$$P_{av\text{-}burst} = P_{RMS} + 10*\log(T/\tau) \qquad (4.3\text{-}1)$$

where:

$P_{av\text{-}burst}$: average burst level (dBm)

P_{RMS}: long term RMS reading of the receiver in dBm

T: burst period (s)

τ: burst length (s)

If not known, T and τ can be measured using any standard spectrum analyzer in zero span mode or an oscilloscope connected to the IF of the measurement receiver.

4.3.7 Measurement procedure with swept spectrum analyzer

The optimum RBW to display the actual spectrum of a signal with an analyzer is about *span/sweep points*. This setting, however, can not be used to directly measure any level of a modulated signal. For level measurements the RBW has to be at least as wide as the signal bandwidth. The resulting display will not show the true spectrum, but it allows reading of the level using a marker set to the highest point of the displayed trace.

The peak level of pulsed and continuous emissions can be measured with the peak detector and MaxHold function either in the frequency or time domain (In both cases: RBW ≥ signal bandwidth).

The RMS level of continuous signals can be measured with an RMS detector, the ClearWrite function (not MaxHold) and a long sweep time. If no true RMS detector is available, the sample detector can also be used in conjunction with linear trace averaging.

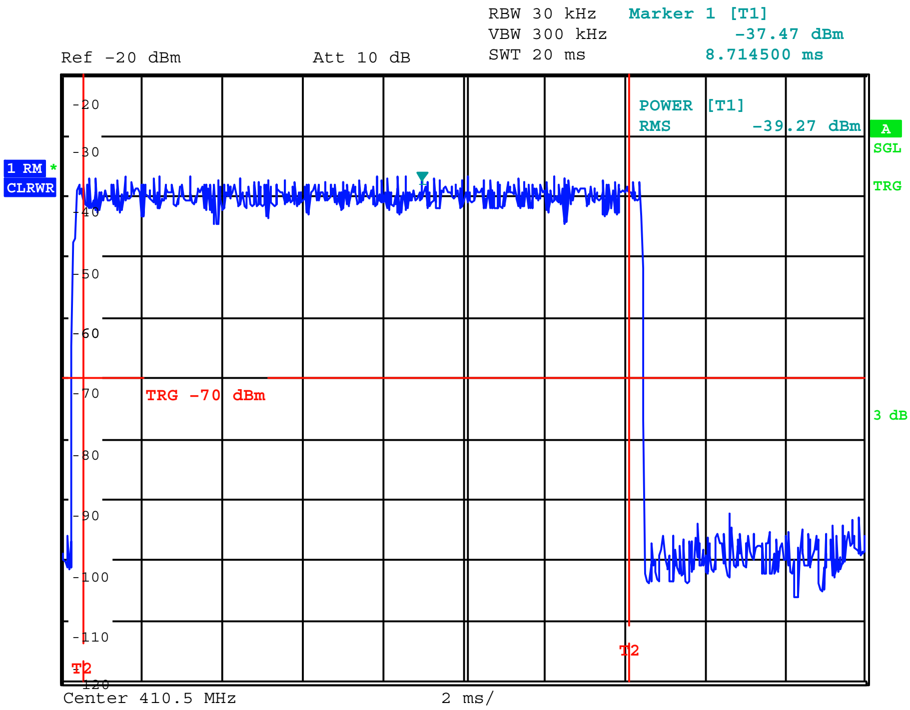
For the RMS level, most modern spectrum analyzers have a built in function that measures the power inside certain frequency boundaries. This function is often called channel power measurement. It records the momentary spectrum (ClearWrite function) with a small RBW and integrates the spectral power levels over the desired frequency range. While this function works fine with continuous signals, even if neighbouring frequencies are occupied, it fails if we have pulsed signals. This is because the time needed by the analyzer to sweep over the channel is longer than the pulse. Therefore the recorded level drops to the noise floor during every pause, resulting in a false spectrum and hence false power integration. This measurement needs the RMS or sample detector. The MaxHold function can not be used.

The preferred way to measure the AV-burst level with a spectrum analyzer is in the time domain. Again, if the signal is FM, FSK or MSK modulated with constant amplitude, the AV-burst level is equal to the peak level and further measurements are not necessary. For the other modulations, however, we need to synchronize the measurement with the signal to make sure that the measurement is only active during a burst. This function may be called "time domain power measurement". At least one burst of the signal is captured in zero span with RBW ≥ signal bandwidth and RMS or sample detector. Then, the measurement function calculates the RMS level over the whole burst. This can either be done by adjusting the sweep time so that the burst fills the whole screen, or, if the analyzer provides the possibility, by setting limits in time that mark the start and end points for the calculation.

Figure 4.3-3 shows a time domain power measurement of a TETRA signal. Every pixel of the trace is already a momentary RMS level because the RMS detector was used. Only those pixels that are between the two time lines T1 and T2 are integrated and result in the indicated AV-burst power of –39.27 dBm.

FIGURE 4.3-3

Time domain power measurement of average burst level



Spectrum-4.3-03

4.3.8 Measurement with an FFT analyzer

Modern FFT or real-time analyzers usually acquire the signal in a bandwidth that is in any case wider than the signal bandwidth, and calculate spectral and total levels using FFT algorithms. The user has great flexibility over the acquisition time, bandwidth and analysis length. As the default, the level indicated is the average power during the acquisition time which corresponds to the RMS level.

The peak level can be measured by selecting the shortest acquisition time possible and using a MaxHold trace function over multiple consecutive FFTs.

Together with the possibility to trigger the acquisition at the burst start, the variable acquisition time makes it possible to synchronize the equipment in a way that only the bursts are analysed, sparing out the pauses. Other than a swept spectrum analyzer where the minimum sweep time is determined by the RBW filter, the FFT analyzer can display the true spectrum of a signal even if only a very short snapshot can be taken. The necessary acquisition time is usually much shorter than burst lengths of digitally modulated signals, so the FFT analyzer can also measure the AV-burst level in the frequency domain using a triggered channel power measurement function.

Figure 4.3-4 shows a burst from an 802.11g WLAN router with COFDM modulation. The left hand window (Time overview) shows amplitude vs. time of the signal for the whole capture or acquisition. The blue line on the top shows the time where the signal is analysed (50 µs) which is only part of the total acquisition time.

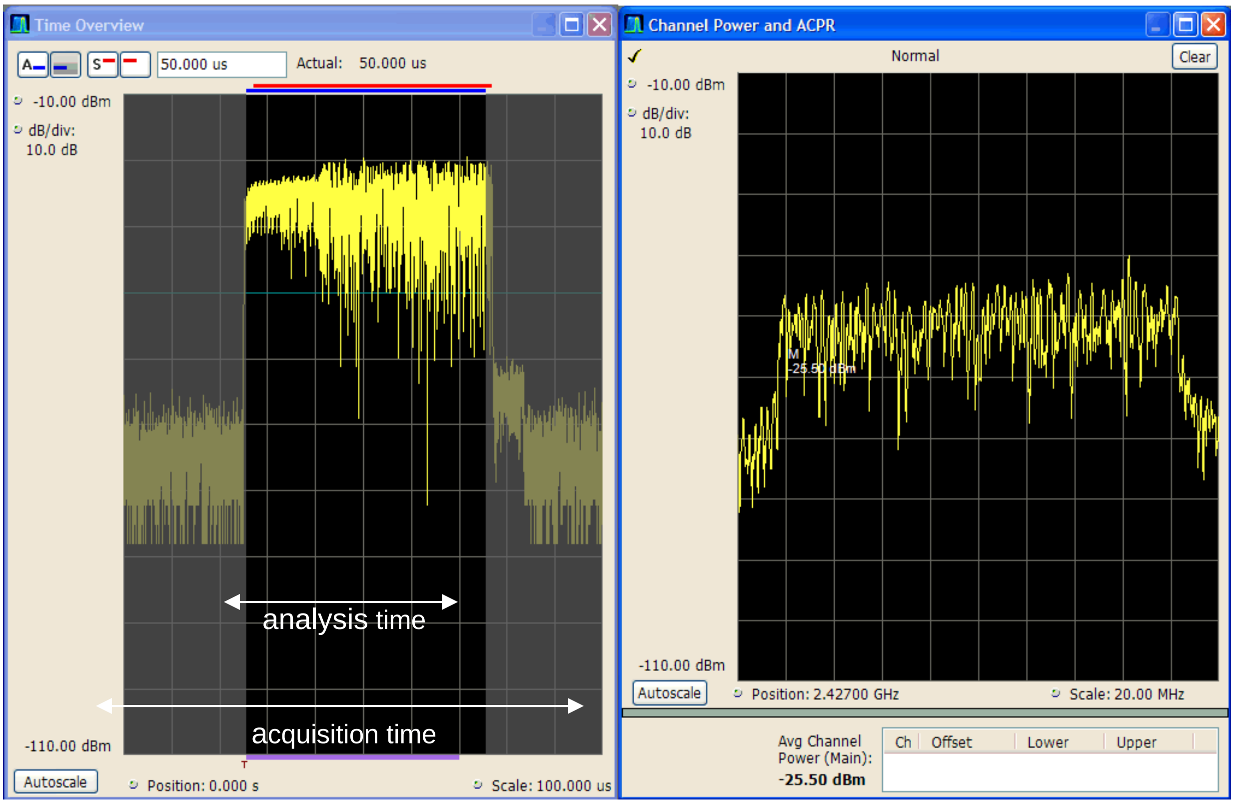
The analysis time has been placed in the acquisition time window such a way that only the burst is analysed. The right side of Fig. 4.3-4 shows the channel power measurement in the frequency domain.

This method works with the FFT analyzer because the actual measurement is only performed during the analysis time (= burst time). Therefore the indicated channel power (–25.5 dBm) is in fact the AV-burst power.

It should be noted that some modern wideband monitoring receivers are also capable of performing the functions of an FFT analyzer. This type of equipment is equally suited for the measurements described in this section.

FIGURE 4.3-4

AV-burst measurement in the frequency domain with an FFT analyzer



Spectrum-4.3-04

4.3.9 Correction for wide band signals

Especially digital signals are sometimes wider in bandwidth than the highest measurement bandwidth available to the equipment. If the RF energy of the signal is evenly spread over the whole bandwidth, like in OFDM systems, all levels can also be measured using a smaller measurement bandwidth and correcting the result with the following formulae:

$$P = P_m + 10*\log(\text{signal bandwidth/RBW}) \qquad (4.3\text{-}2)$$

where:

P: total signal level in dBm

P_m: measured level in a smaller RBW

This method can also help if strong signals on neighbouring frequencies are present and would otherwise influence the result.

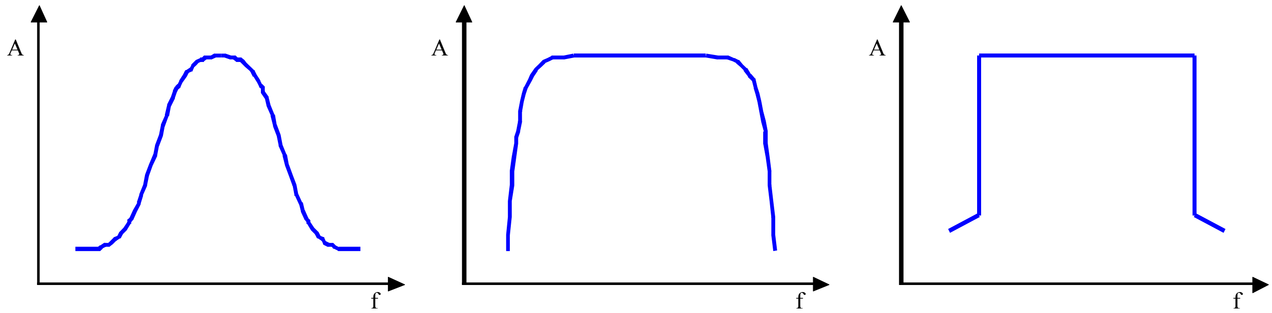
However, it is only applicable to OFDM modulated signals and – with a certain error of usually less than 1 dB – to single carrier digital signals having cosine or root raised cosine (RRC) filtering. It can not be applied to digital signals using Gaussian filtering.

Figure 4.3-5 shows the typical spectra of digital signals.

Analogue modulated signals can have a variety of spectral shapes, but measuring with small bandwidths and correction to the signal bandwidth is generally not possible.

FIGURE 4.3-5

Typical spectra of digital signals



Spectrum-4.3-05

4.3.10 Typical problems encountered

4.3.10.1 Unwanted signals on neighbour frequencies

Level measurements with a measurement receiver or direct measurements with a swept spectrum analyzer only deliver accurate results when signals on neighbouring frequencies are sufficiently suppressed. In typical monitoring situations this is often not the case. Since the measurement bandwidth has to be at least as wide as the signal bandwidth and the measurement filter usually has Gaussian shape, it captures a lot of energy from neighbouring channels as well. If a signal on a neighbouring channel is stronger than the wanted signal, the direct level measurement may be impossible.

One way to overcome this problem is deliberately measuring with a small measurement bandwidth and correction to the signal bandwidth using formulae (4.3-2), but this works only for signals with the energy evenly spread over the whole spectrum (OFDM and broadband signals with cosine or RRC filtering).

Another method that works in the presence of neighbouring signals is the channel power function implemented in most spectrum analyzers, but this can only be used to measure the RMS level and is limited to continuous signals.

Only the FFT analyzer can measure all levels including AV-burst in any case. It works independent of the modulation type of the signal, nearly independent of the signal bandwidth, and also in the presence of strong signals on neighbouring frequencies.

4.3.10.2 Low signal to noise ratios

Each of the discussed measurement methods requires a sufficiently high (S/N) in order to produce accurate results. Some monitoring tasks, however, also require level measurement of signals that are very weak and close to the system noise. In these cases, a correction for the system noise can be applied under certain conditions. This correction depends on the S/N, the detector, the shape of the measurement filter and sometimes even the modulation of the wanted signal.

Figure 4.3-6 shows the necessary corrections for peak, RMS and AV levels of continuous signals when the measurement filter has a Gaussian characteristic.

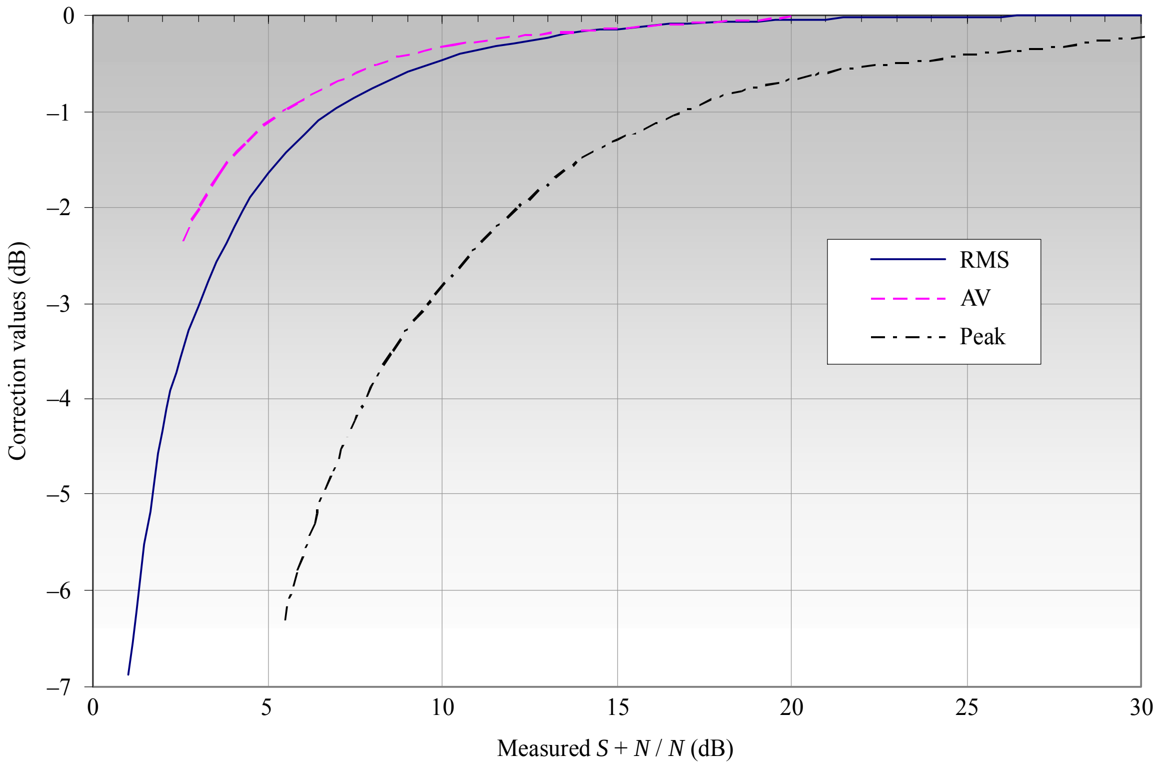
The values for the AV and Peak detector in Fig. 4.3-6 only apply to wanted signals with constant RF amplitude (unmodulated carriers, FM, FSK, (G)MSK). For amplitude modulated signals, the corrections to AV and Peak detector values depend on the actual signal (e. g. type of modulation, coding) and can not be generalized.

For average burst levels, the RMS correction applies.

Long-term RMS or AV levels of pulsed signals can not be corrected as the necessary correction value would also depend on pulse length and pulse repetition frequency. The same applies to QP levels.

FIGURE 4.3-6

Corrections to indicated level measured under low *S*/*N* ratios



Spectrum-4.3-06

The correction values in Fig. 4.3-6 have to be added to the measured signal level. Because the correction is negative, the actual signal level is lower than measured.

Table 4.3-2 summarizes the minimum (*S*+*N*/*N*) conditions under which level measurements can be made without correction under the condition that the measurement accuracy is better than 1 dB.

TABLE 4.3-2

Minimum (*S*+*N*/*N*) for 1 dB level measurement accuracy

	Minimum (*S*+*N*/*N*) for 1 dB accuracy		
Modulation	**AV (dB)**	**RMS (dB)**	**Peak (dB)**
Unmodulated carrier (N0N)	6	8	18
Constant amplitude (FM, FSK, MSK)	6	8	18
Amplitude modulated (AM, ASK, PSK, QAM, OFDM)	6	8	14

4.3.11 Calibration of measuring receivers

If receiving equipment is used that does not provide internal calibration, gain calibration may be made with a CW standard signal generator tuneable over the desired frequency range, an impulse generator or a random noise generator of known and stable output characteristics and having an output impedance equal to the receiver's input impedance with which it is to be used. The output level of CW signal generators can be calibrated using RF power meters. For adaptation of the output power to the required receiver input level the use of calibrated attenuators is recommended. Calibration is usually not the result of a single measurement, but of a series of measurements, for the characteristics of the instrument to be calibrated are always functions of frequency and of signal level. Stray pickup because of poor shielding, through power circuit cables, discontinuities in cabinet shielding, etc., may reduce the accuracy of the readings in some cases.

In modern automatic equipment a calibration source is usually built into the measuring receiver/analyzer and automatic procedures are provided that permit the calibration of the measuring receiver over its full frequency and level range for all receiver bandwidths and detector functions. In these cases a regular verification of the built-in calibration reference is recommended, e.g. every two years. Modern microprocessor controlled equipment also uses built-in self-test functions for an early detection of hardware errors, thus avoiding the collection of erroneous data over a long time.

4.3.12 Measurement errors

The accuracy obtainable includes both systematic and stochastic errors. The amplitude response of a well-designed synchronous detector does not contain any systematic errors.

Analogue selective level meters and spectrum analyzers can have systematic errors caused by the shape of the selectivity curve, sweep rate and detector response. The actual errors will depend upon the particular design and method of application.

FFT signal analyzers have an inherent but predictable amplitude error caused by the finite sampling interval time. The amplitude of the error depends on the ratio of the digital channel sampling frequency to the signal frequency, as well as the actual weighting factor used in the equipment. In the worst case, the FFT processing amplitude error, when Hamming weighting is used, does not exceed 1.5 dB [Randall, 1977]. This systematic error can easily be compensated for, during signal processing, by means of the software program.

It should be noted that as the receiver is tuned to a fixed frequency while the signal analyzer scans the passband of the receiver, any ripple in the IF passband response of the receiver will be a source of error.

Bibliography

RANDALL, R. B. [1977] *Application of B&K Equipment to Frequency Analysis*. Brüel & Kjaer, 17-089.

4.4 Measurement of field strength and power flux-density

4.4.1 General considerations

Introduction

In many cases, the monitoring service has to determine the field strength or power flux-density of an emission. These parameters are generally calculated from RF level measurements which are described in § 4.3. The procedures to determine field strength or power flux-density are based on the procedures and results of the RF level measurement.

The terms "measurement of field strength" and "measurement of power flux-density (pfd)" as used herein are intended to apply to four general categories of measurement:

– measurements performed with portable or mobile facilities, to obtain relatively instantaneous or short-term data at one or several locations;

– measurements performed with mobile facilities to obtain statistical parameters of coverage in the field of mobile radio;

– short-term measurements at a fixed location, generally in support of other monitoring operations;

– long-term measurements involving field strength recordings and analysis of chart records, respectively storage and analysis of measured data using computers.

Purpose of measurements

Measurements of field strength and pfd are generally made for one or more of several purposes including:

– to determine the adequacy of a radio signal strength and the effectiveness of the source of an emission (e.g., a transmitter) for a given service;
– to determine the interference effects of a given intentional radio emission (electromagnetic compatibility);
– to determine the signal strength and interference effects of unintentional emissions of any wave shape from equipment which radiates electromagnetic energy, and to assess the effectiveness of suppression measures;
– to measure propagation phenomena, for the development and verification of propagation models;
– to ensure compliance with the relevant RR;
– to assess the human exposure to electromagnetic fields.

Approximate field strength values for a specific receiving site can be obtained using prediction methods and computer models. It is, however, important to remember that there are many unknown factors which necessitate and/or justify on-site measurements. Under realistic conditions propagation of radio waves shows deterministic behaviour with superimposed random space and time dependence.

Influence quantities to take into account for the measurement of field strength and power flux-density should be:

– receiver reading;
– attenuation of the connection between antenna and receiver;
– antenna factor;
– receiver sine-wave voltage accuracy;
– receiver selectivity relative to occupied bandwidth;
– receiver noise floor;
– mismatch effects between antenna port and receiver;
– antenna factor frequency interpolation;
– antenna factor variation with height above ground and other mutual coupling effects;
– antenna directivity;
– antenna cross-polarisation response;
– antenna balance;
– shadowing and reflections due to obstacles.

This section on field strength and pfd measurements harmonizes measurement procedures so that field strength and pfd data can be exchanged between administrations.

As a measure of precaution field strength or pfd measurements must in some cases be complemented by other measurements of the signal quality such as FM-to-AM conversion in propagation of FM transmissions, BER and channel impulse response (CIR) for digital mobile communication systems due to multipath transmission.

4.4.1.1 Quantities and units of measurement

4.4.1.1.1 Measurement conditions

The area surrounding a transmit antenna is usually divided into three regions:

1. Reactive near-field region.

2. Radiating near-field region (Fresnel).
3. Far-field region (Fraunhofer).

The reactive near-field region is defined as "that portion of the near-field region immediately surrounding the antenna wherein the reactive field dominates".

The radiating near-field region is defined as "that region of the field of an antenna between the reactive near-field region and the far-field region wherein radiation fields predominate and wherein the angular field distribution is dependant upon the distance from the antenna".

The far-field region is defined as "that region of the field of an antenna where the angular field distribution is essentially independent of the distance from the antenna".

Antenna parameters provided by manufacturers are available in this region and the ratio E over H is equal to 377 Ω.

Figure 4.4-1 shows how limits of each region might be defined.

FIGURE 4.4-1

Definition of field regions

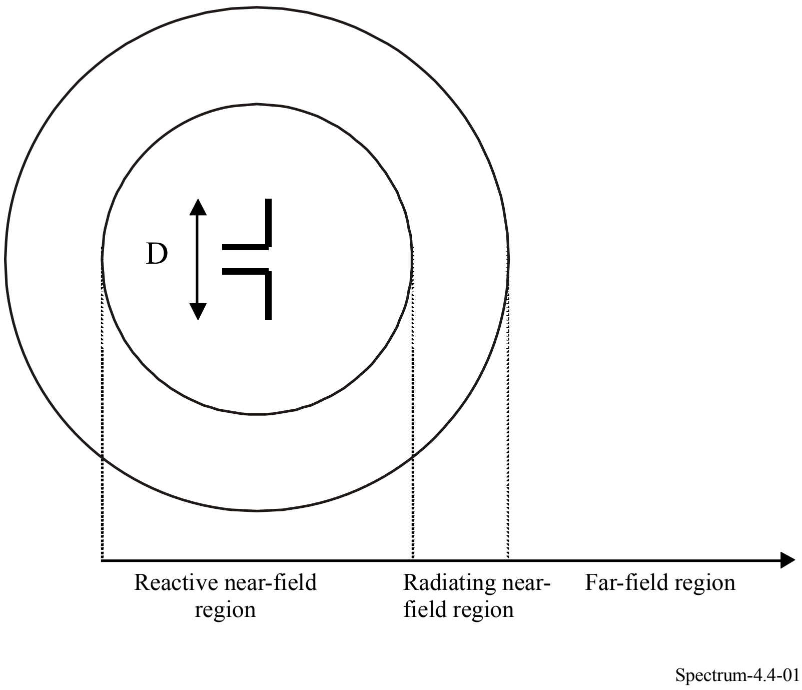


Table 4.4-1 provides some values to determine boundaries between each region.

4.4.1.1.2 Electric and magnetic field strength

The unit of measurement of field strength commonly used is (V/m) and decimal sub-multiples thereof.

This unit is rigorously only applicable to the electric component (E) of the field but is generally also used for expressing measurements of magnetic field strength or the magnetic components of radiated fields by relation to the propagation impedance, usually free space (377 Ω) in which case the magnetic field (H) (A/m) in the far-field is given by:

$$H = \frac{E}{377\ \Omega} \qquad (4.4\text{-}1)$$

TABLE 4.4-1

Definition of field regions

Region	Reactive near field region	Radiating near field region	Far field region
Region edges, measured from antenna, where: λ: wavelength D: largest dimension of the antenna	$0 \ldots \max.\begin{pmatrix} \lambda \\ D \\ \frac{D^2}{4\lambda} \end{pmatrix}$	$\max.\begin{pmatrix} \lambda \\ D \\ \frac{D^2}{4\lambda} \end{pmatrix} \ldots \max.\begin{pmatrix} 5\lambda \\ 5D \\ \frac{0.6D^2}{\lambda} \end{pmatrix}$	$\max.\begin{pmatrix} 5\lambda \\ 5D \\ \frac{0.6D^2}{\lambda} \end{pmatrix} \ldots \infty$
$E \perp H$	No	Effectively yes	Yes
$\eta = E / H$	$\neq \eta_0$	$\approx \eta_0$	$= \eta_0$
Component to be measured	E and H	E or H	E or H

For radiation or far-fields in free space the energies in the two fields are equal (for the definitions of near-and far-field, see Kraus [1950]). The type of antenna selected should be appropriate for the particular signals involved. If the bandwidth of the emission being measured is broader than the bandwidth of the field strength equipment, consideration must be given to the degree to which the limited bandwidth of the field strength meter affects the reading of the actual field strength of the intercepted signal.

Field strengths are measured using antennas with known antenna factors. The electric antenna factor K_e of a receiving antenna is the electric field strength E of a plane wave divided by the output voltage V_o of the antenna at its nominal load resistance (which is normally 50 Ω).

$$K_e = E/V_o \tag{4.4-2}$$

Reciprocally, the magnetic antenna factor for a loop antenna is the magnetic field strength H of a plane wave divided by the output voltage V_o of the antenna at its nominal load resistance (which is normally 50 Ω).

$$K_h = H/V_o \tag{4.4-3}$$

The relation between the electric and the magnetic antenna factor in far-field and in free space is done by:

$$K_e = 120\pi \cdot K_h \quad \text{or} \quad K_e = K_h + 51.5 \text{ dB} \qquad \text{dB/(m)} \qquad (4.4\text{-}4), (4.4\text{-}4\textit{bis})$$

Frequently, instead of the antenna factor, the gain G of an antenna relative to the isotropic antenna is given. The relationship between the isotropic gain G and the antenna factor K_e is derived by:

$$K_e = \frac{1}{\lambda\sqrt{G}} \cdot \sqrt{\frac{4\pi Z_0}{R_N}} = \frac{9.73}{\lambda\sqrt{G}} = \frac{f/\text{MHz}}{30.81\sqrt{G}} \tag{4.4-5}$$

where:

$Z_0 =$ 377 Ω and $R_N = 50$ Ω.

Since voltage and field strength values are normally measured as levels in dB(µV) and dB(µV/m) the antenna factors are also used in their logarithmic form:

where:

$$K_e = 20 \log K_e \quad \text{and} \quad G = 10 \log G$$

the antenna factor k_e is given in dB/(m) as:

$$K_e = -29.77 \text{ dB} - g + 20 \log (f/\text{MHz}) \tag{4.4-6}$$

and so the level of the field strength e can be measured from the antenna output voltage level v_o using:

$$e(\text{dB}(\mu\text{V/m}) = v_o(\text{dB}(\mu\text{V})) + k_e(\text{dB}/(\text{m})) \tag{4.4-7}$$

Since k_e normally does not contain the attenuation a_c of the transmission cable between antenna and measuring receiver, the equation has to be extended to (v_o being now the voltage at the input of the measuring receiver):

$$e(\text{dB}(\mu\text{V/m})) = v_o(\text{dB}(\mu\text{V})) + k_e(\text{dB}/(\text{m})) + a_c(\text{dB}) \tag{4.4-8}$$

Example: An antenna with a gain of 6.5 dB at 100 MHz has an antenna factor of 3.7 dB at this frequency. With an input voltage v_o of 33.4 dB(μV) and a cable attenuation a_c of 1.1 dB the field strength will be 38.2 dB(μV/m).

4.4.1.1.3 Equivalent incident field strength

The voltages measured at the input of a receiver can be expressed in terms of the corresponding voltages induced into the receiving antenna and hence the associated field strengths.

In the case of simple antennas e.g. vertical rod or loop, which respond only to waves from a single polarisation direction e.g. vertical or horizontal, it is convenient to introduce the concept of equivalent-incident field strength. This term is especially used in the HF range. It refers to the resultant field with the same polarisation as that to which the antenna responds. For any signal, it can be regarded as the sum of the sky wave and the ground reflected wave.

Commercial portable field strength meters and fixed installations using short vertical or loop antennas are normally calibrated in terms of equivalent-incident field strength. However, it should be noted that the concept of equivalent-incident field strength has little physical significance when used with extended antennas with limbs in different directions e.g., rhombic or with off-axis reception when using dipole on loop antennas.

The relationship between equivalent-incident field strength and the voltage induced in the receiving antenna is a function of frequency, and unlike the corresponding relationship for r.m.s. sky-wave field strength, it is independent of wave-arrival direction and ground constants.

Equivalent-incident field strength is therefore a more suitable parameter to use when comparing the results of measurements made at different locations and by different equipment. The use of r.m.s. sky-wave field strength would require a knowledge of the prevailing wave-field components, polarisations and arrival angles; in addition to an exact knowledge of the antenna pattern (see Recommendation ITU-R P.845).

4.4.1.1.4 Median available receiver power

The recommended ITU-R prediction method (Recommendation ITU-R P.533) for estimating sky-wave signal intensities gives values expressed in field strength or median available receiver power in the absence of receiving-system losses. The preferred signal-intensity parameter for the purpose of comparing predicted and measured results is the median available receiver power as it is independent of wave-arrival directions and polarisation (see Recommendation ITU-R P.845).

4.4.1.1.5 Power flux-density

At higher frequencies, especially above 1 GHz, measurement in terms of pfd (S), will in many cases, provide more conventional information concerning the effective strength of the emission. The unit of measurement of pfd is (W/m^2).

For a linearly polarized wave in free space $S = E^2/Z_0$

where:

E: the field strength (V/m).

Z_0: the value of the impedance of free space 377 Ω.

Definition of the effective area, A_e for the measurement of the pfd is as follows:

With P being the received power (W), S being the pfd (W/m^2) and G being the isotropic antenna gain (dB), the effective area A_e is:

$$A_e = P/S \, \frac{\lambda^2 G}{4\pi} = \frac{\lambda^2 G}{12.57} = \frac{(84.62 \text{ m})^2}{(f/\text{MHz})^2} G \qquad (4.4\text{-}9)$$

where:

$$S = P/A_e$$

Using $p = 10 \log P$ and $s = 10 \log S$, the effective area a_e in logarithmic quantities, dB(m^2) is:

$$a_e(\text{dB(m}^2)) = 38.55 + g - 20 \log (f/\text{MHz})$$

Thus $s(\text{dB(W/m}^2)) = p(\text{dB(W)}) - a_e(\text{dB(m}^2))$.

If the received power p is given in dBm, the pfd s dB(W/m^2) may be derived using:

$$s(\text{dB(W/m}^2)) = p(\text{dBm}) - a_e(\text{dB(m}^2)) - 30 \text{ dB}$$

Since a_e normally does not contain the attenuation a_c of the transmission cable between antenna and measuring receiver, the equation has to be extended to:

$$s(\text{dB(W/m}^2)) = p(\text{dBm}) - a_e(\text{dB(m}^2)) - 30 \text{ dB} + a_c(\text{dB}) \qquad (4.4\text{-}10)$$

Example: An antenna has a gain g of 15 dB at 1 GHz, then the effective area a_e is –6.45 dB(m^2). With a received power of –73.6 dBm and a cable attenuation of 3.5 dB, the pfd (s) will be –106.6 dB(W/m^2) or + 13.4 dB(pW/m^2).

NOTE 1 – Sometimes it is useful to calculate the effective area from a given antenna factor or vice versa. For that purpose the following equations are given (with the quantities as defined above):

$$A_e = \frac{1}{K_e^2} \frac{Z_0}{R_N} \quad \text{and} \quad a_e(\text{dB(m}^2)) = 8.77 \text{ dB} - k_e(\text{dB/(m)}) \qquad (4.4\text{-}11), (4.4\text{-}12)$$

4.4.1.2 Division into frequency ranges

It is sometimes convenient to classify techniques for the measurement of field strength and pfd into three frequency ranges:

– below about 30 MHz;

– between about 30 and 1 000 MHz;

– above about 1 GHz.

This division is useful because the optimum technique differs for these ranges. This results to some extent from the relationship between the dimensions of practical antennas and the wavelengths of signals to be measured, and also from the proximity effects of the terrain, which affects measurements in different respects in the three ranges. Below about 30 MHz (wavelengths longer than about 10 m), practical antennas are usually small (0.1 λ) compared to the wavelength. The most common measuring antenna is a loop of one or more electrically shielded turns, with a diameter of the order of 0.6 m, or a vertical rod antenna the length of which is short compared to one-quarter of the wavelength. These antennas may be either active or passive. If an active antenna is used care must be taken to avoid overload. The vertical rod antenna is used with counter poise on the Earth. The rod antenna has the advantage of being omnidirectional.

Below roughly 30 MHz it is usually necessary to measure field strength at heights electrically near the Earth. The characteristics of the ground and nearby vegetation, wires, and structures affect differently the strength of the electric and magnetic components of the field and the angle of polarisation. They may also influence the antenna impedance. Measurements using electrically shielded loop antennas are usually influenced by nearby objects to a considerably smaller degree than those using rod antennas.

From about 30 to 1 000 MHz (wavelength from about 10 m to 30 cm), practical antennas have dimensions, which are comparable to the wavelength. For a fixed frequency in this range the antenna most commonly used for field strength measurements is a half-wavelength resonant dipole. The dipole is connected to the measuring instrument by means of a balanced-to-unbalanced transformer (balun) and a coaxial transmission line. The resonant dipole antenna differs from the loop and short rod-antenna in that it is highly efficient (loss resistance very low relative to radiation resistance). With dipole antennas care must be taken to avoid (or reduce) mutual coupling with the environment and the antenna cable as a source of uncertainty. Broadband antennas or directional antennas are frequently used in the upper portion of this frequency range, particularly the log-periodic and conical-log-spiral type. Directivity will normally avoid or reduce mutual coupling with the environment.

Above about 1 GHz (wavelength smaller than about 30 cm), the aperture area of the dipole becomes too small to provide the necessary sensitivity. At these frequencies, it is the normal practice to employ antennas that collect energy from apertures that are large in relation to the wavelength, e.g., horns and parabolic reflector systems. These antennas are usually characterized by high efficiency (in excess of 50%) and appreciable directivity. Coaxial or waveguide transmission lines are employed.

4.4.2 Choice of measurement sites

As described above, the field strength at a receiving site depends on space and time. Therefore measurements of field strength with an antenna at a fixed location (fixed position on the ground, fixed direction and height) can only show the time dependence of field strength.

4.4.2.1 Fixed installations

As far as possible, a site should be selected where the fields of the emissions to be recorded will be relatively undisturbed by local structures or terrain features. Nearby overhead conductors, buildings, large trees, other antennas and masts, hills and other man-made and natural features may seriously distort or disturb the wave front of the emission. The degree to which these conditions limit the validity of the measurements depends on a number of factors including the frequency range and the type and orientation of the antenna used with the field strength measurement equipment. At frequencies in the HF and lower ranges, it is common practice to use vertical monopole antennas or broadband arrays with essentially vertical polarisation reception characteristics and in some instances e.g. at the top of buildings vertical or horizontal dipoles which however must be used with caution in view of calibration difficulties. Such antennas are especially vulnerable to overhead conductors and structures.

At the higher frequencies, where highly directional antennas are used, it is important that the path in the general direction of the signal source be clear; additionally multiple-path reception due to local reflection or re-radiation of the wanted signal must be minimized. Where an antenna with a high front-to-back gain ratio is used (e.g., antennas mounted in parabolic or corner reflectors) reflection or re-radiation sources behind the array are not so likely to cause trouble as with antennas having more limited directional characteristics.

Fixed sites are primarily used for measurements below about 30 MHz. For that purpose the following criteria are suggested:

– the immediate vicinity of the site should consist of level terrain situated in a relatively level area;
– for ground level vertical monopole antennas soil with relatively high conductivity and free of gravel or outcroppings of rock is desirable;
– there should preferably be no overhead conductors (e.g., antennas, power and telephone lines or metal roofed or guttered buildings) within 100 m of the antenna site. At the lower frequencies, where 100 m represents one-half wavelength or less, at the operating frequency, it is desirable that overhead conductors be 20 m or more removed from the receiving antenna for every 1 m of height above ground of the overhead conductor, out to a distance equal to at least one-half wavelength.

4.4.2.2 Mobile installations

Mobile installations i.e. field strength measuring equipment in a monitoring vehicle, have the following advantages over fixed installations: they can be used in stationary applications when the vehicle is not moving and in mobile application and can thus be used to observe both space and time distribution of field strength.

4.4.2.2.1 Stationary application

In many cases field strength measurements on several points but with variable height of the measuring antenna are the preferred solution in order to find the expected value of field strength especially in the VHF/UHF range. This can be achieved by moving the vehicle from point-to-point and by measuring the field strength on the frequencies of interest at different heights. The antenna is mounted on top of a telescopic support attached to the vehicle at a height normally 10 m above ground. In view of the propagation characteristics in these bands, the antenna has to be adjusted to the direction and polarisation of the received signal.

4.4.2.2.2 Measurements with a portable field strength meter

Measurements with a portable field strength meter are done manually with the antenna close to the person reading the field strength values. Rod antennas must however be positioned on the ground. In general, the same desirable site criteria apply as for fixed installations except that somewhat greater latitude can be allowed provided that the “cluster measurement” technique is used. This technique involves making several separate measurements with the antenna at a slightly different location for each measurement (of the order of one to five metres separation depending on the frequency, with the larger value applicable to the lower frequencies). The result is a cluster or group of measurements around a central point. The individual measurement values are then averaged to arrive at a final value. In measurements using a shielded loop antenna, a few measurements will usually suffice since this type of antenna, which is responsive to the magnetic component of the wave, is usually less affected by locally disturbed conditions (reflection and re-radiation effects) than is the case with rod or dipole antennas. If the field strength meter utilises a loop or other directional antenna and if the approximate azimuth of the station being measured is known with respect to the measuring site, the presence of local disturbances can often be detected by adjusting the antenna for maximum signal pick-up and noting whether the indicated direction of arrival is in agreement with the actual direction of the station. Where the indicated and true directions differ appreciably it would be well to select a different site for the measurement. For measurements in the VHF and higher ranges it may be found that an undisturbed site cannot be located, in which case the cluster technique involving ten or more consistent individual measurements may be required to arrive at reasonably accurate results.

Considering measurement carried out by such standalone equipment, the influence of quick motion of the equipment and the vicinity of the user may influence and may lead to a mistaken result. So, for a good measurement, this type of equipment should be installed on a tripod to carry out the measurement.

For HF sky-wave signals, the use of the “cluster technique” may be replaced by time-averaged measurements at a single location.

4.4.3 Methods of measurement

Many methods of performing field strength measurements at monitoring stations may be used depending on the information desired, including:

– continuous recording over extended periods (in obtaining propagation information with respect to seasonal and sunspot cycle variations, data have been collected over particular paths in the MF broadcast band covering approximately 30 years);
– continuous recording over shorter periods to determine day-night or other short-term variations in signal level;
– sampling at short intervals (for example, for 5 s every 2 min);
– sampling at longer intervals (for example, for 10 min each 90 min).

In some instances, especially where a ground wave is being observed, a single short period of measurement may suffice, depending upon the purpose for which the measurement is required. In certain cases, e.g., measurements for the purpose of HF propagation studies, one may require information concerning the overall propagation conditions over a band of frequencies.

Therefore, it may be expedient to make short records lasting about 10 min, over the entire high-frequency band at intervals of about 90 min of stations known to be working 24 h a day, so chosen that the ranges of frequencies and distances of interest are well represented. In the case of sky-wave signals, it may also be necessary to take measurements on different days to take account of day-to-day variations in the ionosphere.

Recommendation ITU-R SM.378 recommends that, except where there are limitations due to the receiver noise-level, atmospheric noise or external interference, the accuracy to be expected in field strength measurements should be better than ± 2 dB for frequencies below 30 MHz and ± 3 dB for frequencies above 30 MHz.

Microprocessor controlled equipment can switch frequencies, switch antennas if appropriate, discharge receiver pass-band residual energy, measure on a new frequency including applying correction factors, and digitally record results within a period of a few tens of milliseconds. This type of system is useful when a number of frequencies need to be measured or when long-term sampling will produce too much data to manually store and analyse. The results are, of course, stored in a computer because of the great amount of data collected in a short time.

4.4.3.1 Measurements at a fixed measuring point

4.4.3.1.1 Instantaneous measurements

At a given measurement point located at a given distance from the transmitter samples of the distribution of field strength can be taken. At the required height the antenna should be turned in the direction of the transmitter. During the measurement period the height and orientation of the antenna should be varied to read and record the maximum field strength.

4.4.3.1.2 Short-time and long-time measurements

To measure the time distribution of field strength, a permanently installed system e.g. at a fixed station or a containerized station, short- or long-time measurements can be executed. The measurements can be continuous or repeated at regular intervals permitting the observation of several frequencies. A measuring program executed according to a plan provides adequate results to determine propagation properties, varying by the time of the day or the seasons or the sun spots. Very long-time measurements require short regular calibration checks. Long-time measurements are also possible using manual measuring equipment together with a data recorder.

4.4.3.1.3 Measuring the spatial-distribution of the field strength

For high reliability estimation of the expected field strength at a point at a given distance from a transmitter, one should know the spatial distribution of the field strength in the environment local to the point of measurement. To that end measurements should be taken at several points on a demarcated area. Based on a normal distribution the required number of samples, for a certain degree of reliability, that the field strength lies within a certain range of values around the expected field strength, depends on the standard deviation σ. By finding the best and worst reception points of that area E_{max} and E_{min} can be measured. Based on practical experience an estimate of the standard deviation can be obtained using: $E_{max} - E_{min} = 5\sigma$.

The required number of samples can be determined from Table 4.4-2 (*D* is the achieved accuracy):

TABLE 4.4-2

Required number of samples depending on $E_{max} - E_{min}$

		$E_{max} - E_{min}$ (dB)			
Confidence level (%)	***D*** **(+/–dB)**	**0 to 5**	**5 to 10**	**10 to 15**	**15 to 20**
90	1	3	11	24	43
90	1.5	2	5	11	19
95	1	4	15	35	61
95	1.5	2	7	15	27

4.4.3.2 Measurements along a route

Influenced by the local receiving conditions, the real values of the field strength can significantly differ from their predicted values. Therefore they must be checked by measurements for establishing the radio field strength coverage of a large area.

The test results must be recorded along with their geographical coordinate data for locating the scenes of measurements and for mapping the results that were gathered on the most accessible roads of the area in question.

Instead of measuring the actual field strength, there is sometimes the necessity for measuring the output voltage of a user antenna (the typical antenna for the service under investigation) for radio coverage evaluation.

Digital network systems (such as GSM, UMTS, or DAB) are sensitive to the effects of reflected reception. In this case, besides measuring the field strength, the reception quality measurement, made by the measurement of the bit-error ratio (BER) or channel impulse response (CIR) measurement, is also necessary to determine the system performance evaluation. Using automatically made calls, these measurements can be made in cellular phone networks without affecting normal operation.

For measurement purposes along a route a continuous transmission is necessary.

4.4.3.2.1 Results of mobile field strength measurement

Due to the effect of reflected signals, the field strength along a route shows severe fluctuation. The result of a single measurement can coincide with the minimum or maximum value of reflection and is also influenced by the chosen height of the receiver antenna, the season, the weather, the vegetation and the wetness of surroundings, making that false.

Considering the factors mentioned above, reproducible field strength test results can be calculated from a large number of raw data readings, by means of statistical processing of them.

4.4.3.2.2 Necessary number of measuring points and the averaging interval

For statistical evaluation (Lee method) the number of sample points should be chosen in such a way that the results should display the process of slow changing in the field strength (effect of long-term fading) and, more or less, they should also reflect the local (instantaneous) individuality (effect of short-term fading) of the field strength distribution.

For obtaining 1 dB confidence interval around the real mean value, the samples of test points should be chosen at each 0.8 λ (wavelength), over 40 λ averaging interval (50 measured values within 40 λ).

4.4.3.2.3 Velocity of the vehicle

The velocity of the vehicle must be appropriate for the wavelength (taking into account the Lee method), the simultaneously measured number of the tested signals with different frequencies and the applicable shortest measuring time of the test receiver.

$$v = \frac{864}{(f\ (\mathrm{MHz})) \cdot (t_r\,(\mathrm{s}))}\ (\mathrm{km/h}) \tag{4.4-13}$$

where t_r is the minimum time given by the receiver specifications to revisit a single frequency.

4.4.3.2.4 Measuring antennas

During the measurement the chosen height of the test antenna is 1.5-3 m. The result will be considered as being carried out at a height of 3 m.

The received signal comes from different angles to the test antenna, therefore the effect of the antenna diagram on the field strength test result should be known.

The antenna factor (k) accuracy should be within 1 dB.

The deviation of the horizontal radiation diagram of the measuring antenna from a non-directional diagram should not exceed 3 dB.

4.4.3.2.5 Navigation and positioning systems

Dead Reckoning System

The distance from the starting point is reckoned with the help of a distance-to-pulse transducer attached to a non-motor driven wheel of the test vehicle, while the mechanical gyroscope provides the heading information. The location accuracy depends on the accuracy of the starting point registration and the distance covered by the test vehicle.

GPS System

An accuracy of 100 or 200 m is quite sufficient when testing broadcasting coverage of a TV or radio station. This can be achieved by using standard GPS systems.

Testing a digital micro-cell system in an urban area requires an accuracy of positioning information within several metres. In such a case differential positioning systems should be used.

Complex Navigation System

This system is the combination of the above-mentioned systems. Without the need for manual operator intervention, these navigation systems continuously provide position and time data, heading and waypoint information.

4.4.3.2.6 Measurement result collecting with data reduction

By means of statistical processing, this method allows the amount of registered raw data to be reduced considerably.

Averaged values

Some of the test receivers are able to perform internal classification of test results over predefined user intervals. The user can select the evaluation intervals of up to some 10 000 measured samples, but each interval must contain at least 100 values.

Only the arithmetic averaged values of the predefined number of test results are stored and are indicated on the final map of radio coverage.

Classification of results according to level exceeding probability

During measurements the results are classified according to exceeding probability, between 1 and 99%. These percentage values represent the probability of overstepping for the applicable field strength level. Their typical values are 1; 10; 50; 90 and 99%. The median value, 50% is preferred for propagation studies.

It deserves attention that receivers require some milliseconds for the evaluation of the classification, so during millisecond this time the trigger pulses are ignored, therefore no new measurements are obtained.

4.4.3.2.7 Data presentation

Using the process controller's built-in monitor, colour monitor of an external PC, printer or plotter the following representations should be possible:

Representation of raw data in tabular form.

Disadvantage: Too much volume of data. The individual results are unrepeatable.

Advantage: Gives detailed information about local fading effects. The results can be converted into any kind of easy to view results by mathematical or statistical process.

Plotting in Cartesian coordinates

Graphical representation of processed field strength data is plotted in Cartesian coordinates versus distance with indications of these calculated median values.

Disadvantage: It is difficult to relate the results to the exact places of the measurements.

Advantage: It gives a fast, easy to view result about distribution and locations below a given threshold level of the field strength.

Mapping

A multicoloured line is displayed to represent the processed field strength levels (e.g. with 10 dB(μV/m) scale) or the level exceeding probabilities (between 1 and 99%) on the road map.

The scale of the selected map should correspond to the size of the area covered by the radio signal under investigation and the required resolution of processed field strength results. Due to the scale of the map, the represented intervals can include the multiples of the averaged intervals. The resolution of the presented result should be chosen in such a way that it can plot local peculiarities without the coloured line being too colourful.

If there is a need to represent the averaged intervals with higher resolution (e.g. when representing results in microcells), the system should be able to zoom the map is at disposal.

If during the measurements two data series are registered simultaneously (e.g. field strength and BER) it is expedient to represent them together, by two parallel coloured lines along the plotted roads of the map (see § 6.2 for more details about maps).

Disadvantage: The resolution of the plotted interval can be greater than the processed interval. Therefore it can gloss over the local characteristics of field strength.

Advantage: The test results can be joined to exact spot of measurements. It gives fast, easy to view results about distribution and getting to below a given threshold level of the field strength.

4.4.3.3 Comparison of measured and calculated data

The e.i.r.p. of the emitter is utilised to compute the coverage of the station.

The monitored data may be utilised:

– to estimate the e.i.r.p.;

– to evaluate and verify the propagation model and the DTM.

The calculated data may be utilised:

– to estimate the amplitude calibration of the receiving system: antenna, cables, receiver;

– to evaluate the calibration.

4.4.3.3.1 Comparison of predicted and measured field strength in FM broadcasting

Radio signals vary over time and with small differences in location. This variability is incorporated into many propagation prediction methods. In most cases, monitoring measurements are made at one location and for a period of time that may be too small to fully define the time variability. As a result, measurements must be considered carefully when comparing them to predictions. The example here is for a situation where the variability may be small and comparisons can be made with confidence. But there are many cases where variance will be larger and comparisons must be made with careful consideration of the differences observed.

The Regional Agreement (Geneva, 1984) contains the planning bases of FM broadcast stations in Region 1. In this plan can be found which countries may use what frequencies with parameters such as power, antenna height, antenna diagram, polarisation etc. The Master International Frequency Register (MIFR) reflects the actual situation in the ITU bi-weekly BR IFIC DVD.

It is the task of national administrations, by means of their monitoring service, to check that these broadcast stations comply with the assigned parameters. This can be done by means of physical inspection of all stations on a regularly bases, for instance once every year (or two years). For time and cost saving, a monitoring system measures the broadcasting stations from one or more fixed monitoring stations and compares the results with the predicted values. If the results of this comparison indicate that the emitted power of the station is too high (or the antenna is mounted higher than permitted) a physical inspection can be carried out.

4.4.3.3.2 Planning software and databases

The frequency management often uses software to calculate the necessary parameters for their stations to be planned or check coordination requests from neighbouring countries. The planning software may also produce a so-called frequency scan. In this case, the programme scans the database containing information of the band 87.5 to 108.0 MHz and automatically generates a list for a given location containing all 204 channels with the predicted field strength of all the stations working on that frequency. The number of stations in this list with the calculated field strength on a certain frequency depends on the size of the database used and on a pre-defined level of field strength, which should be taken into account.

4.4.3.3.3 Predicted field strength from remote monitoring stations

As an example, a network of 12 remotely controlled stations is used in one country. For each location of these remote monitoring stations the planning tool can produce a list of predicted field strength values for all 204 FM broadcasting channels. Only the strongest station on each channel is needed. However a more extended list is desirable because the station with the strongest calculated field strength may work with reduced power so another station might be received instead. Predictions for this example were made using the propagation model in superseded Recommendation ITU-R P.370. Future predictions may, for example, be made using Recommendation ITU-R P.1546.

4.4.3.3.4 Measured signal strength from remote monitoring stations

All remote monitoring stations consist of two receivers using the same antenna via a splitter. Receiver one scans the frequency band on all stations sequentially. The results are displayed in 12 windows on two 21-inch screens. The second receiver can be used to identify stations displayed on the screen as a result from the measurements of the first receiver. Every 10 s a scan is made of the whole band. The values of the measured signal strengths of all steps are stored after each scan. The system measures continuously for 24 h (but could also be less e.g. during day-time only). The channel separation in FM broadcasting in Region 1 is 100 kHz. So, for the processing of the values of the measured signal strengths in order to compare with the predicted field strength, only those on the exact channels (87.6 MHz, 87.7, 87.8, etc.) are needed. From every channel the median value over the measured 24 h is taken. In this way the effects of changing propagation during the day is minimized.

4.4.3.3.5 Comparison of predicted and measured values

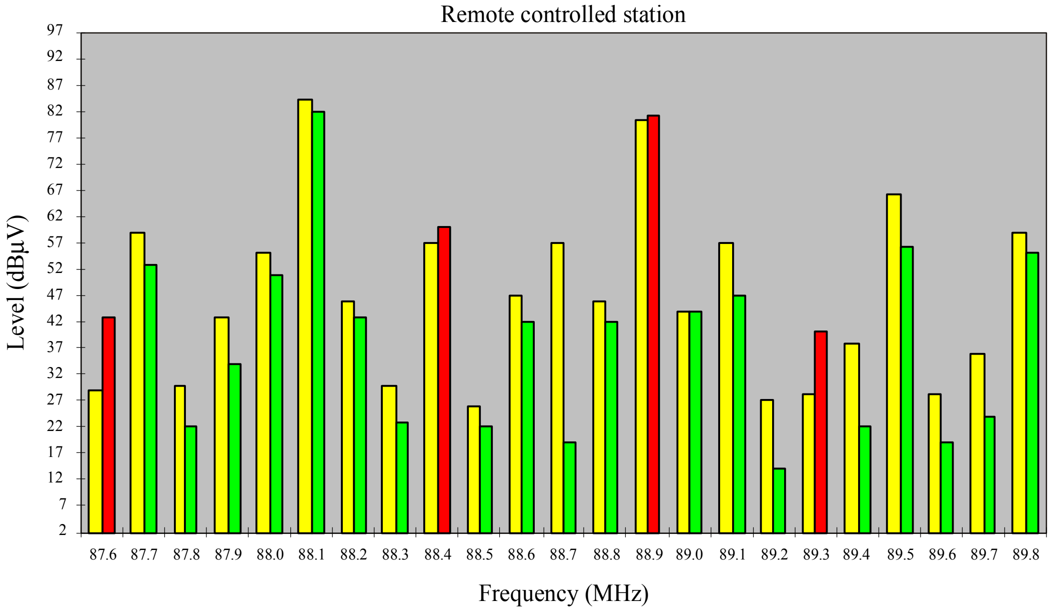
For each of 12 locations the predicted and the measured median values are available. These values can be compared with each other automatically and presented on a screen in portions of, for example, 23 channels (see Fig. 4.4-2).

The green bars (measured levels) change into red in case the measured value is equal to or exceeds the predicted value. From here it is possible to zoom in on the transmitter of interest. Detailed information with earlier measurements of the station of interest is available. It can be taken into consideration whether an inspection engineer is sent to (one or more) stations exceeding the predicted values. The described measurements should be repeated regularly, so it can be used to give additional information such as:

– produce presentations containing historical trends on each channel per location, graphically or in ordinary text;
– display the measured values over time in a distribution plot;
– calculate all the measured exceeding on each remote station;
– automatically detect unauthorised stations per measurement/station and produce overviews about the trends in illegal use. In this way, the effects of enforcement efforts can be presented;
– carry out checks on antenna diagrams of broadcasting station by comparing the predicted field strengths from one broadcast station measured from more than one (as many as possible) remote monitoring station from different directions.

FIGURE 4.4-2

Predicted (yellow) and measured (green or red) levels between 87.6 and 89.9 MHz from a remote monitoring station



Spectrum-4.4-02

4.4.4 Evaluation, processing and documentation of measurement results

4.4.4.1 Definition of statistical parameters of field strength and pfd

The method used in deriving data from recordings depends primarily upon the purpose for which the data will be used. In propagation studies, it is common practice to determine the signal level exceeded during a specified percentage of time, or the maximum or minimum value over a predetermined period of time; for example:

– the median value (the level exceeded 50% of the time);

– the 90% value;

– the 10% value;

– the highest signal level;

– the lowest signal level.

The median value (dB(µV/m)) is a desirable form of presentation of measurements at discrete frequencies for propagation studies. Although 60 min periods are widely used (at HF) as the basic period of time for the analysis, shorter or longer periods (e.g., 1 min, 10 min or several hours) may be preferable in specific instances. At the lower frequencies, especially below 30 MHz, where there is a wide variation in signal level depending upon the time of day, such as occurs in the MF and HF broadcasting bands, analysis may be made over hourly periods centred on sunrise and sunset at the midpoint of the path between the transmitter and the receiver. Use of a computer for this purpose simplifies and speeds the analyses.

Frequently the level of field strength in dB(µV/m) shows Gaussian (normal) distribution both with time and space dependence. For other distributions see Recommendation ITU-R P.1057.

The distribution of measured field strength values, when expressed in linear units (e.g. V/m, mV/m or µV/m), frequently follows a log-normal distribution. When these data are converted to dB, the distribution then follows a normal (Gaussian) distribution, and different formulaes are required. For the case of Gaussian distribution the following definitions apply:

The corrected empirical variance of field strength:

$$s*^2 = \frac{n}{n-1} s^2 \qquad \text{dB} \tag{4.4-14}$$

where:

n: number of samples

s^2: empirical value.

$$s^2 = \sum_{i=1}^{n} (e_i - \bar{e})^2 \qquad \text{dB} \tag{4.4-15}$$

where:

e_i: sampling value of field strength (dB(μV/m))

$\bar{e}$: arithmetic mean of samples (dB(μV/m)).

4.4.4.2 Evaluation of space and time dependency of field strength

In an area located at a distance L from the transmitter, where there is a sufficient number of samples, knowing the mean field strength (arithmetic mean $\bar{e}$ of samples) and the standard deviation by location σ_L, the distribution function $N(\bar{e}\ \sigma_L)$ can be derived. Adequately, during a relatively long period of time, where there is a sufficient number of samples, knowing the mean value of the field strength (arithmetic mean $\bar{e}$ of samples) and the standard deviation by time σ_t, the distribution function $N(\bar{e}\ \ \sigma_t)$ can be derived.

With the reduced value of standard deviation by location and variance by time, the distribution function $N(\bar{e}\ \ \sigma_{L,t})$ can be determined.

$$\sigma_{L,t} = \sqrt{\sigma_L^2 + \sigma_t^2} \qquad \text{dB} \tag{4.4-16}$$

For further details see Recommendations ITU-R P.1546 and ITU-R P.845.

4.4.4.3 Example checklist for coordination data

The European cooperation agreement [Vienna Agreement, 2000] has among others stated the following measurement procedure in cases of disagreement concerning the results of evaluation related to a specific coordination request, to facilitate the enhancement of existing networks and in cases of harmful interference between stations in border regions in the VHF/UHF ranges. Results of field strength measurements shall be exchanged, and therefore the measurement procedures have been standardized.

Measurement sites shall be selected so that there are no reflecting objects or as few as possible within ten times the wavelength (10 λ). Visual contact with the transmitting antenna should exist where possible.

Depending on the conditions of measurement different records of the measurement including the setup must be made, so that the results are reproducible. The whole equipment shall be specified.

In cases of fixed point measurement the height of the measurement antenna(s), measured from the ground, has to be varied between 3 and 10 m. Within this range the highest field strength value shall be recorded, as well as the height of the antenna where this value was measured. This value has to be regarded as being a field strength value at a height of 10 m.

A record of every measurement set-up and every measurement must be stored in a data base. All data relevant to explain the measurement results have to be recorded for later calculations.

Relevant measurement data (in cases of harmful interference):

Interfering assignment:

– Administration;

– frequency (MHz);

– supposed location or direction to interfered assignment;
– designation of emission;
– measured field strength (dB(μV/m)).

Interfered assignment:

– Administration reference number;
– frequency (MHz);
– location name;
– location coordinates (degrees/min/s);
– class of station.

Type of measurement:

– fixed point, number of points;
– measurement over longer time period;
– mobile.

Measurement data:

–	Number of the measurement	
–	Measured frequency	
–	Measured bandwidth	
–	Date	(DD/MM/YY)
–	Time period (from/to)	(HH/MM to HH/MM)
–	Location name	
–	Geographical location	(degrees/min/s)
–	Location height	(m above sea level)
–	Height of measurement antenna	(m above ground)
–	Polarization of measurement antenna	(h/v)
–	Customer's antenna	☐ yes ☐ no
–	Description of transmission path	
–	Propagation (weather) conditions	
–	Remarks (IF bandwidth, modulation, bit-error rate, if required).	

Measurement results: (in case of measurements over a longer time period)

–	Quasi-maximum value (10%):	(dB(μV/m)).
–	Quasi-minimum value (90%):	(dB(μV/m)).
–	Measured (Median) value:	(dB(μV/m)).

4.4.5 Calibration of measuring instruments and antennas

Calibration of the field strength measuring apparatus normally includes the separate calibration of the measuring receiver and of the measuring antenna including the transmission cable.

Only in early examples of (manual) HF field strength meters was the antenna a part of the tuning circuit and included in the calibration procedure.

The frequency of calibration is dependent on the equipment being used and the environment where it is being used e.g. antenna recalibration may be required more frequently for mobile operation or for locations with seasonal changes in ground conductivity.

4.4.5.1 Calibration of measuring receivers

The calibration of measuring receivers is described in § 4.3.11.

4.4.5.2 Calibration of the measuring antennas

The portion of the calibration factor, which is determined by the antenna system characteristics (i.e., gain, together with line and transformer losses) is called the antenna factor (see § 4.4.1.1.2). In general, the calibration factor varies with frequency. Calibration methods may be classified under three basic categories, standard field method, standard antenna method and standard distance or standard site method. All methods must deliver antenna factors valid for the free space under far field conditions. It is important that antennas be mounted for measurement so that the antenna characteristics are not influenced by the antenna masts, cables, other antennas or reflecting objects in the vicinity.

4.4.5.2.1 Standard field method (direct calibration)

The standard field method is the most basic calibration method. It is directly derived from the definition equation of the antenna factor. The antenna is exposed to an electromagnetic field, the strength of which is accurately known. The field strength may be determined by calculations based on the measured current in a transmitting antenna of known dimensions and current distribution. For practical reasons the application of this method is limited to the calibration of loop antennas, since for other antenna types other methods give more accurate results.

4.4.5.2.2 Indirect calibration of antennas

Direct calibration is usually not employed to calibrate instruments having short rod antennas, since it would be necessary to establish accurately known uniform fields within a large test area occupied by the instrument and its antenna. In this method, the calibration factor is calculated from the computed or measured characteristics of the antenna and measured instrument characteristics. The passive radiator is removed from the field strength measuring equipment and replaced by a calibrated standard signal generator having impedance substantially equal to that of the antenna. An appropriate artificial antenna is usually used to calibrate the remaining equipment (impedance matching device plus measuring receiver) as a radio-frequency voltmeter (or power meter) against the standard signal generator. An antenna factor is computed for each frequency from the dimensions and current distribution of the antenna, from consideration of the antenna as an aperture, or from the measured gain of the antenna. If a transmission cable is used, it may be convenient in some cases to consider it a part of the receiver and to connect the calibrating generator to it, thus avoiding the need for separately determining cable loss and making allowances for it. A field strength meter with a shielded loop antenna can be used to cross-check the rod antenna calibration in the undisturbed far field of a radio station.

4.4.5.2.3 Standard antenna method (substitution method)

In the standard antenna method a plane wave of unknown field strength is measured using an antenna with an accurately known antenna factor (standard gain antenna, e.g. standard dipole), which is then replaced (substituted) by the antenna to be calibrated. From the difference of receiver input voltage levels the antenna factor in dB can be determined. The antenna factors of standard gain antennas themselves are either calculated from their dimensions and the measured properties of adapting elements (e.g. baluns) or determined using an accurate calibration procedure. Compared with the method described in § 4.4.5.2.4 the substitution method has the disadvantage that the error of the antenna factor contributes to the total error of the method. Further errors can result from the different shapes of the standard gain antenna and the antenna to be calibrated when the field is not an ideal plane wave. Halfwave dipoles used as standard gain antennas have in addition the disadvantage that they have to be mechanically tuned at every new frequency.

4.4.5.2.4 Standard distance or standard site method

When the standard distance method is applied, the antenna calibration is reduced to a precise measurement of the attenuation between two identical antennas, whose result is compared with the calculated value of site attenuation. For the determination of the free-space antenna factor, if possible, a free-space calibration set-up shall be used, which delivers the most accurate results. In this case the two antennas shall be mounted such that reflections from surrounding objects can be neglected. This is normally possible for directive antennas. If free-space conditions cannot be established e.g. a reflection method can be used where the two antennas are mounted above a reflecting ground plane and the attenuation is compared to the theoretical value assuming addition of the direct and reflected wave at the location of the receiving antenna. This method has to be applied with great care since mutual coupling between antenna and ground plane can influence the antenna factor. Therefore the distance between the antennas and between each antenna and ground plane must be great enough that effects of mutual coupling are negligible. Special attention has to be paid to the location of the phase centres of the antennas. This potential source of error can be eliminated by adequate consideration of the effect on the measured attenuation in the calculation of the site attenuation.

As far as the evaluation of the results of the standard distance method is concerned a distinction must be made between the two-antenna method and the three-antenna method. If only an attenuation measurement with two antennas is executed, only the sum of both antenna gains in dB can be truly determined. The antenna factor, which is to be calculated, can only be attributed to one antenna when the data of the other antenna are known in advance. This limitation can be avoided by application of the three-antenna method, where three attenuation measurements with three antennas combined to three cyclically exchanged pairs (a+b, b+c, c+a) are executed. By solving a set of equations with three unknown variables, the gain (and antenna factor or effective area) of each individual antenna can be determined.

4.4.5.2.5 Computation of antenna factor from dimensions and current distribution

The computation of an antenna factor is facilitated by the use of simple types of antenna. Thus, for example, a thin short vertical rod antenna (shorter than 0.1 wavelength) located over an extensive ground plane, is assumed to have a linear current distribution, making its effective length one-half its physical length. Its impedance can be simulated approximately by a series capacitor connected between the standard signal generator and the input of the measuring apparatus. A second example is the thin half-wave dipole antenna, with assumed sinusoidal current distribution, which is frequently used for calibration purposes. This antenna has a computed effective length of λ/π and a radiation resistance of 73.3 Ω in free space. A practical cylindrical dipole must be cut noticeably shorter than one-half wavelength to achieve resonance. Its radiation resistance and effective length are lower than the corresponding values for an infinitely thin antenna. These differences are due to the effect of the finite thickness on the current distribution. The directional pattern of a practical dipole, however, does not differ much from that of the theoretical thin dipole, and the conclusion from this observation is that its gain and available power remain very close to the values of the theoretical thin antenna. These considerations indicate that a practical dipole may be considered equivalent to the theoretical thin antenna, plus a transformer to account for the change in radiation resistance. The balun is an additional transformer, the use of which may introduce significant errors unless its impedance matching characteristics are optimised and its loss taken into account. Commercially available precision dipoles have additional attenuators to stabilise the load impedance of the dipole, which is of advantage for antenna calibration. The method of moments (MoM) [Harrington, 1968] computes the antenna factor when the dimensions of the antenna are known. Care must be taken to properly apply the MoM to this problem, and it is desirable to use a measured crosscheck whenever possible.

4.4.5.3 Calibration of fixed recording installations

To achieve the desirable accuracies given in Recommendation ITU-R SM.378, the initial calibration of these installations may be made by comparison against a calibrated field strength meter of known accuracy and under controlled conditions. Such a calibration will be valid only so long as all of the conditions under which the initial calibration was made remain unchanged. Therefore, significant changes in antennas, transmission lines, or impedance matching devices, or in the site itself (e.g., addition or removal of nearby antennas or other overhead conductors or obstructions) will normally require recalibration of the facility. Additionally, periodic calibration checks (normally daily) should be made against the local calibration source (standard signal generator, noise generator or built-in calibration source). Local broadcast stations may be used with care as another calibration check. If measurements are to be made over an extended frequency range, a calibration curve may be prepared based on comparison measurements at frequent intervals within the frequency range of interest. When performing these comparisons the monitoring station antenna and the field strength meter antenna should have the same polarisation (e.g., both antennas adjusted for reception of vertically-polarised emissions or both for horizontally-polarised emissions).

For measurements below 30 MHz, where a field strength meter with a shielded loop antenna is commonly used to calibrate a recording installation having a vertical monopole antenna, satisfactory results will normally be obtained with the field strength meter at a convenient level near the ground (e.g., 1 m or so). For frequencies above 30 MHz where dipoles or other resonant antennas are normally used and where the Earth does not play a major part in the propagation, it is desirable that the antenna of the field strength meter be installed at the same height as the recording antenna (usually about 10 m above the ground). To avoid interaction between the antenna of the field strength meter and the recording antenna, it may be desirable to remove the recording antenna temporarily and to place the antenna of the field strength meter at the same location to obtain the reference field strength; then the antenna of the field strength meter is removed and the recording antenna re-installed. This presupposes that the signal source which is being used is constant in level during the calibration procedure. If a signal of varying intensity must be used, simultaneous measurements should be made with the two antennas near one another but spaced sufficiently to cause a minimum of interaction between the two antennas.

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ITU-R Recommendations and Reports

NOTE – In every case the latest edition of the Recommendation and Report is encouraged to be used.

Recommendation ITU-R SM.378 – Field-strength measurements at monitoring stations.

Recommendation ITU-R P.529 – Prediction methods for the terrestrial land mobile service in the VHF and UHF bands.

Recommendation ITU-R P.533 – Method for the prediction of the performance of HF circuits.

Recommendation ITU-R BS.638 – Terms and definitions used in frequency planning for sound broadcasting.

Recommendation ITU-R P.845 – HF field-strength measurement.

Recommendation ITU-R P.1057 – Probability distributions relevant to radiowave propagation modelling.

Recommendation ITU-R M.1172 – Miscellaneous abbreviations and signals to be used for radiocommunications in the maritime mobile service.

Recommendation ITU-R P.1546 – Method for point-to-area predictions for terrestrial services in the frequency range 30 MHz to 3 000 MHz.

Report ITU-R BS.516 – Field strength resulting from several electromagnetic fields.

4.5 Bandwidth measurement

4.5.1 General considerations

4.5.1.1 Influences of the bandwidth to the radiocommunication services

The various modulation schemes used by the different radiocommunication services are producing spectral components of different frequencies.

In order to achieve a given service quality grade it is necessary to reproduce the spectral distribution of the emitted signal at the reception site to a given extent of exactness.

The bigger are the differences between the original spectrum and the reproduced one the poorer is the service quality which can be achieved.

On the other hand, spectral components coming from other signal sources than the wanted one will also cause quality degradation by distorting the original spectral distribution. In order the quality requirements can be formulated in terms of physical quantities the bandwidth must be properly defined.

4.5.1.2 Bandwidth definitions

Necessary bandwidth

According to RR Article 1, the definitions used at the present time are as follows:

"1.152 *necessary bandwidth:* For a given class of emission, the width of the frequency band which is just sufficient to ensure the transmission of information at the rate and with the quality required under specified conditions."

NOTE 1 – The necessary bandwidth can be calculated using the formulae as given in Recommendation ITU-R SM.328 for the different classes of emission.

NOTE 2 – The emission of a transmitter outside of the necessary bandwidth is called unwanted emission and it consists of two parts (see RR Article 1, No. 1.146):

"1.144 *out-of-band emission:* Emission on a frequency or frequencies immediately outside the *necessary bandwidth* which results from the modulation process, but excluding *spurious emissions*".

Recommendation ITU-R SM.328 describes limiting curves concerning the out-of-band spectrum for various classes of emissions.

"1.145 *spurious emission:* Emission on a frequency or frequencies which are outside the *necessary bandwidth* and the level of which may be reduced without affecting the corresponding transmission of information. Spurious emissions include harmonic *emissions*, parasitic *emissions*, intermodulation products and frequency conversion products, but exclude *out-of-band emissions*".

NOTE 3 – Frequencies due to out-of-band emission and spurious emission may overlap. Therefore two further definitions are introduced as follows:

"1.146A *out-of-band domain* (of an emission): The frequency range, immediately outside the necessary bandwidth but excluding the *spurious domain*, in which *out-of-band emissions* generally predominate. *Out-of-band emissions*, defined based on their source, occur in the out-of-band domain and, to a lesser extent, in the *spurious domain*. *Spurious emissions* likewise may occur in the out-of-band domain as well as in the *spurious domain*." (WRC-03).

"1.146B *spurious domain* (of an emission): The frequency range beyond the *out-of-band domain* in which *spurious emissions* generally predominate." (WRC-03).

NOTE 4 – Recommendation ITU-R SM.329 specifies the limits of spurious emissions and contains guidelines concerning the boundary between the out-of-band domain and the spurious domain. According to the principles stated in RR Appendix 3, the spurious domain generally consists of frequencies separated from the centre frequency of the emission by 250% or more of the necessary bandwidth of the emission. However, this frequency separation may be dependent on the type of modulation used, the maximum bit rate in the case of digital modulation, the type of transmitter, and frequency coordination factors.

Occupied bandwidth

The definition of occupied bandwidth as formulated in RR Article 1, No. 1.153 has been arrived at over many years by a process of modification made necessary by increasing spectrum congestion and by an increased appreciation of the problems involved in making the definition more generally applicable.

The definition used at the present time is as follows:

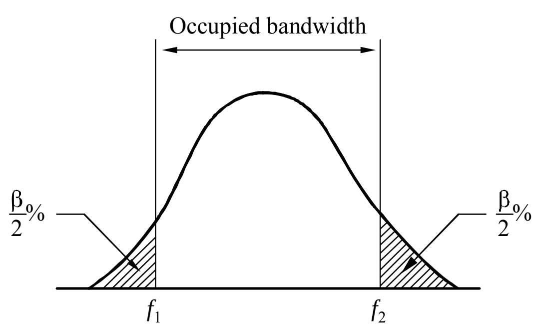
"1.153 *occupied bandwidth:* The width of a frequency band such that, below the lower and above the upper frequency limits, the *mean powers* emitted are each equal to a specified percentage β/2 of the total *mean power* of a given *emission*.

Unless otherwise specified in an ITU-R Recommendation for the appropriate *class of emission*, the value of β/2 should be taken as 0.5%."

The concept of this definition is given in Fig. 4.5-1.

FIGURE 4.5-1

Definition of occupied bandwidth as formulated in RR Article 1, No. 1.153



Digital signal processing (DSP) techniques can be used to calculate the β% bandwidth from the power spectral density (PSD). First, the noise floor of the PSD is estimated with one of several DSP algorithms. The PSD values are set to zero if the power is less than Y dB above the noise floor. For most signal environments, $Y = 6$ dB provides excellent results. The total signal power, P, is computed by summing the values for the PSD bins containing the signal energy. The running integral of the PSD is computed and the data are interpolated to find the frequency, f_1, where the integrated power equals $P_{\beta/2}$. This is repeated from the other end of the spectrum to get the upper frequency, f_2, where the integrated power equals $P_{\beta/2}$. The bandwidth is $f_2 - f_1$.

NOTE 1 – According to § 2 of Recommendation ITU-R SM.328 "an emission should be considered optimum from the standpoint of spectrum economy when its occupied bandwidth coincides with the necessary bandwidth for the class of emission concerned".

The "*x*-dB" bandwidth

The above two definitions reflect both the quality and the interference aspects of the bandwidth. However, it may be difficult to apply them directly to measure the bandwidth of a given signal in certain cases.

A third definition is given therefore in Recommendation ITU-R SM.328 as follows:

"*x*-dB *bandwidth:* The width of a frequency band such that beyond its lower and upper limits any discrete spectrum component or continuous spectral power density is at least *x*-dB lower than a predetermined 0 dB reference level."

NOTE 1 – Research results show that the "*x*-dB" bandwidth can be used to estimate the occupied bandwidth under well-defined conditions as to the class of emission and the modulation characteristics of the signal. There are cases, however (e.g. that of some digital modulation schemes), when the "*x*-dB" bandwidth is not a good estimate of the occupied bandwidth.

4.5.1.3 Monitoring of the bandwidth of emissions at monitoring stations

Monitoring of the occupied bandwidth of an emission should be performed in accordance with the formal definition of RR Article 1, No. 1.153. These definitions relate to a momentary bandwidth. However, as the measurement of an emission at a monitoring station must be made under actual traffic conditions over a propagation path, subjected to the fluctuation of the measured values, the effects of noise and interference, the response speed of the measuring equipment, etc.; therefore measurement methods have to be refined continuously.

The bandwidth of FM and AM signals constantly changes with the modulation contents. In these cases, monitoring stations will be interested in determining the maximum occupied and "*x*-dB" bandwidth in a given time frame. Therefore, all measurement methods described here result in this maximum occupied bandwidth.

Recommendation ITU-R SM.443 recommends that monitoring stations should adopt, provisionally, as an estimation of bandwidth, a method consisting of measuring the bandwidth at 26 dB (i.e. "*x*-dB" bandwidth with $x = 26$).

Modern measurement/monitoring receivers are based on digital signal processing. Using this technology allows to determine the bandwidth by both methods – the "*x*-dB" or the β% method. The β% method allows for bandwidth measurements independent of the signal modulation. Therefore it should be the preferred method, especially for measuring the bandwidth of digital signals, when their technical identification is not available and in low *S*/*N* cases. However, in interference cases, the "*x*-dB" measurement values may be much more relevant.

4.5.1.4 Accuracy considerations

The factors having influence to the uncertainty of bandwidth measurement are:

– measurement principle (FFT or swept spectrum analysis);

– resolution bandwidth;

– non-linearity of amplitude display;

– spectral shape of the signal;
– measurement procedure (e.g. for TDMA signals);
– receiver/analyzer reading;
– characteristics of the receiver/analyzer (e.g. sensitivity);
– number of measurements;
– Electromagnetic environment (e.g. Noise, interference, vicinity of others emissions).

4.5.2 Methods of bandwidth measurement

4.5.2.1 Measurement of occupied bandwidth

Measurements of occupied bandwidth by direct methods are conducted as specified in Recommendation ITU-R SM.328. The relationship between the errors in the measurement of occupied bandwidth δ' and the errors in the power comparison υ is obtained from the spectrum envelope approximation described below and shown in Fig. 4.5-2. The solid lines correspond to the approximation according to equation (4.5-1):

$$S_1(f) = S(f_m)\left(\frac{f_m}{f}\right)^{\gamma} \qquad (4.5\text{-}1)$$

$$\gamma = 0.33\ N$$

where $S(f_m)$ is the power on a given frequency f_m, and N is a number of dB by which the spectrum envelope is reduced within a single octave of band widening. The dashed lines correspond to the approximation according to equation (4.5-2):

$$S_2(f) = S(f_m)\exp\left[-\frac{0.23N_1}{f_m}(f - f_m)\right] \qquad (4.5\text{-}2)$$

where N_1 represents the number of dB corresponding to the first octave of band widening. Fig. 4.5-2 shows that, for the most common values of $N = 12$ to 20 dB/octave, it is sufficient to carry out the power comparison at a very low accuracy of about ± 15 to 20% to ensure an occupied bandwidth measurement accuracy of ± 3 to 7%.

These methods consist in comparing the total power of the emission with the power remaining after filtering, either by means of two low-pass filters or two high-pass filters, or by a high-pass filter, or by a high-pass and a low-pass filter, the cut-off frequencies of which can be shifted at will with respect to the spectrum of the emission. Alternatively, the relevant power constituents can be determined by evaluating the power spectrum as obtained by a spectrum analyzer.

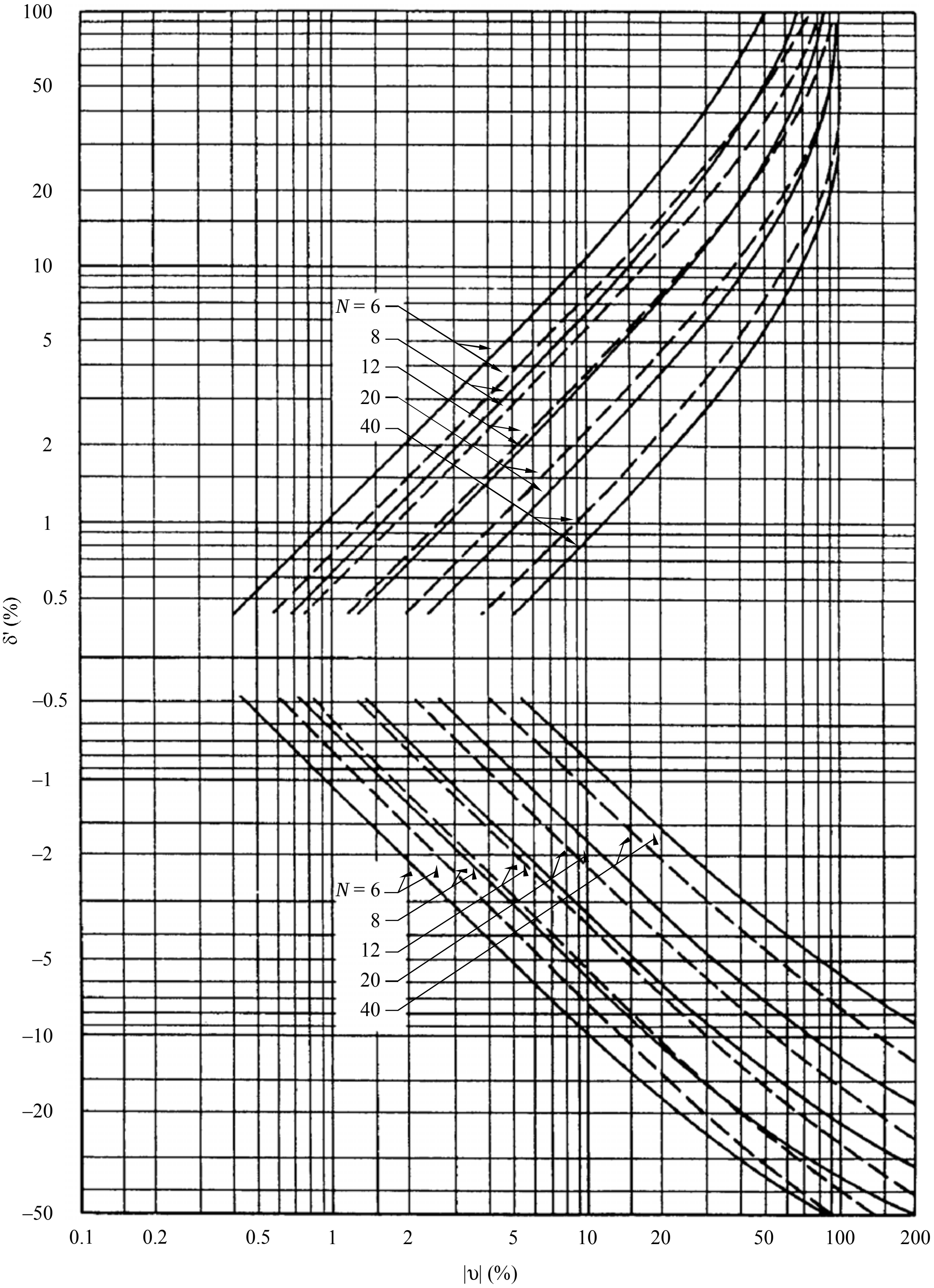
4.5.2.1.1 Method using a spectrum analyzer

With this method the two frequency limits referred to in the definition of the occupied bandwidth (see § 4.5.1.2) are determined by evaluating the power spectrum of an emission as obtained by spectrum analysis. The relevant power values are determined by summing the powers of the individual spectral components.

This assumes a line spectrum, which exists only for periodic signals. The spectrum of actual traffic signals, however, is a continuous spectrum. Nevertheless, this method can also be applied in the latter case, for it is sufficient for the determination of the occupied bandwidth to select samples of the spectrum with equidistant frequency separation. This frequency separation need only be chosen in such a way that the samples reproduce the envelope of the spectrum sufficiently well. Even in the case of a true line spectrum e.g., of a radar emission, where for practical reasons the analysing filter bandwidth anyhow cannot be made as narrow as would be required to resolve each spectral line, it suffices to evaluate a restricted number of samples, as long as the conditions described for the continuous spectrum are met. Thus, this method is particularly suited for determining the occupied bandwidth of signals containing digital or quantized information with quasi-periodic spectra, e.g., telegraphy, data and radar signals.

FIGURE 4.5-2

Relationship between the percentage error (δ′) in measuring the occupied bandwidth and the percentage error (υ) in the power comparison, for different values of *N*



Spectrum-4.5-02

The recording of the spectrum by means of an X-Y graph greatly facilitates its evaluation, for which normally a pocket calculator is sufficient. This method is also especially suitable for automation. A spectrum analyzer with a digitally controlled synthesizer scans the spectrum in definite frequency steps, and a digital memory sends the measured values to a computer, which in turn performs the calculations. Since a conventional spectrum analyzer performs a sequential and not a real-time analysis of the spectrum, it is advisable to make a number of scans.

4.5.2.1.2 Methods relying on FFT

Fairly simple digital signal processing methods relying on FFT make it possible to measure the occupied bandwidth of an emission in the sense of the formal definition (RR Article 1, No. 1.153), at least in the case of a signal received with sufficient S/N (see § 6.7 for some explications about the FFT). Such direct methods are advantageous as compared to "x-dB" methods, which always rely on assumptions to derive the occupied bandwidth, assumptions which depend on the modulation used and on the modulating signals. Standard assumptions were given for traditional analogue and RTTY signals, and no new values have been standardized so far. It seems that the new digital signals may have rendered *a priori* relationships between "x-dB" bandwidth and occupied bandwidth less easy to use, since:

– for strictly identical modulations (such as a 64-QAM signal), exact bandwidth would depend on baseband filtering, RF filtering, sharing of Nyquist filtering between transmit and receive parts of the system, linearity of the emitter and possible use of pre-distortion techniques, etc., all techniques that are used to achieve various technical tradeoffs depending on manufacturers;
– additional difficulties such as substantial power from adjacent channel interference may impair the measurements;
– on the other hand, digital signals having a fixed bit rate have a stationary behaviour and in this respect are easier to measure than randomly modulated analogue signals.

FFT-based power-ratio measuring methods require little or no knowledge about the detailed parameters of the modulation and are able to interpret the part of the signal spectrum that emerges out of the noise floor. Also, the power-ratio method is much less sensitive to the windowing chosen than the "x-dB" values. SNR, when insufficient to determine the 99% power bandwidth, could be increased by longer integration with finer grain resolution FFT. However, this is not possible for noise-like digital modulations.

In any case, the SNR required to perform bandwidth measurement with the 99% power method need not be unreasonably high; on many signals, accurate results can be obtained with 15 to 20 dB of SNR (defined here as the difference of peak signal and of noise floor), which is a reasonable value in many cases, and lower than the 26 dB value.

Effect of different factors when measuring bandwidth with FFT power-ratio methods

Effect of windowing

The FFT generates a bank of filters that are not perfect rectangular filters that sample the power in $f \pm \delta f$ only but which present side lobes.

Various windowing functions have been devised (see § 6.7) in order to take into account the preference of accuracy of level measurement or of frequency measurements. For bandwidth measurements according to the β% method, one would preferably select a windowing that generates an overall low side lobe power content, so as to operate in conditions as close as possible to the definition, which requires perfect rectangular filters.

Numerous measurements on different signals show, however, that influence of the windowing method is relatively small for common signals and in usual practical measurement conditions.

Effect of FFT resolution

Another characteristic to be chosen is the number of FFT lines. Test measurements (with different types of digital modulation signals and in absence of noise) show that the 99% power method is much less sensitive to the resolution chosen to compute the FFT. It gives very accurate results as soon as more than a 100 to 200 lines cover the occupied bandwidth of the signal measured.

Effect of the duration of signal sample

The duration of the signal sample plays also an important role when using FFT-based power-ratio methods. The FFT analysis is based on the assumption that the signal measured was of finite duration and totally captured. Therefore, the observation window must be long enough to cover the entire signal.

The measurement of bandwidth has to be carried out on a significant portion of the signal being investigated, but monitoring stations will observe the signal for a period of time only. It is needed to develop measurement methods that can be applied on a short portion of the signal, so that automatic measurements can be performed on a large number of transmitters in a reasonable time.

Simulation tests with stationary signals (such as those common with digital modulation, in absence of fading) show that reliable results are obtained for about 1 000 symbols. A good rule of thumb when making bandwidth measurements on digital signals could therefore to target a minimum of 1 000 symbols of the modulation.

Effect of noise

Under noisy conditions, it is essential to filter the signal emerging from the noise; the importance of filtering increases when the SNR is low and when the observation filter is wide compared to the signal's bandwidth. If a direct measurement is attempted without precaution (i.e. if the observed band exceeds the occupied bandwidth considerably) then the 99% bandwidth of the signal+noise will be measured instead that of the signal alone leading to absolutely wrong results.

The shape and the exact positioning of the filter are not very sensitive, so far as it is positioned to isolate the emerging main lobe of the signal. Some theoretical signals may have 99% power bandwidth including some side lobes, but such signals are seldom encountered in practice since filtering at the transmitter usually limits the emission to the first lobe for spectrum efficiency. However, caution should be exercised when analysing signals with wide side lobes raising to levels reaching –26 dB, or with narrow side lobes reaching similar levels with slow decay. Two symmetrical side lobes, each of width equal to half the main lobe, raising to –20 dB would amount for 1% of the signal power, and would therefore contribute to the 99% bandwidth of the signal.

Practical settings that can be used for a suitable filter is –50 dB maximum side lobe level and 0.1 dB passband ripple. Slope of the filter is to be adjusted to reject after intersection of the signal with what is assumed to be the noise floor. The right filtering often starts on the signal slope so as to reach total rejection where the noise floor starts. As a practical mean to validate the measurement, and also to improve the result, it is necessary that an operator defines a narrower filter to repeat the measurement. Note that first measurement in the total capturing filter can be used as a basis to help in defining the additional filtering.

Effect of factors unknown to the monitoring personal

So-called "hidden" modulation parameters (such as the BT factor of a GMSK modulation) cannot be determined in an easy way at a monitoring station. Similarly, it cannot be deduced from the measured signal whether baseband or RF filtering were applied to the measured emission at the transmitter side; it is the same for eventual transmitter non-linearities.

These factors are generally unknown and cannot be measured at a monitoring station. However, a serious increase of occupied bandwidth can be produced by a strong non-linearity caused by a drift of polarisation of the power amplifier of the transmitter. A monitoring station, when comparing with previous occupied bandwidth measurements can discover such a problem. Otherwise, the "hidden" parameters have a strong effect on the shape of a transmitted spectrum, thus making it nearly impossible to derive a method of converting –"*x*-dB" measurements into 99% power bandwidth, even when considering a given type of modulation. This is a reason for which direct methods should be preferred to –"*x*-dB" methods.

Effect of the max-hold function

The max hold function makes it possible to take into account the extreme variations of the signal that would be missed in averaging due to their low occurrence. The max hold function may not be a proper way to estimate the 99% power bandwidth. However, it is suitable when analysing whether a signal is below a given spectrum mask, since it retains any peak likely to overshoot the limit.

Limits of applicability of FFT power-ratio methods to bandwidth measurement

Automation considerations

Full automation of occupied bandwidth in a spectrum monitoring context is difficult in the general case: the signal to be measured should be filtered in a way so that adjacent channel and adjacent noise do not unduly impact the measurement. The signal should be isolated, which implies that multiple emissions in the filter should be distinguished from multiple carriers or side lobes of the signal to be measured. If the signal is intermittent, provision should be made so that measurement occurs only during the presence of the signal. Other parameters may also impact the measurement, such as AGC variation in the receiver, propagation fading, etc. Therefore, bandwidth measurements are to be conducted preferably under reasonably high SNR (say >20 to 30 dB) to limit contributions of noise when the analysis filter is not optimally set around the wanted signal, and in channelized bands where pattern of emissions is well known. /

When automatic measurements are conducted in a blind manner on unknown signals, it is desirable that an operator checks their validity before the results be further used. Routine systematic measurement of bandwidth on known emissions can be a way to generate alarms when the wanted signal is replaced by an intruding signal or interference. They can also be used to check some parameters of an emission. Generally, routine automatic bandwidth measurements are performed on a short sample of the target signal, such as a few hundred of milliseconds. This is due to the necessity of the monitoring receiver to process a large number of signals in a short time, to revisit frequencies often enough to be able to detect irregular or faulty spectrum use.

When bandwidth measurements are taken with an observation window that is too short to cover the power spectral density, the measurement is generally not a valid one if the target signal is a non-stationary signal, such as AM, SSB or FM voice. On the contrary, valid results are easily obtained on fast data transmissions (such as a 277 kbit/s permanent GSM beacon signal). However, the short duration bandwidth measurement may have some value even on non-stationary signals when it is used to check if the signal exceeds a maximum value.

4.5.2.2 Direct methods of measuring the "*x*-dB" bandwidth

These methods are designed to obtain, in various ways, the spectrum of the signal from which the "*x*-dB" bandwidth may be derived by direct reading. Various characteristics of the out-of-band spectra such as the initial starting point levels and the decay rates may be derived. A description of the method of fixing the 0 dB reference levels for determining the "*x*-dB" bandwidth and the values of "*x*-dB" levels for various classes of emission are given below.

The "x-dB" level:

The "*x*-dB" level, measured with respect to the zero level, may be specified individually for each class of emission.

However, results are obtained which are in better agreement with RR Article 1, No. 1.153 by measuring the bandwidth of classes of emission at specially calculated "*x*-dB" levels, the values of which are given in Table 4.5-1.

NOTE 1 – Although the derivation of the 99% bandwidth from –"*x*-dB" measurement might be a viable method for different classes of emissions as proposed formerly, it seems that these methods cannot be easily continued in a "digital" spectrum, since the complexity of the digital modulations does not allow to define a simple rule to derive the 99% bandwidth from measurements taken at –"*x*-dB".

Reference zero level of frequency modulated (broadcast) signals

A reference (0 dB) level, representing the peak value of the emission, is sometimes difficult to establish for the purpose of bandwidth measurements in the case of frequency-modulated emissions because of amplitude-reduction of the carrier with modulation. In some radio systems, modulation is continuous, rarely permitting the full power of the transmitter to return to the carrier frequency so that a reference level may be established. However, the total emitted power of an FM modulated signal is constant.

Therefore, the reference zero level can be measured by choosing a receiver bandwidth that covers the whole signal while the measuring receiver is tuned to the centre frequency of the emission to be measured. Care should be taken not to include parts of neighbouring emissions when selecting the receiver bandwidth.

For the following measurement of the "*x*-dB" – points, however, the receiver bandwidth has to be reduced in order to achieve sufficient resolution. However, it has to be at least equal to the highest modulating frequency.

TABLE 4.5-1

Empirically-derived value of "*x*-dB" level at which "*x*-dB" and occupied bandwidths are close to each other

Class of emission (See RR Appendix 1)	Values of "*x*-dB" to be used when measuring "*x*-dB" bandwidth for estimation of occupied bandwidth	Remarks
A1A A1B	–30	For $\alpha^{(1)} \geq 3\%$ (all pulse shapes)
A2A A2B	–32	For a modulation depth between 80 and 90%
A3E	–35	
B8E	–26	
F1B	–25	For all signal shapes and a modulation index $2 \leq m \leq 24$
F3C	–25	For all types of transmitted pictures and modulation indexes $0.4 \leq m \leq 3$
F3E G3E	–26	
F7B	–28	
H2B	–26	
H3E	–26	
J2B	–26	
J3E	–26	
R3E	–26	
C7W (8-VSB)	$-12^{(2)}$	Average of more than 300 sweeps
G7W (T-DAB)	$-8^{(2)(3)}$	Average of more than 100 sweeps

(1) The relative build-up time, α, of a telegraph signal is defined in § 1.10 of Recommendation ITU-R SM.328.

(2) According to Recommendation ITU-R SM.328, the unit of these values is dBsd because the reference level was chosen to the maximum value of power spectral density (psd) within the necessary bandwidth.

(3) This value is derived from experiments with T-DMB using a T-DAB network taken from Report ITU-R BT.2049.

Reference zero level of amplitude modulated signals

The method of establishing the reference level (0 dB) described above may also be used for measurements of the "*x*-dB" bandwidth of amplitude-modulated and pulse-modulated emissions.

Amplitude-modulated signals like broadcast emissions usually have a bandwidth in the order of the highest modulating audio frequency. In this case, the minimum required receiver bandwidth for the actual measurement of the *x*-dB points as described above may not be accurate enough due to the reduced resolution when using high measurement bandwidths. To overcome this problem, AM signals can also be measured with smaller resolution bandwidths. For this measurement, however, a spectrum analyzer is necessary to establish the 0 dB reference level as follows: The spectrum is recorded with the required narrow resolution bandwidth using the Max-Hold function. The reference level is taken as the maximum level of the spectrum inside the sidebands, not considering the carrier level that will display as a single peak in the centre.

Reference zero level of digitally modulated signals

Digitally modulated signals usually have a bandwidth that is higher than the measurement bandwidths required obtaining a reasonable resolution of the recorded spectrum. However, because the digital signal is noise-like, reduction of the level due to the narrow measurement filter will be equal at all frequencies throughout the emitted spectrum. Therefore, the reference zero level is set to the maximum level displayed when recording or scanning the spectrum. Measurement of the *x*-dB points then has to be made with the same measurement bandwidth.

If the measurement aims to prove conformance with a given spectrum mask, the measurement has to be done with the resolution bandwidth used to define that mask. However, if these masks are referenced to the total emitted power, this level first has to be measured using a receiver bandwidth sufficient to capture the entire signal. When the bandwidth is then reduced to record the spectrum shape, the degradation of the maximum level measured has to be considered.

Test equipment required

This equipment requires that the signals under test should produce a spectrum, the components of which are stable in amplitude and frequency. Amplitudes are measured by means of a calibrated attenuator with reference to a constant level (either internal or external to the measurement receiver/analyzer).

An accuracy of ± 1dB in the measurement of the relative amplitude is obtainable. The accuracy of "*x*-dB" bandwidth measurement depends on the accuracy of amplitude measurement and the shape and slope of the spectrum at the measurement point.

The following methods of spectrum analysis are used.

4.5.2.2.1 Method with single band-pass filter (sequential spectrum analysis)

This method, the most common one, consists in completely analysing the spectrum of the emission by means of a sweeping narrow-band filter, e.g. a spectrum analyzer. In using this method, the "*x*-dB" bandwidth is considered to include discrete components attenuated less than 26 dB below the peak level of the emissions. This procedure admittedly will not give a precise measurement of occupied bandwidth in terms of the definition in the RR. For example, it is possible that a particular emission will have numerous low-level components on either side of the main emission such that their sum on each side would be equal to much more than 0.5% of the total mean power while having none of these discrete components exceeding the –26 dB level . In such a case, the occupied bandwidth, as determined at the transmitter by measuring power ratios, would presumably be somewhat greater than the "*x*-dB" bandwidth measured at a distance by this method.

A major shortcoming of spectrum analyzers, which use a single filter to sweep the entire band under surveillance, is the incompatibility between high resolution and rapid sweep rates, especially where a band of considerable width must be studied. A fast sweep rate is necessary to obtain a representative display of transient components.

However, as the sweep rate is increased, the resolution becomes poorer so that significant components of the emission will not be displayed accurately.

However, more and more modern wideband analyzers or wideband receivers based on FFT realtime signal processing allow measuring with a large instantaneous bandwidth (more than 100 MHz). In many cases, such equipments allow carrying out bandwidth measurement with a single band-pass filter. The acquisition of the signal is sufficiently fast to measure transient emissions. Moreover, some of them use buffering techniques to limit breaks during the signal acquisition process.

4.5.2.2.2 Uncertainty of "*x*-dB" bandwidth measurements

The relationship between the relative error (δBx) of the "*x*-dB" bandwidth measurement (Bx) and the aggregate error (δx) of the "*x*-dB" level readout and of the measurement (representation) of the spectral power density (SPD) levels of the signal at the boundaries of Bx, for different values of SPD reduction rates expressed as N dB for an octave of frequency band widening, is illustrated in Fig. 4.5-3. The values shown in Fig. 4.5-3a) correspond to an SPD envelope approximation within the boundaries of Bx in accordance with equation (4.5-1), and in Fig. 4.5-3b) in accordance with equation (4.5-2). The solid lines in Fig. 4.5-3a) correspond to positive Bx measurement errors, while the dashed lines correspond to negative errors.

It is clear from Fig. 4.5-3 that the Bx measurement error with SPD approximation in line with equation (4.5-1) is approximately 1.5 times smaller, and with both types of approximation it is very dependent on the SPD envelope reduction rate N within the boundaries of Bx, increasing sharply for low values of N. Where $N = 12$ dB/octave, in order to obtain Bx measurement accuracy to within 5%, it is necessary to achieve an aggregate accuracy of "*x*-dB" level readout and measurement (representation) of SPD levels in the order of 0.6-0.9 dB, which is extremely problematic, while for $N = 6$ dB/octave (AM or FM/PM transmission of rectangular pulses with a low modulation index), Bx measurements with an accuracy better than 7-8% are practically unachievable.

4.5.3 Conditions to be considered in measuring bandwidth

The present definition of occupied bandwidth suggests the principle described in Recommendation ITU-R SM.328, of measuring the ratio of the total power to the power remaining outside of the bandwidth being measured. To do this, it would be necessary to locate the upper and lower edges of the band, by totalling the power in the out-of-band components on the high side until the 0.5% value is obtained and then repeating this procedure for out-of-band components below the band, starting in each case sufficiently far from the centre frequency so that no appreciable energy is omitted from the measurement.

Although a determination of the occupied bandwidth of an emission, by the method of measuring total power and out-of-band power, can be accomplished when the measurements are made near the transmitter, this method is not generally applicable for measurements made at a distance from the transmitter where the presence of interfering emissions or noise tend to mask the out-of-band signal components of interest. This is particularly true in the crowded MF (band 6) and HF (band 7) portions of the spectrum, which are regions of primary interest to international monitoring stations.

In spite of the very definite limitations, which observations made at a distance place upon the accuracy of measurements of occupied bandwidth, approximate determinations have been found useful when monitoring the spectrum for enforcement of bandwidth limitations.

However, these non-precise measurements made at a distance, which are subject to inaccuracies for the reasons previously given, should be considered as advisory only. Where greater accuracy is required, measurements at the transmitter may be desirable.

To secure correct measurement, it is necessary to know the precise effects of noise, interference and fading, as discussed below.

4.5.3.1 Effect of interference

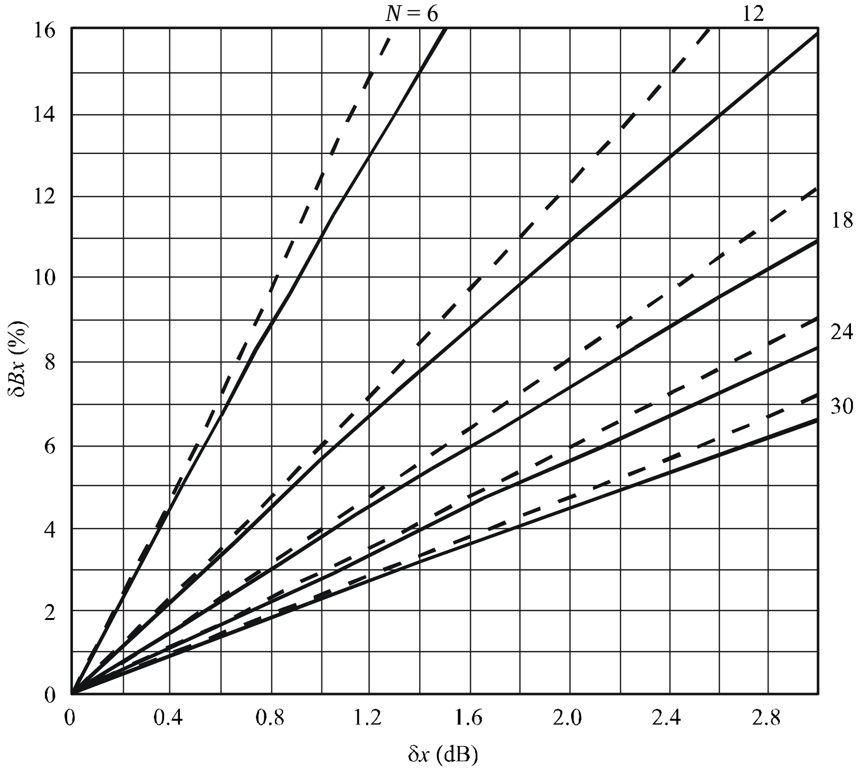
The actual characteristics of interfering emissions are extremely complicated, and it is difficult to discuss all the cases here. The effects of interference are discussed on the following assumptions:

– both emissions, the one to be measured and the interfering one, have stable spectral distributions;
– an interfering emission does not cause blocking, intermodulation or other extra spectra.

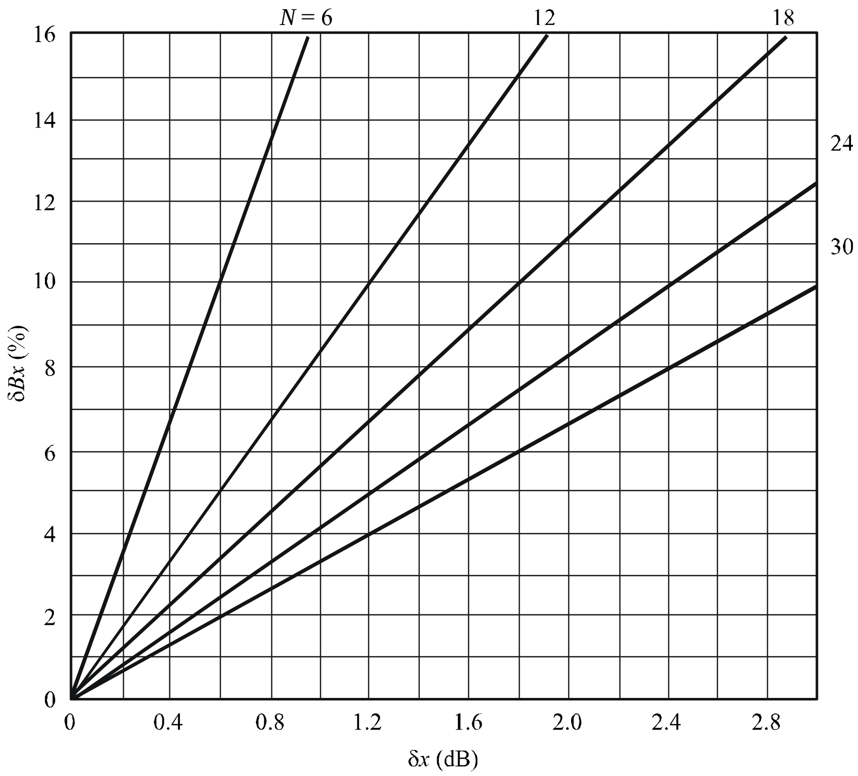
FIGURE 4.5-3

"*x*-dB" bandwidth measurement error

a)



b)



Spectrum-4.5-03

In measurement methods using spectral analysis, the presence of interference can be recognized by observing the spectral distribution, and the consequent effects can be deduced and removed. An example based on the power-ratio method, which is subject to interference, is dealt with in the following.

In Fig. 4.5-4 the assumption is made that there is no noise or interference present but only the emission to be measured in the passband of measuring equipment.

FIGURE 4.5-4

Spectral distribution without interference

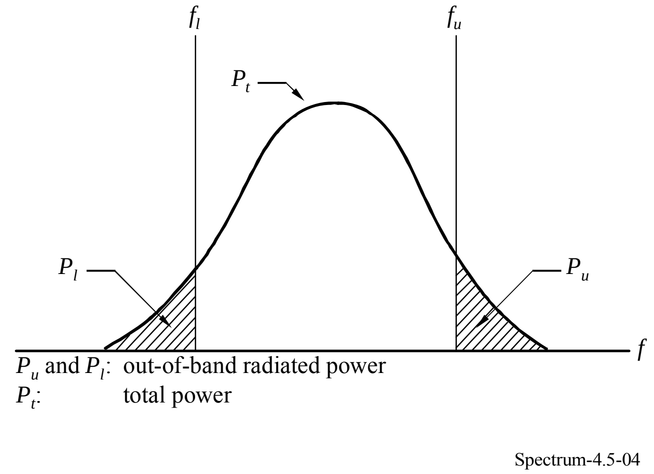
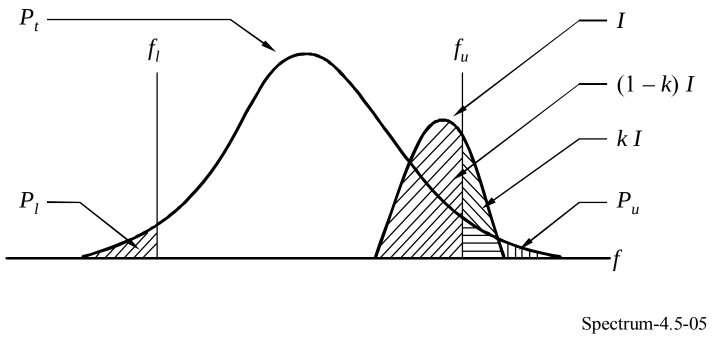


Figure 4.5-5 shows the case where an interfering emission exists.

FIGURE 4.5-5

Spectral distribution with interference



The ratio of the total power of a (wanted) signal to the total power of (unwanted) interfering emissions is expressed by W/U, and the ratio of the power of the interfering emissions remaining outside the occupied bandwidth to the total power of interfering emissions is expressed by k.

Using k as a parameter, the effect of the interference is given in Fig. 4.5-6. This diagram is valid irrespective of the type of modulation and the spectral distribution of emissions.

If k is equal to the ratio of the out-of-band radiated power of the emission to be measured to its total power, the interference does not affect the measured value.

In general, as W/U becomes smaller, the error becomes larger. When $k = 0$, the interfering emissions are completely within the band and the measured value of the occupied bandwidth apparently becomes narrower.

When k = 1, the interfering emissions are entirely outside the band and the apparent bandwidth becomes wider.

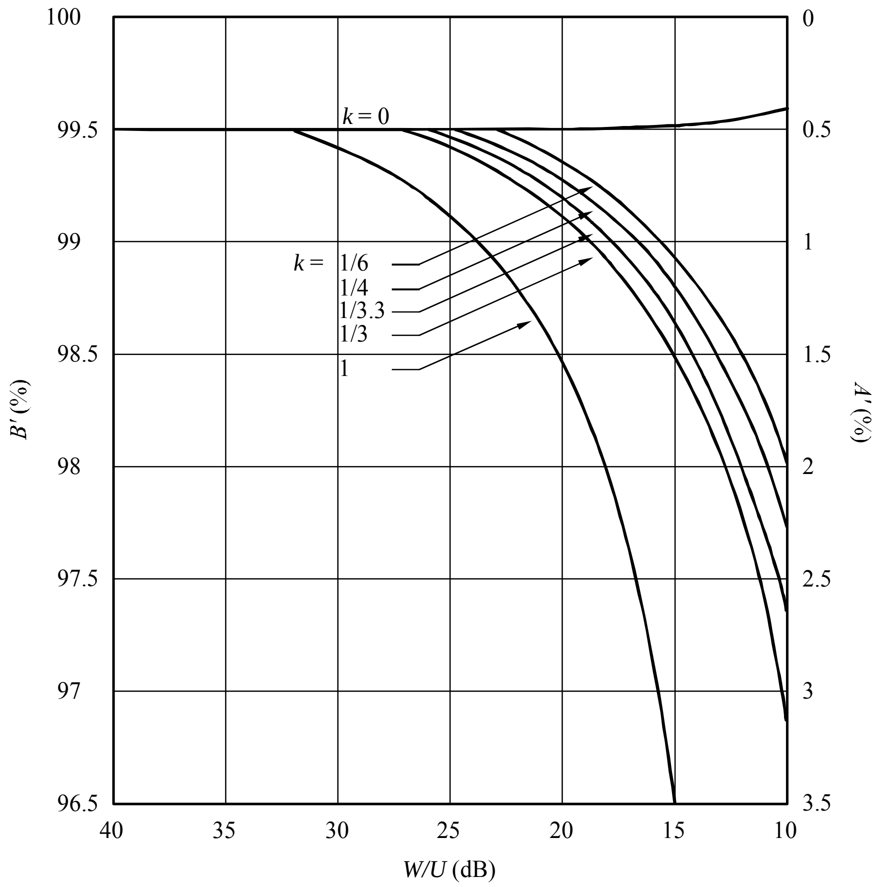
In practice, the interference does not always conform to the above description, and its effects are detrimental. However, in the actual measurement, it is sufficient to consider the largest error, i.e., $k = 1$ (interfering emission is completely out-of-band).

According to Fig. 4.5-6, it is understood that a value of the ratio W/U of more than 30 dB is required to confine the measuring error of the power ratio to less than 0.1% of the total power.

It is recommended that when measurements are made, a spectrum analyzer or other means should be used to determine the nature of the interfering emissions.

FIGURE 4.5-6

Relations between W/U, A′ and B′



A′: virtual value of ratio of out-of-band radiated power to total power
B′: virtual value of ratio of in-band radiated power to total power

Spectrum-4.5-06

4.5.3.2 Effects of noise

As with interference, the effects of noise may be deduced and removed when a spectrum analyzer method is used. However, the resultant effect of noise is complicated as the characteristics of noise depend upon the source of generation.

The effects of random noise, which is easy to treat theoretically, and other kinds of noise, together with an example based on actual measurements using the power ratio method subjected to the effects of noise, are given in the following sections.

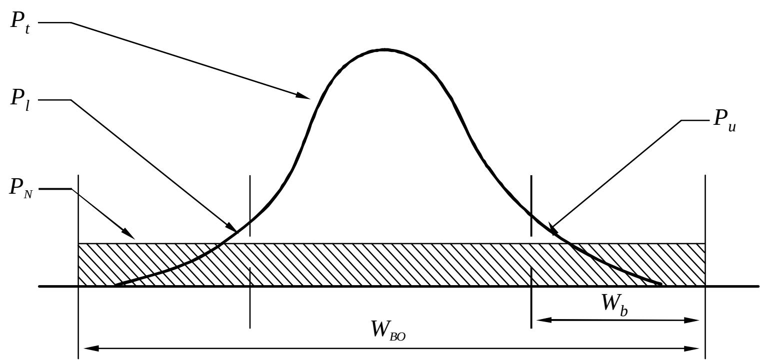
Effect of random noise

If noise is regarded as random, its effect is evaluated as follows:

Figure 4.5-7 shows the schematic of spectral distribution with random noise. The effects of random noise on the measured value of bandwidth are the same as those of interference, replacing k by k_n (= W_b/W_{BO}), W/U by S/N (= P_t/P_N) in Fig. 4.5-6. However, actual cases where $k_n = 0$ or $k_n = 1$ do not exist with random noise.

FIGURE 4.5-7

Spectral distribution with random noise



W_{BO}: equivalent noise bandwidth of the measuring equipment

P_N: total power of random noise passing through W_{BO} (flat power distribution over W_{BO})

Spectrum-4.5-07

Therefore, Fig. 4.5-6 shows that as the signal-to-noise ratio, S/N, of the emission to be measured becomes smaller, the apparent out-of-band radiated power increases and the occupied bandwidth apparently extends.

For example, to confine the measuring error of the power ratio to less than 0.1%, the value of S/N for the emission to be measured should be greater than about 25 dB, for values of k less than about 1/3, which is considered appropriate for a monitoring station.

4.5.4 Practical measurement of bandwidth

4.5.4.1 Condition for practical measurement

In actual measurements at monitoring stations, problems exist because under normal traffic conditions measurements must usually be made at a distance from the transmitting station. The problems are as follows:

– the emission to be measured is, in general, of low field-strength and must be selected from among many emissions;

– there is the possibility that the measured value can differ from the value at the transmitting station, due to the effects of propagation disturbances;

– there is the possibility that noise and interference can influence the results of the measurement;

– the response time of the measuring equipment should be short enough to follow variations in the occupied bandwidth, resulting from the traffic condition of the emission to be measured.

Of the above-listed problems, the first three were discussed in § 4.5.3, together with the problems of measurement. In actual monitoring, where the first of these problems exists, the system of measurement is made up of a combination of equipment for measuring occupied bandwidth and receiving equipment. For the fourth problem, the requirements for the equipment used for receiving and for measuring occupied bandwidth are given in § 4.5.4.2.

4.5.4.2 Requirements for equipment used in monitoring

4.5.4.2.1 Requirements for receiving equipment

The receiving equipment suitable for the measurement of occupied bandwidth at a monitoring station must satisfy the following conditions:

– the frequency characteristic of the passband should be flat within ±0.5 dB over the range of the spectrum of the emission to be measured;

– the frequency selectivity should be such as to discriminate adequately against out-of-band noise and interference whilst not introducing a loss of more than 2 dB at the edges of the passband relative to the level at the middle of the passband;

– the equipment should exhibit good linearity for an input variation of at least 60 dB, in order to cope with possible variations of the field intensity of the emission to be measured.

4.5.4.2.2 Equipment for the spectrum analysis

Whenever a spectrum analyzer is used for bandwidth determination with the "*x*-dB" method, the mode of operation "maximum hold" (also known as peak memory) must be available. The equipment should have a good linearity and display range for input voltage variations of at least 60 dB.

For the measurement of narrowband emissions, a spectrum analyzer having a high degree of resolution is desirable, so that an accurate display of the emission spectral distribution may be obtained. A typical instrument has a maximum resolution of 10 Hz and provides a swept frequency range adjustable from 1 kHz to 100 kHz, together with a sweep rate adjustable from 1 to 30 sweeps per second.

For the analysis of wideband emissions, spectrum analyzers are available which incorporate a complete receiver as well as those designed for use with general-purpose receivers. Available instruments cover a frequency range up to 44 GHz with a sweep width continuously variable up to 100 MHz (at the higher frequencies). The sweep rate is adjustable from 1 to 60 sweeps per second.

For low sweep rates the display tube used should have a suitable long persistence in order that effective observations can be made.

4.5.4.2.3 Equipment for the power-ratio method

Because of the severe accuracy requirements imposed on the comparison attenuator, the method of comparing the in-band power with the total power is not recommended; therefore the equipment should be designed for comparing the out-of-band radiated power with the total power (as it is performed by equipment presented in § 4.5.2.2).

As a general-purpose measuring equipment, it is advisable that the equipment should be able to display each of the threshold frequencies, for which the mean powers above or below the indicated frequency is equal to 0.5% of the total power, to calculate the occupied bandwidth automatically and to record it directly.

The equipment should have a dynamic range of at least 30 dB. If the input level varies more widely, it is advisable that a variable attenuator is used for automatic control in accordance with the variation of input levels.

It is advisable that the measuring equipment should be able to reach full-scale indication within 0.3 -0.5 s, so that it can follow up the actual fluctuation of occupied bandwidth of an emission.

In order to make the accuracy of measuring the out-of-band radiated power better than 10%, the flatness of the passband should be better than ±0.5 dB and the loss in stop-band should be at least 30 dB. Also, the slope in the transition band should be steep.

4.5.4.2.4 Equipment using FFT-techniques

Reliable estimate of the occupied bandwidth of many PSK, CPM and QAM digital signals can be obtained using a β% method. For this method to provide meaningful results, it is necessary to perform suitable filtering of the measured signal, so as to avoid noise contributions to the bandwidth measurement. As a matter of fact, for most digital transmissions, the 99% power bandwidth is contained within the first lobe of the signal spectrum. A remarkable exception is the unfiltered PSK2 signal, which is seldom found as such on the air; however, practical PSK2 transmissions are often filtered at the transmitter side, so that the corresponding radiated waveform generally complies with the assumption of 99% power contained in the first lobe.

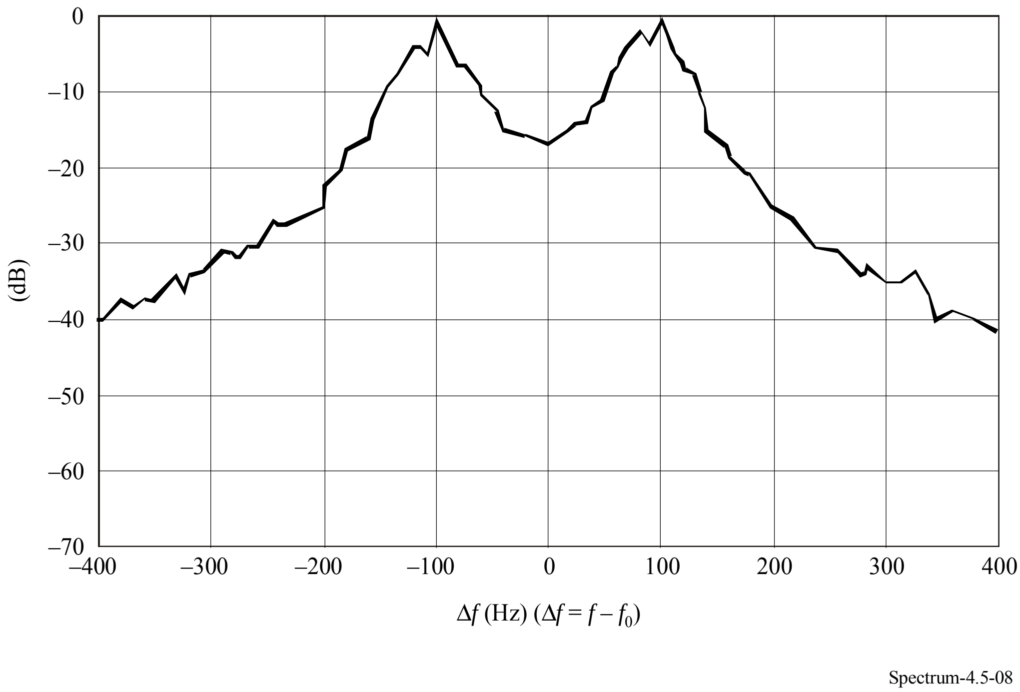
Thus, the equipment should offer an easy way to set different filter characteristics because of the effect of noise as described in § 4.5.2.1.2.

4.5.4.3 Method of occupied bandwidth measurement using a spectrum analyzer

This method is described by means of an example. Figure 4.5-8 shows the spectrum of an F1B emission using 50 bauds and 200 Hz shift on 123.7 kHz, and recorded with a spectrum analyzer in mode of operation "maximum hold", 5 scans, analysing filter bandwidth 30 Hz, sweep time 100 s per 2 kHz. The step width for the evaluation is 20 Hz, as can be seen from the graticule superimposed on the spectrum, which is merely used to determine the attenuation values for a given frequency.

FIGURE 4.5-8

Spectrum of an F1B emission using 50 bauds and 200 Hz shift on 123.7 kHz, and used to calculate the occupied bandwidth



Some modern spectrum analyzers have firmware functions for the evaluation of the occupied bandwidth working in a similar mode as described above. As long as these spectrum analyzers do not really show the r.m.s. values of the spectrum they give only a rough value of the occupied bandwidth.

Table 4.5-2 indicates the calculation steps in detail. For ß/2 = 0.5%, the calculation yields:

100% of relative power = 4.372984

0.5% of relative power = 0.021865

lower limit of occupied band ≈ f_0 – 180 Hz (see Note 1)

upper limit of occupied band ≈ f_0 + 170 Hz (see Note 2)

occupied bandwidth ≈ 350 Hz

NOTE 1 – The 0.5% value of the relative power is very close to the power value of 0.023266 for $\Delta f = -180$ Hz (see first and fourth column of Table 4.5-2, double-line borders).

NOTE 2 – The 0.5% value of the relative power at the upper end of the spectrum envelope lies approximately in the middle between the power values of 0.015718 and 0.031567 for $\Delta f = -180$ Hz and $\Delta f = 160$ Hz, respectively (see first and fifth column of Table 4.5-2, double-line borders).

TABLE 4.5-2

Calculation of the occupied bandwidth

Δf (Hz)	**p (dB)**	$P_{relative}$	$\sum_{-400\text{ Hz}}^{\Delta f} P_{relative}$	$\sum_{-400\text{ Hz}}^{\Delta f} P_{relative}$
–280	–31	0.000794	0.002321	.
–260	–31	0.000794	0.003115	.
–240	–28	0.001585	0.004700	.
–220	–27	0.001995	0.006695	.
–200	–24	0.003981	0.010677	.
–180	–19	0.012589	0.023266	.
–160	–14	0.039811	0.063076	.
–140	–8	0.158489	.	.
–120	–4	0.398107	.	.
–100	0	1.000000	.	.
–80	–5	0.316228	.	.
–60	–11	0.079433	.	.
–40	–14	0.039811	.	.
–20	–15	0.031623	.	.
0	–17	0.019953	.	.
20	–14	0.039811	.	.
40	–12	0.063096	.	.
60	–7	0.199526	.	.
80	–2	0.630957	.	.
100	0	1.000000	.	.
120	–6	0.251189	.	.
140	–13	0.050119	.	.
160	–18	0.015849	.	0.031567
180	–21	0.007943	.	0.015718
200	–26	0.002512	.	0.007775
220	–27	0.001995	.	0.005263
240	–31	0.000794	.	0.003268
260	–31	0.000794	.	0.002474
280	–33	0.000501	.	0.001679

Choosing a step width of 40 Hz and considering only the components between –260 Hz and 260 Hz, gives a result, which is also approximately 350 Hz. Thus, it is sufficient, in general, to choose a step width approximately equal to or less than 10% of the occupied bandwidth expected, provided that the envelope is still reproduced, and to consider only those components, which are approximately equal to or greater than –30 dB relative to the peak of the spectrum envelope.

In the example given the relative power level of 0 dB passes through the peak of the spectrum envelope.

This is convenient for the calculations but not essential; any other reference level will lead to the same result.

Note that the display readings are in dB (second column) while the definition requires summarising power values. Therefore the dB values are converted into relative power (third column).

References

ITU-R Recommendations

NOTE – In every case the latest edition of the Recommendation is encouraged to be used.

Recommendation ITU-R SM.328 – Spectra and bandwidth of emissions.

Recommendation ITU-R SM.329 – Unwanted emissions in the spurious domain.

Recommendation ITU-R SM.443 – Bandwidth measurement at monitoring stations.

4.6 Modulation measurement

4.6.1 Introduction

The basic fundamentals of the various modulations are covered in § 6.6. Section 4.6 focuses on the measurement of different modulation parameters, the identification of the modulation and analysis methods only.

4.6.2 Principle instrument sets

The instruments suitable for modulation measurements can be divided in three basic groups:

– General purpose instrumentation: Spectrum analyzer, standard (analogue) monitoring receiver and oscilloscope. The use is limited to analogue modulation measurements or for specific parameters of digital modulation.

– Dedicated devices: Modulation meter and modulation analyzer.

– Modern (digital) monitoring receivers and vector signal analyzers (VSA) associated with digital processing. This type of equipment may allow measurement of all modulation parameters.

4.6.3 Analogue modulation

4.6.3.1 Amplitude modulation

The key parameter to measure in analogue amplitude modulation (AM) is the modulation depth:

$$m\,(\%) = \frac{E_{max} - E_{min}}{E_{max} + E_{min}} \times 100$$

which for normal operation is between 0 and 100% and can directly be read from standard measurement receivers.

A critical state occurs when the carrier is overmodulated and m > 100%. This occurs if $E_{min} < 0$. However, it is not indicated by a measurement receiver. Instead, another definition of the modulation depth:

$$m \pm (\%) = \frac{E_{max} - E_{min}}{2E_c} \times 100$$

with E_c being the average level can be used. E_{max}, E_{min} and E_c can be measured for example with measurement receivers and spectrum analyzers. If $m+ = m- = m\pm$, the modulation can be considered symmetrical (i.e. the value of the carrier amplitude (= E_c) is not changed by modulation), the modulation percentage is < 100% and no overmodulation takes place.

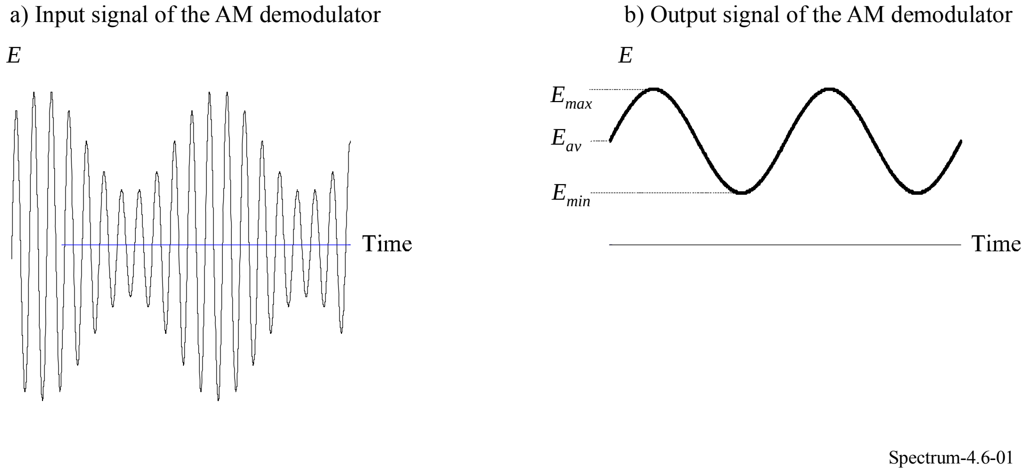
A more thorough investigation of modulation parameters is possible with special instruments called modulation meters or modulation analyzers (if they are equipped with special circuits which allow a closer examination of the demodulated signal, e.g. distortion and *S*/*N* ratio).

Usually modulation meters also indicate the value of the carrier frequency because this can be accomplished in state-of-the art instruments without additional effort.

The output of the AM demodulator is, for example, the positive envelope voltage of the modulated wave, as shown in Fig. 4.6-1. Figure 4.6-1a) shows the input and Fig. 4.6-1b) shows the output signal of the demodulator.

FIGURE 4.6-1

Input and output signals of the AM demodulator



The indication circuit now calculates the modulation depth. Correspondingly, the instrument indicates $m+$, $m–$, or $m\pm$. Comparison of these values shows whether modulation is non-symmetrical or overmodulation occurs ($m+ >1$).

Sometimes only the instantaneous values of the modulation depth corresponding to modulation peaks are required to check that there is no overmodulation. In this case, an oscilloscope connected to the intermediate frequency output of a receiver may be sufficient for a fast check. A spectrum analyzer with zero span (time domain) or a vector signal analyzer may also be used.

On the other hand, it may be interesting to know the mean modulation depth over given time intervals to ensure that the transmitter is used properly. Moreover, in some cases modulation quality may be of interest, as for example signal-to-noise ratio or distortion contents. In all these cases the use of a modulation analyzer, which also contains a precision modulation-depth meter, is necessary. Such an instrument presents the results in any desired form, e.g. on the front panel, on the screen of a PC or graphically, either printed or plotted.

4.6.3.2 Frequency and phase modulation

As explained in § 6.6, frequency and phase modulation (FM/PM) are principally the same and result in the same RF signal. For frequency/phase modulated signals, the key parameter to measure is the frequency deviation Δf which can directly be read from standard measurement receivers. The modulation index:

$$m = \frac{\Delta f}{fm}$$

can be calculated from the measurement result for Δf.

All properties of frequency and phase deviations can be measured using modulation meters. Another possibility to measure the deviation of FM broadcasting stations is the application of an IFM-based modulation domain analyzer, or a modern monitoring receiver (or VSA) with digital processing capabilities. The sampling rate must be chosen according to the modulation (e.g. at a minimum of 40 ksamples/s if the maximum modulating frequency is 15 kHz), and the measuring repetition time (time window) should correspond to the lowest frequency at which we wish to determine the deviation. The longer the measuring time, the lower is the modulation frequency that can be seen after processing the samples.

Phase and frequency deviation measurements of wanted signals are performed as peak value measurements, because by definition, phase and frequency deviations of communication signals are peak deviations. However, if noise or signal-to-noise or SINAD measurements have to be performed, r.m.s. values or quasi-peak weighted values of the respective deviations have to be taken into consideration. Therefore, PM and FM meters are usually equipped with detectors to give r.m.s., SINAD and quasi-peak (Recommendation ITU-R BS.468) results as well.

Measurement and evaluation of maximum deviation and modulation power of FM broadcast emissions over the air during normal programme operation is described in detail in Recommendation ITU-R SM.1268.

4.6.3.3 Simultaneous measurement of AM and PM/FM

Multipath propagation is a general problem for FM signals in the VHF bands and at higher frequencies. The result of multipath propagation in FM systems is unacceptable distortion of the modulated signal. Due to multipath propagation, PM or FM is converted into a certain percentage of AM by vectorial addition at the receive antenna. Therefore multipath propagation can be found by measuring the AM of a frequency-modulated carrier. For this purpose the modulation meter has to measure AM and PM/FM simultaneously. When it is necessary to determine whether the quality of the FM broadcast signals is sufficient, the percentage of PM/FM versus AM conversion has to be measured.

For this purpose, instruments are available which offer parallel measurements of deviation and modulation depth with immediate calculation of the conversion factor, expressed in % modulation depth over kHz FM deviation.

Recommendation ITU-R SM.1268 defines maximum values for the amount of AM as well as other prerequisites for an accurate measurement.

4.6.3.4 Special analogue modulations

4.6.3.4.1 TV broadcast modulations

One important property of the modulation of analogue TV broadcast (VSB) transmissions in the VHF/UHF bands is the level of the subcarriers (e. g. for sound and colour burst) relative to the vision carrier. This can be measured with a spectrum analyzer using a resolution bandwidth of at least 100 kHz. The nominal values are system dependent and can be taken out of the appropriate standard documentation.

According to the respective standard, parts of the TV signal are kept constant in amplitude, independent of the picture content. For this reason, conventional modulation depth measurement of the video modulation makes no sense.

The presentation of the IF signal or demodulated video signal on an oscilloscope is useful and gives a good impression of the modulation. A minimum bandwidth of 5.5 MHz of the IF output and – if used – the video demodulator of the receiver is a prerequisite for the correct presentation.

Special analogue TV analyzers are available that allow the detailed analysis of the picture modulation including contents of the test lines inserted between subsequent frames.

Deviation measurements of the sound channels can be performed in the conventional way, provided that the selectivity of the modulation meter is sufficient.

4.6.3.4.2 Single sideband modulation with suppressed carrier

With this modulation type, the carrier is suppressed and the modulation depth is not defined. Consequently, the modulation depth cannot be measured.

4.6.3.4.3 Independent sideband modulation

The statements above regarding single sideband (SSB) with suppressed carrier also apply to independent sideband modulation (ISB) with suppressed carrier (B8E).

No measurement of the modulation characteristics in the conventional way is possible.

4.6.3.4.4 Dynamic amplitude modulation

As explained in § 6.6, this modulation reduces the carrier level whenever the modulation depth is low to save transmit energy. The carrier power is a function of the modulation level. In this case, without knowledge of details of the characteristic of the transmitted signal, the indication of a conventional modulation meter cannot be correct. To find out whether Dynamic amplitude modulation (DAM) is used or not, the average carrier level has to be measured with a slow time-constant.

4.6.4 Single carrier digital modulation

Depending on certain system parameters, single carriers being amplitude, frequency and/or phase modulated such as ASK, FSK, PSK, MSK and QAM have similar if not equal spectra and cannot easily be distinguished using a swept spectrum analyzer. Measurements of the modulation depth and frequency deviation using standard modulation meters or measurement receivers are often not possible. Instead, the following modulation properties may be of interest:

– identification of modulation and number of constellation states;

– symbol rate;

– baseband filtering;

– modulation errors.

4.6.4.1 Symbol rate

In order to decode a digital signal, the receiver must be time-synchronized to the transmitter which means that the symbol rates must match exactly. Unless the equipment used has digital signal identification capabilities, monitoring receivers and vector signal analyzers only work when the correct symbol rate has been entered by the operator. Standard measurement equipment can not measure the symbol rate and if it is unknown, further analysis and decoding is not possible.

Due to the smooth change of amplitude and/or phase of baseband filtered signals, it is generally not possible to measure the symbol rate with an oscilloscope connected to the IF of a monitoring receiver.

As a rule of thumb, however, it can be taken that the symbol rate is roughly equal to the occupied bandwidth of the signal. Table 4.6-1 shows some examples for common digital single carrier systems.

TABLE 4.6-1

Symbol rates and bandwidths of example single carrier systems

System	Bandwidth	Symbol rate
TETRAPOL	7.2 kHz	8 kSymb/s
TETRA	21 kHz	18 kSymb/s
DECT	1.1 MHz	1.152 MSymb/s
GSM	250 kHz	270.833 kSymb/s
UMTS (European)	4.2 MHz	3.84 MSymb/s
Bluetooth	950 kHz	1 MSymb/s
WLAN DSSS (802.11b)	13 MHz	11 MSymb/s

Special digital modulation analyzers and especially equipped modern monitoring receivers are able to measure the symbol rate by applying mathematical methods. These are explained in the next section.

4.6.4.2 Identification of modulation and number of constellation states

As said earlier, it is not possible to uniquely identify each single carrier modulation with standard measurement receivers or swept spectrum analyzers. However, certain "hints" can be obtained by measuring the difference between peak and RMS level (for pulsed signals: the difference between peak and average burst level). For details see § 4.3. This difference is called the CREST factor. If it is zero (both levels are equal), the modulation can only be FSK or MSK, because all other single carrier modulations have inherent amplitude modulation.

For FSK and MSK modulations, the frequency shift can be measured with an oscilloscope connected to the IF of a standard measurement receiver.

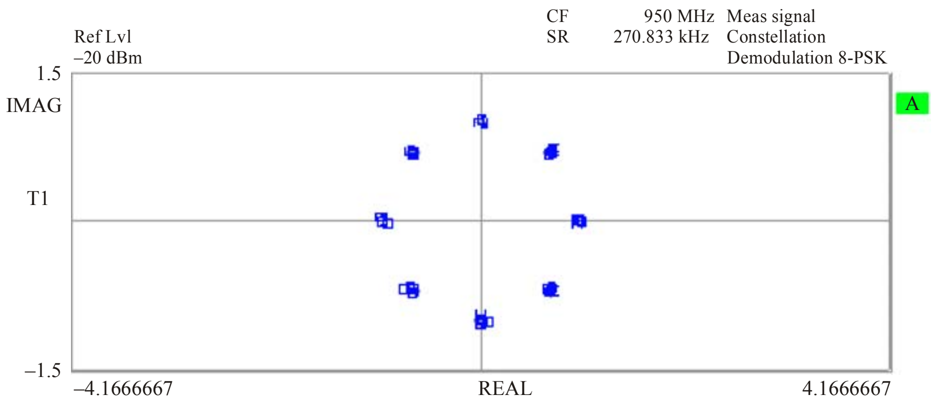
For ASK modulation, the modulation depth can be measured with a spectrum analyzer in zero span mode or an oscilloscope connected to the IF of a standard measurement receiver.

To further identify the modulation used, equipment performing the functions of a vector signal analyzer or FFT analyzer/receiver is needed that is capable to retain amplitude, frequency and phase of the modulating signal. After entering the symbol rate, these analyzers/receivers allow displaying the constellation diagram like in Fig. 4.6-2. For details on the constellation diagram, see § 6.6.

Further information on the modulation properties can be gained if the analyzer also displays the RF vector between the constellation points (i. e. continuously at any time). The resulting display is commonly called vector diagram. Figure 4.6-3 shows the vector diagram of the 8-PSK signal from Fig. 4.6-2.

FIGURE 4.6-2

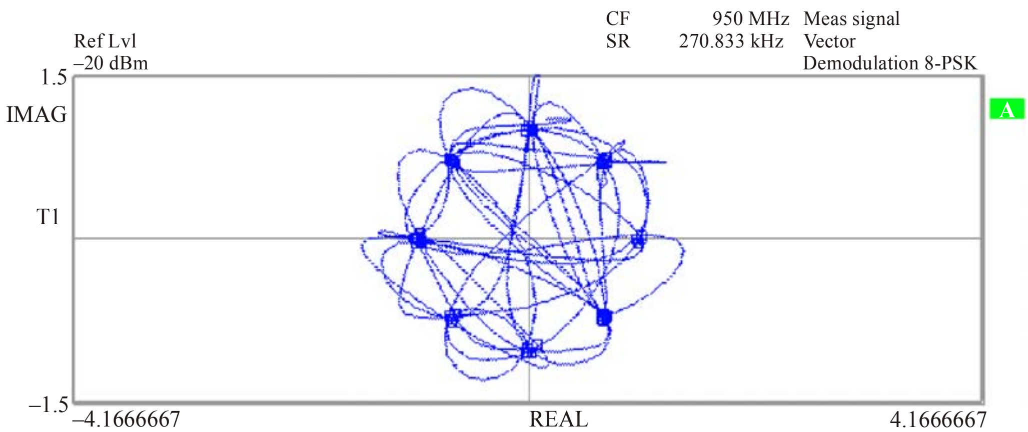
Constellation diagram of an 8-PSK signal



Spectrum-4.6-02

FIGURE 4.6-3

Vector diagram of an 8-PSK signal



Spectrum-4.6-03

Special digital modulation analyzers are available that allow under certain conditions the identification of the modulation and the measurement of the symbol rate of a complete unknown signal. These analyzers are often software solutions running on a standard PC and fed with a pre-recorded sequence of the signal under investigation. Measurement techniques are based on signal transform functions such as:

Spectrum correlation and moments method

A cyclic autocorrelation of the spectra derived from several subsequent FFT processes is performed. The result may be plotted as a two dimensional diagram showing distinct peaks at the constellation points and the time it takes for the transition between them. Figure 4.6-4 shows an example of a BPSK signal.

Spectrum of the signal raised to the power of N

This method is based on the Fourier Transform of the signal previously raised to the power of 2 or 4. Depending on the modulation, the result shows distinct peaks which represent the number of constellation states.

Histogram method

A histogram of instantaneous frequencies or amplitudes or phases is calculated.

Depending on the modulation type, the values of calculated peaks characterize the modulation parameters.

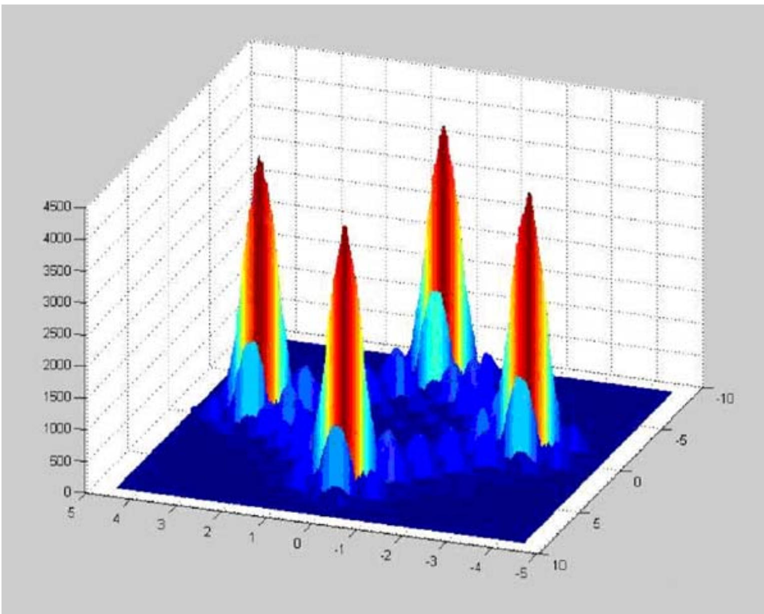
Spectrum of zero-crossing

This method evaluates the momentary frequency of the complex baseband of the input signal. The centre frequency of this baseband is zero. The zero crossing function now creates a peak in the time domain whenever the frequency of the (modulated) baseband signal crosses zero. Then the times between consecutive peaks (t_n) of the zero crossing function are determined and a new "spectrum" is calculated using the relation $f = 1/t_n$.

Figure 4.6-5 illustrates the process.

FIGURE 4.6-4

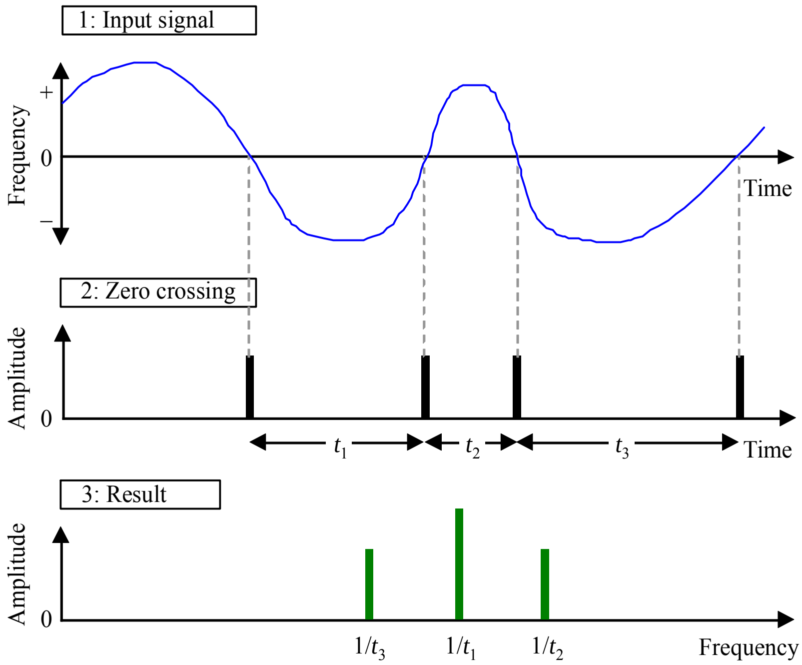
Spectrum correlation result of a BPSK signal



Spectrum-4.6-04

FIGURE 4.6-5

Principle of the zero crossing method

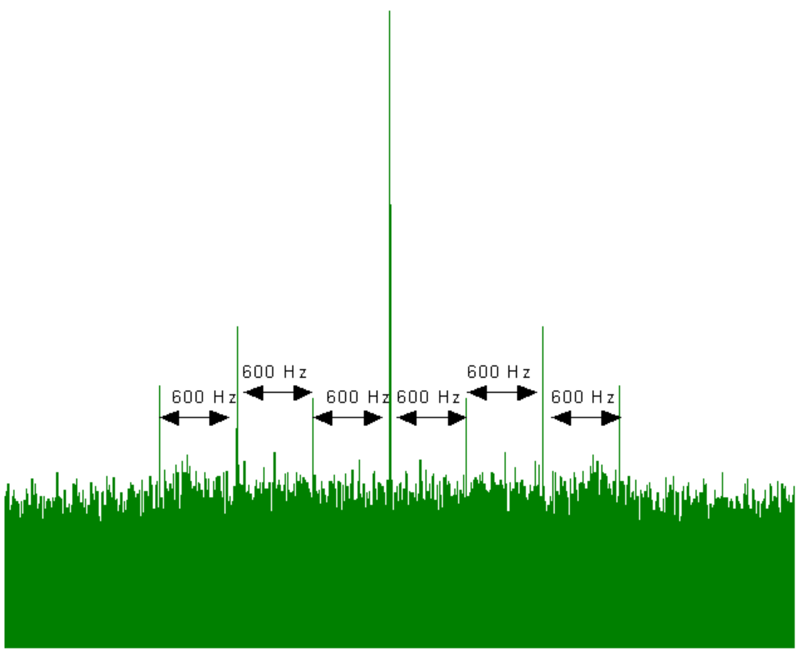


Spectrum-4.6-05

An example of the result of the zero crossing method is shown in Fig. 4.6-6.

FIGURE 4.6-6

Zero crossing for a QPSK signal with 600 symb/s



Spectrum-4.6-06

These methods often provide more information than just the number of modulation states. Table 4.6-2 summarizes the capabilities of each of the methods mentioned above.

TABLE 4.6-2

Possible measurement methods for digital modulation parameters

Modulation	Measurement of...	Spectrum correlation and moments method	Spectrum of the signal raised to the power of *N*	Histogram method	Spectrum of zero-crossing
ASK	Carrier frequency	√			
	Symbol rate		√ (N = 2)		
	Number of states			√	
FSK	Carrier frequency			√	
	Symbol rate	√			√
	Number of states		√ (N = 1)*	√	
PSK	Carrier frequency	√	√ (N = 2)		
	Symbol rate		√ (N = 2or 4)	√	√
	Number of states			√	
MSK	Carrier frequency		√ (N = 2)		
	Symbol rate		√ (N = 2)		√
	Number of states			√	
QAM	Carrier frequency	√			
	Symbol rate		√ (N = 4)		√
	Number of states	(Not possible with these methods)			

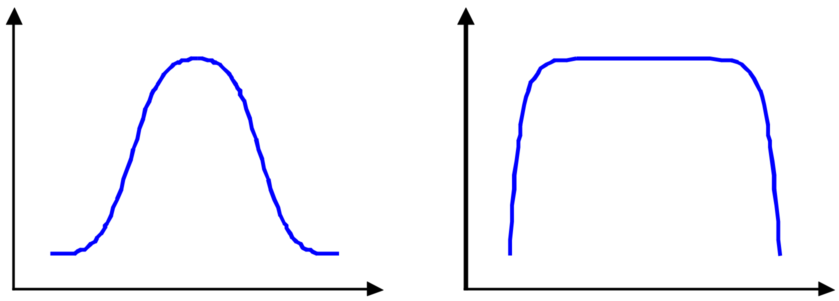
* Depending on modulation index.

4.6.4.3 Baseband filtering

As explained in § 6.6, only Gaussian and Cosine (or root raised cosine (RRC)) filtering is used to reduce the bandwidth of digital single carrier signals. Which type of baseband filtering is used can be taken from the characteristic shape of the RF spectrum (see Fig. 4.6-7).

FIGURE 4.6-7

Spectra of filtered digital single carrier signals



Spectrum-4.6-07

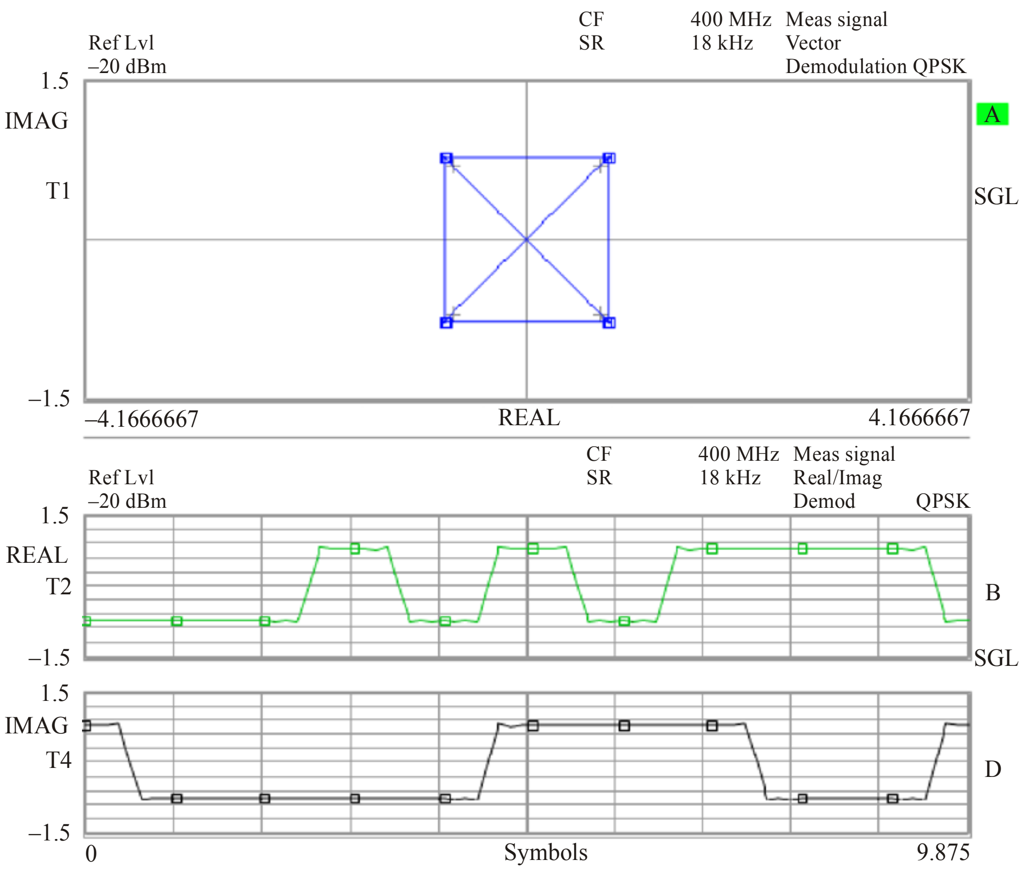
A vector signal analyzer is usually capable of displaying the I and Q components of the modulating signal in the time domain. Figures 4.6-8 and 4.6-9 show this with the example of a QPSK modulated signal for the length of 10 symbols. In Fig. 4.6-8, no baseband filtering was applied. Figure 4.6-9 shows the same signal with cosine baseband filtering.

It can be seen that the baseband filtering “smoothes” the sharp edges in the modulating baseband while still ensuring that the RF vector reaches the nominal constellation points exactly at the time of decoding.

The smoother changes of the I and Q components result in “overshooting” the constellation points sometimes which raises the peak amplitude of the RF signal. However, the bandwidth is significantly reduced.

FIGURE 4.6-8

Vector diagram and I/Q time domain of an unfiltered QPSK signal



Spectrum-4.6-08

4.6.4.4 Modulation error

Vector signal analyzers and modern digital monitoring receivers are usually also capable to measure at least the following errors:

– quadrature offset;

– gain imbalance;

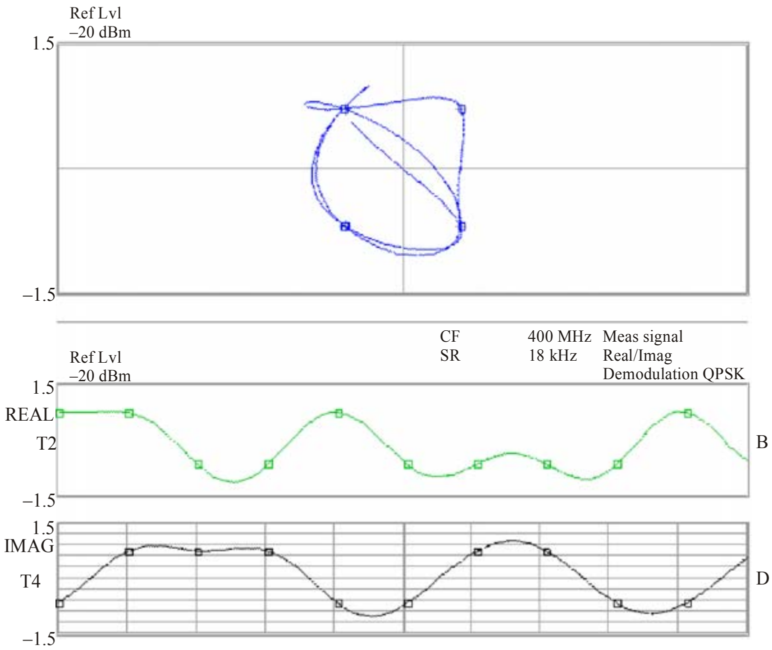
– I/Q offset.

Figure 4.6-10 shows the error measurement of a 16-QAM signal with considerable I/Q offset.

The sum of all these modulation errors can be expressed as the error vector magnitude (EVM). It is usually given in %.

FIGURE 4.6-9

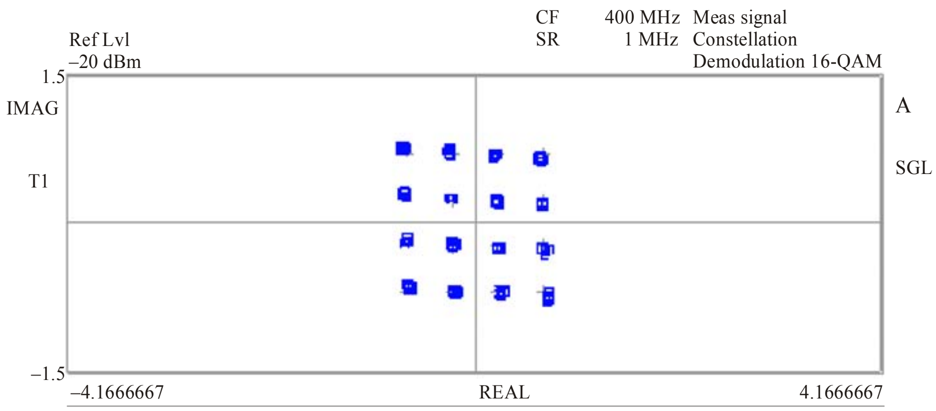
Vector diagram and I/Q time domain of a QPSK signal with Cosine filtering



Spectrum-4.6-09

FIGURE 4.6-10

Modulation error measurement example



Symbol/Errors
Demodulation 16-QAM

Symbol table

0	11000111	00010000	10101111	01111000	11011001
40	00110111	10100011	01010100	00111010	01010011
80	01010010	11010001	01010111	11010000	11100001

B

Error summary

SGL

Error vector magnitude	4.97% r.m.s	9.26%	Pk	at	sym	292
Magnitude error	4.13% r.m.s	–9.25%	Pk	at	sym	292
Phase error	2.36% r.m.s	–7.88°	Pk	at	sym	39
Frequency error	–22.17 Hz	–22.17 Hz	Pk			
Amplitude droop	11.12 dB/sym	Rho Factor				0.9953
IQ offset	0.07%	IQ imbalance				6.02%

Spectrum-4.6-10

4.6.5 Multicarrier digital modulation

Many modern digital communication systems use orthogonal frequency-division multiplex (OFDM). For OFDM signals, the following modulation parameters may be of interest:

– modulation type;

– number of carriers;

– carrier spacing;

– symbol time;

– guard interval.

4.6.5.1 Modulation type

As with single carrier systems, the modulation type can not be determined by using standard monitoring equipment like spectrum analyzers. Even most vector analyzers only work with single carrier systems.

To separate the single carriers of an OFDM ensemble, specialized signal analyzers are necessary. Some modern monitoring receivers in conjunction with suitable signal processing software may also be suitable.

They can usually display the constellation diagram either of all carriers or of selected carrier numbers only. From this display the modulation of the subcarriers may be identified.

4.6.5.2 Number of carriers and carrier spacing

Due to their modulation, the spectra of the subcarriers overlap. It is therefore difficult to visually separate them with a standard spectrum analyzer.

However, with a long-term trace average mode in conjunction with a narrow resolution bandwidth (RBW < 1/10 Δf), the spectrum analyzer would show a picture like in Fig. 4.6-11.

The spectrum in Fig. 4.6-11 is part of a DAB signal where a carrier spacing Δf of 1 kHz can be measured.

The number of carriers can be calculated by the bandwidth between the outer carriers which is easily determined by a spectrum analyzer and the carrier spacing.

4.6.5.3 Symbol time

The symbol time T_s is:

$$T_S = \frac{1}{\Delta f}$$

where Δf is the frequency separation between two neighbouring subcarriers. In the example in Fig. 4.6-11, the resulting symbol time would be 1 ms.

A more precise way to measure the symbol time requiring special equipment or software is to calculate an autocorrelation function of the (pre-recorded) time signal. An example is shown in Fig. 4.6-12.

The autocorrelation figure will show a peak at a time offset equal to the symbol time.

The length of the guard interval T_g can not be measured with standard monitoring equipment. Instead, specialised OFDM signal analyzers have to be used.

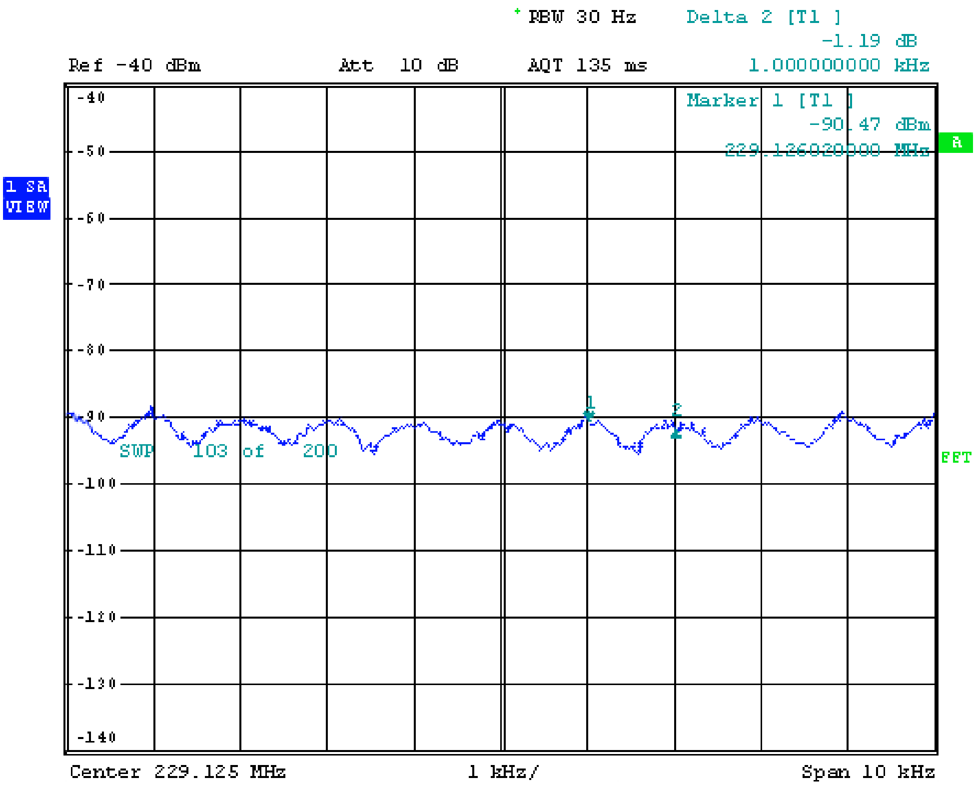
One way to determine the guard time with this type of equipment is by performing a cyclic autocorrelation process on the time signal.

The result will show peaks for those time intervals where some of the transmitted information repeats itself.

These times will be $T_s + T_g$. If T_s is known (or has been measured before), T_g can be calculated. Figure 4.6-13 shows an example.

FIGURE 4.6-11

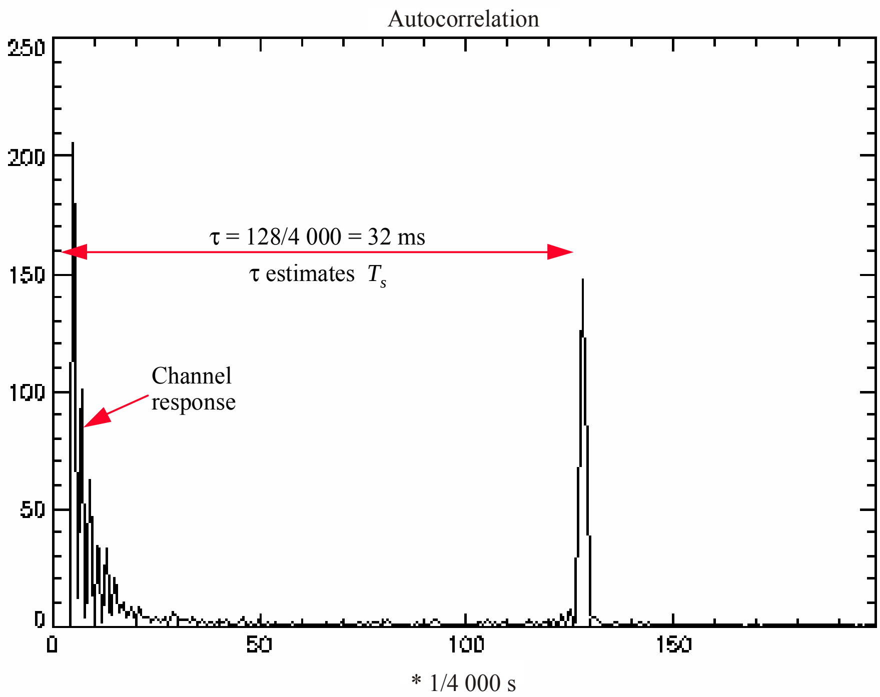
Part of an OFDM spectrum with high resolution



Spectrum-4.6-11

FIGURE 4.6-12

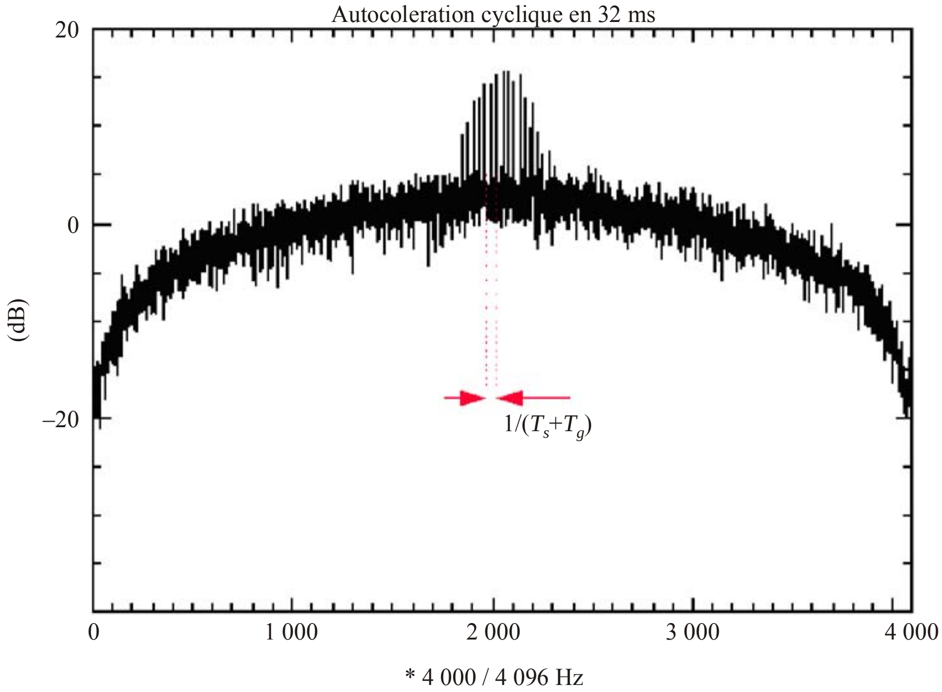
Autocorrelation of an OFDM signal



Spectrum-4.6-12

FIGURE 4.6-13

Cyclic autocorrelation of an OFDM time signal



Spectrum-4.6-13

4.6.6 Measurement errors

Possible sources of measurement errors are:

– an instrument bandwidth narrower than the modulated signal;

– noise or interfering co-channel signals;

– interfering signals on adjacent channels;

– reflections and multipath reception.

To avoid this problem, measurements have to be performed at the most favourable *S*/*N* ratio of the receiver (modulation meter) and using a directional antenna to eliminate as much as possible unwanted signals and obtain the maximum voltage of the wanted signal. The measurement bandwidth has to be selected in a way that it just covers the wanted signal.

Especially deviation measurements of FM signals with high AM content due to multipath propagation give erroneous results. The indicated value can be excessively high (e.g. by a factor of 2). Multipath reception must be avoided in any case when deviation measurements are performed.

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ITU-R Recommendations

NOTE – In every case the latest edition of the Recommendation is encouraged to be used.

Recommendation ITU-R BS.468 – Measurement of audio-frequency noise voltage level in sound broadcasting.

Recommendation ITU-R SM.1268 – Method of measuring the maximum frequency deviation of FM broadcast emissions at monitoring stations.

4.7 Radio direction-finding and location

4.7.1 General considerations

The purpose of radio direction-finding (DF) is to determine the line of bearing (LoB) of any source of electromagnetic radiation by means of the propagation properties of radio waves.

Considering in this general manner, DF can be used to determine the direction of a radio transmitter or a source of radio noise.

The use of several direction-finders (triangulation method) or direct location methods become necessary in the following cases:

- location of a transmitter in a distress situation;
- location of an unauthorised transmitter;
- location of an interfering transmitter which cannot be identified by other means;
- determination of the site of a source of harmful interference of reception, such as electrical equipment, defective insulators on a power line, etc.;
- identification of transmitters, both known and unknown.

The purpose of § 4.7 is to give a comparison of the different methods used to perform direction finding and location of an emitter.

4.7.2 Radio direction-finding

A DF is a sensor determining the direction of the arrival or azimuth (and elevation, if at HF) of an electromagnetic wave (under ideal conditions) with regard to a reference direction.

Without going into details of the phenomena involved in radio propagation, it is assumed that propagation is always along the arc of the great circle linking the radiation source to the receiving point.

In these circumstances, with appropriate receiving equipment giving the direction of the incoming wave, it is possible to take bearings of the source (transmitter and interfering current) and to know the direction of that source at the place of reception.

The functional architecture common to all (DFs) includes:

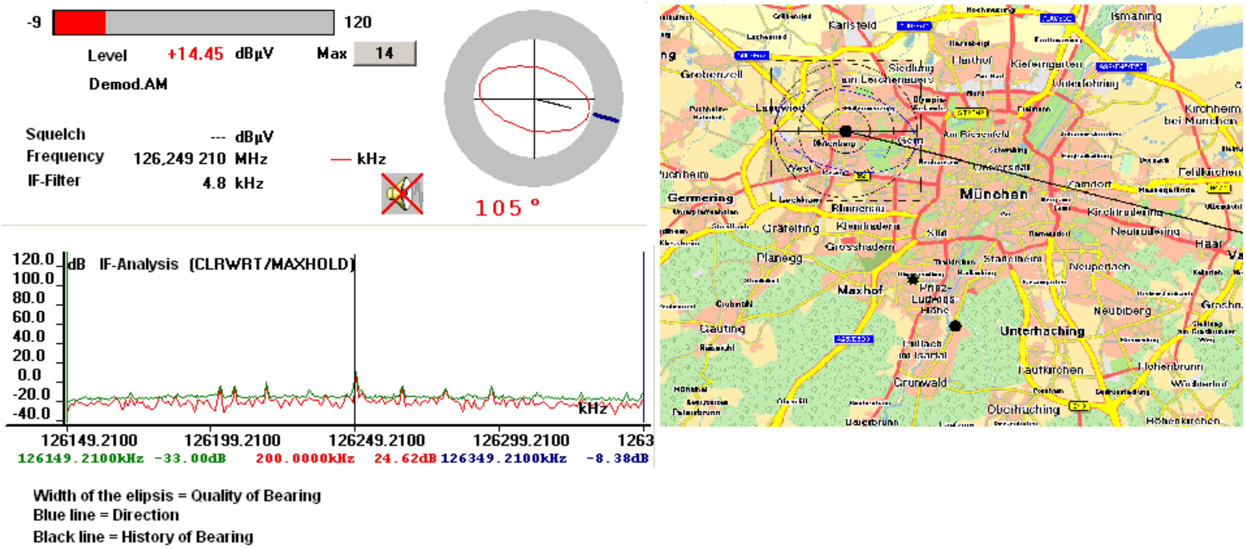
- an antenna array;
- a receiving assembly;
- a DF processor.

An example of the DF's display is shown in Fig. 4.7-1.

The elementary results should appear: angle of arrival, signal level, bearing quality, spectrum and map display.

FIGURE 4.7-1

An example of the direction-finder's display



Spectrum-4.7-01

4.7.2.1 Discussion of basic architecture, performance and problems

Selecting a direction-finding system is always delicate as it represents selection of a compromise on performance facing a given operational situation. There are a number of characteristic features which a direction-finder must have, irrespective of the DF principle used. The operational and design features of the equipment (mode of display, operational concept, remote-control capability, temperature range, mechanical robustness, shape, weight, power consumption, etc.) must meet the requirements of the particular application.

The main DF engineering features are:

- accuracy;
- sensitivity;
- immunity to distorted wavefronts;
- insensitiveness to depolarisation;
- effects of co-channel interference;
- resistance to receiver desensitisation;
- minimum signal duration time.

In comparison of different DF methods, such as that which follows below, only these main DF features are relevant and therefore only these will be considered here.

Typical specifications for direction finders may be found in § 3.4.6.

4.7.2.1.1 Accuracy

Accuracy

As to the specified accuracy, it should be noted that the system error has two components.

The first component, azimuth error, depends on the direction of incidence of the signal, siting and surrounding topography. The second component, frequency error, is a DF error as a function of the selected frequency.

The DF accuracy may be tested in a real environment, on an open-air test site or on a laboratory platform.

It should be clear that values of DF accuracy can differ considerably depending on the test environment.

The accuracy of the system can be measured according to three methods as described in Report ITU-R SM.2125:

– in a real environment which represents the final operational environment, with a variety of modulations and using signals of the minimum *S*/*N* ratio specified by the manufacturer of the system;

– at an Open air test site (OATS) which is normally defined for signals with a sufficient (> 20 dB) *S*/*N* ratio and where no reflections from nearby obstacles, ambient noise, and other radio signals may interfere with the measurement; the DF errors, which result from the propagation medium (e.g. ionosphere) and multipath effects are of course not included;

– on a platform: the DF station without its antenna is connected to a simulator and a generator.

Calibration and correction

All the DF techniques must implement calibration to ensure that the required high level bearing accuracy is obtained.

Two calibration techniques may be implemented:

– Calibration of the physical structures of the DF. In order to reduce impact of mast interference, and/or resonances between antennas and/or vehicle roof interference, a calibration should be accomplished. This calibration occurs in-factory mainly for VHF/UHF DF. This is especially important when the antenna is fixed on the roof of a vehicle. However, precisely built DF antennas on top of masts without mast resonances in the frequency range of the DF antenna, and without obstacles in the vicinity of the antenna, should not need any calibration, which reduces cost and increases flexibility (e. g. spare parts do not need to be calibrated).

– Periodic calibration to correct for time and temperature drifts of each of the DF receiving channels and antenna parameters. This calibration is usually based on injection of in-phase local oscillator signals on all antenna switch inputs to equalize the channels. A double averaging method may also be used to obtain the same drift compensation without need of any periodic calibration.

Once a direction-finder has been installed, there are additional error considerations other than equipment tolerances. Errors related to siting of the DF (multipath, terrain, nearby objects, etc.), also need to be considered, and they will vary depending on site. Bearing errors caused by the surroundings should be corrected after installation in order to correct both sources of error by using known reference transmitter locations in various directions, across the frequency range of operation. Once these corrections have been established a curve can be plotted or the data stored showing. For each frequency band the correction to be applied to the direction-finder readings to obtain true bearings.

4.7.2.1.2 Sensitivity

The sensitivity of a direction-finder is a very important feature, especially in radio monitoring. Whereas in air traffic control, for instance, there is no special requirement for maximum sensitivity but rather for sufficient margin of the S/N ratio, radio monitoring is often faced with the problem of evaluating signals that are hardly detectable.

Good sensitivity is important in two aspects:

– for extending the coverage of direction-finders under good receiving conditions;

– for sufficiently reliable direction-finding under less favourable conditions.

Quite generally, the sensitivity of a direction-finder is closely linked to the duration of observation (time for averaging of several measurements) and is usually defined together with a specified bearing fluctuation (due to noise).

The variation of the sensitivity is inversely proportional to the D/λ ratio (D – diameter of DF antenna, λ – wavelength of the received signal), the S/N ratio, the available integration time and the selected bandwidth.

Report ITU-R SM.2125 discusses sensitivity in more details and summarized procedures for measuring sensitivity.

4.7.2.1.3 Effect of multipath propagation and multiple sources

Multipath propagation

In some circumstances (urban areas or mountainous locations), severe propagation effects (mask and shadowing effects, flat and selective fading) can be observed.

Multipath phenomena is due to multiple signals coming from the same source arriving at the receiver antenna with different angles and times of arrivals due to reflection or due to diffraction during the radio propagation, as shown on Fig. 4.7-2.

The effects of multiple paths for the angle-of-arrival (AOA) determination are variable:

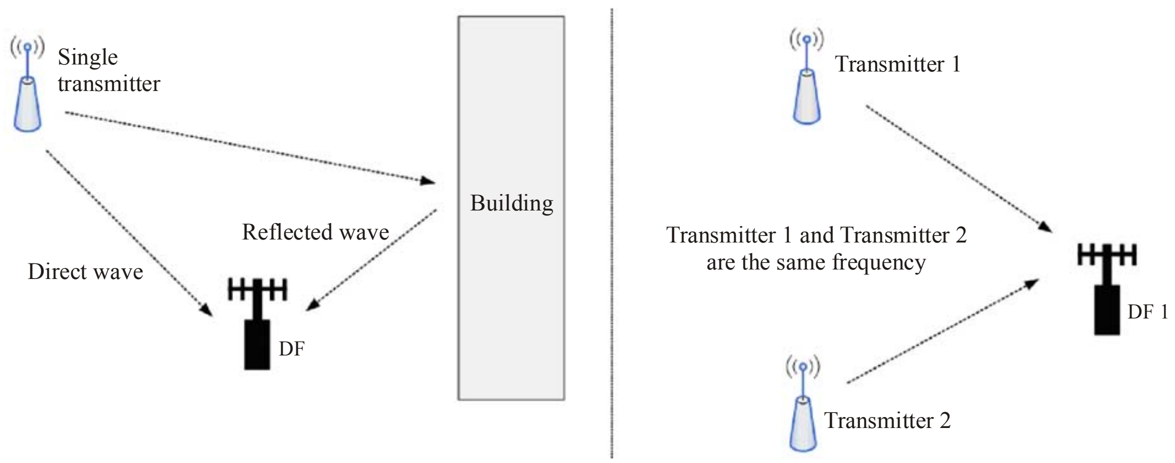
– usually, long range multiple paths (i.e., multiple paths that are caused by reflections) generate only bias in the AOA determination;

– the situation is rather different when the reflectors are close to the direction finder. If one multipath reflected by a close building or vehicle is stronger than direct one, DF result may be false. If the signal reflected by a close building or vehicle is not as strong as the direct one, DF result may be biased;

– in the right picture, signals on the same frequency arrive at the direction finder from different directions also creating a multiple source situation.

FIGURE 4.7-2

Example of multi-path situation (left picture) and multiple sources (right picture)



Spectrum-4.7-02

Multiple sources

A multiple source situation appears when two transmitters at different locations are using the same frequency. In such situations, AOA in combination with other methods must be adapted to the complex radio-electrical environment.

Four main cases can be observed:

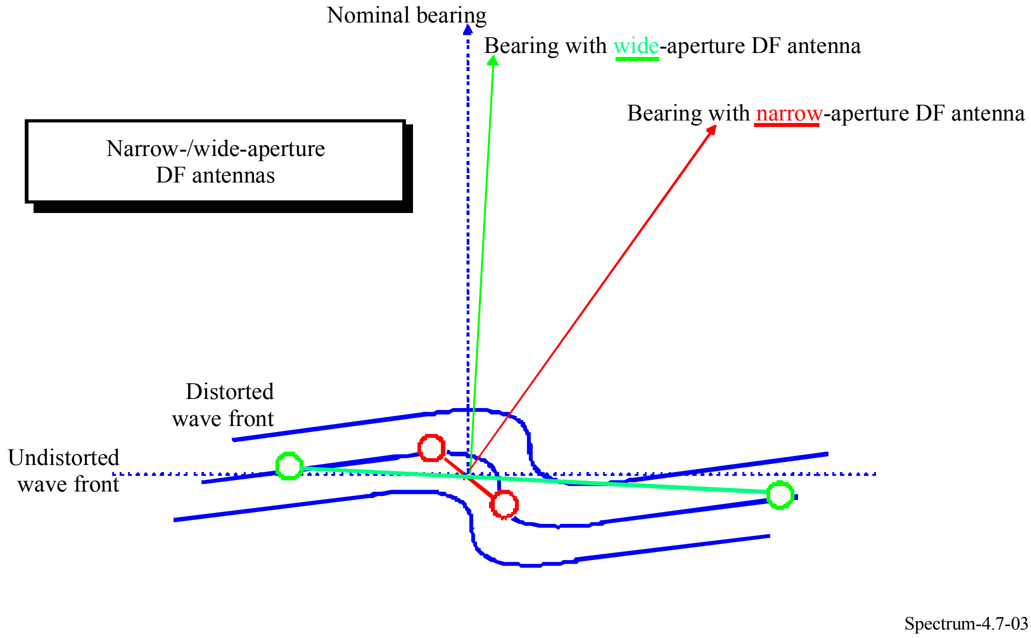
1. Intra-network interference: both signals come from different transmitters that belong to the same network. Frequency re-use schemes may lead to such interference if propagation is favoured along one long path.
2. Extra-network interference: the two signals come from different communication systems.
3. The signal of interest interferes with a signal external to the network.
4. During digital network deployment when analogue and digital transmitters operate at the same time.

Consequences for DF techniques

Irrespective of the DF technique, each direction-finder derives its directional information from the electromagnetic field, which is generally assumed to be homogeneous, with undisturbed propagation. In this ideal case, which in fact hardly ever exists, the wave fronts are planar; the lines with equal phase and equal amplitude are parallel straight lines (see Fig. 4.7-3).

FIGURE 4.7-3

Narrow/wide aperture DF antenna



Along their propagation path electromagnetic waves are reflected by obstacles and diffracted by edges. There is also the possibility of multipath reception due to special, mostly frequency-dependent, propagation conditions. As a result there is interference and the original planar wavefront is distorted. Different distortions result from the relationships in amplitude, phase, number and differential angle of the mutually interfering waves.

Depending on its diameter *D*, a DF antenna detects only a small part of the wavefront. The direction determined is always the line perpendicular to the averaged wavefront section. In a distorted field extremely different results are to be expected, depending on the DF antenna aperture relative to the spatial period of the isophase ripple in the distorted field. It is therefore advisable to choose a DF antenna with large dimensions relative to the wavelength λ to minimise the errors caused by field distortions. A ratio of $D/\lambda > 1$ refers to wide-aperture direction-finding, whereas D/λ less than 0.5 applies to narrow aperture direction-finding antenna. The intervening ratio generally applies to medium aperture direction-finders.

The capability of operating with a wide aperture is of prime importance to limit the influence of obstacles close to the DF antenna, which generate the most disturbing multipath as they can be widely spaced in azimuth from the direct path while having similar amplitudes.

4.7.2.1.4 Effect of depolarisation

Depolarisation is a shift of the polarisation plane between the DF antenna and the incident wave. The polarisation response of a direction-finder is strongly dependent on the antenna system used and consequently also on the DF method.

In this case, nearly all manpack or vehicular transmitters use vertical polarisation, for both practical and propagation reasons, and so the VHF and UHF DF antennas are often composed of vertical dipoles. In so far as the horizontal component of the receiver field is small, the error induced in direction-finding is negligible. Adaptation to horizontal polarisation is justified in the case of FM broadcast or TV transmitters or in the case of moving aircraft or helicopter direction-finding. In this case, either the direction-finder operates on the vertical component of the transmitted wave, or DF antennas matched to horizontal polarisation can be used.

4.7.2.1.5 Minimum signal duration

Depending on the operating principle of a direction-finder, the signal must be available for a certain minimum time to allow bearings to be taken. Signal duration less than 1 ms are achievable with narrow and broadband receivers.

This performance mainly depends on the DF techniques and on the signal processing capabilities of the equipment.

4.7.2.2 Different DF techniques

Selecting a DF system for one specific application is typically a matter of combining features in antenna, receiver and processor design in some optimum arrangement. Radio direction-finding techniques have traditionally been divided into three basic approaches: amplitude sensing systems, phase sensing systems, and systems that sense both amplitude and phase. Many modern DFs employ combinations of phase and amplitude sensing techniques. This section compares a sampling of DF techniques in a simplified overview and illustrates the differences in the most popular methods. A comprehensive discussion of the theory of operation for each of these techniques is beyond the scope of this Handbook. Those readers who desire a more technical explanation are referred to texts on DF techniques.

Modern DF techniques are:

- rotating antenna;
- Doppler and pseudo-Doppler;
- adcock / Watson-Watt;
- phase interferometer;
- correlative interferometer;
- advanced resolution.

Each technique is examined in terms of performance factors and highlighted in terms of its unique features.

4.7.2.2.1 Rotating antenna

A very simple way of detecting the angle of arrival of a signal (AOA) is the use of a rotating antenna / antenna system. A loop antenna can be manually rotated to steer a null in the direction of arrival. A remote controlled antenna and receiver can be used to show the input level of the receiver as a function of angle. A vertically or horizontally polarised directional antenna can be used. To improve the bearing result an antenna system of two identical antennas that provides the sum or the difference of the input levels of the two antennas can be used. The difference results in a very sharp minimum when the antennas are pointed in direction to the transmitter. The summing signal has a higher sensitivity but the directivity is much lower, see Fig. 4.7-4.

This direction finding method can be used for all transmissions which are longer on air than the equipment needs for two revolutions of the antenna system. This method also proved its usability in radio systems using more than one transmitter on the same frequency like DVB-T, TETRA, GSM, etc.

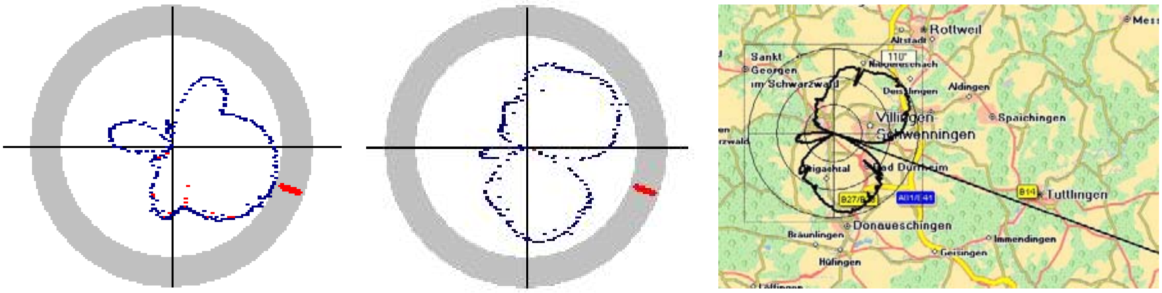
Fast rotating antenna systems may have a rotating speed up to 200 r.p.m whereas slow ones need more than 1 min for a whole circle. The received polarization depends only on the antenna mounting.

Another advantage of this method compared to others is that it can be used for vertically and horizontally polarised signals.

The lower frequency limit is determined by the mechanical dimensions of the antenna and will usually not be below 80 MHz. The upper frequency is mainly limited by the specification of the swivel coupler between the mast and the antenna. So called spinning antennas are available for frequencies up to 40 GHz.

FIGURE 4.7-4

Antenna pattern a) Sum, b) Difference, c) Difference displayed in a map



a) b) c)

Spectrum-4.7-04

TABLE 4.7-1

Examples of installations

Frequency range	Polarization	Antenna coupling	Rotating speed
80 – 1 000 MHz	vertical, horizontal	sum, difference	60 r.p.m
80 – 1 300 MHz	Vertical	sum, difference	1 r.p.m
500 MHz – 40 GHz	45°	sum, difference	≤ 200 r.p.m

4.7.2.2.2 Doppler and pseudo-Doppler

Doppler and pseudo-Doppler were developed in the 1950s, by studying the Doppler shift imparted by a moving antenna on a received signal. The rate of mechanical rotation for the direct Doppler principle is generally impractical at frequencies below the UHF band, so an electronic switching method was developed to simulate the antenna rotation scheme with a fixed, circular array. This technique is known as the pseudo-Doppler method.

To obtain unambiguous DF results, the spacing between the individual antenna elements must be less than half of the operating wavelength, in practical installations one third of the wavelength is selected.

DF systems using (pseudo-) Doppler technology have a good sensitivity combined with a good immunity against multipath propagation compared to Adcock or Watson-Watt methods.

4.7.2.2.3 Adcock/Watson Watt

Adcock/Watson-Watt (WW) systems (see Table 4.7-2) exploited improvements in antenna and signal processing to provide a system with a near-instantaneous readout.

The Adcock antenna array used in these systems (developed in 1918) is comprised of dipole or monopole antenna pairs combined through a 180° hybrid circuit to exhibit the familiar "figure of eight" reception pattern seen in a loop antenna.

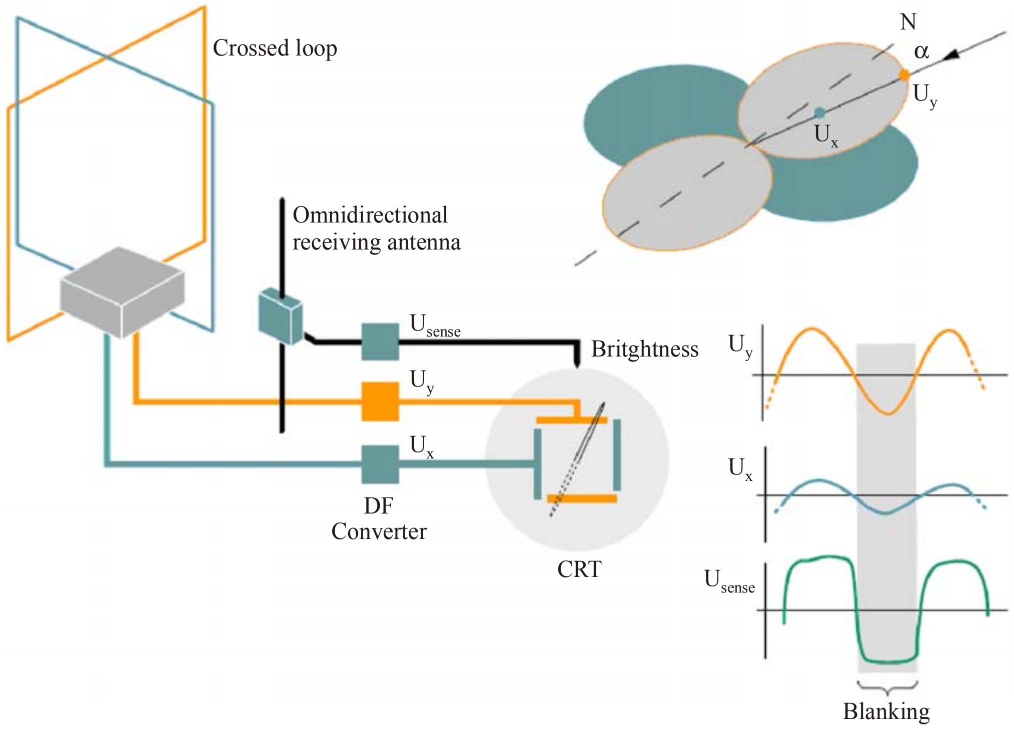
Two Adcock pairs, arranged on orthogonal baselines, exhibit a response to the signal direction of arrival, which varies with the sine of the direction of arrival at one antenna, and varies with the cosine of the direction of arrival at the second antenna.

The Watson-Watt DF technique employs three phase-matched receivers and displays the angle of arrival, in terms of the sine and cosine functions and a third, omnidirectional channel to solve the ambiguity problem.

Modern Watson-Watt direction finders use DSP techniques for calculating the bearing.

FIGURE 4.7-5

Principle of Watson-Watt DF system



Spectrum-4.7-05

TABLE 4.7-2

Adcock/Watson-Watt DF systems

DF antenna array measurements	Amplitude measurements are performed at the output from three antennas. Antennas configured to respond with the signal angle of arrival in sine, cosine, and omnidirectional patterns. Synchronous amplitude measurements made, typically using three coherent receiver channels.
Measurement conversion to DF bearing	Bearing = arctan (sin θ/cos θ); this calculation is sometimes refined by factors from a calibration table. Ambiguity problem solved by (omnidirectional) sense channel.
Accuracy (without site influence)	1° to 2° r.m.s.
Sensitivity	Med-High. Performance based on antenna selection.
Minimum signal duration	1 ms, the bearing is indicated without delay.
Immunity against depolarisation	When using highly balanced antennas, bearing errors are low for depolarisation < 45°; depolarisation compensation algorithms cannot be used.
Immunity against distorted wavefronts (coherent interference)	Limited, as no wide aperture antenna arrays possible.

TABLE 4.7-2 (*end*)

Immunity against co-channel interference (non-coherent interference)	Separation possible using analogues CRT display techniques. Operator interpretation of CRT used in resolving interference pattern. Digital signal processing cannot algorithmically separate time coincident co-channel signals. Histogram techniques may be employed for non-time coincident signals.
HF skywave capability	Cannot determine elevation angle for skywave signals; can maintain good sensitivity for high angle signals. Crossed-loop antenna may be used in applications where extremely high angles of arrival are of interest.
Remarks	These systems have the advantage of more than 50 years development and represent the most successful early DF techniques; they retain relevance in part due to the very short system minimum signal duration time and their ability to measure the bearing to the source of transient signals (including lightning for which they were originally developed).

4.7.2.2.4 Phase interferometer

Interferometer methods (see Table 4.7-3) were developed in the 1950s and 1960s as a means for very accurate, instantaneous LoB measurement. This system uses a differential phase measurement between at least two independent antennas. The critical element of this type of system is the phase detector, which returns an estimate of the phase delay between the two received signals.

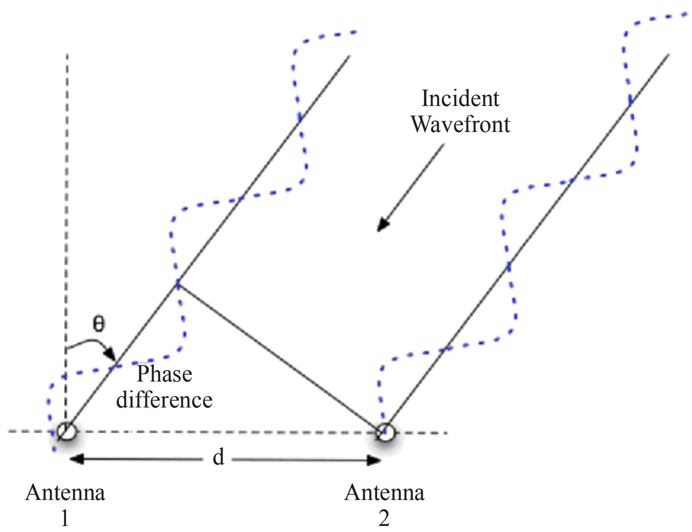
Using this delay, an angle of arrival can be estimated. Combinations of 3, 4, 5 or more antennas can be used to obtain a 360° field of view, without rotating the antenna. Triangular installations are useful below 30 MHz, at higher frequency ranges circular arrays are preferred.

Multi-channel receiving systems and antenna switching have been used successfully as a means of measuring inputs from several antennas.

The Fig. 4.7-6 shows the phase difference when an incident wavefront arrives with an angle θ on two antennas, separated by a distance "d".

FIGURE 4.7-6

Phase interferometer: phase difference principle



Spectrum-4.7-06

TABLE 4.7-3

Phase interferometer

DF antenna array measurements	Differential phase measurements between a subset of the possible pairs of antennas within the antenna array. For more details, refer to § 3.4.4 – Number of receivers.
Measurement conversion to DF bearing	Bearing calculated by combining information about the antenna array with differential phase measurements obtained for pairs of antennas in the array. Phase measurements for a specific pair can be used to compute an angle of arrival, based on knowledge of the antenna spacing. Using knowledge about the array geometry, measurements from several pairs may be combined to resolve ambiguities in azimuth, and to calculate the elevation angle of arrival.
Accuracy (without site influence)	≤ 1° r.m.s.
Sensitivity	High
Minimum signal duration	10 ms 1 ms* * systems which use antenna switching to a pair of coherent measurement channels, are common. Minimum signal duration can be shorter if one receiver is used for each antenna element and all measurements are made in parallel.
Immunity against depolarisation	Function of antenna element polarisation linearity only since polarisation compensation algorithms cannot be used; typical depolarisation errors are low for polarisation slant up to 60° and become large for greater polarisation slant.
Immunity against distorted wavefronts (coherent interference)	High when using wide aperture antenna arrays.
Immunity against co-channel interference (non-coherent interference)	Separation possible using histogram techniques for non-time coincident signals; for time coincident signals only the signal that is stronger by 3 to 5 dB can be evaluated.
HF skywave capability	Can also determine elevation angle for skywave signals; can maintain good sensitivity for high angle signals when the antenna array consists of crossed-loop antennas.
Remarks	Phase interferometers are compatible with modern digital signal processing techniques; there are a number of systems now on the market that use personal computers to perform the DF processing; they are not constrained to using circularly disposed antenna array systems.

4.7.2.2.5 Correlative interferometer

The correlative interferometer uses phase and amplitude information of the signal.

Typically, these systems estimate the LoB for the resolved signals, by correlating the received amplitude and phase data to an amplitude and phase calibration database for the antenna array.

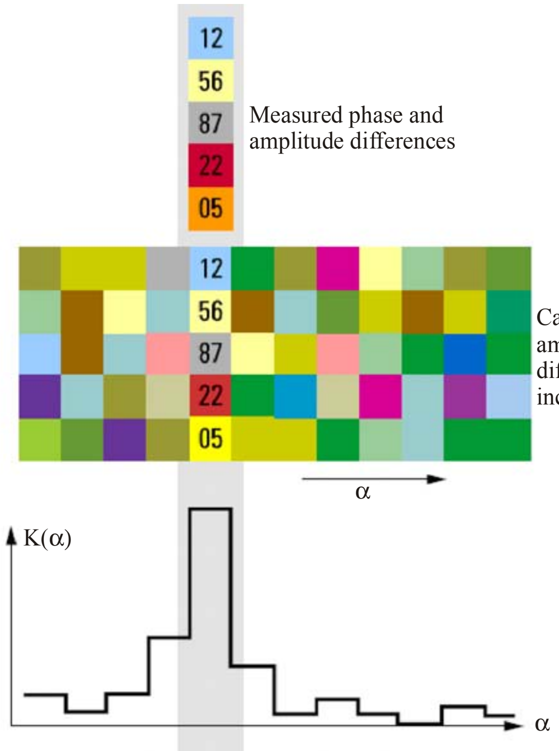
The comparison is performed by calculating the quadratic error of the correlation coefficient.

If the correlation is made for the different azimuth values of the reference data set, the bearing is obtained from the data for which the correlation coefficient is at a maximum.

This is shown in Fig. 4.7-7. This method is capable of eliminating instrument and site-related errors and can be adapted for use with a wide variety of antenna arrays.

FIGURE 4.7-7

Principle of correlative Interferometer



Spectrum-4.7-07

TABLE 4.7-4

Correlative interferometer

DF antenna array measurements	The complex signal voltage (amplitude and phase) is measured for each antenna, with measurements made on at least two antennas at a time. For more details, refer to § 3.4.4 – Number of receivers.
Measurement conversion to DF bearing	Correlative interferometer uses calibration vectors generated during factory calibration of the system. The bearing is the interpolated azimuth value that corresponds to the azimuth calibration vector that best matches the measurement vector.
Accuracy (without site influence)	≤ 1° r.m.s.
Sensitivity	High
Minimum signal duration	for HF 10 ms for VHF/UHF 1 ms System processing times will be lengthened if less parallel receiver channels are used than the number of antenna elements.
Immunity against depolarisation	Function of antenna array polarisation characteristics unless using the dual polarised algorithmic compensation suitable with these vector processing systems.
Immunity against distorted wavefronts (coherent interference)	High when using wide aperture antenna arrays.

TABLE 4.7-4 (*end*)

Immunity against co-channel interference (non-coherent interference)	Separation possible using histogram techniques for non-time coincident signals; for time coincident signals in the vector correlation system, only the signal that is stronger by 3 to 5 dB can be evaluated.
HF skywave capability	Can also determine elevation angle for skywave signals; can maintain good sensitivity for high angle signals when the antenna array consists of crossed-loop antennas.
Remarks	These DF techniques are compatible with the new generation digital signal processing; co-processors operating in the new generation personal computers have sufficient processing power to perform these calculations rapidly.

4.7.2.2.6 Advanced resolution techniques

Advanced resolution techniques are often referred to as super and high resolution. These techniques are used to discriminate among signals (either multiple paths or multiple sources) arising from several transmitters at the same frequency.

Two techniques are discussed in this section:

– beam forming and space matched filter **(**e.g. CAPON algorithm**):** a steering antenna array beams in all direction and the algorithm looks for peaks in the input power. The computation of the beam forming and space matched filter algorithm is based on an expression of the steering vector while attempting to minimise the power contributed by noise and interferer signals;

– subspace techniques (e. g. MUSIC algorithm): they are based on the cancellation of the noise, of interference signals and multipath. The computation of the subspace techniques algorithm is based on a principal component (or eigenvalue) analysis of the data samples of all sensors. The wave incident angles are computed by varying the steering vector and looking for angles were the steering vector is orthogonal to the eigenvectors that corresponds to the noise eigenvalues.

TABLE 4.7-5

Advanced resolution

DF antenna array measurements	The complex signal voltage (amplitude and phase) is measured for each antenna, with measurements made on at least two antennas at a time. In practice a minimum of two coherent receiver channels is required. For the subspace technique, voltage pairs for all possible antenna pairings in the antenna array are used to generate what is known mathematically as a measurement "covariance matrix." The matrix is evaluated to resolve co-channel content in the received signal.
Measurement conversion to DF bearing	Multiple bearings are calculated by using interpolated azimuth values. The antenna array being fixed, each of these values corresponds to a calibrated spatial signature. The calibrated spatial signature that best matches the sources signatures provides the azimuths estimation of the sources.
Accuracy (without site influence)	≤ 1° r.m.s.
Sensitivity	High Sensitivity depends on the selected method. Using the subspace technique performs better on signals with low signal-to-noise ratio compared to beamforming technique.

TABLE 4.7-5 (*end*)

Minimum signal duration	for HF 100 ms for VHF/UHF 10 ms System processing times will be substantially lengthened if less parallel receiver channels are used than the number of antenna elements. The signal needs to be stable over the entire measurement period, which is difficult with less receivers than antenna elements, particularly at HF.
Immunity against depolarisation	Function of antenna array polarisation characteristics unless using the dual polarised algorithmic compensation suitable with these vector processing systems.
Immunity against distorted wavefronts (coherent interference)	Beamforming techniques can separate multiple uncorrelated interferers but not coherent interferers. Subspace techniques can separate multiple uncorrelated interferers and partly coherent interferers. Both techniques have improved performances when using wide aperture antenna arrays.
Immunity against non-coherent interference	Both techniques can separate non-coherent interferers.
HF skywave capability	Can also determine elevation angle for skywave signals; can maintain good sensitivity for high angle signals when the antenna array consists of crossed-loop antennas.
Remarks	These DF techniques are compatible with the latest generation of digital processing; co-processors operating in the new generation personal computers have sufficient processing power to perform these calculations rapidly (although probably not in real time); these systems are not constrained to requiring circularly disposed antenna arrays.

4.7.2.2.7 Comparison of AOA techniques

This section compares the various methods and identifies which method is the most effective in dealing with multipath and multiple-source situations.

Table 4.7-6 compares the main AOA estimation algorithms. It summarizes the main performance and use of these methods.

TABLE 4.7-6

Summary comparison of DF techniques

Accuracy/Angle separation	Sensitivity	Immunity to multipath	Minimum signal duration	Remarks
Rotating antenna				
2° to 5° r.m.s. Depending on the used antenna system	High	Good	Depending on the rotating speed, up to 1 min	Simple implementation Real time method Good separation of multisource signals

TABLE 4.7-6 (*continued*)

Accuracy/Angle separation	Sensitivity	Immunity to multipath	Minimum signal duration	Remarks
Adcock/WW methods				
1° to 2° r.m.s. No angle separation	Medium to high	Limited	1 ms	Simple implementation Real time method Operational and widely implemented method
Phase interferometer				
Usual accuracy 1° r.m.s. for a single source Angle separation can be good if time and frequency resolution is high	High	Medium to good for single source, depending on antenna aperture	10 ms 1 ms (Note 1)	Simple implementation Real time method Operational and widely implemented method
Correlative interferometer				
Usual accuracy 1° r.m.s. for a single source Angle separation can be good if time and frequency resolution is high	High	Medium to good for single source, depending on antenna aperture	HF: 10 ms VHF/UHF: 1 ms Depends on number of antenna elements and receivers as well as processing speed	Moderately complex implementation Operational and widely implemented method.
Space matched filter – (CAPON)				
Good for uncorrelated sources. Usual accuracy reaches 2° Processes usually 2 to 3 uncorrelated sources that are angle separated	High	Processes partly coherent radio environments Robust to multiple uncorrelated sources. Cannot process correlated multipath signals	HF: 100 ms VHF/UHF: 10 ms Depends on number of antenna elements and receivers as well as processing speed	Moderately complex implementation if off-line analysis. Complex implementation requiring more computing resources if real time. Requires long integration time to achieve results, during which time the signal environment should be relatively stable

TABLE 4.7-6 (*end*)

Accuracy/Angle separation	Sensitivity	Immunity to multipath	Minimum signal duration	Remarks
Subspace method (MUSIC)				
High accuracy performance < 1° Processes usually 2 to 3 partly-coherent sources. Limited only by calibration errors and integration duration	High	Processes usually 2 to 3 partly-coherent sources. Robust to multiple partly-coherent sources or multiple paths and to noise (processes efficiently S/N ratios < 0). Cannot process correlated multipath signals	HF: 100 ms VHF/UHF: 10 ms	Moderately complex implementation if off-line analysis. Complex implementation requiring significantly more computing resources if real time. Operational for adverse radio environments (urban, mountainous). Requires long integration time to achieve results, during which time the signal environment should be relatively stable

NOTE 1 – Successful systems, which use antenna switching to a pair of coherent measurement channels, are common. The minimum signal duration is shorter when one receiver is used for each antenna and all measurements are made in parallel.

4.7.2.2.8 Combined direction finding techniques

Space match filter and subspace DF method and techniques may be helpful in severe radio environments. It is desirable to have a real-time implementation of these DF methods but this may lead to complex systems, involving an N-channel system with one receiver, processing and recording channel for each antenna element.

To solve this issue, multi-channel equipment implementing a real-time treatment based on a simple algorithm may be associated to a multi channel digital recording system to cope with the more difficult radio-environments in batch mode (some tens of seconds).

It will then be possible for the system to adapt itself to the environment by applying several A.O.A methods of increasing complexity:

1. A correlative interferometer or a vectorial correlation allows a fast and real-time scanning of the radio environment to give a first location of the dominant emitters or sources, as well as a first indication of presence of interferences sources.
2. An advanced resolution method will give a sufficient discrimination/location for the environments of average complexity and\or the needs of limited precision.

Other techniques, using FFT analysis, may also work in complex signal environments.

4.7.2.3 Influence of the environment

4.7.2.3.1 Accuracy of bearings of DF below 30 MHz

Recommendation ITU-R SM.854 classifies bearings into four classes based on accuracy and observational characteristics:

Class A – Probability of less than 5% that error exceeds 2°.

Class B – Probability of less than 5% that error exceeds 5°.

Class C – Probability of less than 5% that error exceeds 10°.

Class D – Bearing with an error greater than those in Class C.

Recommendation ITU-R SM.854 also recommends that administrations provide statistical data to support assigning numerical averaging values to the observational characteristics, e.g. standard deviation, number of samples, actual error, statistical processing of the sample.

4.7.2.3.1.1 Errors caused by the ionosphere

Direction-finders operating below 30 MHz are susceptible to errors induced by reflections of transmissions from the ionosphere. Specialized systems exist for operating in these conditions, if required. These systems are typically associated with long-range, over-the-horizon signal-locating operations. Not every station in a spectrum monitoring system requires this capability.

The ionosphere is an inhomogeneous medium, which is subject to continuous changes.

In practice, propagation between transmitter and receiver may involve different modes, including a ground wave, and single or multiple reflections on E and F layers.

The electromagnetic field intercepted by the antenna array of the direction-finder may be considerably distorted by interference of the multipath rays, thus causing scatter and errors in the bearings measured. Using proper polarisation diversity and algorithms may reduce these.

The reception of transmissions with *one* or *multiple* reflections at the ionosphere thereby leads to different consequences:

– horizontal stratification;

– ion density;

– structure (consists of undulations of varying sizes with up to 2 km deep and several hundred kilometres long);

– fine structure (leads to scattering effects in reflection);

– depolarisation (contra-polarised signals -circular or elliptical- as a result of reflection).

In cases of one single reflection, a relatively slow variation in the bearing will be superimposed the rapid fluctuations caused by scattering from the “fine structure” of the ionosphere. The accuracy of the bearing also depends on the angle of inclination relative to the reflecting surface. For this reason, errors in the bearings increase with the height and the number of reflections and they also increase with decreasing transmitter distance.

In cases of multiple reflections, observation is made difficult by the fact that scatter occurs at one or more points on the ground where the wave is reflected. Because of the scatter due to the fine structure of the ionosphere, the angle at which the wave is received is not constant but is contained within a cone with its vertex at the centre of the antenna array.

The scatter, which takes place at the point of reflection on the ground increases the angle of aperture of this cone and thus increases the amplitude of the rapid fluctuations of the bearing.

4.7.2.3.1.2 Errors due to siting

Section 2.6.1.3 gives information on the siting of a direction-finding station.

The site must be selected with great care to minimise errors due to wave-front distortion caused by sudden changes in ground conductivity or re-radiation from obstacles.

Since actual sites will not be ideal, the nature of the site and the characteristics of the adjacent terrain are bound to introduce errors, which will vary with direction and frequency.

These errors can be corrected by calibrating the installed DF using multiple reference transmitters in known directions across different frequencies (see § 4.7.2.1.1, Accuracy).

4.7.2.3.2 Accuracy of bearings of DF above 30 MHz

Recommendation ITU-R SM.854 classifies bearings into four classes based on accuracy and observational characteristics. It should be noted that the values for the various classes differs from those below 30 MHz.

Class A – Probability of less than 5% that error exceeds 1°.

Class B – Probability of less than 5% that error exceeds 2°.

Class C – Probability of less than 5% that error exceeds 5°.

Class D – Bearing with an error greater than those in Class C.

Bearings obtained with a direction-finder operating above 30 MHz are subject to errors due to:

– equipment (or technique used by the equipment);

– site of the direction-finder;

– propagation.

Errors due to the equipment result from its design and manufacture.

Errors due to the site arise from irregularities in the configuration or composition of the terrain in the vicinity of the direction-finder. These errors vary with direction and frequency. They may thus be regarded as variable errors.

The third type of error is due to irregularities in propagation. These may give rise to side deviations in the direction of propagation relative to the direction of the arc of the great circle between the transmitter and the direction-finder. Moreover, irregularities in propagation give rise to errors due to polarisation.

4.7.2.4 Remote control networking for DF stations

A remotely controllable direction-finder network can offer advantages of both economy of operation and flexibility of use. Remote control of computerised systems is covered in §§ 2.5 and 3.6.3.

4.7.3 Location

In many cases, the line of bearing will not be sufficient for identification and the exact position of the transmitter will be required. Four main methods are used to identify a location:

1. the classical method: to combine two or more DF-delivering AOA (Angle of Arrival) results in order to perform multi-angulations (manually or by computer);
2. the time difference of arrival (TDOA) method;
3. the homing or standalone method by using a mobile direction finder;
4. the Single Station Location (SSL) in the HF range relying on ionospheric propagation: it is possible to determine the position of a transmitter with only one DF station which also delivers the AOA elevation information in addition to its azimuth.

The following sections give details about each of these location methods.

4.7.3.1 Triangulation and multi-angulation methods of location

The triangulation method, which is a particular case, is described hereafter.

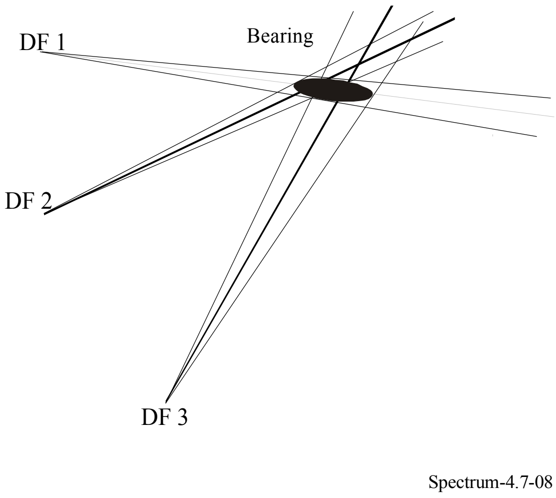
4.7.3.1.1 General

The triangulation method requires a minimum of two and preferably three LoB results. The intersection of LoB determines the emitter location. Due to measurement errors of the directions finders, the result is an ellipse, which represents the possible location of the transmitter. See Fig. 4.7-8.

The better the DF accuracy and the more orthogonal the bearings are the smaller is the area of uncertainty.

FIGURE 4.7-8

Location using triangulation method



The location calculation is directly dependent on the quality of bearings of the various direction-finding stations. To attain a sufficient quality, bearings should be analysed on each step in the location process, that is, in monitoring/ DF stations and at the location centre where the location (fix) is actually computed.

At monitoring/ DF stations, a manual analysis mainly consists of:

– checking for correspondence between a locally heard signal and a signal of interest for the monitoring station;

– classifying the bearings in case of the presence of more than one signal on the same frequency (interference);

– eliminating obviously aberrant bearings;

– calculating the mean value of bearings;

– calculating the variance of bearings.

At the location centre, the analysis of bearings mainly consists of:

– determining the bearings to be used for the location calculation;

– calculating the position of the probable transmission point;

– calculating the uncertainty ellipse.

In manual-location systems, the quality of bearings is highly dependent on the operator's skill in performing such an analysis. In automatic location systems, the analysis is performed through information processing (computer programs).

4.7.3.1.2 Features of the location depending on frequency

Below 30 MHz

Below 30 MHz, in addition to ground waves, waves can also propagate by single or multiple reflections and ducting in the ionosphere.

The signal received by a direction-finder is a composite signal originating from the multiple paths the wave can follow between the source transmitter and the direction-finder. This is accentuated by the fact that, at HF, direction-finders often are remote from the area of interest. Consequently the DF measurements are often made with a low *S*/*N* ratio and, therefore, the measurements can be relatively unstable.

Other features of the range below 30 MHz make calculation of the location difficult:

– spectrum congestion (frequent interference);

– geographical areas and non-visibility periods for some frequency ranges.

A single bearing is not sufficient to allow satisfactory location calculation. To perform a good bearing at HF, several individual bearings are necessary to obtain a significant mean bearing.

But it must be remembered that the complex paths followed by waves through the ionosphere may not correspond to great circles on the earth surface, which brings a bias at the azimuth-measurement level and, therefore, at the location-calculation level.

Above 30 MHz

In the VHF and UHF ranges wave propagation is primarily line-of-sight (or via diffraction or scattering) and consequently direction-finders should be installed in the vicinity of the area to be monitored, typically urban areas. Although the signal-to-noise ratio may be poor, the signal is usually received from a constant and stable direction. Such conditions permit acquiring reliable bearings in a relatively quick and easy way.

However, the measurement can be difficult due to the presence of interference and because of the reflections experienced by waves. This is specially the case in urban areas and when made from mobile DF stations.

Usually, simple measurements may be made in 10 ms or less, but it is desirable to integrate the results over an appropriate period consistent with the signal duration and receiving conditions. This is especially important when using mobile DF stations.

Reliable bearings that minimise the effects of reflections should only be taken while the DF unit is moving, unless it is situated at a spot clear of any obstructions.

Modern direction-finders may perform, in addition to conventional bearings, a number of technical measurements such as centre frequency, modulation rate, and bandwidth.

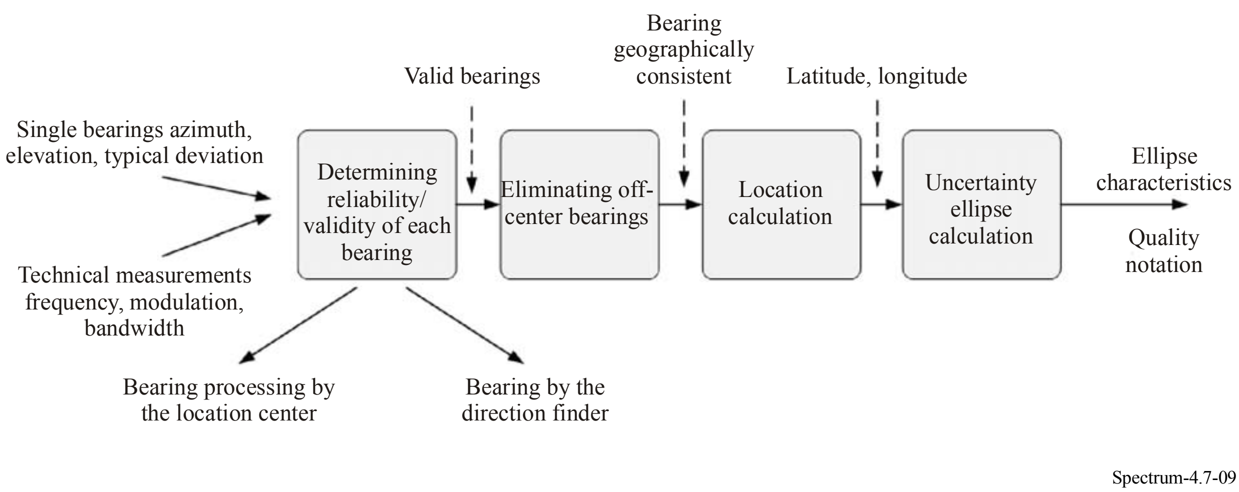
As such measurements may be made under favourable conditions (good signal-to-noise ratio), they can be reliable and permit efficiently performing the bearing data reduction.

4.7.3.1.3 Location calculation steps

Figure 4.7-9 shows a chart of location calculation.

FIGURE 4.7-9

Chart of location calculation



The computer program "TRIANGULATION", that generally follows these steps, is available through the ITU.

Determining reliable bearings

Sorting out the individual DF bearings can be performed at the monitoring/DF stations or at the location centre. Choosing between the two approaches is directly related to the capabilities of the links used between monitoring/DF stations and the location centre for routing the remote controls.

a) Fast links

If links have such a rate that exchanges between calculation monitoring/DF stations are fast (for example, a high-speed Wide Area Network), it may be useful to route to the location centre the bearings of each station in real time. A station bearing is then analysed with respect to bearings obtained by the other station at the same time. Rejecting a doubtful bearing is performed not only with respect to the bearings obtained by the same direction-finder but with respect to the bearings obtained in a synchronous manner by the other stations. At the end of alert, the location centre is provided, for each direction-finder, with a number of individual bearings. These bearings are statistically processed (bar chart, single linkage, etc.), to determine the bearing(s) characteristic of each direction-finder, as well as the corresponding typical deviations.

The advantage of such a type of system is to use simple processing at the direction-finders. This type of operation allows real-time display of the behaviour of direction-finders. At the location centre it is possible to manually select particular measured lines of bearing on the tracked transmission.

b) Slow links

If links have such a rate that each exchange between location centre and DF stations is time costly, that is, when the communication time is greater than the measurement time, making reliable bearings should be performed at the DF station. Making a reliable result is achieved by averaging the individual bearings regarding the signal of interest for the location centre. So, know-how is required at the direction-finder for classifying the individual bearings. Classifying can be performed from several information items:

– azimuth separation;
– consistency of the measured centre frequency;
– consistency of elevation angle between the various bearings;
– likelihood of elevation angle in regard to propagation characteristics;
– technical-analysis parameters enabling identification of the desired signal.

The advantage of this type of system is to make it possible to use low-rate links (e.g. conventional telephone links). On the other hand, this type of system needs direction-finders able to analyse their own bearings and to separate the data in case of receiving multiple transmissions. This type of system is well suited for location in the VHF/UHF range where DF bearings are relatively stable in time.

Eliminating non-convergent bearings

This step is manually performed in some location systems. An automatic method permitting geometrically determining the non-converging bearings is proposed here (see Fig. 4.7-10).

This method consists in examining for each instance the number of shootings consistent with that instance. On each shooting, the area covered by the own angular error of each of the shootings is constructed.

When areas partly overlap, it is said that shootings can be associated. So, for each shooting, the various associations possible are examined. The association including the largest number of shootings is kept. If the largest number of shootings is attained by several associations, then the association obtained with the best bearings and the best aperture angle in regard to the target is kept. Shootings that are not parts of the best association are declared off-centre and are not kept for calculating the location point.

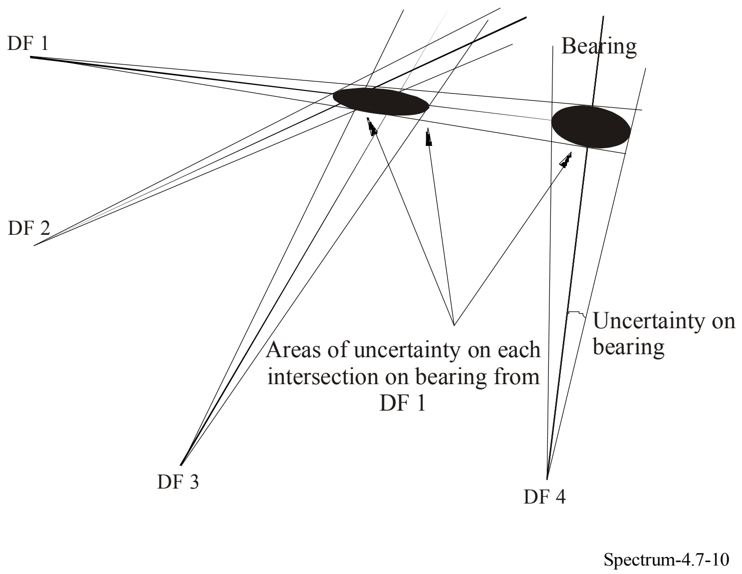
This method offers the advantage of being constructed on the angular errors, valid at short- or long-range.

Evaluating the location point

In this step, a number of bearings consistent with one another is provided, but which do not all cross the same geographical point. The purpose of this step is to determine the optimum position of the location point.

FIGURE 4.7-10

Validation / elimination of bearings unrelated to expected source
(DF 1, DF 2, DF 3 can be associated, DF 4 cannot be associated)



The optimum point is searched applying the least error squares method. The point minimising the angular variations to be applied to each bearing is searched in order to aim at this point.

If P is any one point and d_1, d_2, d_3,... the angular variations to be applied to each bearing to intersect P and v_1, v_2, v_3,... the variances of the various bearings.

Given S_p the following quantity:

$$S_p = (d_1^2 / v_1) + (d_2^2 / v_2) + (d_3^2 / v_3) + ... \qquad (4.7\text{-}1)$$

The optimum point is the point minimizing S_p.

Several approaches exist to solve this problem:

– triangulations;

– methods of large circles, spherical triangles (long distances).

For more approaches, see [Stansfield, 1947], [Barfield, 1947].

Implementing such methods on computers raises no problem. But it must be remembered that all methods calculate an estimate. No mathematical formula exists giving the exact position.

Visually estimating the optimum point is a difficult exercise even with few bearings. When using two direction-finders, the intersection of two bearings gives one point, but because of the errors, it is not possible to assert that this point is the transmitter location. When using three direction-finders, a triangle is obtained but, due to errors on each bearing, it cannot be ensured that the transmitter is located within the triangle.

Calculation of the uncertainty ellipse

The uncertainty ellipse is the area centred around the optimum point.

The calculation of the uncertainty ellipse relies on [Stansfield, 1947]. This calculation is performed from typical deviations of the various bearings. For this typical deviation to be significant, the system must possess enough individual bearings to be capable of calculating a significant typical deviation value.

The present trend for direction-finders is to provide a quality notation incorporating the conditions under which the DF bearing was performed, rather than a real typical deviation. In such a context, the uncertainty ellipse calculation will only be an approximation. The trend of location system is to determine a quality notation for location.

The quality notation for a location represents:

– The agreement of direction-finders with one another on designating the same point.

– The persistence of direction-finders in always designating the same point.

The agreement is strong when several direction-finders designate the same point.

The persistence is strong when a variation in the bearings of a direction-finder has little influence on the optimum point calculated using all of the bearings (inertia).

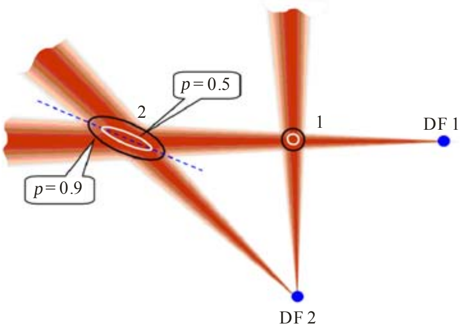
4.7.3.1.4 Distribution of location uncertainty values

Even where there are no extraneous influences on bearings (such as reflections from local features, buildings, metallic structures and so on, as well as the effects of the radio propagation medium) and the bearing lines from all the direction finders used in the triangulation process intersect at a single point, the sought transmitter may be located not at that point but within the bounds of an uncertainty ellipse determined by the instrument (or system) location uncertainty (error) of each direction finder (see § 4.7.2.1.1). This can be seen in Fig. 4.7-11, where the angular bearing line distributions from the two direction finders, DF 1 and DF 2, within the bounds of the specified instrument uncertainty of the direction finders are conventionally portrayed in the form of segments with fuzzy edges. The angular distribution of the bearing lines within such segments may be assumed to be Gaussian where the bearing uncertainty values are from 1°-2° r.m.s.

From the two cases in Fig. 4.7-11 in which the bearing line distribution segments from direction finders DF 1 and DF 2 intersect, it follows that where the two segments intersect at 90° (situation 1) the location uncertainty is at its lowest. In this case, where the bearing uncertainties of the direction finders used in the triangulation process are equal and the distances from the direction finders to the region in which the segments intersect are the same, the uncertainty ellipse becomes circular.

FIGURE 4.7-11

Two cases of intersection of bearing line distribution segments from the two direction finders DF 1 and DF 2



As the angle of intersection between the segments decreases (situation 2), the major axis of the ellipse, which is normally taken as a measure of the location uncertainty, rapidly lengthens, extending to infinity as the angle reaches 0°. The same occurs where the angle increases to 180°. In the case of angles approaching 0° and 180°, location using only two direction finders therefore becomes impossible, making it necessary to bring in a third direction finder located away from the line linking the first two.

From the intersection of the segments in the case of small angles we can clearly see how the change in the length of the major axis of the location uncertainty ellipse relates to the probability ***p*** of locating the sought transmitter within it. As probability ***p*** increases, the axes of the ellipse (major and minor) also increase, resulting in a corresponding increase in the location uncertainty determined by the length of the major axis of the ellipse.

From Fig. 4.7-11 it can be seen that the length of the major axis of the uncertainty ellipse depends on a variety of factors, such as:

– the bearing uncertainties inherent in the direction finders used in the triangulation process;

– the distances between the area in which the bearing line distribution segments intersect and the respective direction finders;

– the angle at which the bearing line distribution segments intersect.

It follows from this that the location uncertainty, determined by the length of the major axis of the ellipse, will take different values at different points within the overall location coverage area.

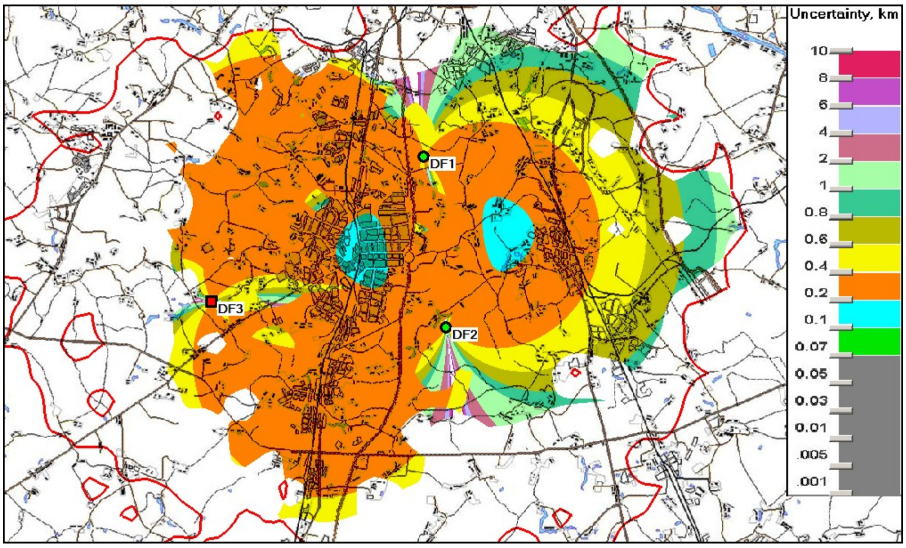
The characteristics of uncertainty ellipses which determine the location uncertainty at each point of the overall location coverage area may be calculated from the two-dimensional probability density of the Gaussian distribution curve, the determination of whose parameters becomes considerably more complex as the number of direction finders involved in the triangulation process increases, particularly where those direction finders have differing bearing uncertainty values. The bases of the mathematical tool for performing such calculations are presented in [Kogan and Pavliouk, 2004a], and the software used to implement the methodology is described in [Krutova *et al*., 2005] and [ITU Handbook, 2005].

The calculation results give the distribution of the location uncertainty values throughout the overall location coverage area. This distribution may be represented graphically in the form of adjacent subareas whose boundaries correspond to the established location uncertainty values, as shown in Fig. 4.7-12.

The location uncertainty gradations corresponding to the subarea boundaries are shown in the palette on the right-hand side of the Fig. 4.7-12. The totality of these subareas within the bounds of the overall location coverage area is referred to as the "location coverage template (LCT)" [Kogan and Pavliouk, 2004a], [Kogan and Pavliouk, 2004b], [ITU Handbook, 2005] and [Krutova *et al*., 2006].

FIGURE 4.7-12

Location coverage template with three direction finders, DF1 – DF3



Spectrum-4.7-12

Figure 4.7-12 shows that for a given arrangement of direction finders within the territory in question, the lowest location uncertainty values lie in the range 0.1-0.2 km (subarea shown in turquoise). These values occur where the bearing lines from direction finders DF 1 and DF 2 intersect at angles close to 90°. The most extensive subarea is the one shown in brown, corresponding to location uncertainties in the range 0.2-0.4 km. The highest location uncertainty values in this example lie in the range 1-2 km (subarea shown in light green). This occurs at the edges of the overall location coverage area, i.e., at the greatest distances from the direction finders. In the narrow strips where the bearing lines from direction finders DF 1 and DF 2 meet at angles close to 0°, the location uncertainty exceeds 2 km (subareas shown in pink and other colours).

The example shows the considerable value spread (a factor of over 20) that is found in the location uncertainty values depending on the above-mentioned factors. This needs to be taken into account in the planning of direction-finder networks.

A detailed analysis of the characteristics of location coverage templates is given in [Kogan and Pavliouk, 2004b] and [Nurmatov and Titov, 2005], while their use in the planning of spectrum monitoring networks is described in § 6.8.

Insofar as the calculation of location coverage templates takes account only of the instrument (system) errors inherent in the direction finders, the location uncertainty values reflected in such templates are the minimum possible and attainable under certain idealised conditions. Nevertheless, this information is of considerable value when it comes to the planning and optimisation of spectrum monitoring networks (see § 6.8).

4.7.3.1.5 Map display

The bearing lines and their cross-point are also indicated on a map display, which allow the operator to easily find the estimated position of the emission. In the case where the emission is made from a mobile unit, the operator can estimate the moving direction of the mobile unit by watching the cross-point on the display.

For more information about mapping, see § 6.2.

4.7.3.2 Time difference of arrival method

4.7.3.2.1 General Principles

Time-difference-of-arrival (TDOA) method determines emitter location using the relative arrival times of a signal at multiple receivers. TDOA systems offer flexibility in antenna selection and placement as TDOA accuracy is minimally affected by nearby reflectors, and antennas and cables are generally not integral to TDOA receivers. This flexibility allows other factors to be considered such as: antenna size, station complexity, ruggedness and frequency coverage. The ability to utilise simple, easily installed antennas allows TDOA geolocation systems to be established easily, especially for temporary installations.

It is often stated that TDOA is less accurate for narrow-bandwidth signals than it is for wide-bandwidth signals. While generally true, this statement only considers signal bandwidth. Wider bandwidth signals have shorter-duration temporal features that can improve TDOA accuracy, especially under high multipath conditions. However, location accuracy is also affect by received signal-to-noise ratios, which is generally better for narrow-band signals at lower-frequencies. TDOA methods are suitable for most intentionally-modulated signals, but cannot be used to locate an unmodulated, continuous signal (since it contains no time reference).

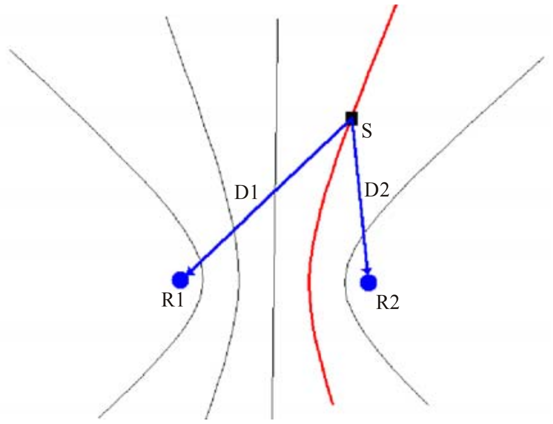
TDOA is based on the simple concept that any difference in the distances between the source of an electromagnetic signal, and any two receivers in a location system, can be directly observed as a difference in time of arrival at those receivers. From the observed time-difference, a difference-distance can be easily computed as the product of the time-difference and the signal's velocity. The TDOA changes approximately 3.3 ns for every meter of distance-difference between the two direct signal paths.

In two dimensions, the difference-distance equation, $\Delta D = D1\text{-}D2$, describes a hyperbolic line. Hyperbolic lines are plotted for five different values of ΔD in Fig. 4.7-13. A signal source "S" is located on one of the lines.

As the hyperbolic line represents a constant distance-difference, the signal source may be re-positioned at any location along the indicated hyperbolic line without affecting the observed time-difference-of-arrival at receivers R1 and R2. The obvious implication of this characteristic is that TDOA systems require more than two receivers to determine location.

FIGURE 4.7-13

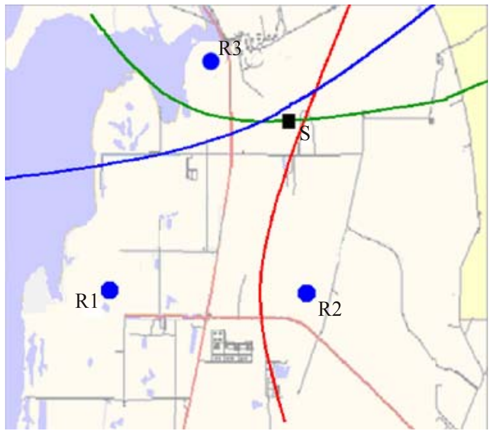
Time-difference based on distance difference ΔD = D1-D2



Spectrum-4.7-13

FIGURE 4.7-14

Signal source is at the intersection of two or more hyperbolas



Spectrum-4.7-14

Ignoring special-case geometries, TDOA systems require a minimum of three receivers to locate a source in two dimensions. As illustrated in Fig. 4.7-14, with three receivers there are three possible pairings of receivers producing three different time-difference observations, and correspondingly, three different hyperbolic lines, which intersect at a common point under ideal conditions. The signal source is located at the intersection of the hyperbolic lines. While three receivers are required, only two pairings of receivers are required for geolocation. In theory, the third receiver pairing is redundant. However, in non-ideal environments the quality of the time-difference data will vary with receiver pairings. For example, in Fig. 4.7-14 the signal source is physically closest to receiver R3. Assuming higher signal strength at R3, the R1-R3 and R2-R3 pairings may both produce better time-difference estimates than the R1-R2 pairing. Advanced location algorithms often take advantage of this redundancy to improve location accuracy.

4.7.3.2.2 TDOA Implementations

There are two fundamental methods for computing the time-difference-of-arrival for a signal arriving at a pair of receivers. In the first method, each receiver determines and reports a signal's time-of-arrival (TOA) to the TDOA compute engine. The compute engine then subtracts one receiver's TOA estimate from another to compute the time-difference. In the second method the receivers digitize the signal and send the time-stamped samples to the compute engine where any number of numerical methods may be used to estimate location.

TOA method

Establishing a signal's time-of-arrival at the receiver is attractive in situations where data communications bandwidths are restricted. With this method, only the time at which a signal arrives needs to be communicated. The drawback to this method is that, unless the signal has known characteristics which enable the receiver to accurately determine time-of-arrival under poor channel conditions, this method requires: high signal-to-noise ratios (SNR's), high signal-to-interference ratios, and limited multipath distortion at all receivers.

The accuracy of the TOA method can be enhanced using known information from digitally modulated signals. The data-aided method applies to systems that have standardized parameters ("discriminant signals") in service channels or in traffic channels that are transmitted continuously or at regular intervals: training sequences in the case of TDMA protocols, PILOT codes or synchronisation codes in the case of CDMA protocols, continuous or scattered pilots in OFDM waveforms (DVB-T, DVB-H, Wimax), etc. By exploiting the discriminant signal characteristics in the TDOA calculations, it is possible to:

– benefit from a significant gain in signal detection, which improves the sensitivity and the reliability;

– separate the sources in the same band when they use different discriminant signals for synchronisation (several midamble codes in TDMA bursts, several CDMA codes, diversity of scattered pilots over OFDM symbols, etc.).

TDOA method

With the TDOA method the receivers digitize the signal and then transfer the time-stamped samples to the TDOA compute engine. The drawback to this method is that hundreds, potentially even thousands of samples from every receiver need to be communicated to the compute engine for every update of a signal's estimated position. Slow data networks will limit the rate at which location estimates are updated. The primary advantage of this method is that it supports the use of algorithms which work on most signals, under poor channel conditions, without requiring significant knowledge of the signals characteristics. It also reduces the need for significant computational resources in the receiver, and can provide an operator with more information, such as time, spectrum, and correlation plots. For most spectrum monitoring applications, this method will be preferred for both its location performance and flexibility.

Computing Location in TDOA systems

A common and direct approach for computing location in TDOA systems is to first estimate the time-difference-of-arrival for each receiver pairing. Algorithms then determine the point-of-intersection for the hyperbolic lines corresponding to the time-difference values. This is analogous to the lines-of-bearings (LoB's) approach used in direction-finding systems. In DF systems, angular errors will often prevent three or more LoB's from converging on a single location. In TDOA systems, timing estimation errors have a similar affect on the hyperbolic lines as illustrated in Fig. 4.7-14.

Other, usually proprietary computational techniques may also be used to estimate location. These techniques are generally more sophisticated at dealing with multipath, multiple co-channel signals, and other TDOA complexities. These techniques may also incorporate amplitude information, and in the case of antenna arrays, angle-of-arrival information. The results of these computations are often presented in the form of likelihood maps, where colour or intensity is used to indicate probable signal locations as shown in Fig. 4.7-15.

4.7.3.2.3 Factors affecting accuracy

Geometry

The relative positions of receivers and signal sources impacts TDOA location accuracy.

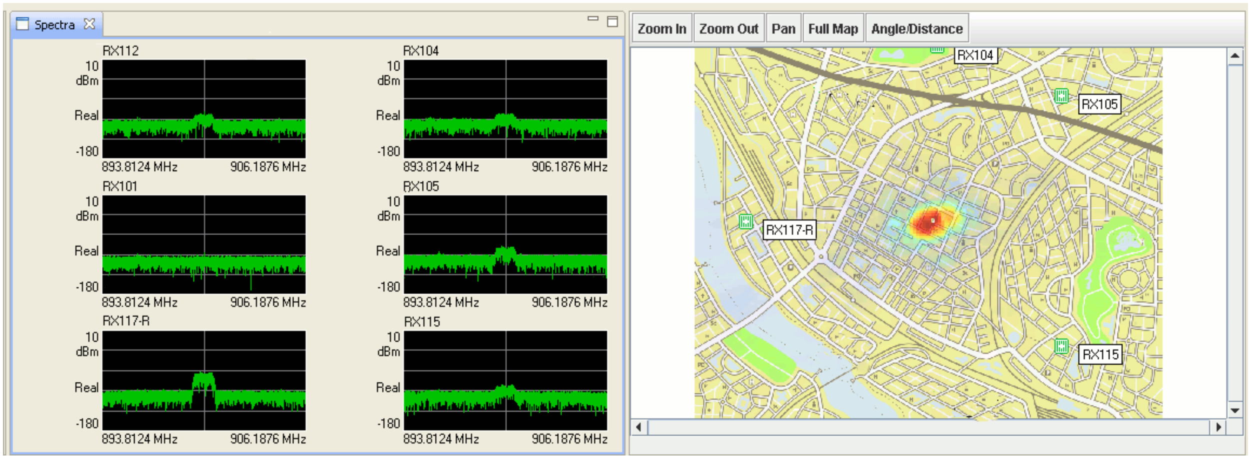
Figure 4.7-16 illustrates the basic error mechanism. In this figure hyperbolic lines are plotted for all three receiver pairings across a range of uniformly spaced time differences. Assume the lines in this example are spaced at 1 μs intervals, and that multipath and other errors can introduce up to 1 microsecond of error in the time-difference estimation.

Under these conditions, the shaded areas represent the areas of uncertainty bounded by time-shifts of +/–1 μs using all three receiver pairings. From this figure it is easy to observe that the best accuracy is near the centre of this particular arrangement of receivers. Accuracy degrades outside of the triangular area defined by the three receivers, and is clearly poor in the areas immediately "behind" the receivers. In regions well outside of the area defined by the three receivers, the hyperbolic lines tend to run parallel to each other, limiting TDOA systems to reporting something similar to a line-of-bearing.

Location accuracy is often intentionally compromised to take advantage of existing receiver sites and other infrastructure. Figure 4.7-17 illustrates a straight-line geometry. With this geometry horizontal accuracy is generally poor. Also the location system cannot distinguish between a signal source to the left of the sensor line, and one to the right that is the mirror image about a vertical line connecting the sensors.

FIGURE 4.7-15

Example of a likelihood map and corresponding spectral plots. When available, spectrum, time, and correlation plots can aid in the interpretation of TDOA results



Spectrum-4.7-15

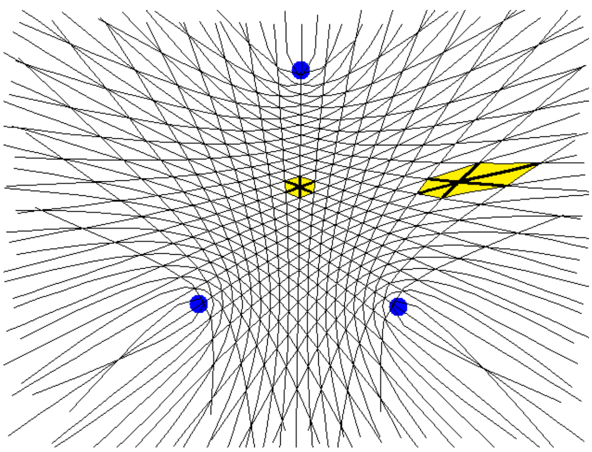
Signal bandwidth, periodicity and multipath

The inverse relationship between time and frequency domains is well understood. As illustrated in Fig. 4.7-18, a wide rectangular shape (RECT) in the frequency domain translates to a narrow sin(x)/x (SINC) shape in the time domain. A narrower rectangular shape in the frequency domain produces a wider sin(x)/x time pulse. All other considerations aside, wide-bandwidth signals may be located with greater precision as it is easier to determine the timing of the signal's more sharply defined time-domain features in the presence of noise and multipath distortion.

While it is generally desirable to match the TDOA receiver bandwidth to the signal bandwidth, doing so is not absolutely required, nor is it always the best approach. There are many signals that have most of their energy concentrated around a carrier allowing narrow receiver bandwidths to improve SNR, or to provide better isolation from adjacent or overlapping signals.

FIGURE 4.7-16

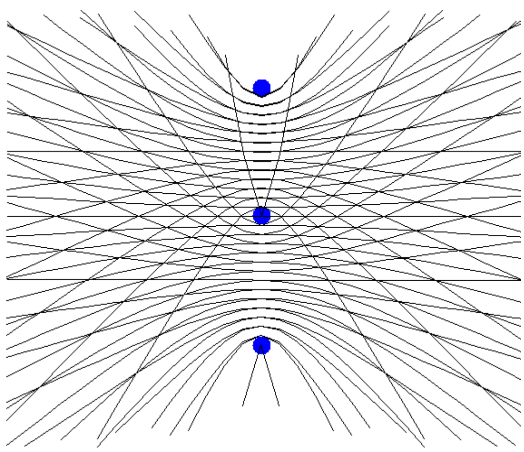
Geometry affects on TDOA accuracy



Spectrum-4.7-16

FIGURE 4.7-17

Poor receiver geometry

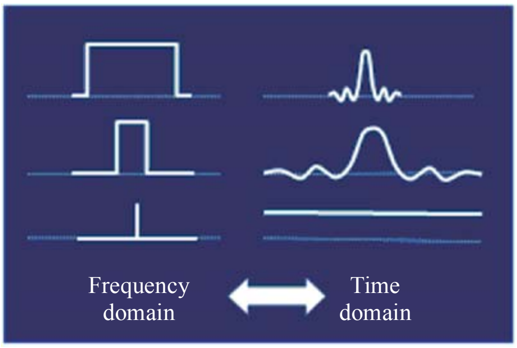


Spectrum-4.7-17

Multipath is evident in direction-finding systems when multiple copies of a signal arrive from multiple bearings. In TDOA systems, multipath is evident when multiple copies of a signal arrive with different delays. Multipath is potentially more of an issue for narrow bandwidth signals when the signal's temporal characteristics are wide relative to the delay spread as shown in Fig. 4.7-19. Under these conditions the pulse-shape distortion caused by the multipath is harder to discriminate, adding error to the time-difference estimation.

FIGURE 4.7-18

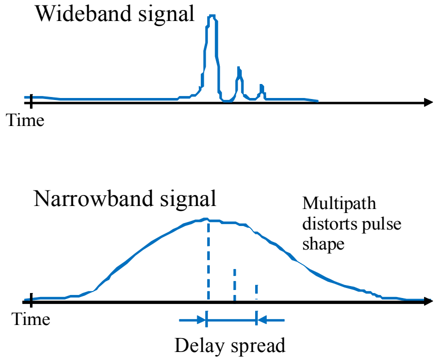
Time-frequency relationships



Spectrum-4.7-18

FIGURE 4.7-19

Multipath and signal bandwidth



Spectrum-4.7-19

While the probability is low, it is possible for correlation-based TDOA algorithms to produce incorrect answers with signals that contain periodic elements. Examples of periodic elements include repeating data sequences and synchronisation pulses. Incorrect answers are also a possibility when the location system detects signals from multiple transmitters using common synchronisation signals. In this situation the system may be unable to distinguish between the cross-correlation peak of a common signal arriving at two different TDOA receivers, and the correlation peak due to common signal elements embedded in two different signals. This problem may be minimised by avoiding receiver spacing that is wide relative to the spacing of the transmitters.

Timing accuracy

Timing accuracy is fundamental to location accuracy in TDOA systems, just as angular accuracy is fundamental in direction finding systems. While good timing accuracy is necessary, it is not sufficient to ensure accurate locations. Common accuracy approximations of "a foot/ns" or "30 cm/ns" give a sense of what is possible for a given timing accuracy specification, but should not be relied on as accurate predictors of TDOA system performance. These approximations do not take into account the relative locations of the receivers, or the signal source characteristics as described above. Nor do they account for the relative timing errors between receivers, or delay errors introduced by antenna cables and filters.

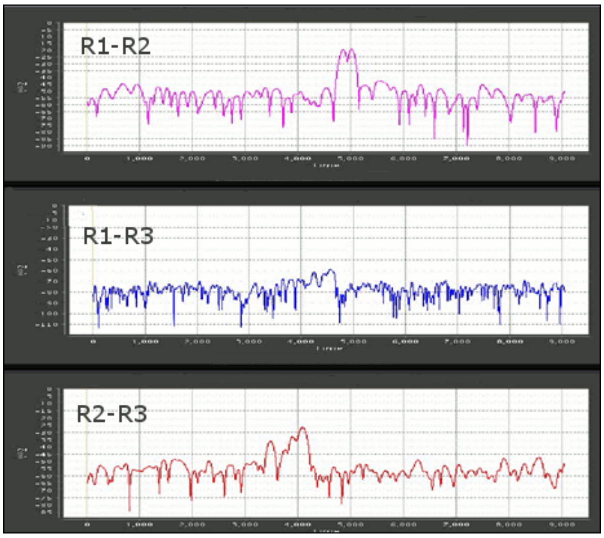
Effects of signal level, duration and velocity in correlation based TDOA

One method for determining the TDOA involves computing the cross-correlation between signals from two receivers. The cross-correlation function indicates the commonality of two signals as a function of time offset. For a signal observed over the same time interval at two different receivers, the position of the amplitude peak in the cross-correlation function indicates the delay-difference for that pair of receivers.

Figure 4.7-20 contains the cross-correlation plots from a single measurement in a three-receiver system. Ideally, each plot would contain a single pulse, the position of which is shifted left or right depending on the time-difference. As this data comes from an actual measurement, it exhibits the effects of real-world impairments. All three cross-correlation plots exhibit multiple pulses indicating multipath. In addition to multipath distortion, the second cross-correlation R1-R3 also exhibits the symptoms of low SNR. While the cross-correlations in this example are far from ideal, it is possible for sophisticated TDOA algorithms to extract location information from data of this quality.

FIGURE 4.7-20

Cross-correlations distorted by noise and multipath



Spectrum-4.7-20

The magnitude of the cross-correlation peak is a function of the received signal power at both receivers. The cross-correlation noise level is a function of the noise level at both receivers; the degree to which the noise from each receiver is correlated and the length of interval over which the cross-correlation function is computed.

Noise reduction is one of the benefits of TDOA based systems. It allows geolocation of signals that are received with negative SNR at one or more of the system's receivers. While there is no theoretical limit to the amount of noise reduction that can be achieved, there are practical limits, such as the duration of the signal.

Relative motion between the signal source and the TDOA receivers introduces a frequency shift (Doppler). The frequency shift will be different for each receiver depending on the rate at which the signal source and receiver are moving towards, or away from each other. The magnitude of the frequency shift is also a function of the signal's frequency. Correlation-based TDOA systems must correct for *relative* frequency shifts between receivers to accurately estimate the time-difference.

4.7.3.2.4 System considerations

Receivers

Receivers should have adjustable IF bandwidths to: allow signals to be spectrally isolated from other signals; minimise noise power; and allow to maximum use of a signal's bandwidth for geolocation accuracy.

To minimise network requirements, receivers that transfer sampled signals to the TDOA compute engine should use the minimum sample rate necessary to represent the signal without aliasing. Timing accuracy should be independent of sample rate. In other words, a 20 kHz sample rate should not imply a 50 µs (1/20 kHz) timing accuracy.

To further minimize network and computational requirements, receivers should avoid as much as possible the transfer of sampled signals when signals are not present.

A receiver's absolute timing accuracy should be specified at the receiver's antenna connector under most, if not all operating conditions. This will avoid the introduction of timing errors by the switching of internal pre-selection filters, attenuators, or other changes to the receiver's analogue and digital signal processing elements that might otherwise affect the receiver's total group delay.

Receiver timing accuracy should apply at all frequencies within a receiver's IF bandwidths. This will ensure that signals that occupy a significant percentage of the IF bandwidth are not further distorted by group-delay distortion. It will also ensure that a signal that is narrow relative to the IF will have good timing accuracy at any frequency offset within the IF. A receiver's final IF filter is generally the narrowest filter in the receiver, and is likely to be the largest source of timing error in the receivers internal signal path.

The TDOA system, or each receiver in a system, should have a facility for adding delay calibration coefficients for each receive site.

Number of receivers

A minimum of three receivers are required for TDOA-based geolocation. When available, using data from more than three receivers is likely to improve geolocation accuracy. Accuracy can be significantly improved with four or five receivers, for example. The number of receiver pairings can be computed as N (N-1)/2 where N is the number of receivers. With five receivers, there are ten pairings, and therefore ten time-difference estimates. The quality of the data from each pairing will vary greatly depending largely on signal level and multipath. Systems incorporating advanced TDOA algorithms will intelligently combine or discard data from multiple receiver pairings to improve location accuracy. At some point, adding more receivers becomes counterproductive as the computational load increases exponentially while yielding minimal improvements in accuracy.

Additional receiver and site considerations

There are a number of additional considerations in planning a TDOA system. Factors which should be included during the system planning process include:

– desired location accuracy;
– system complexity;
– availability of electrical power;
– availability of networking, and networking performance;
– propagation environment;
– signal environment (utilisation, frequency re-use);
– types of signals to be located (bandwidths, power, duration, frequency);
– available sites (elevation, proximity to transmitters);
– antenna performance;
– receiver performance.

Depending on these considerations, recommended receiver spacing will range from hundreds of meters, to tens of kilometers.

Time references

TDOA systems will typically use GPS receivers to establish a common time reference. To achieve the best timing accuracy, the GPS receiver may be operated in a mode where the location is fixed. Fixed-mode operation enables the GPS receiver to solve for time with greater precision.

Receivers should not rely on GPS, or other RF based timing services if the TDOA system will be used to locate signals which interfere with those services.

Network considerations

Network requirements are driven by:

– the TDOA method;

– the specific implementation;
– and user requirements for speed and reliability.

Networking capacity and speed requirements will be greatest for TDOA systems that return sampled signals to the TDOA compute engine. TDOA systems that establish TOA at the receiver will have more modest bandwidth requirements. In both types of systems, data transfers are likely to be highly asymmetrical with upload requirements exceeding download requirements at the receiver. Network bandwidth requirements will generally be greater at the TDOA compute engine as data from all receivers is collected at one location.

Low latency is generally desirable in all TDOA systems. High latency may negatively impact the location update rate. It may also impact the ability to schedule TDOA measurements.

In large location systems, multiple networking technologies may be required, such as wireless, DSL, cable-modem and fibre-optic. In these systems, network connections may suffer variations in capacity and reliability due to weather, interference, and loading from other network users. TDOA systems should be capable of gracefully accommodating differences in performance between the various network links, as well as outages to one or more receivers. When wireless networking is used, care should be taken to avoid interference between the TDOA receiver and the RF modem.

When public networks are used as part of the TDOA system, virtual-private-networks (VPN's) or other similar networking technology should be used to secure data transfers and prevent direct attacks on the receivers. TDOA receivers will generally have limited computational resources and may be easily overloaded by unnecessary or malicious network traffic.

4.7.3.3 AOA homing and standoff methods

Emitter location can be performed using re-locatable direction-finders, with the advantage of using fewer DF stations. Mobile DF stations are mounted in a vehicle, which contains all necessary equipment, power sources and antennas. Portable DF stations are re-locatable assets, which may require set-up and deployment before measurements can be performed. These types of units are devised to operate using two basic methods: standoff methods and homing methods.

The standoff method involves obtaining several discrete LoB measurements from fixed locations, which are a suitable distance from the subject emitter. The suitable distance is likely to be a function of the accuracy of the DF system, local terrain, or other conditions. Successive measurements may be made, at different locations, with as few as one portable or mobile station and combined using standard triangulation methods.

Disadvantages of the standoff method include the fact that measurement site selections are susceptible to interference from surrounding structures, and that simultaneous measurements are often impossible from multiple locations. Signal transmission times or transmitter movements may introduce location errors. The choice of the DF principle for these types of measurements should consider susceptibility to site effects, and physical arrangements for mobile and portable application.

Homing methods are successful using mobile equipment of minimal complexity and only moderate accuracy. They are also effective in interference clearance operations using mobile monitoring vehicles.

This second strategy makes use of mobile equipment (usually in an automobile or aircraft), which can be rapidly moved into the vicinity of the transmitter by following successive approximations of the true line of bearings. As the distance to the transmitter is decreased, the magnitude of the absolute distance error also decreases to a manageable value even if the relative error in degrees remains constant. Advantages of this strategy include equipment which is lower in cost and complexity, the fact that adequate results can usually be obtained in a reasonable time, the additional fact that site error problems are much less important because the unit is mobile and /error contributions can be "averaged" over a long baseline, and finally, the DF information can be derived from sub-audible and locally-induced homing system modulation which does not disrupt the information being transmitted.

Widely available homing systems have been found to operate either in a "homing" configuration without the ability to clearly hear normal modulation components, or in an "audible" configuration when the homing circuit is switched off. This limitation is inherent with design of equipment that superimposes audible, local modulation proportional to the direction of signal arrival. Only one DF homing system is required to locate a signal source, although simultaneous use of others may speed transmitter location. Disadvantages are that inconspicuousness of stand-off capability is sacrificed, and multiple transmissions over a reasonable time period are required for adequate location of the transmitter.

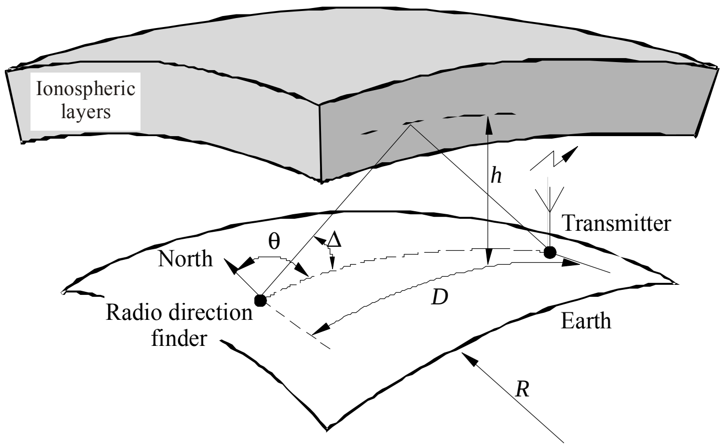
Modern automatic direction finders are compact enough to be installed in vehicles.

4.7.3.4 Single site location method for HF emissions

The single station location (SSL) system allows determining the geographical position of a transmitter with a single radio direction-finder (see Fig. 4.7-21). Processing data supplied by the radio direction-finding (azimuth, elevation, position) associated with ionospheric measurements or predictions allow estimating the transmitter distance from the radio direction-finder. The SSL concept thus allows performing the location mission when, for geographical, timing, or availability reasons, a complete triangulation radio direction-finding location system could not be installed. SSL may also be considered as a complement to an existing location system.

FIGURE 4.7-21

SSL Principle



θ: geographical azimuth
Δ: elevation angle
D: distance
h: virtual reflexion height
R: Earth radius

Spectrum-4.7-21

SSL radio direction-finders simultaneously determine the azimuth and elevation angle of the signal received by the antenna array. Propagation may be by both ground wave and ionospheric wave through multiple paths corresponding to different elevation angles. As a result, the SSL direction-finder supplies an elevation angle evidencing time variations due to multipath interference. Processing algorithms are used to determine elevation values relating to the said multiple paths.

Such processing, associated with ionospheric measurements or predictions, allows estimating the transmitter distance from the SSL radio direction-finder at distances ranging up to 2 500 km (although estimates of transmitter distances greater than 1 000 km or so are subject to significant error due to the low elevation angle of arrival and the geometry of the situation). Association of the azimuth, distance and radio direction-finder position data, allows estimating the geographical coordinates of the HF transmitter.

The basis of the SSL approach is the so-called Classical Method of Range Estimation. This method assumes that the actual HF propagation may be modelled by assuming that reflection takes place from a simple horizontal mirror at the appropriate height. The height of this mirror is derived from a vertical incidence ionogram, as the virtual height at a frequency called the equivalent incidence frequency. The classical method is based on three simple fundamental relations, the Secant Law, Briet and Tuve's Theorem, and Martyn's Equivalent Path Theorem with correction terms to account for the curved Earth and ionosphere.

Limitation of SSL technique

The SSL principle is based on the assumption that the signal is reflected from the ionosphere only once (single hop). Multi-hop propagation leads to calculation of distances that are shorter than real distances. Also, ionospheric height values may be ambiguous. Thus the reflection may take place from layers of different heights. This may give the result that different distances to the targets are indicated by the SSL system.

4.7.3.4.1 Estimation of the ionosphere height

SSL systems include one or more of the following methods to determine the height of the ionosphere:

– real-time ionospheric characterisation can be obtained from the process of ionospheric sounding. Equipment that performs this process is known as an ionosonde, or sounder. A sounder is able to determine the propagation characteristics of the ionosphere at all frequencies and thereby characterise the ionosphere in the vicinity of the sounder. A sounder requires a transmitter, a dedicated antenna and analysis software;

– calibration with the help of a transmitter with known position (see [Touré, 2004]). This method requires an updated database of the position of the emitters. It is generally not as accurate as SSL results based on ionospheric sounders because calibration on one or a few individual transmitters will not completely characterise the ionosphere at all frequencies as will a sounder;

– Data base with ionosphere prediction files. Some national scientific organisations provide accurate results from complex computations including the solar activity, the propagation layer of the ionosphere, etc. However the predictions are only an average and do not account for any local, temporary or other propagation effect which can be detected with real time measurements. These predictions are useful when real time information is not available, including cases of propagation with reflection points far from a sounder.

4.7.3.4.2 Location software

The radio direction-finding software can provide the following elementary results of measurements:

– azimuth (degrees);

– elevation (degrees);

– number of measurements integrated to the average;

– HF level at receiver input (dBm);

– lateral and longitudinal distance errors.

All these data items may be displayed on the operator screen.

4.7.3.4.3 Program generating predictions

In order to be able to determine the position of a transmitter, the location software may include ionospheric predictions files in addition to, or instead of measured ionograms. The prediction software allows generating ionospheric predictions files for a selected geographical site. Modelling is performed in compliance with Recommendations ITU-R P.1239 and ITU-R P.1240.

The ionospheric propagation paths are determined by a radius-plotting program from the knowledge of vertical electronic density distribution. As the ionosphere is an isotropic medium, two characteristic waves exist, which are associated with an angle of the data: the ordinary wave (O) and the extraordinary wave (X). It is then necessary to generate the predictions related to the modes used by the SSL. The prediction file provides, for given time, date, frequency and place, all of the distances corresponding to the requested elevations (histograms).

4.7.3.4.4 Location range calculation

The location software may be used to enter the following parameters:

– elementary DF results;

– current time and date;

– working frequency;

//– relevant ionospheric measurements or prediction file.

The different steps of the distances calculation process for the HF transmitter are:

a) Elevation histograms.

b) Filtering elevation histograms.

c) Determining the packets.

d) Processing "low" elevations.

e) Obtaining ionospheric measurements or generating predictions.

f) Determining the four basic distances.

g) Determining the final distance.

From the four distances a final distance is extracted by resection (see Fig. 4.7-22).

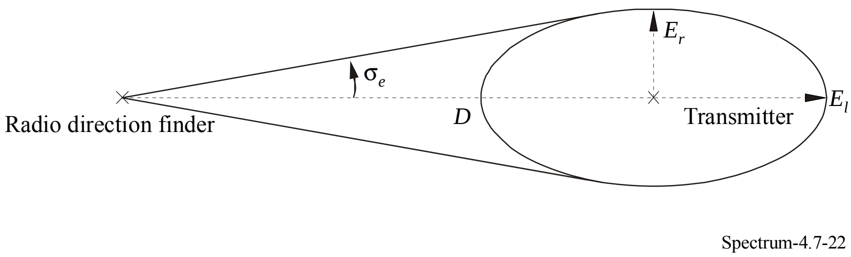
h) Calculating the geographical coordinates.

i) Integrating elementary locations.

j) Location results.

FIGURE 4.7-22

Distance determination



For each emission, the location calculation can give the following results:

– average azimuth (degrees);

– number of elementary measurements;

– mean HF level;

– radial error;

– longitudinal error;

– geographical coordinates of the transmitter.

The results are accessible by graphic display and printer.

4.7.3.4.5 Validity

The validity of the Classical SSL method relies on the validity of several assumptions that:

1. the Earth's magnetic field can be neglected at certain times;

2. the virtual height obtained from the local ionogram is the same as would be contained at the circuit midpoint;
3. the equivalent ionospheric mirror is horizontal.

For longer circuits, assumption 2) starts to fail, and at some point it is necessary to change over to a ray re-tracing procedure using a model of the ionosphere updated to be consistent with the local ionogram. Such models exist and are in a state of continuing improvement by ionospheric physicists throughout the world, including taking the effects of the Earth's magnetic field from assumption 1) into account. Computational power and speed continue to improve the execution of multi-dimentional ray re-tracing procedures through complex ionospheric models. Existing HF Propagation prediction programs such as Ioncap, *et al*, are useful for planning purposes but are of limited value in SSL applications since they are based on 12 month averages and do not take the real-time state of the ionosphere accurately into account.

The assumption 3) that the equivalent mirror is horizontal leads to the largest errors on short circuits. This error depends inversely on the cosine of the elevation angle. In practice, the ionospheric reflecting surface may be tilted by as much as 4° or 5° from the horizontal due to large-scale gradients (such as at sunrise or in the vicinity of the equatorial anomaly) and small-scale gradients (or "tilts") associated with travelling ionospheric disturbances (or "TIDs"). Consequently, for SSL work on short circuits, it is desirable that the ionosonde also be capable of measuring the local ionospheric tilts so that they may be taken into account. However, there is some evidence that measuring tilts does not improve Line of Bearing results [BRAMLEY, 1953].

4.7.3.4.6 SSL elevation angle

With the exception of taking the Earth's magnetic field into account in determining the value of the equivalent vertical frequency the assumptions that determine the validity of the Classical SSL Method start to fail as a function of range to the HF emitter, primarily at the two extremes of short- range and long-range. From an understanding of why the Classical Method assumptions start to fail, SSL methods have been developed to make valid range estimates at these two extremes. For a discussion of these methods, the range spectrum may be divided into three categories; short-range, medium-range and long-range.

4.7.3.5 Comparison of location methods

TABLE 4.7-7

Location method comparison

Item	Homing / Standoff	Triangulation	TDOA location	SSL (HF only)
Required number of stations	1 with homing or standoff functionalities	2 for AOA location 3 for unambiguous locations	At least 3 stations are required and additional stations help to solve ambiguity	1
Required material	DF antenna on a vehicle No network required	One direction finder per site Low data rate network to exchange coordinates and AOA results	Data network to transfer digital signals Low requirements for antenna and receivers Shared synchronisation (which are usually GPS systems)	1 station that measures elevation and azimuth, and an ionosphere characterisation method like ionospheric sounder, predication or calibration

TABLE 4.7-7 (*end*)

Item	Homing / Standoff	Triangulation	TDOA location	SSL (HF only)
Performance depends on transmitter/locations system geometry	Not applicable	Accuracy is better in the centre of the triangle if 3 DF are used Outside the triangle, the location accuracy decreases slowly	Accuracy is the best within the area bounded the receiver sites Outside the triangle, the accuracy decreases to approximate a single line of bearing	SSL is unambiguous for one hop signal only
Performance depends on the bandwidth of the incoming signal	No Requires permanent or long duration signals	Depending on the method used	TDOA may not be suitable for very narrow bandwidth or unmodulated signals	No
Dedicated for mobile or fixed stations	Mobile only	Fixed and mobile	Fixed and mobile; mobile may not be practical depending on data-link requirements	Fixed
Able to solve multipath/multiple source signals	Not typically, since it often uses conventional methods such as interferometers	See Table 4.7-5 regarding partly-coherent sources	Yes with advanced TDOA processing techniques	See Table 4.7-5 regarding partly-coherent sources

4.7.3.6 Location combined methods

In general, there is no single method such as the ones based on measuring time difference of arrival (TDOA) and angle of arrival (AOA) that will provide accurate location estimation under all circumstances. Each method has its own advantages and limitations in terms of location accuracy.

TDOA location methods generally provide better location accuracy for wideband signals than the AOA-based location method.

However, the TDOA-based methods require relatively more stations than the AOA-based methods to perform location of emitters. For instance, the TDOA-based methods require at least three properly distributed stations for location.

The AOA methods, on the other hand, require two stations for location. However, a small error in the angle measurements will result in a large location error if the station is far away from the transmitter.

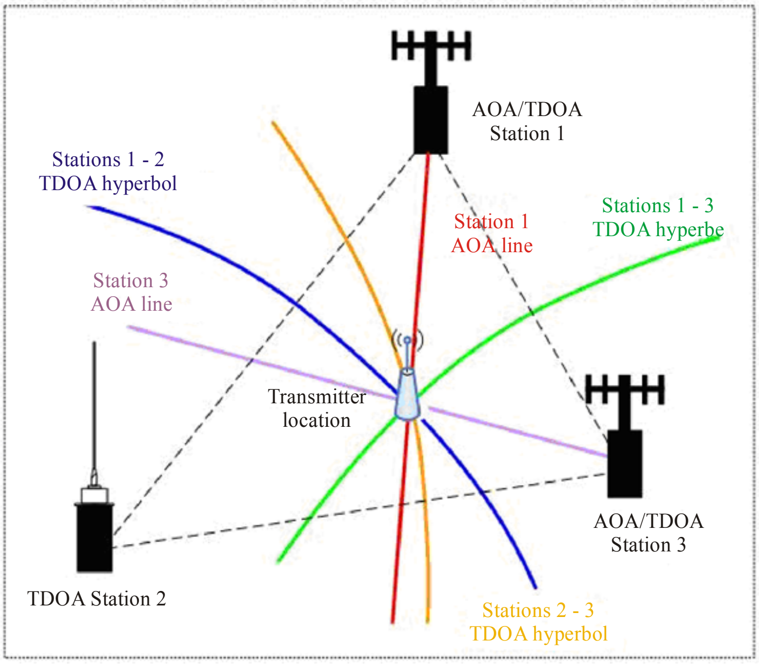
Therefore, to achieve better location accuracy, a combination of two or more location schemes should be considered in order to complement each other.

The location is performed by processing the information available from each station, including AOA measurements, TDOA measurements and station position information.

Combining the AOA method with the TDOA method can assist in eliminating location ambiguity associated with TDOA alone and can enhance location accuracy. This is illustrated on the Fig. 4.7-23.

FIGURE 4.7-23

Improved results based on AOA/TDOA combined techniques



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ITU-R Recommendations

NOTE – In every case the latest edition of the Recommendation is encouraged be used.

Recommendation ITU-R M.428 – Direction-finding and/or homing in the 2 MHz band on board ships.

Recommendation ITU-R M.489 – Technical characteristics of VHF radiotelephone equipment operating in the maritime mobile service in channels spaced by 25 kHz.

Recommendation ITU-R M.589 – Technical characteristics of methods of data transmission and interference protection for radionavigation services in the frequency bands between 70 and 130 kHz.

Recommendation ITU-R P.1239 – ITU-R Reference ionospheric characteristics.

Recommendation ITU-R P.1240 – ITU-R methods of basic MUF, operational MUF and ray-path prediction.

Recommendation ITU-R SM.854 – Direction finding and location determination at monitoring stations.

Recommendation ITU-R TF.767 – Use of global navigation satellite systems for high-accuracy time transfer.

Report ITU-R SM.2125 – Parameters of and measurement procedures on HF/VHF/UHF monitoring receivers and stations.

4.8 Signal analysis and transmitter identification

4.8.1 Introduction

Radio monitoring is changing, nowadays signals do not only tend to be more digital but also the "rest-capacity" of the more conventional signals is exploited to transmit additional information. Moreover new developments and techniques can be used to perform traditional monitoring tasks more efficiently. Because of this, signal analysis has become more important as a monitoring tool and is particularly helpful for the purpose of transmitter's identification. Signal analysis is the art of extracting any possible information from a transmitted signal. This may lead to the characterisation of a transmitted signal (frequency, modulation, etc.), the characterisation of a transmitter (location) and/or extracting of transmitted information.

The discussion below is related to narrow-band signals such as analogue PMR or PACTOR as well as wideband signals such as UMTS, pulse signals or OFDM modulated signal.

It should be understood that signal analysis is a complex task of spectrum monitoring which needs to be conducted by specially trained monitoring experts. They need specialised hardware and software which they might need to assemble themselves if there is no equipment and software commercially available for a specific measurement task.

4.8.1.1 Identification in the framework of the spectrum monitoring regulation

In order to emphasise the need of identification in terms of regulation, the Article 19 of the RR (Identification of Stations), No. 19.1, states that: "All transmissions shall be capable of being identified either by identification signals or by other means."

This could be assumed by means allowing a direct identification like call sign, name of station, operating agency, maritime mobile service identity, official registration mark, flight identification number, selective call identification number or other clearly distinguishing features readily recognised internationally. Another way consists in analysing characteristics of a signal or an emission and deducing the identification.

Nevertheless, RR No. 19.1.1 also recognizes that the transmission of identifying signals for certain radio systems (e.g. radiodetermination, radio-relay systems and space stations) is not always possible. The class of emission can be used as form of identification in any case. As an example, a sample of the codes developed for maritime mobile and maritime mobile-satellite services is shown in Annex 1. A possible code extension by supplementary code characters in order to extend the possibilities for classification and identification is shown in Annex 2.

4.8.1.2 The need of identification for spectrum monitoring activities

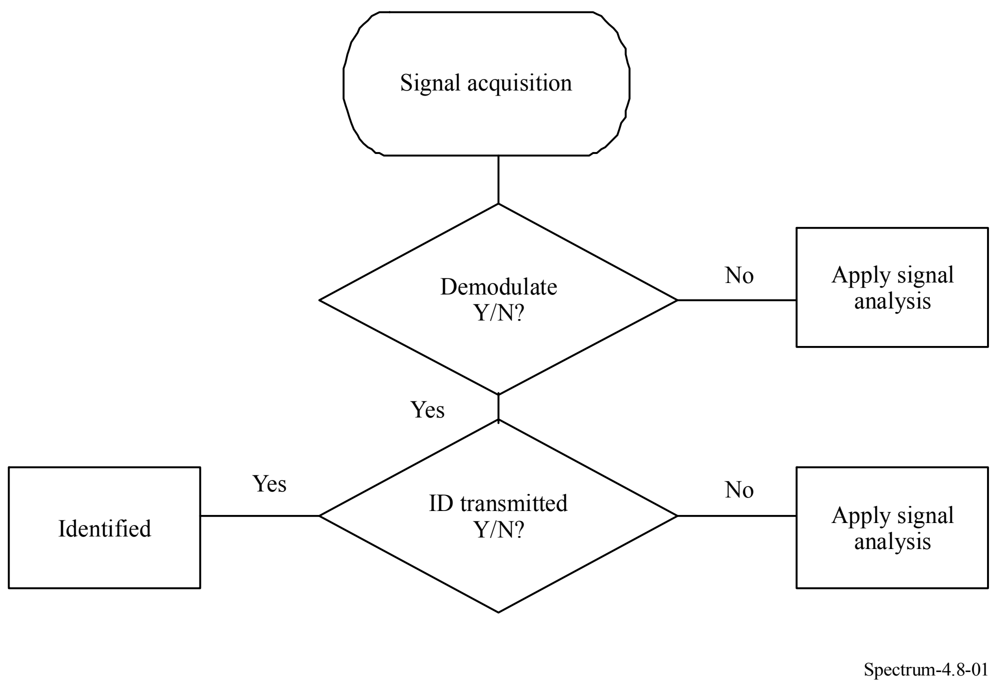
In the framework of a spectrum monitoring department, identification might be required in order to perform such tasks as below:

- identification of users of the spectrum;
- determination of spectrum utilisation;
- compliancy with the licence conditions;
- spectrum use efficiency;
- detection and identification of illegal use;
- detection and identification of interferers;
- localising the origin of signals.

Figure 4.8-1 shows basic process followed for transmitter's identification by its signal.

FIGURE 4.8-1

Basic tasks for transmitter identification



4.8.1.3 Applications of signal analysis in spectrum monitoring

In spectrum monitoring matters, signal analysis is often used for signals identification and is particularly required when basic tools of spectrum monitoring are not sufficient to identify a signal as implied in Fig. 4.8-1. Signal analysis consists of detecting, spectrum analysis, modulation recognition, analogue and digital demodulation, code recognition and channel decoding. Correlation analysis, cryptography and steganography are to some extent part of the subject. Some of these related techniques are discussed elsewhere in the Handbook. Depending on national laws some of these techniques may be forbidden.

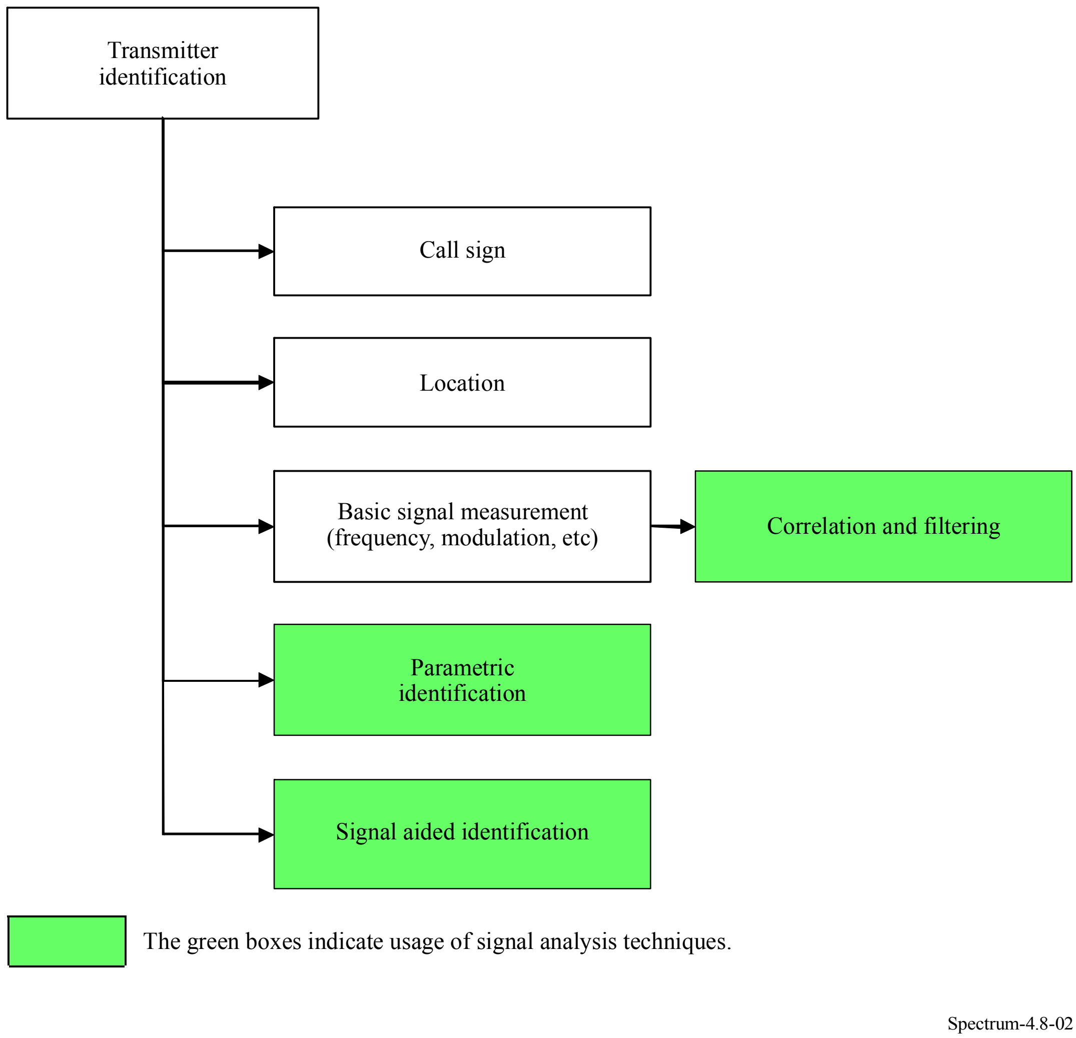
Signal analysis is not necessarily a complex task to perform and listening radio stations with the goal of identification might be considered as a signal analysis task.

Although such tasks could be performed manually, most of them could be automated to improve the processing, in particular, in terms of time processing for example.

In order to achieve the process of identification of a transmitter or a signal, different methods are available. The main ones are summarised in Fig. 4.8-2.

FIGURE 4.8-2

Transmitter identification



4.8.2 Identification with call sign or basic signal measurements

4.8.2.1 Identifier recognition method or identification through call sign recognition

Such techniques allow, with a single parameter measurement, to identify an emission and a transmitter.

Formation of call signs

The formation of call signs is derived from an international series allocated to countries in accordance with the Table to be found in RR Appendix 42. Additional information concerning the formation of call signs within the various services may be found in Section III of RR Article 19, as well as in Resolution 13 (Rev.WRC-97).

An example of these transmissions is given in Annex 1.

Radiotelegraphy systems

Transmissions may consist of a single channel, a time division multiplex system, a frequency-division system or a combination of them. In single-channel systems the call sign may be transmitted in Morse code or in a teleprinter code with the same type of modulation as is used for traffic on that particular channel. Often bit-interleaving is employed (for instance TORG-10 or FEC-100). In frequency division multiplex systems, where many different traffic channels are radiated, it is sometimes arranged that one channel is used by circuit engineers themselves. Most often, this is the only channel that is used for identification purposes, especially if arrangements are made on the traffic channels to secure the communications using scramblers or encryption devices. Engineering channels are usually left open.

Radiotelephony systems

The most common method of identification is to transmit the call sign in clear speech; however, in single-sideband telephony transmission, the method of superimposing the call sign with amplitude modulation of the reduced carrier with Morse code may be used.

Mixed-service radio systems

A mixed system typically uses a single-sideband emission for one or more telegraph channels arranged in time or frequency-division multiplex, and one or more telephone channels modulating the same radio-frequency carrier, which may be at full, reduced or suppressed amplitude.

In mixed-service channels, any of the methods indicated for identification of time-division multiplex or single-sideband frequency-division telegraph stations may be used for identification purposes.

4.8.2.2 Basic signal measurements for identification of transmitters without call sign

Without call sign, identification may be performed either by localising the transmitter (see § 4.7 on direction finding and location) or by characterising the received signal (with receiver or spectrum analyzer).

In some cases, demodulating a signal might be a way to identify a signal. However, modern speech scramblers are often used by maritime mobile services and by the military. These utilise various techniques basically consist of rearranging the speech spectrum in frequency and time. In this way standard receiving equipment will not permit “clear speech” to be heard without specialised equipment. Complex modern cryptographic techniques are commonly used in the transmitting equipment and it is difficult to identify any of the original speech from the received signal.

Characterising a signal means to measure each basic parameter like frequency, modulation and all parameters which can be used to specify the waveform of the signal. As an example, information to characterise a pulsed signal is available in § 4.9.

In some cases, for such a signal, an oscilloscope may be used to obtain some sort of recognisable pattern that could be identified and catalogued for future use. Such procedure is essential to create a database of detected signal in order to facilitate future identification.

During monitoring observations, parameters (including frequency, shift, baud rate, bearing, users group, etc.) of each detected signal may be stored in computer files.

This database, abstractions for submission to the ITU/BR, in accordance with RR Article 16 can be designed in the desired format. Searching for vacant spectrum of any desired size becomes very simple and it’s also helpful for the identification of interferences.

RR Article 5 (Frequency allocations), including the footnotes, an abstraction of the IFL and a list of all known stations transmitting press bulletins are also examples of help files to elaborate the database.

It is recommended to use automated files, because they make it easy to find certain items or make selections. Nevertheless, there are still “Handbooks” compiled by monitoring organisations containing a lot of information that cannot easily be stored in files. These books are very useful for identification purposes.

4.8.3 General approach to signal analysis process

Identification in terms of signal analysis process can be described according to the diagram in Fig. 4.8-3. In the framework of spectrum monitoring, signal analysis is used to assume following tasks (in regard of spectrum detection):

- assign a name if it is a known system;
- extract hidden information if possible;
- determine parameters of the signal if it's required (in the case of the previous options fail):
  - its modulation characteristics (as symbol rate, frequency shift, linear/non-linear modulation, kind of modulation: analogue/digital, phase, frequency or amplitude modulation, number of modulation states, constellation for linear modulation);
  - its time characteristics (burst wave forms);
  - or its spectrum characteristics (narrow/wide band, single carrier or multi-carrier signals, etc.).

Start and stop time and duration of an emission may also be used to describe a signal.

Considering the diagram in Fig. 4.8-3, the first step is to identify the signal to analyse and to check if the signal may be easily measured. The next step consists in determining if the signal may be demodulated and, if it's the case, the suitable demodulator may be applied.

Afterward, analysis of the demodulated information could be done and a decoding stage might be necessary to post-process data. This means the extraction of information from the demodulated data stream. If the demodulation is not possible, the signal should be specified by its intrinsic parameters (frequency, bandwidth, etc.).

The two first steps of signal analysis process are illustrated by an example in Fig. 4.8-4 which shows a sequence of tasks which could be applied to identify a narrow band signal contained in a wideband signal. This is performed by tools dedicated to signal analysis which are detailed in the next section.

4.8.4 Considerations on capabilities of a system to perform signal analysis

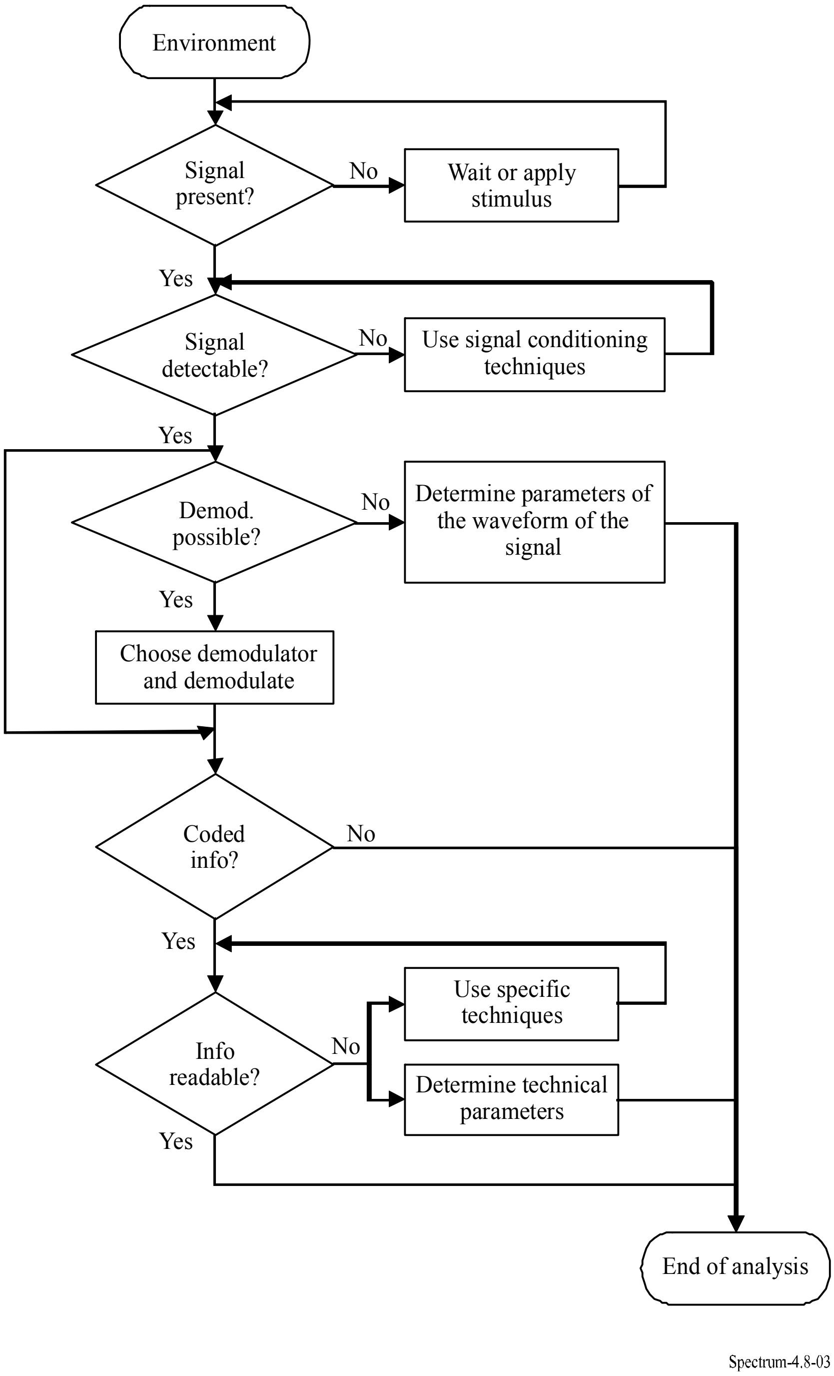
A summary of requirements is as follows:

- modularity of hardware and software;
- usage of general standards (e.g. PCI, DSP standard links, LAN, LXI…);
- real-time capability when needed realised with real time operating systems and DSP operating systems;
- dual channel capability may be required for some application (for example correlation process);
- components and signal processing algorithms, optimised for specific frequency ranges like HF, VHF/UHF or SHF;
- capability of the system to record wideband and (or) narrow-band signals; the bandwidth of the signal and the duration of the recording determine the technical features of the system, e.g. the size of the memory;
- remote control from a workstation with a powerful and reconfigurable user interface;
- optionally by a low speed connection over for example a telephone line adapted to the users need;
- possibilities to interface to existing equipment like receivers and recorders;
- training supported by the supplier;
- software expandable by the user and the manufacturer when needed.

Some analysis tools cannot work in real time because of the required processing. Other tools require time-consuming manual adjustment, which is undesirable when the signal occurs only incidentally. It is therefore necessary to have some recording devices to record either the wideband or the narrow-band signal. Important issues of these recording devices are the bandwidth, the dynamic range and the maximum time of unattended recording. Another reason for using recorders is the fact that not every signal analysis system is portable and this aspect, in some situation, may be required.

FIGURE 4.8-3

Signal analysis process



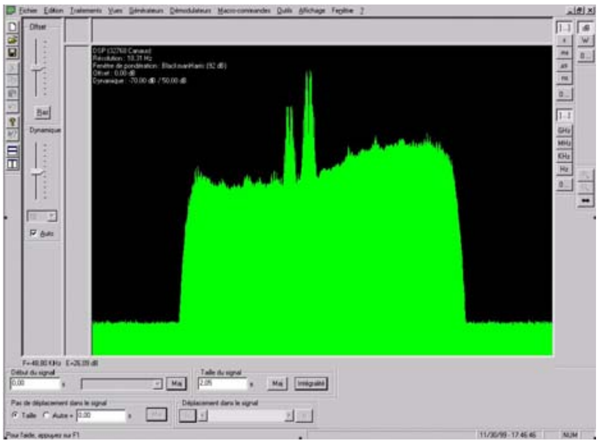
4.8.5 Signal analysis tools

Tasks included in the signal analysis process could be applied either as a manual or as automated operation with a dedicated system. This last solution should be open and flexible in both hardware architecture and functionalities in order to adapt its capacity of signal analysis with new signals and new techniques.

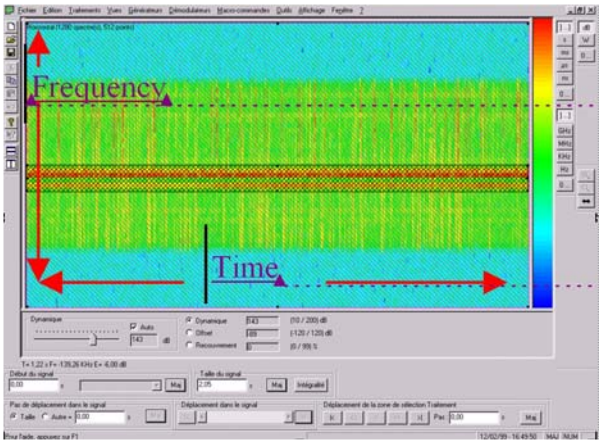
In practice, the starting point for analysis of a signal is to identify the signal itself usually by the measurement of the frequency. Signal identification and measurement techniques should be based on suitable representations of the sampled signal. Tools and facilities like zoom, copy/paste in time and frequency domain should be implemented in the interface. An example is shown in Fig. 4.8-5. Such tools are particularly suitable to isolate the signal to analyse.

FIGURE 4.8-4

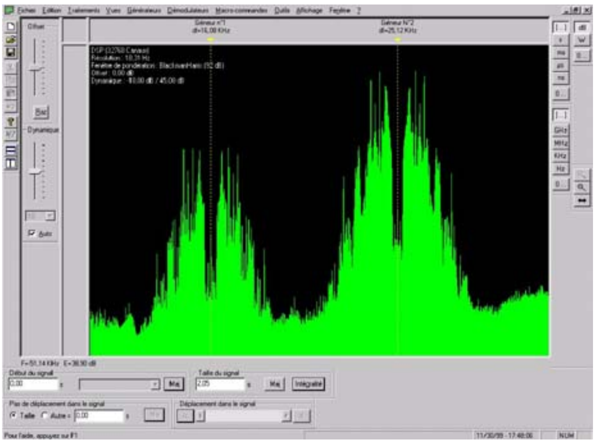
Example of extracting a narrow-band signal from a wideband signal



Step 1: Find narrow band signals at the wideband display

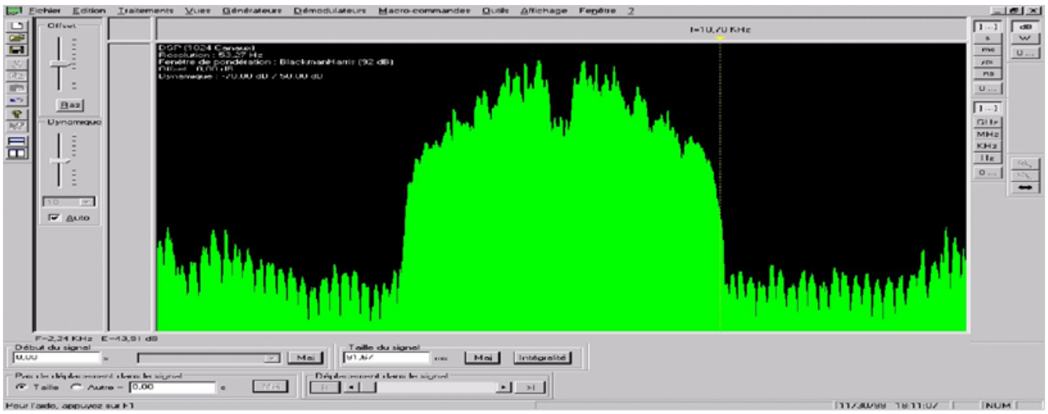


Step 2: Analysis of the persistence of the signal by using spectrogram



Step 3: View of the base band extracted signals (two signals)

Step 4: Design a digital filter for further measurements on a single signal



Step 5: Final spectrum representation of the filtered signal

Spectrum-4.8-04

In Fig. 4.8-5 spectrum representation of the signal and spectrum analysis helps to classify the signal by examination of carrier and subcarriers. For example, a spectrum comparison function can be used to perform an automatic identification of communication systems with a definite spectrum. For an automated search of carriers and their counting, just as for the measurement of the emission bandwidth, it is possible to use a high resolution spectral display and different search algorithms. A panoramic representation of the signal with variable spectral resolution and integration time is recommended. A combination of time and spectrum time representation of signals helps for identification and measurement of burst signals.

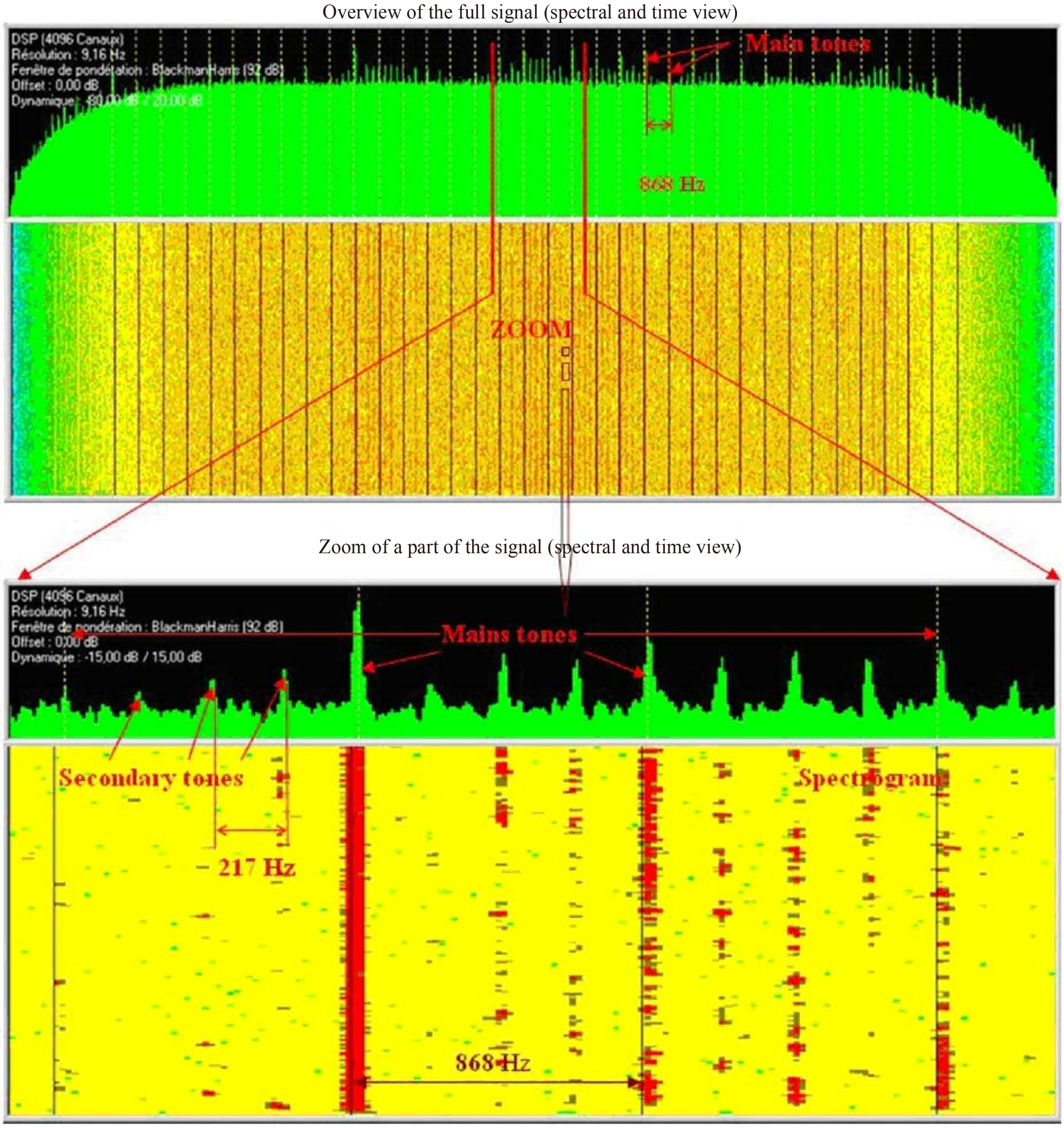
With such tools, it is easy to extract basic information directly derived from the spectral shape of the signal (in frequency and time domain). However, some of them require more advanced processing tools which essentially consist in mathematical tools as described in next sections. In the rest of this section, the differences between basic and advanced parameters are made. Basic parameters are defined as parameters which could be deduced from the spectral shape of the raw signal and advanced parameters of a signal are related to parameters available after the demodulating of the signal.

FIGURE 4.8-5

Examples of specific interfaces for supporting analysis, identification and measurement

Overview of the full signal (spectral and time view)

Zoom of a part of the signal (spectral and time view)



Spectrum-4.8-05

4.8.5.1 Determination of basic signal parameters

Although basic signal parameters may be determined by graphical means as described above, some mathematical tools may also be used. Some of them are given in this section. One technique might be the estimation of the 2nd and 4th order moments of the signal.

This provides a precise determination of carrier, symbol rates and chip rates for regular single-carrier, multi-carrier signals, and pseudo-noise/CDMA signals. A digital modulated signal can in most cases be identified by the determination of technical characteristics e.g. the symbol duration T_S, the guard time T_g and the number of subcarriers.

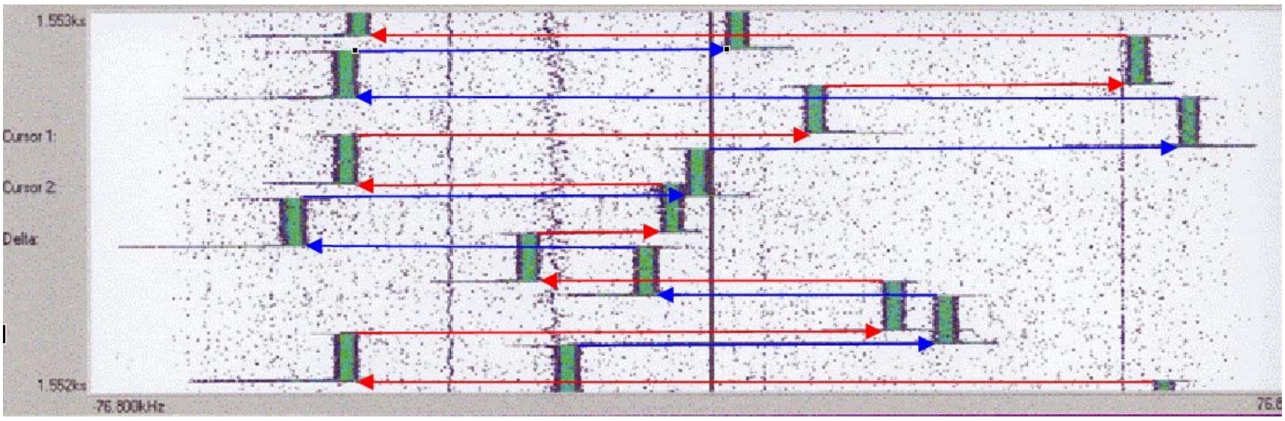
These issues are discussed in § 4.6. Facing to wideband or complex signals, such "blind" techniques provide very useful identification elements for further analysis.

An example of signal analysis operation for the determination of basic parameters, using a frequency hopping signal characterisation, is illustrated in Fig. 4.8-6.

Figure 4.8-6 illustrates the capacity of the analysis in the time domain to discriminate two signals with different frequency hopping patterns. Each pattern (red and blue arrows) has been identified manually. Such operation may also be performed automatically.

FIGURE 4.8-6

Example of frequency hopping signal characterisation



Spectrum-4.8-06

After such analysis, the conformity to a standard can be checked and the signal demodulated using a conventional demodulator. If it is not possible to demodulate the signal, parameters as instantaneous frequency, amplitude and phase can be used to make a technical description of the signal.

For example, a common radar signal can be described by its time signal and a frequency hopper by its hopping pattern (time and frequency).

Some methods for the extraction of the centre frequency, the symbol rate and other technical parameters of digital signals are summarised in Table 4.8-1.

These parameters can also be used to classify conventional non-digital signals.

To illustrate the content of Table 4.8-1, the symbol rate of a QAM signal can be determined by the spectrum of the instantaneous amplitude A_i.

The plots below illustrate the results of the symbol rate estimation of a QAM signal (in this case 16-QAM and a symbol rate of 62.5 kHz).

TABLE 4.8-1

Some methods to extract technical information depending on the modulation of the analysed signal

Parameters to be measured	Analysis tools	Modulation type
PRF or burst length	Amplitude time signal	OOK, Radar
Presence of signal	Cross-correlation of instantaneous amplitude A_i with reference signal	Any modulation type but specially for DSSS signals
	Spectral power density	Any modulation type
Modulation – rate of asynchronous or synchronous modulation (Symbol rate)	Histogram of the duration of instantaneous amplitude, A_i, instantaneous frequency, F_i, and instantaneous phase, Φ_i	OOK, Unfiltered FSK, Unfiltered PSK
	Spectrum of instantaneous amplitude, A_i	PSK filtered or not unfiltered CPM or after severe filtering QAM filtered or not
	Spectrum of instantaneous frequency, F_i raised to N power N (= 2(2FSK), 4 (4FSK))	Unfiltered FSK
	Spectrum of zero crossing on instantaneous frequency, F_i	FSK filtered or not PSK, QAM, MSK
	Spectrum of signal module raised to power N (= 2 or 4)	PSK & QAM filtered or not
	Spectrum of signal module raised to power N after a severe filtering in frequency	FSK filtered or not
	Spectrum of the signal raised with power N (N = 1/h)	CPM filtered or not
Carrier frequency Subcarrier frequencies	Spectral power density	Any modulation type
	Histogram of instantaneous frequency, F_i	FSK
	Average of instantaneous frequency, F_i	FSK
	Spectrum raised to power N (= 2 (PSK), 4 (QAM) or 1/h for CPM)	PSK, QAM, CPM
	Spectrum correlation and moments method	ASK, PSK, QAM
Emission bandwidth	Spectral power density Comparing with mask or limit line function	Any modulation type
Frequency distance between subcarriers (Shift for FSK)	Spectral power density Harmonic search and/or harmonic markers	FSK, OFDM, COFDM
	Histogram of instantaneous frequency, F_i	

Figure 4.8-8 provides an example where the symbol rate of 62.5 kHz of a 2 FSK signal is obtained from the instantaneous frequency F_i raised to the second power.

4.8.5.2 Determination of advanced signal parameters

For characterisation of the modulation scheme of the signal, the following methods/tools can be used (after the determination of the carrier frequency and the time behaviour of the signal):

– a symbol synchronisation display such as eye diagram and/or constellation of phase diagram according to the type of modulation;

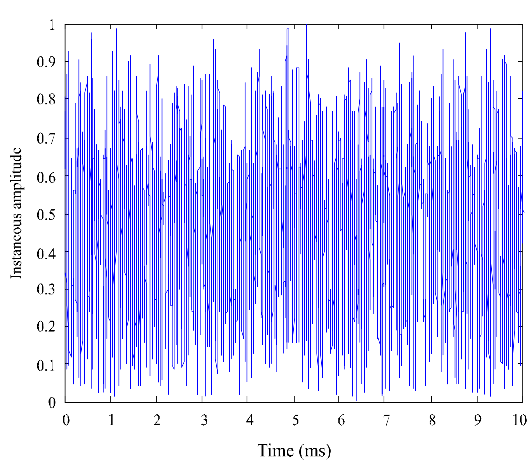
– a polar representation for the linear modulation types (validation of synchronisation, determination of the points of the constellation and the transitions between symbols);

– histogram representations for the phase or frequency modulations (validation of synchronisation, determination of the number of subcarriers).

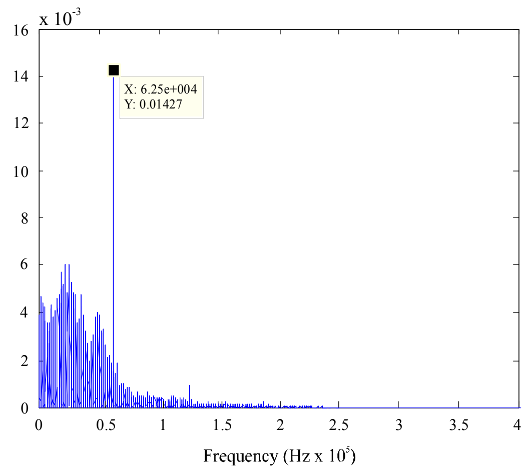
Some of the algorithms for digital modulation parameter estimation are summarised in Table 4.8-2. Note that many of these methods are also useful to characterise analogue signals.

FIGURE 4.8-7

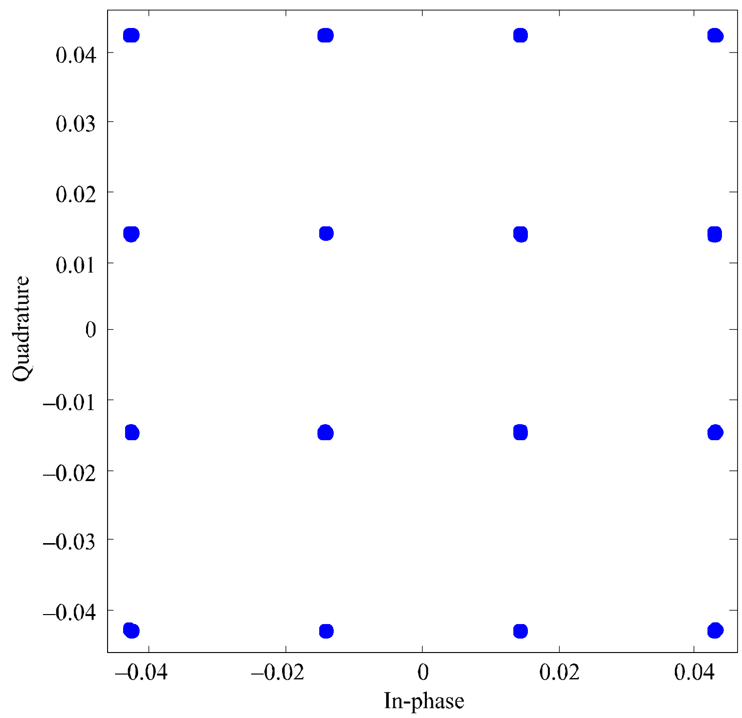
Example of determining the symbol rate of a 16-QAM signal by its instantaneous amplitude



Instantaneous amplitude, A_i



Spectrum of instantaneous amplitude, A_i

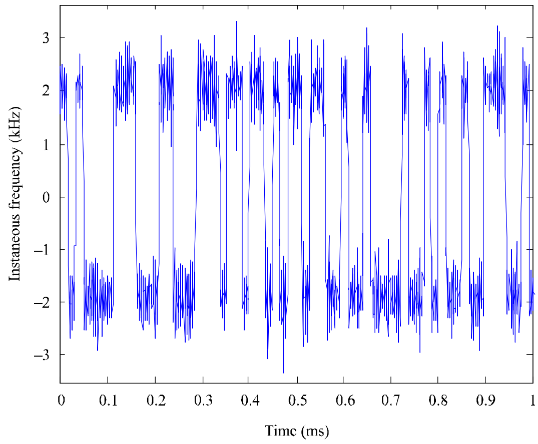


Constellation of 16-QAM signal

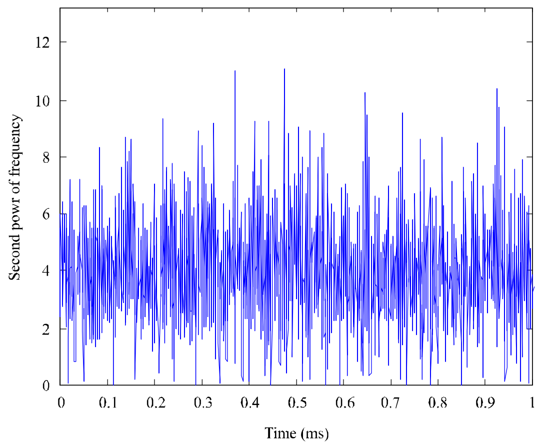
Spectrum-4.8-07

FIGURE 4.8-8

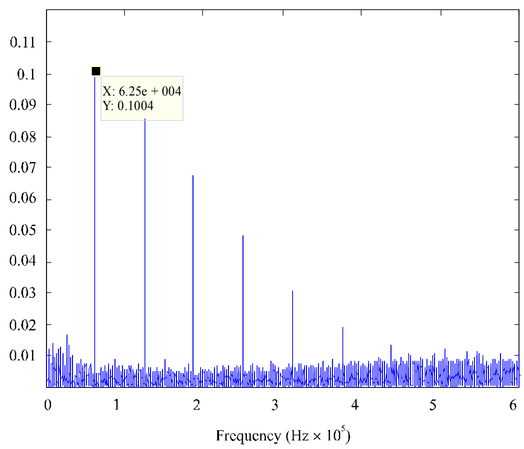
Example of determining the symbol rate of a 2 FSK signal by its instantaneous frequency raised to the second power



Instantaneous frequency, F_i



Instantaneous frequency, F_i raised to the second power



Spectrum of instantaneous frequency, F_i raised to the second power

Spectrum-4.8-08

TABLE 4.8-2

Some methods to determine the advanced signal parameters depending on the modulation of the analysed signal

Parameters to be measured	Analysis tools	Modulation type
Number of states	Constellation diagram/vector diagram	PSK, SQPSK, π/2 DBPSK, π/4 DQPSK, QAM
	Histogram of instantaneous amplitude, A_i	OOK, ASK
	Histogram of instantaneous frequency, F_i	FSK
	Histogram of instantaneous phase, Φ_i	PSK
	Spectral power density	OFDM,COFDM, multiplexing
Number of subcarriers or tones	Spectral power density	Any modulation
	Histogram of instantaneous frequency, F_i	FSK
Symbol synchronisation	Eye diagram I/Q, A_i/F_i + vector diagram	PSK & QAM filtered or not
	Eye diagram A_i/F_i + histogram display frequency, F_i	FSK filtered or not
	Constellation diagram + histogram display of frequency, F_i and phase, Φ_i	CPM filtered or not

As an example, Fig. 4.8-9 illustrates the extraction of modulation parameters and modulation characterisation for a 16-QAM signal.

4.8.5.3 Demodulation and decoding

One of the last steps is the extraction of the actual information. A demodulator should have a bit stream analyzer applying correlation techniques on the bit stream for determining the used coding scheme.

The bit stream should be mapped to different information units such as an alphabet.

Figure 4.8-10 illustrates an example of a digital demodulator with bit stream analyzer display for one of the more conventional modulation types (FSK).

4.8.5.4 Intercorrelation with a test signal

Another efficient way for identification and measurement of signals can also be performed using intercorrelation techniques with test signals and search functions acquired through intercorrelation.

The peak value of the intercorrelation of the analysed signal with a test signal makes it possible to detect the presence of the test signal inside the analysed signal.

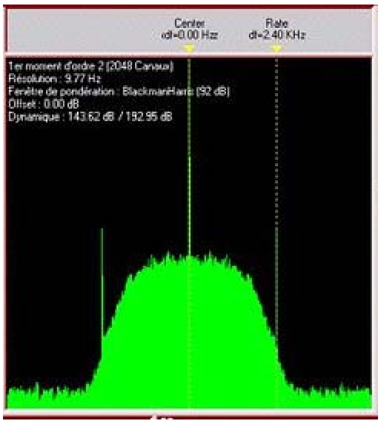
Additional information can easily be obtained such as estimation of the channel impulse response, the verification of demodulation quality and information on the channel or timeslot occupancy.

The method can also be used on synchronisation or Pilot sequences for decoding and identification purposes.

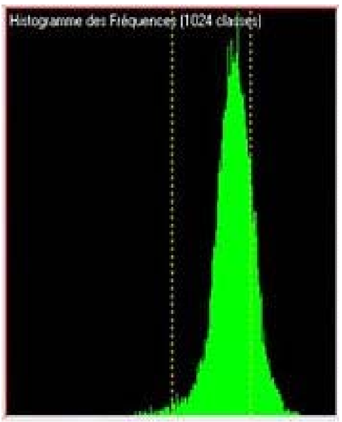
A test signal from a database can be used or the test signal can be generated using a reference signal. Techniques like this can be applied to conventional (analogue) systems as well.

FIGURE 4.8-9

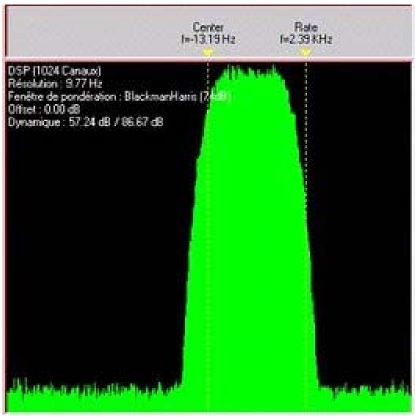
Examples of a complete characterisation of a digital signal



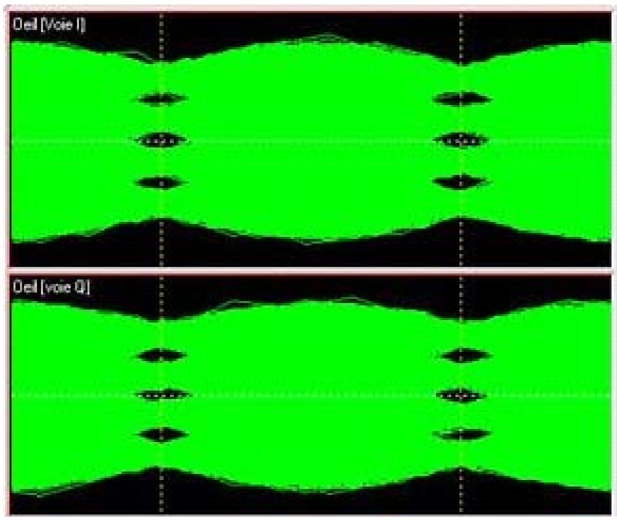
Extraction of technical parameters
(carrier, baud rate, etc.)



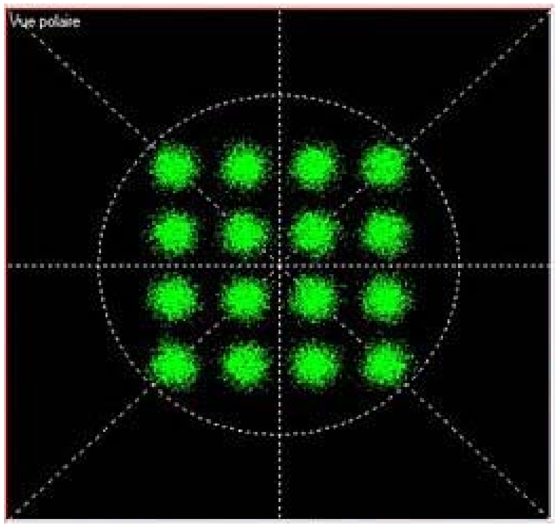
Histogram (A_i, F_i, PH_i)



Spectral power density



Eye diagram (I, Q or A_i, Ph_i, etc.)

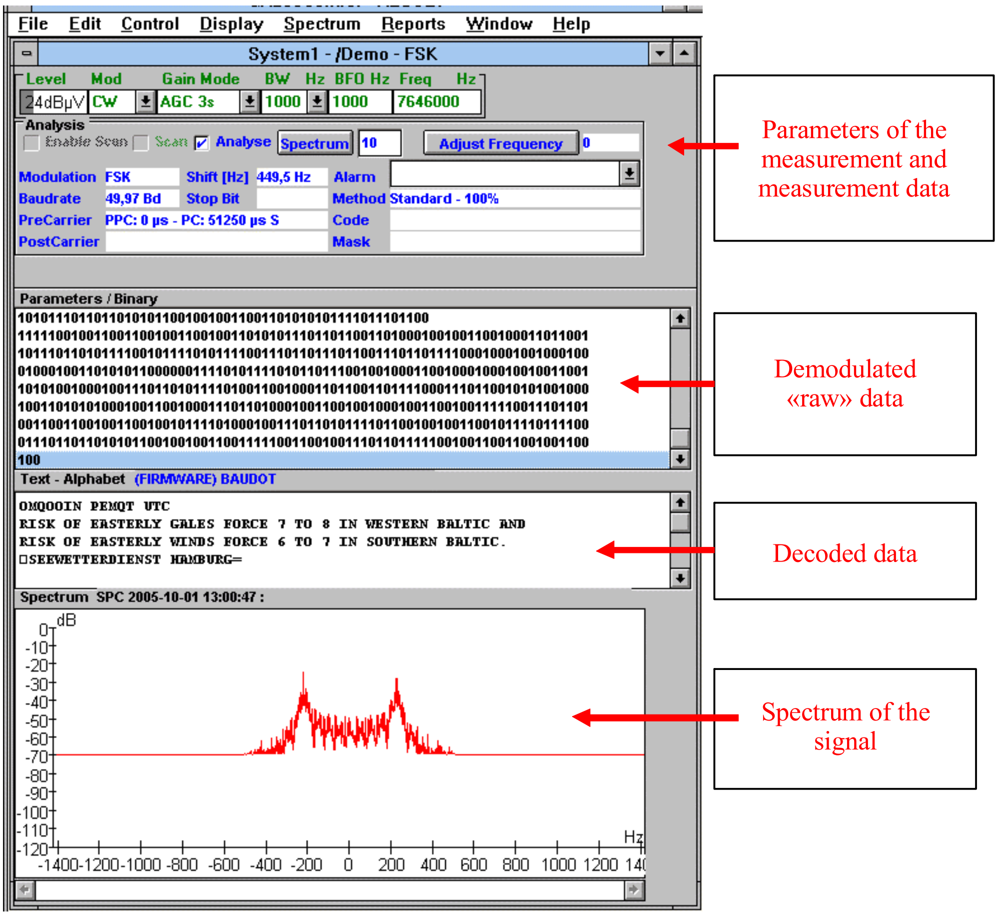


Constellation diagram

Spectrum-4.8-09

FIGURE 4.8-10

Example of a digital demodulator with bit stream analyzer and decoder



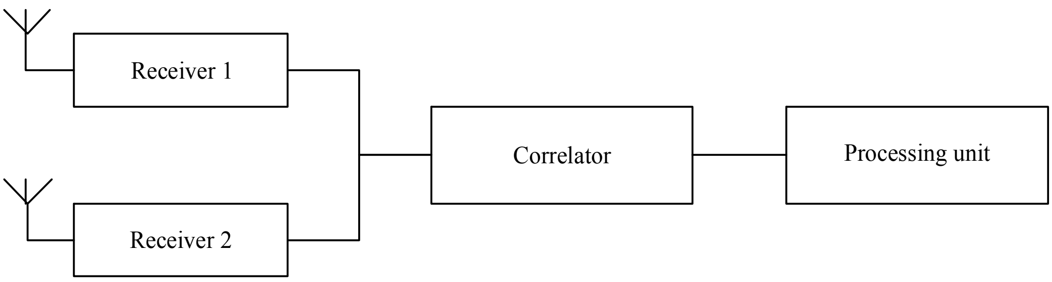
Spectrum-4.8-10

4.8.5.5 Cross-correlation techniques for interference analysis

The cross-correlation method implemented in a signal analysis system can be employed to investigate how interference is formed and to identify the interferers. A simplified diagram is given in Fig. 4.8-11.

FIGURE 4.8-11

Cross-correlator for interference analysis



Spectrum-4.8-11

A correlator performs the cross-correlation process. Two separate receivers are used; one is tuned to the interfered signal and the other to the suspected interferer. By calculating the correlation coefficients between the IF signals or the demodulated signals an identification of the interferer may be obtained. The following types of interference can be detected:

– spurious emissions;

– intermodulation emissions;

– spurious and intermodulation channels of a receiver;

– effects of blocking and cross modulation;

– adjacent channel interference.

Correlation techniques are not only applicable for interference investigations but also applicable for other monitoring tasks.

Detailed information about the correlation method can be obtained from [Kharchenko, 1984] and [Ralnikov and Kharchenko, 2001].

4.8.5.6 Adaptive filtering techniques for source separation of TDMA and CDMA signals

The application of adaptive techniques allows in a multi-source context and under severe conditions of interference to carry out the synchronisation on the traffic and beacon channels of TDMA and CDMA signal, as well as the measurement of level and *C*/*I* ratios on these same signals, together with the demodulation and the decoding of the messages contained in signalling channels thus enabling their identification.

A real example is given in Figs 4.8-12 a) and b) for GSM traffic signals. Figure 4.8-12 a) shows that it is possible to detect the signals and to obtain the identity of the sources even under very low *C*/*I* ratio, approximately 16 dB in the case of the signal indicated as traffic channel 4 (TCH4(BS2)). In this example, TCH4 has been identified as the interfered traffic channel.

The identification of the interfered traffic channel is performed using information extracted from the related base station broadcasting channel.

Figure 4.8-12 b) shows successful demodulation and decoding for a source received with a strongly negative *C*/*I* ratio of about 16 dB and a signal level of –103 dBm. The adaptive techniques are particularly well suited and effective in difficult situations of interference, both for continuous and burst signals such as propagation in dense urban environments, intensive frequency re-use in the networks, errors of network engineering, etc.

where:

– TCH1(BS1): Traffic channel 1 of base station BS1.

– TCH4(BS2): Traffic channel 4 of base station BS2.

4.8.5.7 Measurements (of power flux-density) below the noise floor

Introduction

There are passive services, which require protection from unwanted emissions below the noise floor, since their observations happen at power flux-density (pfd) levels below the noise floor. Passive services such as the radio astronomy service, therefore, use techniques of multiple measured probes which, when stored, are processed in such a way that random noise cancels itself out, whereas wanted signals appear out of the decreasing noise. That is why, pfd limits have been agreed internationally the values of which are below noise. However, interested parties such as the radio astronomers keep complaining that radio astronomy will get blind if the interference will not be monitored and consequent action will be taken. Consequently, monitoring, especially satellite monitoring, needs to use similar techniques to discover the interference hidden in noise.

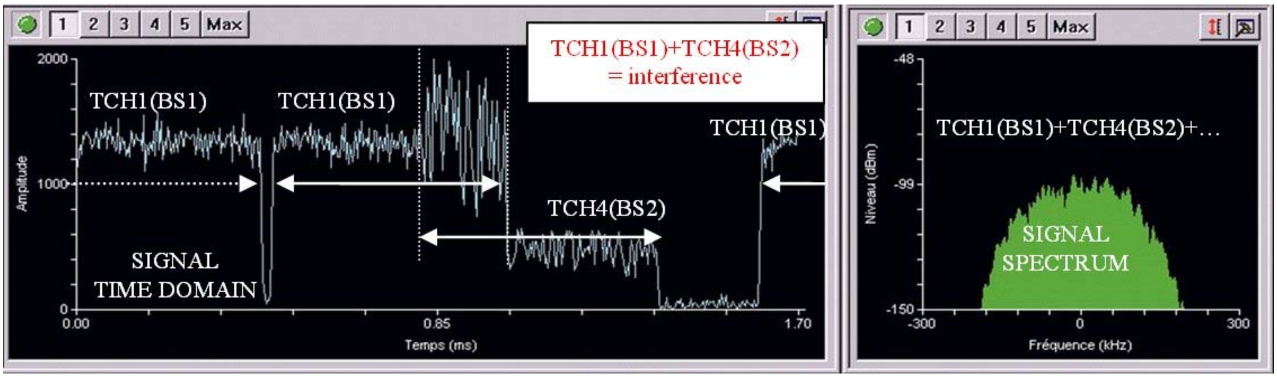
Principle

In order to monitor a wanted signal below noise level, a series containing a high number (say in the order of tens of thousands) of spectra, in which the wanted signal is present, need to be taken, digitized, stored and averaged. The same number of spectra not comprising the wanted signal, but containing the same sort of random noise, need also to be taken, digitised, stored and averaged but then inverted. The two different series of the spectra can be obtained either by changing antenna pointing or, if the wanted signal is of burst type, by taking them during on and off-time. In those two resulting processed spectra the noise has been considerably suppressed. When processing also these two already processed spectra, other signals of unknown origin are compensated due to the said inversion. More information about this technique is available in Recommendation ITU-R SM.1681.

FIGURE 4.8-12

Illustration of the results obtained in analysis of interference and separation of GSM TCH sources using adaptive techniques on GSM signals in urban area

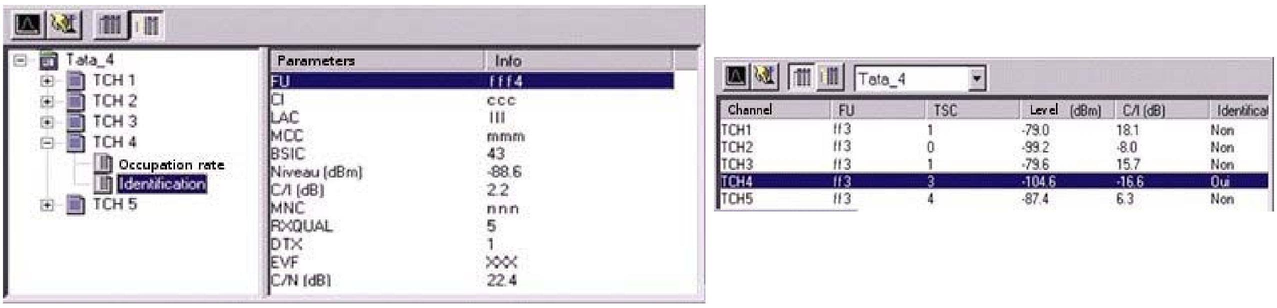
a) Example of an interference situation at a GSM TCH frequency



Time domain display

Panoramic display

b) Result of the interference analysis by adaptive filtering



Identification of the source of emission

Detected traffic channel

Spectrum-4.8-12

4.8.6 Signal analysis for the purpose of identification of transmitted signals

After the description of signal analysis tools, the following section provides some more detailed information on signal analysis process in order to identify a transmitted signal. These techniques are not necessary in all cases but they can be beneficial for identification of complex digital signals.

4.8.6.1 Required equipment

There are real-time/on-line as well as off-line analysis tools available on the market.

Real-time/on-line systems may include:

– specific decoders for a small number of codes;

– parametric decoders or demodulator-decoders with or without measurement capabilities;

– automatic demodulators-decoders with measurement and recognition capabilities.

When real-time analysis has failed, operators need to process the signal with off-line analysis tools, which may include:

– signal analysis tools (time domain, frequency domain, phase domain programmable demodulators);

– bit-stream analysis, i.e., tools for attempting to "break" the code structure and determine alphabet input;

– methods for code description by mathematical operations which can be then used to program a programmable decoder for future on-line decoding.

When decoding and alphabet selection is successful, the operator will be able to get a text which is more and more often encrypted, except sometimes during the transmission of the identification.

4.8.6.2 Practice of identification

Depending on whether a call sign or other means of identification is used or not by the transmitter, several methods can be used for purposes of identification:

1. When no dedicated mean of identification is used by the transmission, parametric identification method can be used. Such identification consists of measuring the parameters of the transmitted signal: modulation parameters, e.i.r.p., carrier frequency, etc, and the direction of arrival of the signal or the position of the transmitter.
2. When no dedicated mean of identification is used by the transmission, signal aided identification method can be used. Such identification consists of a comparison of the structure and characteristics of the transmission with a model in a database.
3. When means of identification are used by the transmission, identifier recognition method can be used. Such identification consists of decoding the transmitted information as part of the signal, for example, call sign, name of station, maritime mobile service identifier, etc., as described in § 4.8.2.

These methods assume that the transmission has been acquired and is available for analysis by these methods. However, in many cases of interference and other issues of concern to the monitoring service, the transmission may be intermittent or its exact frequency may not be known so the transmission may not be readily available. In these cases it may be necessary to use recording equipment listed in § 4.8.6.1 to record a wide bandwidth of the spectrum presumably including the transmission of interest, so a trained operator can perform the analysis later.

4.8.6.2.1 Parametric identification

Parametric identification deals with the parameters of a signal. A parametric identification for public standard systems can be performed with three steps as shown in Fig. 4.8-13:

1. The technical parameters of the modulation are measured using methods described in § 4.6 for analogue and digital signals.
2. Then, when all the parameters have been measured, an analysis is performed to recognise the modulation among a list of possible candidates.
3. Once the type of modulation is recognised, a further step is to demodulate the signal using the estimated modulation parameters. The demodulated signal may then be used for recognition of audio characteristics or digital codes.

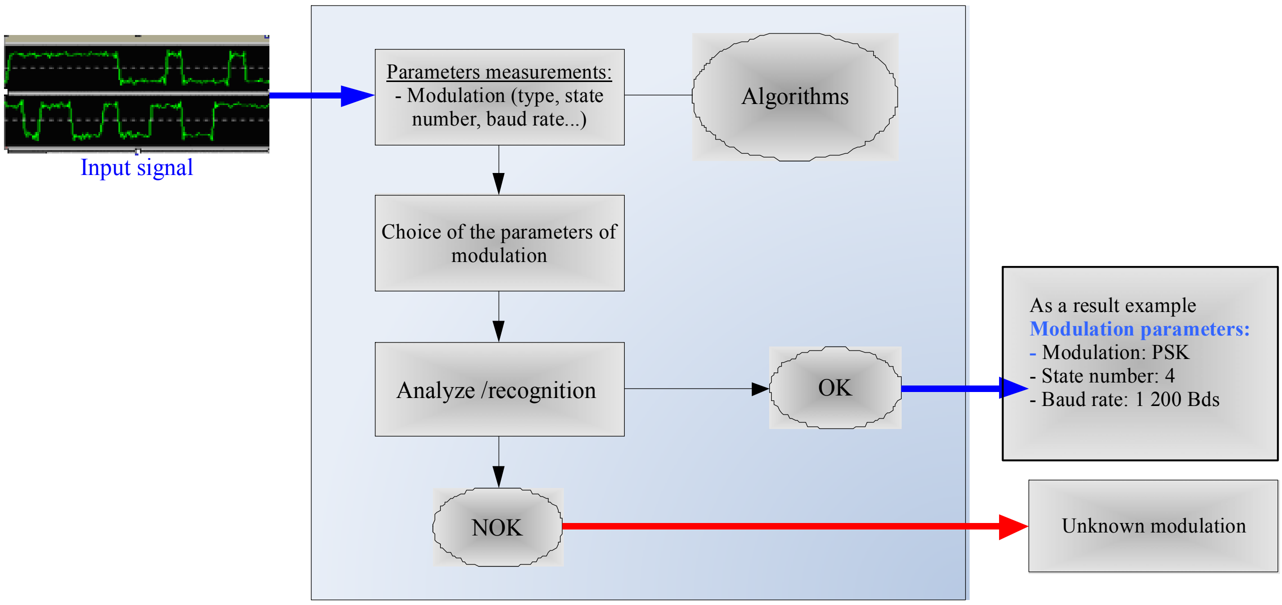
Limitations of parametric identification

The parametric identification method has several limitations because the result of the parametric identification is a list of technical parameters with no indication on the type of system involved (cellular, aeronautical ...).

This drawback is illustrated in Fig. 4.8-14 for the case of a VOR signal (VHF Omnidirectional Range for aeronautical radionavigation). A VOR signal consists of 3 sub-carriers, each of them modulated with different schemes. For such a signal, the parametric identification only characterises the three signals but is not able to identify the system as a VOR system.

FIGURE 4.8-13

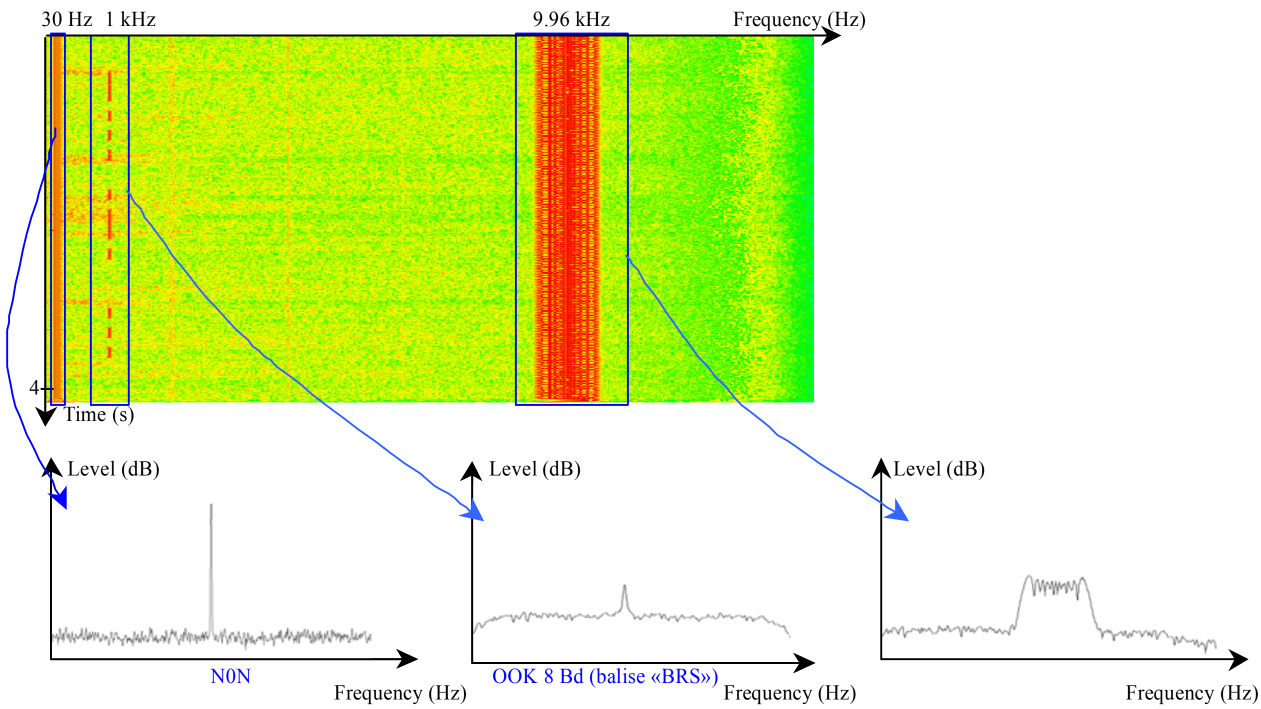
Parametric identification workflow



Spectrum-4.8-13

FIGURE 4.8-14

VOR signal identification



Spectrum-4.8-14

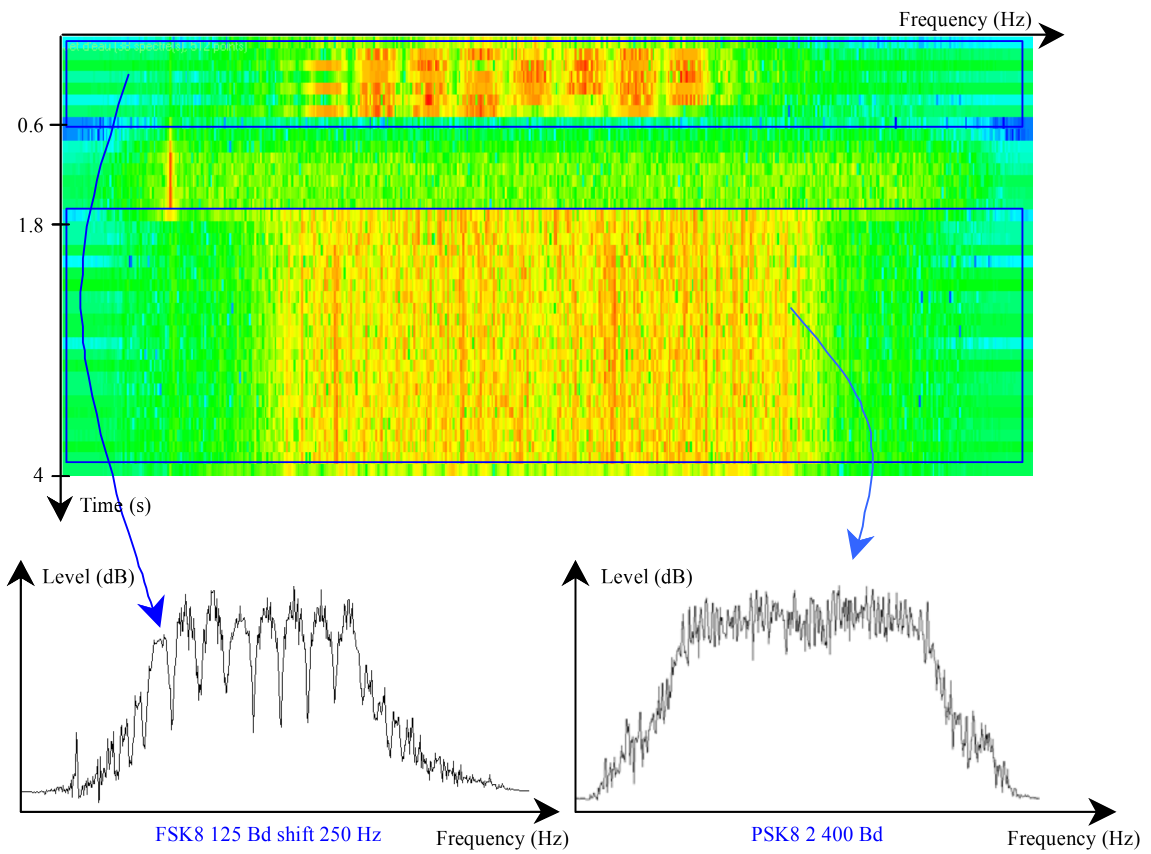
As a first step, the fact that all three emissions belong to the same emission can be proved by using spectrum recorders and narrow band or wide band direction finders. Signals with the same azimuth and simultaneous on/off switching suggest a common source. As a second step, with this knowledge the identification process can continue.

Furthermore, no result is provided if the signal is not on the list of the modulations supported by the method and the incoming signal should have a minimum duration to allow a complete analysis and measurement of all modulation parameters (type of modulation, number of states, symbol rate, etc.).

For example, as shown in Fig. 4.8-15, when the transmission is composed of two consecutive signals, each having a different modulation, the parametric identification method is not able to identify the system.

FIGURE 4.8-15

Signal with modulation changing with time



Spectrum-4.8-15

Parametric identification of an analogue signal

The identification of an analogue signal can be done in 4 steps:

Step 1: Adjust measurement setup in a suitable way.

Step 2: Check whether the signal is a known modulation which can be made audible or visible by demodulation.

Step 3: The third step is an automatic method: identification of speech using the long term characteristics of speech by calculations and histogram of the variance of the peak value of the signal.

Step 4: Simultaneously with the preceding methods:

– panoramic representations and time vs. frequency display of the signal to determine its nature (AM, SSB, FM, etc);

– a basic consultation of database of the analogue signals of radiocommunication;

– measurement techniques previously recommended for the determination of the parameters of modulation:
  – carrier and subcarrier frequencies in the case of frequency division multiplex protocols;
  – bandwidth of the signal;
  – modulation characteristics (amplitude depth, frequency and phase deviations), measured according to ITU-R Recommendations in force.

Parametric identification of a digital signal

Three steps can be used to identify a digital signal:

Step 1: modulation parameters measurement. Refer to § 4.6 for descriptions of ASK, PSK, FSK, QAM, CPM and OFDM modulation measurement methods.

Step 2: when modulation parameters have been measured, the constellation is plotted, then compared to the theoretical constellation.

The Error Vector Magnitude (EVM) may be used to adjust parameters of the measurement in order to obtain the optimum constellation.

Step 3: Demodulation can begin with the correct parameters.

4.8.6.2.2 Signal aided identification

Principle of signal aided identification

In this method, a database of public standard system signals (called models) is used as a reference. Every model in the database is composed of a set of parameters. Signal aided identification is based on comparison of the structure and characteristics of the signal under test to the structure and characteristics of candidate models in the database. The chosen model is the one providing the best matching ratio with respect to the signal under test.

A model may be described by the following parameters:

– frequency range;
– signal bandwidth;
– time "activity" (continuous, burst emission, TDMA signal, etc.);
– modulation;
– coding method;
– identification information (call sign, identification number, etc.).

Signal aided identification provides the following improvements:

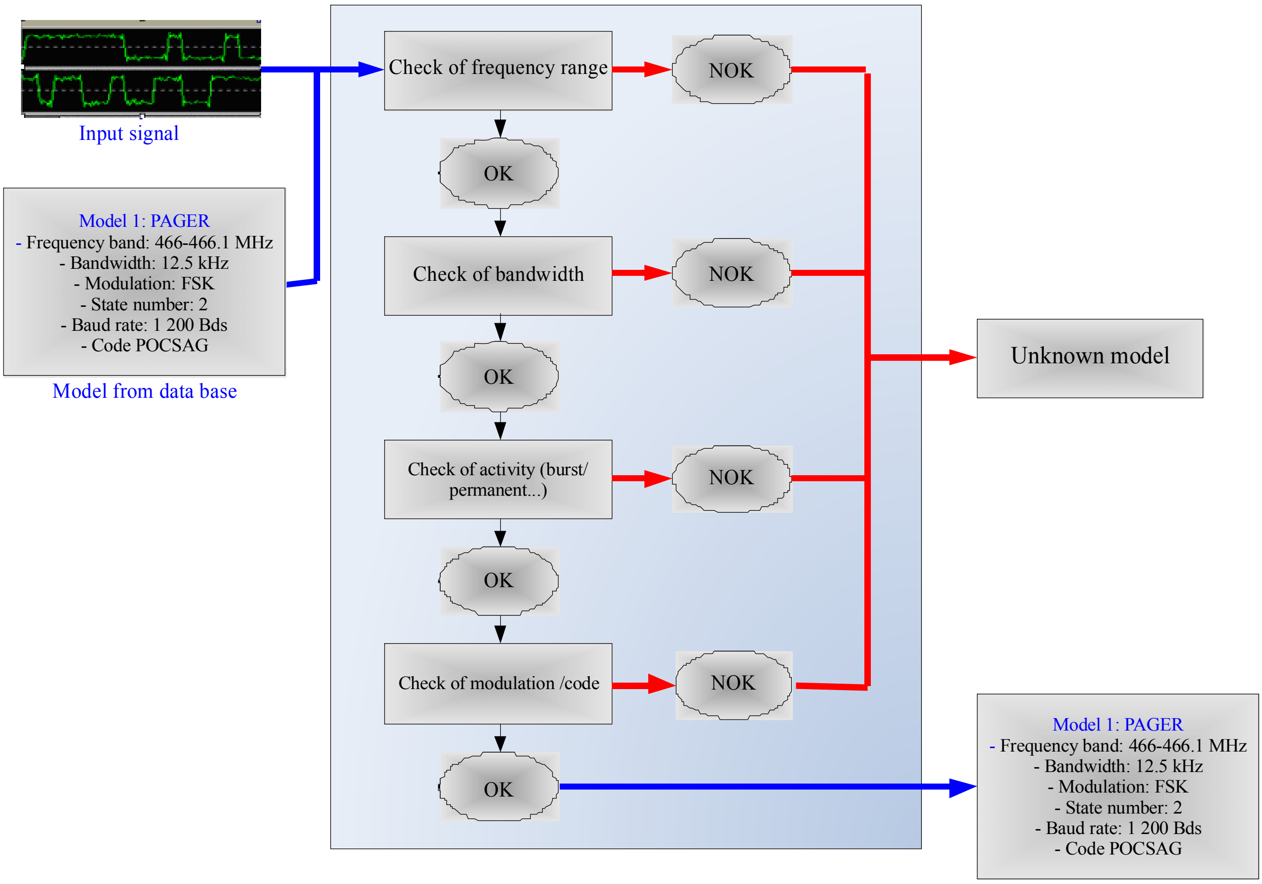
– it provides information on the system itself (not limited to signal technical characteristics), providing to the user additional exploitable operational information;
– it improves the sensitivity and the minimum signal duration as no precise measurement (such as precise modulation parameter measurements) is done but only a comparison between a reference model and the signal to identify;
– it allows to reduce the duration of analysis;
– it can focus only on models that are of interest to the operator;
– new system characteristics can be easily added to the candidate model database.

However, some constraints appear:

– each candidate system is required to have a model in the database in order to be identified;
– the more the number of candidate system models to be compared to, the greater the computing time required.

FIGURE 4.8-16

Signal aided identification workflow



Spectrum-4.8-16

ANNEX 1

Selective calling in the maritime mobile and maritime mobile-satellite services

The description of the procedure is referred to in RR Article 54, No. 54.2.

1 Formation of ship station and coast station selective call numbers

Call numbers of ship stations consist of five-digit numbers. Call numbers of coast stations consist of four-digit numbers. See Recommendation ITU-R M.257. Each digit is represented by an audio frequency from 1 124 to 2 110 Hz according to the following table:

Figure	1	2	3	4	5	6	7	8	9	0	Figure repetition
Audio	1 124	1 197	1 275	1 358	1 446	1 540	1 640	1 747	1 860	1 981	2 110 Hz

The time duration of each tone = 100 ms. A selective call number of a ship transmitted by a coast station lasts 500 ms followed by an interval of 900 ms after which the ship's selective call number is repeated. (Recommendation ITU-R M.257.)

For ship stations using narrow-band direct printing (NBDP) in accordance with Recommendation ITU-R M.476, the five-digit identification is converted to four-character in accordance with Recommendation ITU-R M.491 (Annex 1). For coast stations, the four-digit number is also converted to a four-character code.

According to Recommendation ITU-R M.257 "the sequential single frequency selective-call system (SSFC) may be used for calling ships until the system is superseded by the DSC system described in Recommendations ITU-R M.493 and ITU-R M.541" (see RR No. 54.2).

2 Maritime mobile service identities in the maritime services

The identities must comply with the provisions of RR Article 19, Nos. 19.108-19.117. Maritime mobile service identities (MMSI) are formed of nine digits which are transmitted over the radio path. As an example, the 9-digit code constituting a ship station identity is formed as follows:

M1 I2 D3 X4 X5 X6 X7 X8 X9,

M1 I2 D3 represent the maritime identification digit (MID) and **X** is a figure from 0 to 9 . The MID reflects the nationality of the station. For instance, MID 203 is allocated to Austria, and MID 244 to the Netherlands.

Narrow-band direct printing is not only used in accordance with Recommendation ITU-R M.476 but also in accordance with Recommendation ITU-R M.625. Recommendation ITU-R M.625 on NBDP is compatible with Recommendation ITU-R M.476 and uses the 5-digit identity (converted to a four-character code) as well as the 9-digit code. This 9-digit identity number of the ship may be translated to a 7-signal identity conforming to Annex 2 to Recommendation ITU-R M.491. For example, the 9-digit identity 364775427 is converted to "PEARDBY" which is, in the case of calling this ship station by a coast station, transmitted in three blocks of three characters in simplex TOR mode as follows:

Block 1:	P	RQ	E
Block 2:	RQ	A	R
Block 3:	D	B	Y

RQ = request or signal repetition (YBBYYBB)

3 Maritime mobile service identities in the maritime mobile-satellite service

The identities must comply with the provisions of Section VI of RR Article 19. Ships complying with the International Convention for the Safety at Sea and other ships equipped with automated radiocommunications, including digital selective calling (DSC) and/or carrying alerting devices of the global maritime distress and safety system (GMDSS) should be assigned ship station identities, as set forth in RR Article 19, Nos 19.100-19.126, in accordance with Annex 1 to Recommendation ITU-R M.585.

NOTE 1 – RR Article 19, Nos 19.117 to 19.126 were suppressed by WRC-07.

4 Automatic transmitter identification system

Some countries use an automatic transmitter identification system (ATIS) for RR Appendix 18_frequencies for inland waters, and for satellite uplink video transmissions. The systems provide an automatic transmission of the identification at the end of each transmission and periodically during transmissions. An ATIS sequence may be based on Recommendation ITU-R M.493, or on Recommendation 7 of the Regional Basel Agreement. The radio call sign may be converted to a ten-digit identity.

Z1 M2 I3 D4 X5 X6 X7 X8 X9 X10,

where:

Z: represents the Fig. 9 and shall be used for inland waters only.

MID: identification digits in accordance with the RR, Article 19.

X5 to **X6**: shall contain a figure representing the second letter of the call sign, wherein 01 represents A, 02 represents B etc.

X7 to **X10**: shall contain the number of the call sign.

For example the call sign PC 8075 is converted to: **9 2 4 4 0 3 8 0 7 5**.

5 EPIRB identities

Emissions of emergency position indicating radiobeacons (EPIRBs) participating in the COSPAS-SARSAT system, consisting of low polar-orbit satellites and transmitting on 406.025 MHz, include the 9-digit identity. The 406 MHz EPIRB may also be supplied with a 121.5 MHz homing beacon transmitter. The COSPAS-SARSAT system is a worldwide operating system.

The 1.6 GHz EPIRB (L-band EPIRB or INMARSAT-E) also uses this 9-digit identity and makes use of the INMARSAT system. Because INMARSAT uses GSO satellites positioned over the equator, this is not a global covering system. Coverage is limited to the areas between 70° North and 70° South latitudes for practical applications.

The means of identification in the maritime services are various. *Recommends* 6 of Recommendation ITU-R M.585 states “that any future international automatic maritime telecommunication system should be designed to use the 9-digit ship station identities on the radio path”.

ANNEX 2

Supplementary code characters, sixth and seventh symbols

The sixth character indicates a group of systems. The following characteristics and groups are in use:

Morse	A
Asynchronous (start-stop)	C
ARQ systems with non-interrupted pulse train	E
Burst type ARQ-systems	F
Twinplex	H
Unknown (but number of bits in a frame are known)	J
Forward error correcting	K
Multitone	M
Radionavigation and location	N

The seventh character indicates the system within one the above-mentioned group and is an exact indication of the system in the group. This makes it possible to define 26 different systems within each group (e.g. group A, group C, group E, etc). For example the seventh character B indicates the system Telex Baudot with group C, ARQ E3 in group E.

The table below provides examples for some known systems:

CODE	NAME	ALF	BITS	DETEC/CORR	M/CYC	DUR/DIS/NUM
	Morse	Morse				
C-	START STOP					
CB	telex Baudot	ITA2	7.5			
CC	telex Russian	ITA2_RUS	7.5			
CD	telex Arabic	ITA2_ARAB	7.5			
CK	telex ASCII	ITA5	10	parity		
E-	ARQ pulse train					
EA	ARQ-1000 duplex	ITA2_P	7	parity	RQ	4 5 8
EB	ARQ-E3	ITA3	7	m/s = 3:4	RQ	4 8 3
EC	342 TOR 1 kan	ITA3	7	m/s = 3:4	RQ	4 8 3
ED	342 TOR 2 kan	ITA3	7	m/s = 3:4	RQ	4 8 3
EE	342 TOR 4 kan	ITA3	7	m/s = 3:4	RQ	4 8 3
EF	242 TOR 2 kan	ITA3	7	m/s = 3:4	RQ	2 ?
EK	ARQ-N	ITA2_P	7	parity	RQ	
EL	POL-ARQ	SITOR	7	m/s = 3:4	RQ	
EM	TORG 10-11	ITA2-R11	11			

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ITU-R Recommendations

NOTE – In every case the latest edition of the Recommendation should be used.

Recommendation ITU-R M.257 – Sequential single frequency selective-calling system for use in the maritime mobile service.

Recommendation ITU-R M.476 – Direct-printing telegraph equipment in the maritime mobile service.

Recommendation ITU-R M.491 – Translation between an identity number and identities for direct-printing telegraphy in the maritime mobile service.

Recommendation ITU-R M.493 – Digital selective-calling system for use in the maritime mobile service.

Recommendation ITU-R M.541 – Operational procedures for the use of digital selective-calling equipment in the maritime mobile service.

Recommendation ITU-R M.585 – Assignment and use of maritime mobile service identities.

Recommendation ITU-R M.625 – Direct-printing telegraph equipment employing automatic identification in the maritime mobile service.

Recommendation ITU-R M.633 – Transmission characteristics of a satellite emergency position-indicating radio beacon (satellite EPIRB) system operating through a satellite system in the 406 MHz band.

Recommendation ITU-R SM.1052 – Automatic identification of radio stations.

Recommendation ITU-R SM.1600 – Technical identification of digital signals.

Recommendation ITU-R SM.1681 – Measuring of low-level emissions from space stations at monitoring earth stations using noise reduction techniques.

4.9 Pulse measurements

4.9.1 Introduction

Pulsed emissions can occur from a variety of sources, including:

– Radar emissions.

– Emissions from digital TDMA systems.

– Emissions from electrical or electronic equipment.

To characterise a pulsed emission, measurement of the same parameters as for other emissions is necessary, which are described in other chapters of this Handbook. These include:

– Average level / field strength.

– Frequency.

– Bandwidth.

Section 4.9 provides specific information on the pulse level measurement and on the measurement of other basic parameters of pulsed emissions.

4.9.2 Basic pulse parameters

The basic parameters of a pulsed emission for which measurements are described in this section are:

– Peak level (A).

– Pulse length (τ).

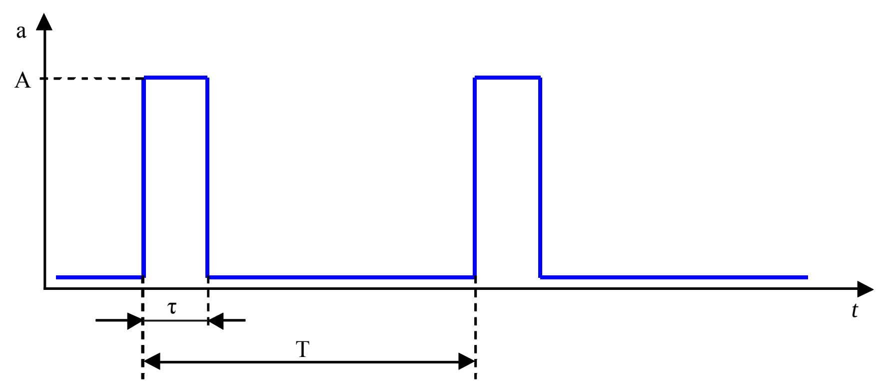
– Pulse period T or pulse repetition frequency (PRF = 1/T).

– Pulse rise and fall time (t_r and t_f).

Mathematical pulses are usually described having a rectangular shape in the time domain, like shown in Fig. 4.9-1.

FIGURE 4.9-1

Rectangular pulsed signal in the time domain



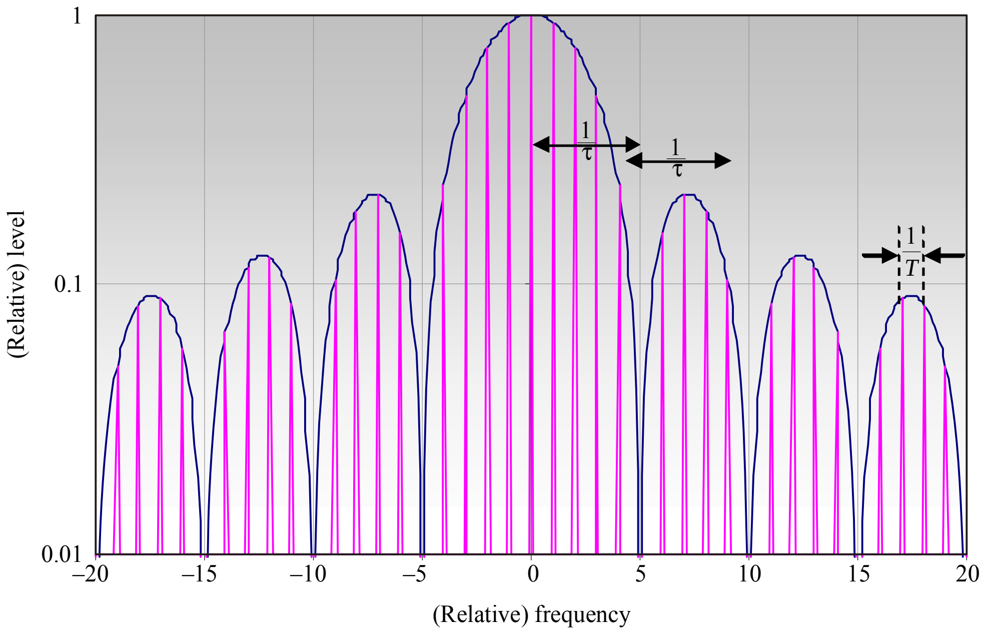
Spectrum-4.9-01

Applying a Fourier Transform to the time signal in Fig. 4.9-1, a rectangular pulsed signal in the frequency domain looks like in Fig. 4.9-2.

The actual spectrum consists of distinct spectral lines spaced by 1/T. The peaks of these spectral lines follow a sin(x)/x function that has minima spaced 1/τ. The “main lobe” in the frequency centre has the width of 2/τ.

FIGURE 4.9-2

Rectangular pulsed signal in the frequency domain



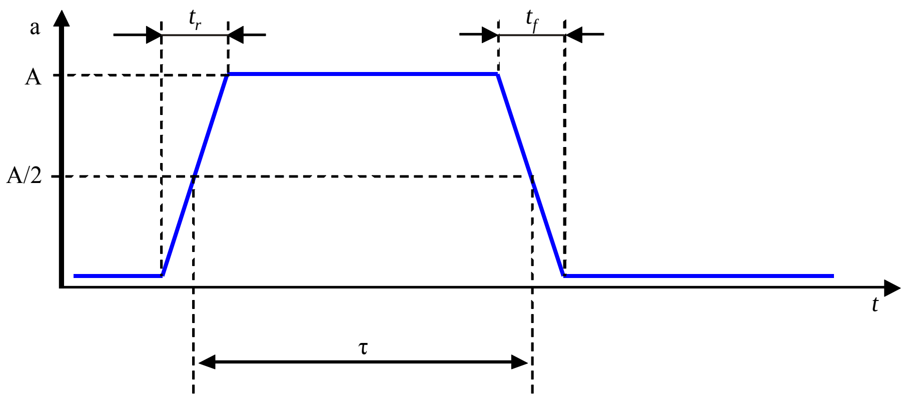
Spectrum-4.9-02

Real pulses can not rise and fall infinitely short. Instead, there will be a characteristic shape of the time domain curve at the beginning and end of each pulse during which the power increases to the peak level and decreases to zero again.

Although being somewhat ideal again, a common description of the pulse shape is trapezoidal.

FIGURE 4.9-3

Trapezoidal pulse in the time domain



Spectrum-4.9-03

The pulse length is usually defined between the points where the amplitude is half of the peak amplitude.

The rise time t_r and the fall time t_f have influence on the actual spectrum and its width. They are therefore important pulse parameters that may be measured to fully characterise the emission. Since real pulses usually do not have ideal sharp "edges" of the rise and fall slopes, it is necessary to state the level range within which rise and fall times are given. Common values are 10%-90% for rise time, and 90%-10% for the fall time.

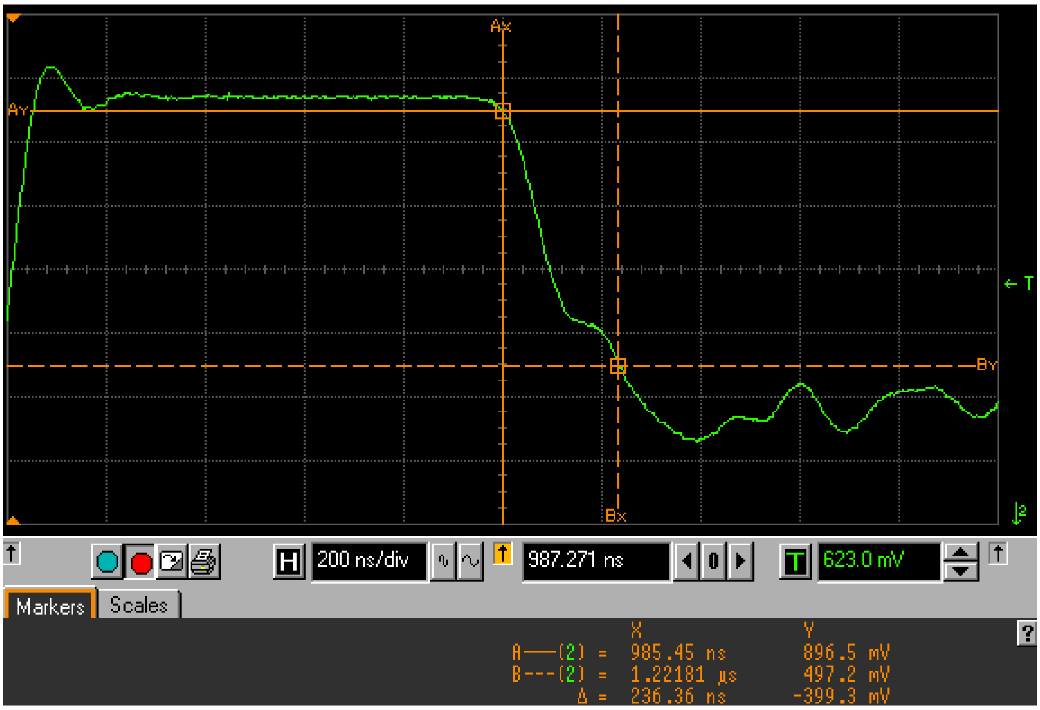
4.9.3 Measurements in the time domain

All pulse parameters mentioned in § 4.9.2 can be measured in the time domain. This is usually done with an oscilloscope connected to the video output of a receiver. It is important that the level of this IF output does not have an automatic gain control and that its bandwidth is sufficient not to influence the timing measurement (see § 4.9.6). Today very fast oscilloscopes are available that may be able to capture and display the RF signal directly.

The fall time of the pulse in Fig. 4.9-4 is the difference between the two markers, displayed at the bottom as $\Delta = 236.36$ ns. Rise and fall times of most pulsed emissions are very short and measurement of them requires a high bandwidth of the equipment. When this measurement is done off the air, the wanted signal has to be very strong compared to other signals on neighbouring frequencies.

FIGURE 4.9-4

Pulse fall time measurement with an oscilloscope



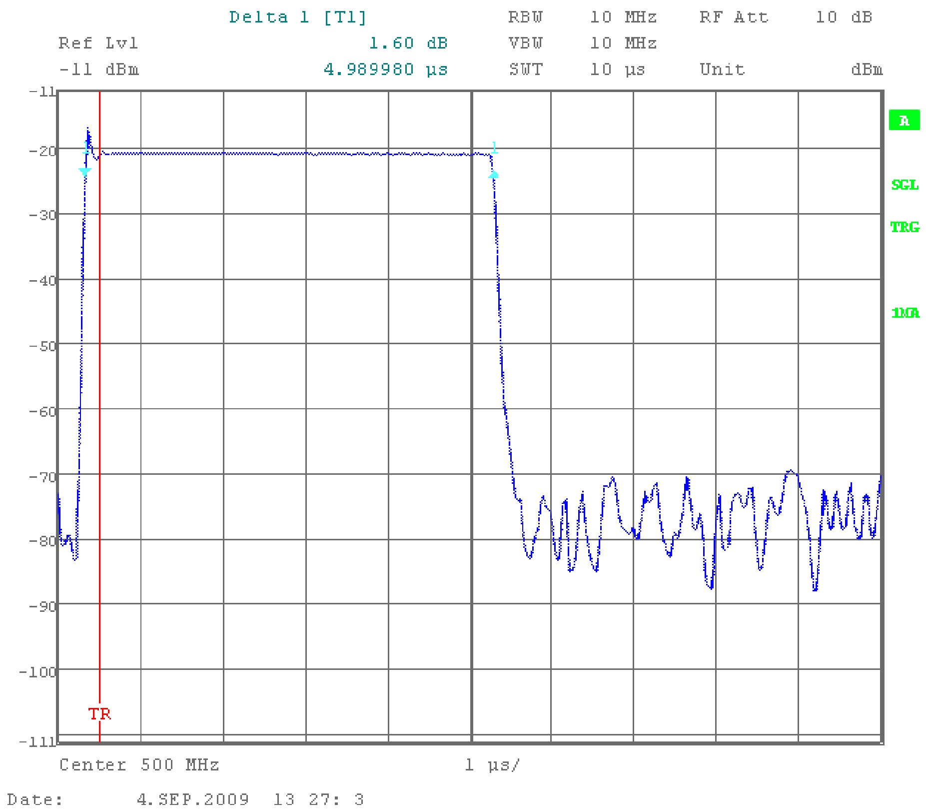
Spectrum-4.9-04

When using an oscilloscope, it must be noted that the level display is usually in linear units, not logarithmic. However, the final display is only linear when the oscilloscope is connected to a linear video output of the receiver or analyzer. Many monitoring receivers and spectrum analyzers only have a logarithmic video output. In this case the level display of the oscilloscope is also logarithmic. The error introduced due to this fact can be neglected for measurements of the pulse length. However, automatic measurement routines for pulse rise and fall times are not valid in this case. They have to be measured manually instead.
The timing parameters can directly be read from the oscilloscope display.

Modern spectrum analyzers often allow very short sweep times in zero span mode which in fact results in a time domain representation of the signal. Together with sufficient resolution bandwidth (RBW), they also allow pulse measurements in the time domain (see Fig. 4.9-5).

FIGURE 4.9-5

Pulse length measurement with a spectrum analyzer



Spectrum-4.9-05

Note that when measuring the pulse length with a spectrum analyzer that has a logarithmic level scale, the correct points to set the markers are 3 dB below the peak level.

When measuring pulse timings with a spectrum analyzer it is important to use the widest RBW available. Care must be taken not to influence the displayed shape of the pulse by too narrow measurement bandwidths. The necessary bandwidth depends on the pulse timing itself. For details, see § 4.9.6.

The peak level of the pulse is more conveniently measured by using the peak detector of a measurement receiver or spectrum analyzer. With a few considerations, however, it may also be measured with the oscilloscope.

First the indicated level at the highest point in the curve is noted. While the oscilloscope usually shows the peak-to-peak voltage (U_{pp}), the peak detector of a measurement receiver or spectrum analyzer would display the effective power level of this reading (or its equivalent receiver input voltage, *u*). This can be calculated by multiplying the peak-to-peak reading with $1/\sqrt{2}$.

For RF measurements we are used to state level results in logarithmic units, so the linear input voltage *u* has to be converted to a logarithmic voltage U:

$$U\,(\text{dB}(\mu\text{V})) = 20*\log(u\,(\mu\text{V})) \tag{4.9-1}$$

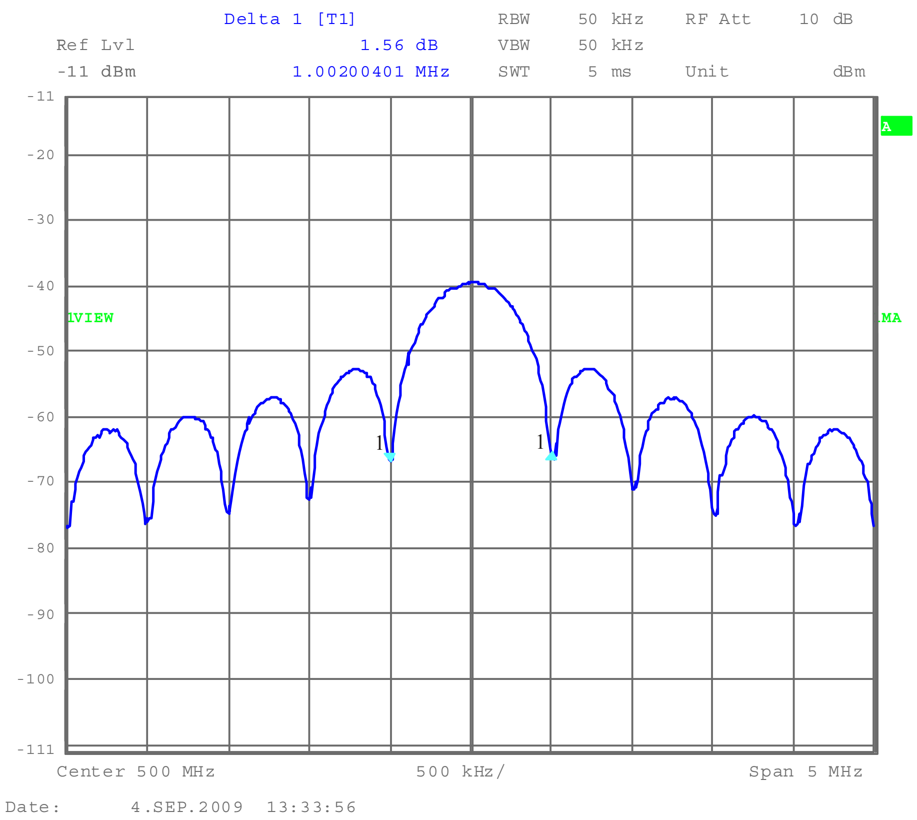
To calculate the RF receiver input voltage of the signal, the amplification of the receiver up to the video output has to be known. The measurement result is reduced by this amplification.

4.9.4 Measurements in the frequency domain

As mentioned earlier, the spectrum of a pulsed emission also allows measurements of some characteristic parameters. However, even with modern spectrum analyzers, only the peak level and the pulse length can be measured in the frequency domain. This is because the spectral lines of which the pulse spectrum actually consists cannot be resolved by the analyzer. Figure 4.9-6 shows an example of measurement of the pulse length.

FIGURE 4.9-6

Pulse length measurement in the frequency domain



Spectrum-4.9-06

The markers in Fig. 4.9-6 have been placed to the first two minima next to the centre frequency. Their distance (delta) is 1 MHz which is twice the distance between the following minima. The pulse length is therefore 2/1 MHz = 200 µs (see also the text below Fig. 4.9-2).

To have a good frequency resolution when displaying the true spectrum of the emission, a narrow resolution bandwidth (RBW) in the order of 1/500 of the span is recommended. However, with this setting, no level measurement can be made. To measure the peak pulse level, the RBW has to be at least 1/pulse length.

In any case, frequency domain measurements of pulsed signals with a spectrum analyzer require the use of the MaxHold function.

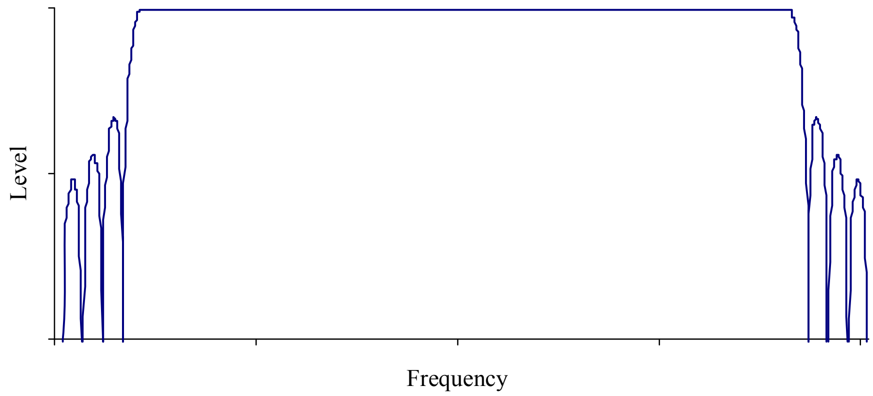
Because the distinct lines of the pulse spectrum correlate in phase, the indicated spectral level increases by 20 dB if the RBW is increased by a factor of 10, whereas the noise floor increases only by 10 dB. Therefore, the maximum signal-to-noise ratio is achieved when the RBW is equal to 1/τ. Finding an optimum display of the spectrum is therefore a trade-off between high *S*/*N* and good frequency resolution.

4.9.5 Special pulse characteristics

The most common application of pulsed (wanted) emissions is radar. However, apart from simple trapezoidal pulses, some special radar systems also modulate the pulse in amplitude, phase and frequency. These radar emissions have spectra that can be significantly different from the spectrum shown in Figs 4.9-2 and 4.9-6. As an example, Fig. 4.9-7 shows a principle spectrum of a radar that sweeps in frequency during the pulse ("chirp radar").

FIGURE 4.9-7

Principle MaxHold spectrum of a chirped radar



Spectrum-4.9-07

In case of a chirp radar, its bandwidth and the spectrum shape are predominantly determined by the modulation whereas the residual parts of the spectrum on the left and right having a substantial lower amplitude are mainly determined by the pulse repetition time. The same applies to radars that have digitally modulated pulses.

Some radar systems use alternating pulse lengths and/or PRF. When measuring the spectrum of such a radar, the level minima and maxima may not be as distinct as in Fig. 4.9-2. As an example, Fig. 4.9-8 shows the spectrum of a system with two different pulse lengths.

It is obvious that for emissions with alternating pulse lengths, this parameter cannot be measured in the frequency domain. Instead, the time domain measurement has to be done where each pulse can be displayed and measured separately.

4.9.6 Equipment requirements

Apart from standard requirements such as capability to tune the desired frequency, accurately measure the peak level and so on, the bandwidth (or RBW) is most critical when pulse measurements should be performed. To measure the pulse rise and fall times correctly, the necessary bandwidth of the whole receiving and measurement equipment (receiver, spectrum analyzer, video output, oscilloscope) must be high enough to correctly follow the pulse level during these times.

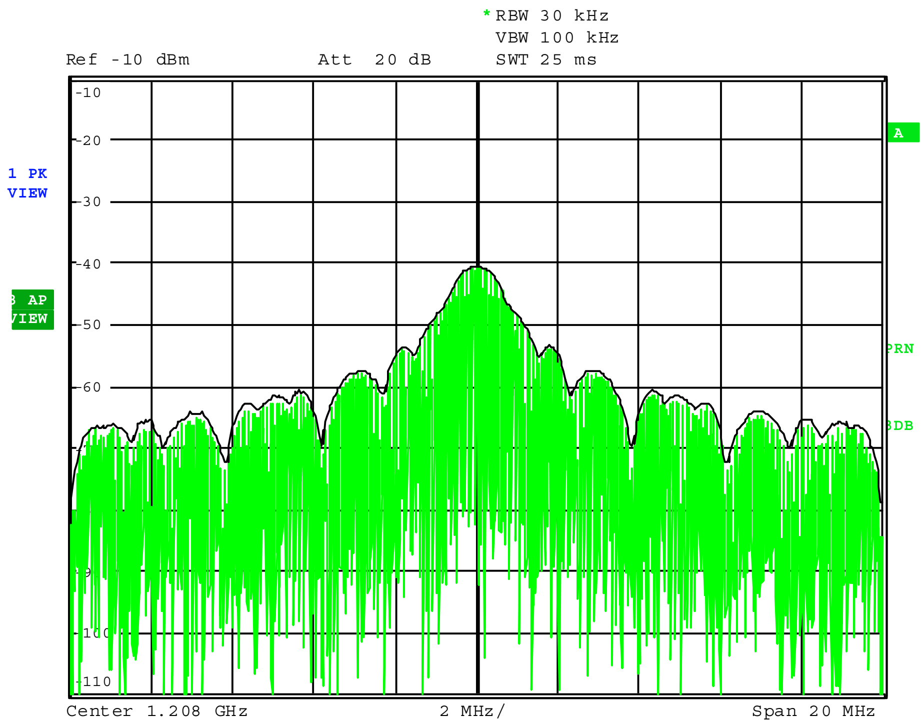
This requirement places high demands even on most modern equipment. With standard receivers and/or spectrum analyzers, it may be impossible to measure rise and fall times.

However, the bandwidth of standard equipment is usually high enough to measure level, pulse length and repetition frequency.

Table 4.9-1 shows the minimum bandwidth requirements for measurements of the different pulse parameters.

FIGURE 4.9-8

Spectrum of a radar with alternating pulse length



Spectrum-4.9-08

TABLE 4.9-1

Minimum measurement bandwidth

Measurement of	Minimum bandwidth	Remarks
Spectrum shape, bandwidth, pulse length in frequency domain	– none –	Recommended maximum RBW is 1/100 of span
Peak pulse level	$\frac{1}{\tau}$	For systems with alternating pulse lengths: 1/shortest length
Pulse repetition frequency	$\frac{1}{\tau}$	For systems with alternating pulse lengths: 1/shortest length Measurement accuracy increases at wider bandwidths
Pulse length	$\frac{1}{10\tau}$	Measurement accuracy increases at wider bandwidths
Rise/fall time	$Min\ (\frac{1}{10t_r};\frac{1}{10t_f})$	Measurement accuracy increases at wider bandwidths

Because of the relatively slow sweep time of conventional sweeping spectrum analyzers, combined with very short pulse length and slow PRF of most pulsed signals, the spectrum like in Fig. 4.9-6 can only be seen after a relatively long time in MaxHold mode. For radar systems, due to slow antenna rotation and low pulse/pause ratios, the necessary observation time may well be many minutes up to hours. With FFT analyzers, however, the whole spectrum is already displayed after one single pulse was captured. If the equipment allows continuous capturing for a whole period, the FFT analyzer is also capable of measuring the pulse length in the frequency domain for radar systems with alternating pulse lengths. Together with the wide acquisition bandwidth available today, FFT analyzers or equipments having full FFT analyzer capability are the preferred equipment type for pulse measurements.

4.10 Spectrum occupancy measurements

4.10.1 General observations

The term spectrum occupancy measurements refers to the recording of emissions over a period of time. From the gathered raw data an almost unlimited number of plots, tables etc can be produced, e.g. the calculated occupancy per frequency band or per channel exceeding a threshold level. Questions concerning the identification of who, where and when occupies a radio frequency channel or band are not considered part of spectrum occupancy but rather are discussed in § 4.8 (Signal analysis and transmitter identification).

Measuring receivers (narrow- or broadband) or spectrum analyzers with characteristics conforming to the relevant ITU-R Recommendations (see Chapter 3) are used as receiving equipment.

To perform good spectrum occupancy measurements the ITU-R Recommendations mentioned in the bibliography should be taken into account.

4.10.2 Measurement techniques

The inventory of the use of the radio spectrum provides information to the frequency management officers about the actual use of that spectrum and gives them the possibility to assign new frequencies in a frequency band. But it also gives the frequency management department information about tendencies in the use of the spectrum. This information can be used to prepare national points of view for international conferences.

The spectrum can be monitored either manually or automatically or both simultaneously.

Manual monitoring complementing automatic monitoring is required in those cases where it is necessary to analyse and identify observed emissions (§ 4.8). However, manual monitoring is very labour-intensive and time-consuming and only expedient when the basic characteristics to be recorded cannot be registered automatically.

Data usage periods or the scope of occupancy of a frequency band are not derived expediently by manual means.

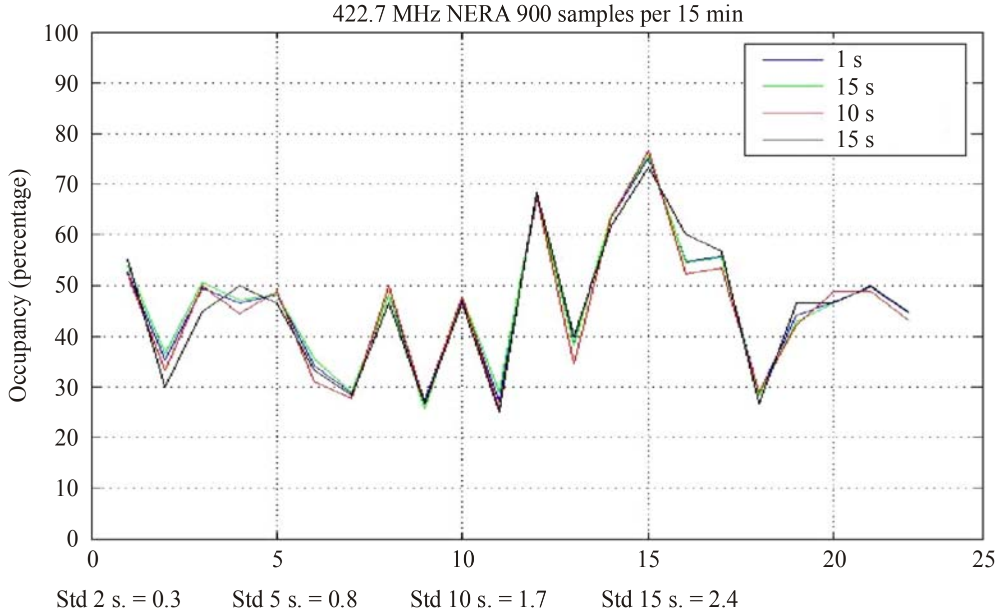
When the above-mentioned manual storage technique is not desired, then a technique of automatic registration is more applicable. This is based on the various tasks of spectrum occupancy monitoring. Automatic monitoring can be divided into 3 different measuring methods:

– Scanning a certain frequency band from F-start to F-stop, in a number of frequency steps, e.g. 1 000, with a certain scan (or sweep time or re-visit time), e.g. 10 s with a certain bandwidth filter. This is normally performed with a spectrum analyzer or a (fast) monitoring receiver. The results shown in different plots, tables etc. give an indication of the occupancy in that particular frequency band over a period of time, normally 24 h. These measurements are called frequency band occupancy measurements (FBO) or frequency band registrations (Recommendation ITU-R SM.1809).
– Measuring a number of preset channels, not necessarily separated by the same channel spacing. These measurements are normally performed with a receiver and are called frequency channel occupancy measurements (Recommendation ITU-R SM.1536).
– Frequency channel occupancy measurements (FCO) use the frequency band measurements as described above. Assume that F-start to F-stop is divided in 1000 frequency steps. These steps could

be considered as channels. In case sweep/scan/re-visit time is for instance 10 s this means that for every step from these 1 000 channels over a measurement of 24 h about 8 630 samples are available. These results could easily be processed as frequency channel occupancy measurement (Recommendation ITU-R SM.1793) Studies have shown that increasing the re-visit time from 1 to 10 s does not influence the results to much, as shown in Fig. 4.10-1.

FIGURE 4.10-1

Comparison of different re-visit times



Spectrum-4.10-01

Many emission parameters such as signal strength (minimum, maximum or median value) and the percentage of time that the signal is above a certain threshold level can be evaluated over the whole measurement period or over smaller periods, e. g. 1 h. The recordable parameters can be determined both by frequency band and frequency channel occupancy measurements and are not bound to specific methods.

Spectrum occupancy monitoring may be carried out with a spectrum analyzer or with a monitoring receiver, both computer controlled. A combination of these two makes little sense. A spectrum analyzer or a wideband monitoring receiver has the advantage of having a higher scanning speed whereas a monitoring receiver allows individual frequencies to be monitored at random.

The frequency range to be monitored depends on systems used in the frequency band to be measured (e.g. transmission length and bandwidth) and the equipment used. Occupancy is a function of time of signals beyond a defined threshold.

Automatic emission monitoring yields information on the following:

Spectrum overview

– This does not comprise the degree of occupancy expressed in per cent but merely general usage information. This includes, among other things, the presentation of level over time, such as spectrograms, min/max/median/average, waterfall plots etc.

Channel occupancy

– A classic occupancy measurement, it reveals the occupancy over any period, normally 15 min, of time (%).

Traffic load

– Occupancy data averaged over periods of 60 min may be expressed as traffic intensity in Erlang. The time dependent behaviour of the traffic may serve as a basis for the determination of channel requirements and a Quality of Service (QoS) evaluation. Of special significance in this context is the determination of the peak hour. The peak hour and busy hour, are specified by the beginning of the relevant measurement interval, e. g. 13:15 and means the occupancy within the measurement interval of e.g. 13:15 – 14:15.

Spectrum occupancy analyses are not necessarily limited to registering emissions in the spectrum but may also be applied to data recorded by other measuring equipment such as protocol analyzers.

Furthermore spectrum occupancy analyses together with a combination of different data sources allow many more parameters to be recorded and evaluations to be presented in a more differentiated manner. Plots and tables can also (automatically) be provided by user information retrieved from, for instance, planning tools, user databases, observations resulting from simultaneously manual monitoring.

Examples are:

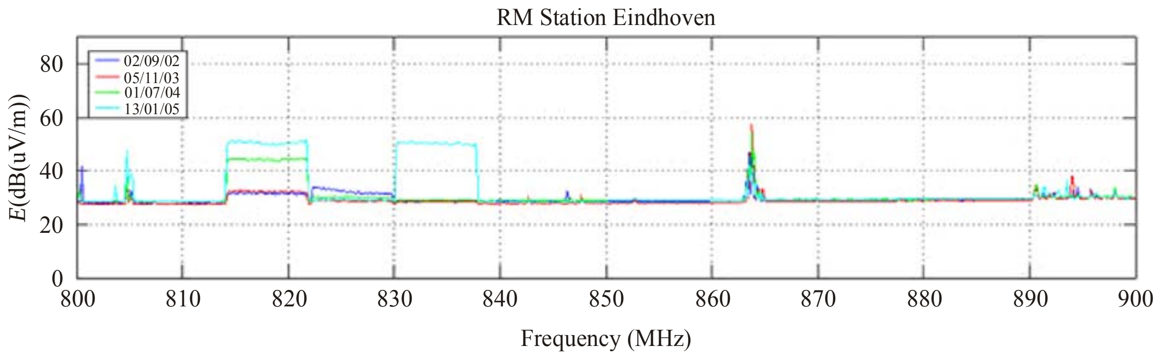
– Determination of the number of users or the spatial distribution of applications.

– Usage behaviour over distribution functions to the length of occupancy sequences. For this kind of determination the occupancy a good knowledge of the user behaviour is essential.

– Determination of usage variability or usage stability by correlating the measurement data of identical periods. This is called Delta monitoring (comparing the results of different measurements of the same frequency band on different dates, by plotting all curves in one plot).

FIGURE 4.10-2

Example of a Delta Monitoring



Spectrum-4.10-02

4.10.3 Receivers for spectrum occupancy monitoring

The monitoring receivers and spectrum analyzers used for this application should be as a minimum requirement compliant with the recommendations reflected in other chapters of this Handbook. The monitoring receiver used for spectrum occupancy measurement should fit the following parameters:

– provide high RF selectivity (in particular, there should be sufficient RF filters properly distributed in the receiver's operating band to prevent, as far as possible, the formation of inter-modulation products);

– be fitted with sufficiently narrow IF filters, and/or an I/Q output for IF filtering by means of external digital signal processing;

– be fitted with a step attenuator;

– be able to use an external frequency standard;

– be able to measure field strength precisely;

– be able to rapidly scan selected channels from a frequency band, especially above 30 MHz.

Whether the measurement of the exact field strength is necessary during an occupancy measurement depends on the task in question. In most cases an input voltage value is sufficient for the detection of occupancy.

When selecting a receiver the circuit design of the measuring equipment should be borne in mind since it affects the measurement result: Receivers with a synthesizer can be set to any frequency. However, their scanning process is slower than that of broadband systems based on FFT. In case of using FFT the measuring bandwidth is divided by a fixed number of calculation points. Therefore it is not possible to measure just any frequency. The setting of the measuring equipment is taken into account, especially in the case of channel occupancy measurements, and it is to choose one in which the FFT points are on the frequencies to be measured.

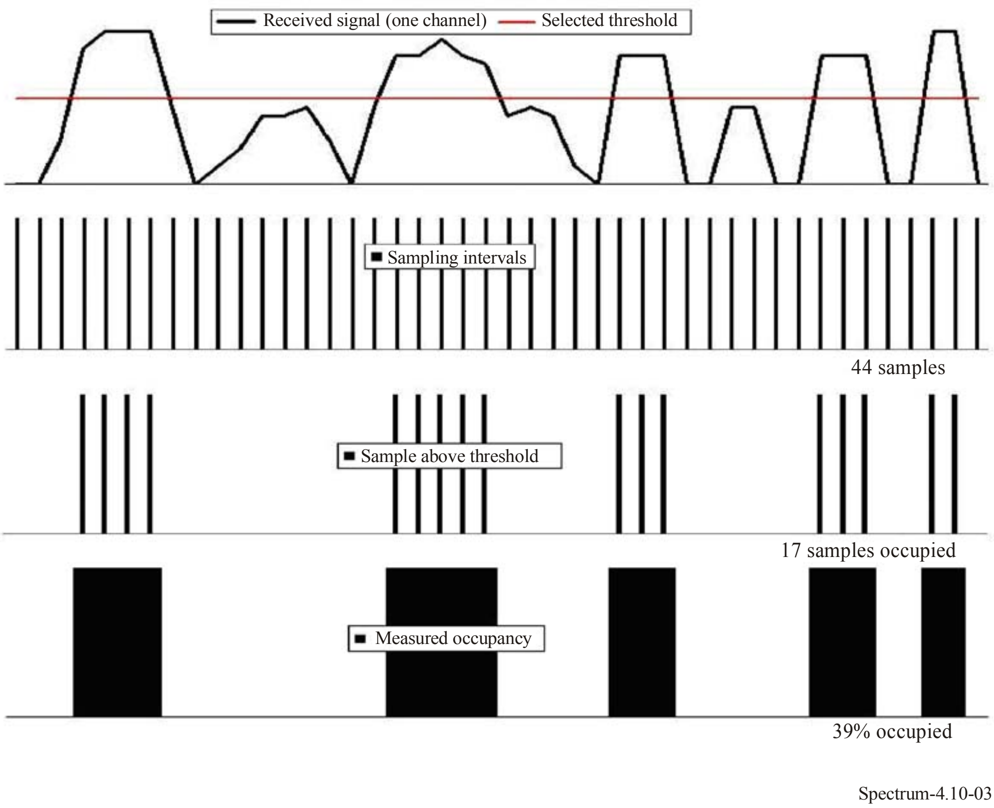
4.10.4 Basic principles and measurement parameters

4.10.4.1 Sampling principles

A typical varying strength signal is shown in Fig. 4.10-3 with a selected threshold as indicated. The sampling instants are shown together with those samples recording “occupied”. In this example 17 of the 44 sampling periods were found to be occupied leading to a 39% occupancy record. This data can be summarized into 1, 5, 15 min, 3 h, 6 h, 12 h or 24 h intervals as desired.

FIGURE 4.10-3

A typical varying strength signal



The sample technique usually gives a good estimation of channel occupancy provided sufficient samples are taken to give statistically significant result. Table 4.10-1 shows the number of samples required to give a reasonable confidence in the results.

TABLE 4.10-1

Number of dependent and independent samples required to achieve 10% relative accuracy and 95% confidence level at various occupancy percentages (assumes a 4 s sampling period)

Occupancy (%)	Number of required independent samples	Number of required dependent samples	Required hours of dependent sampling
6.67	5 368	16 641	18.5
10	3 461	10 730	12.0
15	2 117	6 563	7.3
20	1 535	4 759	5.3
30	849	2 632	2.9
40	573	1 777	2.0
50	381	1 182	1.3
60	253	785	0.9
70	162	166	0.2

In order to achieve certain accuracy with a reliable statistical confidence interval a defined number of samples are required. In the event of occupancy of 100% only a few samples are needed to achieve a good result. Where occupancy is low, more samples are needed to obtain the same accuracy and statistical confidence. The intention of the table is to indicate that the accuracy in relation with the number of samples over time strongly depends on the transmission length of systems in the wanted frequency band and how often they are "on air". In case of a PMR user (e.g. taxi) which is once an hour on air for 12 s should longer be monitored to get a certain accuracy since the broadcast station transmits continuously).

Normally the values in Table 4.10-1 are sufficient to determine the confidence level. For special applications, e. g. very low occupancy, very long sweeptime, etc., the text "On the Definition and Estimation of Spectrum Occupancy" [Spaulding/Hagn, 1977] should be consulted.

The sample numbers given in Table 4.10-1 always refer to the period for which data with the corresponding accuracy is to be obtained. In other words, if dependent sampling (always at the same interval) is done in the case of an anticipated occupancy of 20%, 4 759 samples will have to be taken per interval. If data is needed on the traffic load, the required interval is 60 min. If 4 values per day (i.e. one over 6 h) are sufficient in long-term sampling, then the interval is 6 h.

The requisite measuring speed is hence basically dependent on the interval concerned. In the example given here, for intervals of 15 min samples would have to be taken at least every 0.15 s, for intervals of 60 min every 0.6 s and for intervals of 6 h every 3.5 s.

From the viewpoint of frequency management the measurement of low occupancies is not very critical. Nevertheless, short-term occupancies may also be of interest, e. g. when endeavours are made to discover frequency uses per se. The statements "no use" and "occasional use" are worlds apart.

4.10.4.2 System parameters

In order to assess the occupancy of as many channels as possible, an enormous amount of data has to be collected and processed. For example, a scanning receivers is programmed in such a way that 50 samples are recorded every 2 s from different radio frequency channels. This means that the system operates with a revisit time of 2 s. The receiver needs time to adjust accurately to the channel and generate reliable results. In this example the observation period per channel or dwell time is about 5 ms. The observation period per channel depends on the receiver's scanning speed.

When programming the measurement system it must be borne in mind that in case different types of receivers are used, the settings must be the same to obtain comparable results.

4.10.4.2.1 Transmission length

Different types of users have different transmission lengths. Normally data bursts are shorter of duration than speech. User density differences in urban or rural areas have an influence on the transmission length and the occupancy statistics as well.

A distinction has to be made between the time measured during which an emission is on air and the time during which a communication occupies the channel. For example, in the case of simplex channels the switching time between the radios involved is a part of the channel usage. Intelligent recording systems can register these delay times and add them to the actual periods of occupancy.

4.10.4.2.2 Relationship between some relevant parameters

There is a strong relationship between the observation time, the number of channels, the average transmission length, the wanted accuracy and the duration of monitoring.

The revisit time is directly dependent on the observation time and the number of channels:

$$\text{Revisit time} = (\text{observation time per channel}) \times (\text{number of channels})$$

For this type of measurement the revisit time should be (much) shorter than the average transmission length. In order to maintain a reasonable short revisit time with relatively slow equipment, the number of channels to be measured must be reduced.

The monitoring system should scan at an acceptable speed to detect individual short transmissions to obtain information with accuracy and confidence level according to Recommendation ITU-R SM.182 as mentioned in § 4.10.4.1.

4.10.4.3 Resolution of the measurements

It is not expedient to record raw data since data volumes are too large and difficult to process. It hence makes sense to reduce the data to a specified interval during the actual measurement. Depending on the task on hand and the length of the measurement, intervals of 1 min, corresponding to 1440 data records per day, may constitute an acceptable compromise between the registration of all data and too high a compression loss. If such a resolution is not necessary or if the monitoring period is very long (covering several months), larger intervals of 5, 15 or 60 min may be adequate. However, the time resolution of the measure equipment should be much higher also in these cases in order to obtain a higher precision when creating moving averages.

The monitoring software should therefore be capable of generating the occupancy data for freely selectable resolutions.

4.10.4.4 Site considerations

Various factors should be taken into consideration when selecting a site for frequency channel occupancy measurements.

In common with most sites used for receiving purposes, the monitoring equipment should be placed at a location that is:

– remote from strong radio transmissions;
– remote from structures and buildings which could cause reflections;
– within the service area of the radio systems to be monitored. Coverage prediction software may be a useful tool to determine the range of reception;
– away from sources of electrical noise, i.e. computers, motor speed controllers, etc.

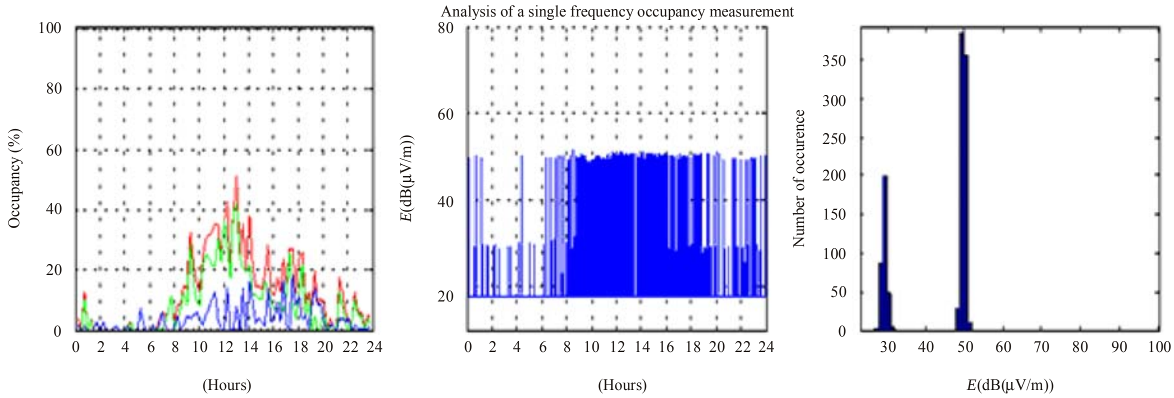
4.10.4.5 Limitations of monitoring and possible solutions

Although accurate occupancy results are expected, it is wise to bear in mind the limitations associated with automatic occupancy monitoring and areas where inaccuracies could occur. Simple automatic monitoring is not able to discriminate between signals received from station A and those from station B (wanted and unwanted emissions, respectively).

Advanced automatic monitoring is able to discriminate between signals from different stations. The occupancy caused by the different stations working on the same frequency channel could be both plotted in an occupancy plot as shown in Fig. 4.10-4.

FIGURE 4.10-4

Example of determining fixed transmitters



Two users can be identified, green is the user received with a level of about 50 dB(μV/m), blue curve shows occupancy caused by the other station (about 30 dB(μV/m)). The red curve is total occupancy (green + blue).

To achieve distinct results (sharp needles, representing the fixed stations in the right diagram of Fig. 4.10-4) a low number of discrete levels with high number of each occurrence is desirable.

4.10.4.5.1 Undesired signals

Most automatic occupancy monitoring systems use a threshold level to establish when a frequency is occupied.

Although the obvious intention is to record the activity of wanted signals, simple automatic monitoring is not able to discriminate between wanted and unwanted emissions. Both types of emission are treated as legitimate channel occupancy.

Undesired signals could originate from any of the following sources:

– unauthorised transmissions;
– strong adjacent channel users;
– spurious and out-of-band emissions from transmitters;
– man-made interference (e. g. unsuppressed electric motors);
– enhanced propagation due to weather and environmental conditions;
– co-channel users from a distant location.

From a user's point of view, however, all types are deemed to constitute an occupancy and as such are uncritical as far as the measurement is concerned.

Care must be taken in system design to either avoid receiver intermodulation products, or to identify these products for removal by software algorithms. An intermodulation product is taken into account by automatically inserting fixed, known RF attenuation on alternate scans and then automatically removing all recorded signals which are attenuated by a greater value. However, this measurement technique halves the recording time. Also, it is not necessarily reliable since it assumes that the emissions do not change between the two sweeps.

4.10.4.5.2 Total occupancy

Even if the monitoring system does not suffer from any of the above problems and receives only legitimate signals, the occupancy results must still be treated with a certain degree of caution.

If more than one user is active on a frequency within the coverage area of the monitoring system, the occupancy recorded will be a combination of the radio traffic from each user.

It is possible that a wanted mobile unit (mobile A) will be located significantly further from the monitoring site than the user's own base site (Base A). Therefore the received signal strength may be less than the monitoring threshold value set although strong enough at the intended base site to be usable. Conversely, a mobile unit from an out-of-area user (mobile B) may be received at the monitoring site but not be heard at the main user's base site.

These two examples may lead to incorrect interpretations of the occupancy results. These error options need to be evaluated and documented in a measurement report. The selection of the measurement site and the quality of the receiving chain has a significant impact on the measurement result.

4.10.4.6 Threshold setting

A distinction is made between setting a fixed and a dynamic threshold.

A fixed threshold can be defined as the minimum field strength necessary for radio coverage. It would thereby emulate the situation of a radio station in the monitored radio network. In case a fixed threshold value is used one can compare the results from the latest measurements with those from previous measurements. In case a dynamic (changing) level is used, one can not compare the results.

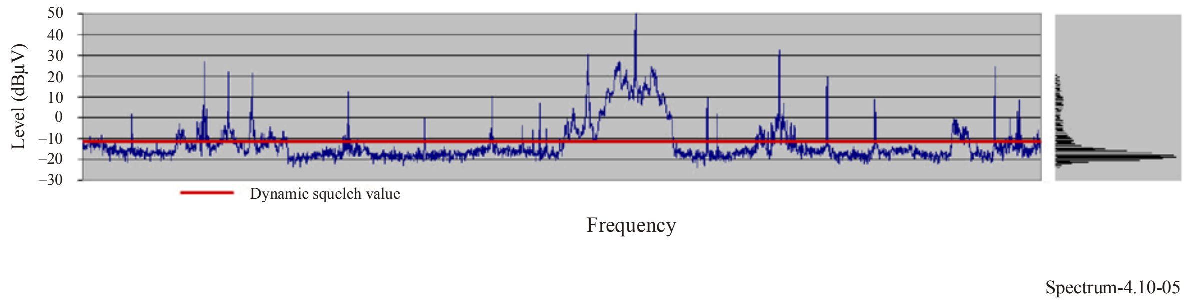
The threshold may also be defined by having knowledge of the levels at the measurement site. To determine the threshold, a margin of 8-12 dB may be added to the noise. The actual value which should be added to the noise level depends on "what is expected to see". If there is a need to have knowledge of all signals within the coverage area of the receiver then, not more than 3 up to maximum 5 dB should be added to the calculated noise level. In case of a fixed threshold level, one should determine the noise level from all the (remote) sites (receivers) and store them into a simple database. The values in this database should be used when processing the data.

It will be evident that the background noise level for processing results in the FM broadcasting band 87.5 MHz-108 MHz will be different from the frequency band 118 MHz-133 MHz of the Aeronautical Service.

Where measurements are carried out with a spectrum analyzer or receiver, a dynamic squelch can be calculated by means of various algorithms. It can be derived most easily from the frequency distribution of the samples over a sweep. A fixed margin of 5-10 dB is added to the level, which is represented by the highest number of discrete level values. In this way the threshold for the occupancy detection of this particular sweep is constituted (see Fig. 4.10-5).

FIGURE 4.10-5

Determination of the dynamic squelch

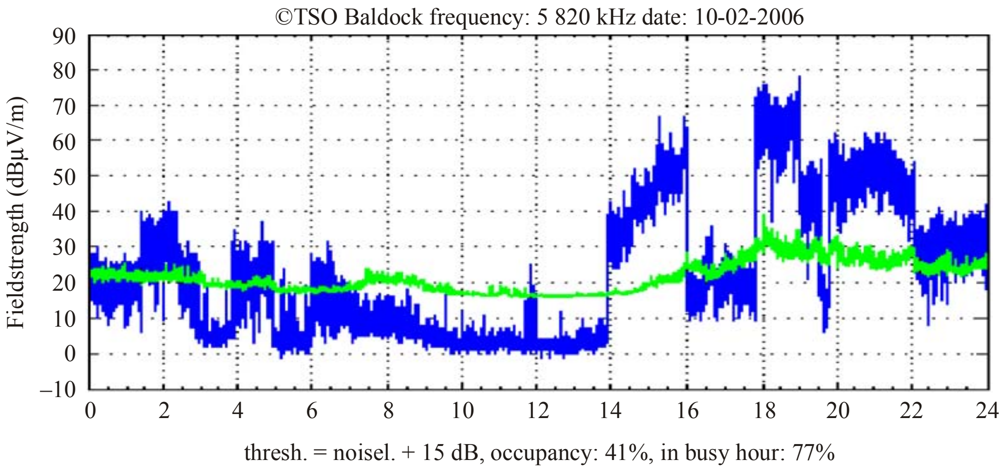


In this manner a new threshold is calculated for each sweep. This method offers a big advantage in longer measurement cycles. Changes in the noise level or broadband unwanted signals do not falsify the occupancy measurement or render it unusable. However, care must be taken to ensure that the spectra recorded contain an adequate number of samples replicating the noise. The noise floor will change slightly over time in VHF/UHF/SHF. However, the change is under normal conditions not more than a few dB. Since a number of dB (3 to 5 dB) are added to the noise, this will have no influence. This shows that it is not always needed to calculate a new threshold for every sweep. In case the noise floor is changing more than 5 dB then there are exceptional (propagation) conditions and the results may be corrupted and should not be relied on.

For the HF bands the situation is completely different. The noise level is changing during the day and season with big differences over 24 h. In that case one should indeed calculate a dynamic threshold versus time. And one should add more dB to the noise level to determine the threshold. In the Fig. 4.10-6 15 dB may be added.

FIGURE 4.10-6

Variation of HF-Noise during a day



Spectrum-4.10-06

A later change of the threshold value is not expedient since this would require raw data to be registered.

Assuming a 24-hour measurement with a sweep time of 500 ms and 1 000 steps this would yield a data volume of about 700 MB. (1 000 data points with 4 bytes each = 4 kB per spectrum sweep or spectrum scan), 172,800 spectra in 24 h * 4 kB = approximately 700 MB).

Depending on the transmission length of signals expected in the frequency band to be measured, it is not always necessary to use a sweep time of 500 ms, For instance broadcast frequency bands can be measured with a 10 s sweep time (file size about 35 Mb). But even in the case of 500 ms, a data file of 700 MB will shrink to about 230 MB when zipped.

An external hard disk from 1 Tb is very easy to obtain and one can store more than 4 000 zipped files, each containing a 24 h measurement with 500 ms

Even if sufficient hard-disk storage space would be available, saving such an amount is problematic and data evaluation difficult. A data reduction during data collection certainly makes sense for various reasons but does imply that the parameters to be set must be known before the measurement is begun.

4.10.5 Measurements in frequency bands

Conducting spectrum occupancy measurements below and above 30 MHz is in principle the same. The same methodology as described in Recommendation ITU-R SM.1809 can be used for the entire radio spectrum.

On frequencies below 30 MHz normally no frequency channel occupancy measurements are used. (One exception is the channel occupancy on HF broadcasting channels during European monitoring campaigns in the preparation for WRC-2007).

For frequency channel occupancy above 30 MHz, normally the measurement method described in Recommendation ITU-R SM.1536 or the frequency band measurements as described in Recommendation ITU-R SM.1809 combined with the processing method from Recommendation ITU-R SM.1793 is applied. This last mentioned method gives the possibility to discriminate between more than one user on the same channel.

4.10.5.1 Frequencies below 30 MHz

For manual occupancy monitoring below 30 MHz, the analysis unit must provide a judicious choice of analysis filters of bandwidth between about 100 Hz and 10 kHz. Frequency measurement (up to an accuracy of 1 Hz) assists the occupancy measurement process in particular by helping to identify signals.

As a rule it should be possible to adjust the measurement equipment in such a way that it is capable of recording the emissions correctly. In order to increase sensitivity in occupancy determination, it is also possible to measure in a narrower band.

The measurement period and the associated number of measurement samples/intervals depend on the task on hand. It may suffice to measure only a short period (e. g. one day) but with a higher resolution, e. g. to identify the peak traffic hour, or in the case of long-term measurements over weeks or months, to measure with the same number of measurement samples over longer intervals.

Occupancy measurements can be based on channels or frequencies. The latter only makes sense if a spectrum analyzer is used. If the occupancy of a single channel/single frequency is of no interest for the task on hand, band-related measurements should be preferred. In principle, in such measurements the individual occupancies are added and thus information is gleaned about the frequency band or the channels observed. The loss of individuality on the individual channels/frequencies results in findings with a lower variance.

4.10.5.2 Frequencies above 30 MHz

Also spectrum occupancy measurements above 30 MHz can support various frequency management and enforcement tasks.

– Channel occupancy registration.
– Frequency band registration.
– Traffic analyses.
– To show that a frequency band is available for new usage after "refarming".
– Identification of illegal frequency use.
– Interference prevention.
– Long-term analyses.
– Analysis of cellular networks with dynamic channel assignment (determination of the behaviour of a cell a as a whole).

4.10.5.2.1 Frequency channel occupancy measurements

In most countries the frequency bands above 30 MHz are planned according to well known planning systems as for instance the honeycomb structure. Radio channels are assigned to users according to availability. Information about licensed users retrieved from frequency management databases only indicates that the use of the frequency is authorized. The number of assignments on a frequency does not always give adequate information about the actual use of that particular frequency.

Therefore in congested areas, it is necessary that frequency assignments be based on more realistic data. Measurements of traffic density on radio channels will result in more accurate values for the occupancy of these channels. Repeating these measurements at regular intervals enables frequency managers to establish trends from historical data.

4.10.5.2.2 Services

Private mobile radio services have been traditionally based on analogue speech. However, data transmission has been introduced either as an add-on facility or as a principal means of communication. Where users wish to incorporate the exchange of data messages in their existing mobile networks, data appears on shared radio channels. In that case, the regulatory authority will have to know the characteristics of the radio channel in order to determine how the data communication system will perform. Some users may have requirements that can only be met by the assignment of more appropriate radio channels.

In general, new services also will have an impact on the occupancy of a radio channel on a per-mobile-station basis. This generally increases the total traffic volume in a radio channel. As this does not show up in an administrative system that only registers the number of mobile stations additional details have to be taken into account.

4.10.5.2.3 Additional information about certain users

Apart from the single determination of the signal strength above the threshold in form of a yes/no statement, there are many more parameters that can be stored such as signal level, type of modulation or information for identification purposes (e. g. selective calls).

Apart from merely registering occupancy it is useful to record the maximum, mean and minimum level values in each interval. This not only yields occupancy data but also enables further analyses about frequency activities because, for example, regular short-term emissions are recognised which would otherwise be concealed by the averaging process.

The recorded behaviour over time also allows information to be derived about the type of use.

4.10.5.2.4 Slow channel scanning

This method is very similar to the frequency occupancy measurements described before except that frequencies are scanned at a very much slower rate, perhaps only 2 frequencies/s. This method can be used when the identity of the user is transmitted throughout the entire length of the user's transmission and can therefore be obtained by sampling at any point.

This is possible with the following systems:

– continuous tone-coded squelch system (CTCSS).

– digitally coded squelch (DCS).

If a more differentiated statement about the frequency uses is required it is usually necessary to record and evaluate additional protocol data.

In digital radio systems which are transmitting continuously, e. g. TETRA, GSM, recording of the protocol contained in a control channel constitutes the only means of deriving information about the occupancy level.

4.10.5.2.5 Static channel monitoring

This enables the collection of information about transmission length and can also be used in systems where the end user only sends its identification once per transmission. It is not possible to employ scanning techniques because the receiver must remain on a single frequency in order not to miss any information (see Fig. 4.10-7).

nThis is applicable for the following types of system:

– 5-tone Selective Calling (SELCAL).

– Automatic Transmitter Identification System (ATIS).

– MPT 1327 trunking control channel.

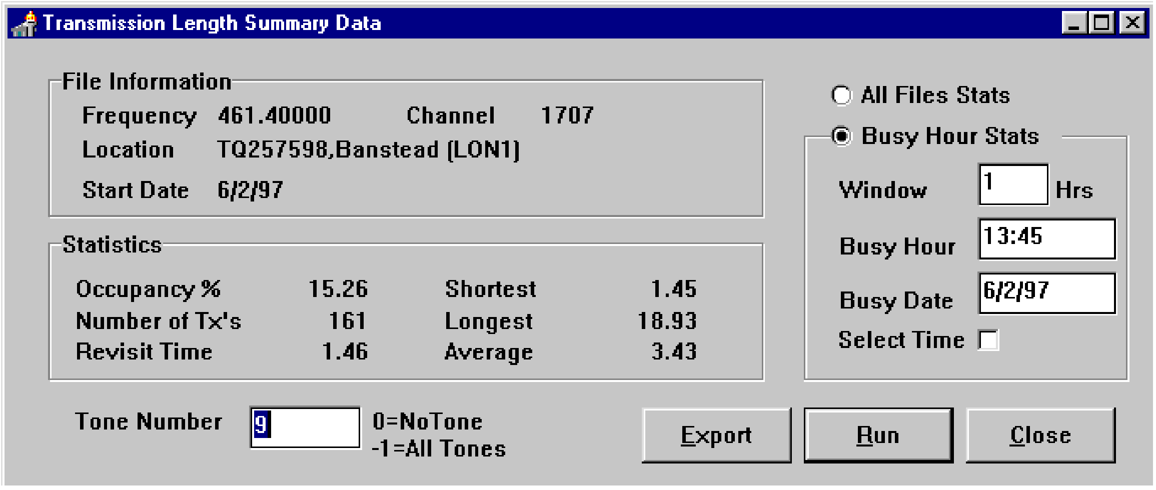
– POCSAG paging.

If additional information on individual users is obtained, it is then possible to sub-divide the total occupancy for that frequency into specific occupancy values for each user.

In the case of applications controlling traffic flow over control channels, e. g. as in trunked radio, or which can be reduced to a single channel (e. g. DSC, POCSAG) it is possible to derive a very accurate traffic analysis from the recorded protocol data.

FIGURE 4.10-7

Example of static channel monitoring



Spectrum-4.10-07

4.10.5.2.6 Frequency band occupancy measurements

Generally the following approach is valid:

Automatic monitoring starts with frequency band occupancy (FBO) measurements. There is no threshold needed for a number of plots (e.g. spectrogram, waterfall, min/max/med etc). A threshold level is needed only to calculate the frequency band occupancy.

So one should start with frequency band occupancy measurements (Recommendation ITU-R SM.1809), but if more detailed information per channel is required, then frequency channel occupancy measurements should be carried out. Or even better process the with Recommendation ITU-R SM.1809 obtained result as FCO described in Recommendation ITU-R SM.1793

The settings of the receiving equipment depend on the frequency band to be scanned. The scan time depends on the amount of desired data. The setting of the threshold level must be as low as possible, avoiding, however, the recording of noise. It is very helpful if the threshold level can be changed afterwards thus allowing for different kind of evaluations. The signal level is recorded at every sweep, e. g. at 900 sweeps during 15 min at 1 sweep/s. Frequencies at levels above the selected threshold level are regarded as occupied. Using dedicated software there is also a possibility to zoom the scanned frequency band in time and frequency.

Monitoring receivers with highly selective IF filters with a shape factor of 2:1 or better are preferable to spectrum analyzers for spectrum occupancy measurements. For speed requirements often spectrum analyzers are used. They are normally equipped with Gaussian IF filters to prevent ringing. However, this type of filter does not discriminate adequately against signals in adjacent channels. Nevertheless, a Gaussian filter is the best compromise between speed and resolution. As a result, spectrum analyzers tend to overestimate the actual occupancy. Using monitoring receivers, the bandwidth of their IF filters of should be matched to the bandwidth of channelized bands. Therefore, a set of IF filters is required which matches the channel widths of the bands to be monitored. It is recommended that the receiving equipment has preferably low noise figures.

Also, tuneable preselection filters are highly desirable and the low-noise amplifiers can be integrated in the preselector after the filter. Special band pass filters may be required to help improve the measurement system's dynamic range for some monitoring situations when using either a monitoring receiver or a spectrum analyzer.

For example, such filters may be needed to obtain valid occupancy data on channels containing relatively small (low-level) signals in bands adjacent to bands containing relatively large signals (e. g. broadcasting bands).

Finally it may be necessary to use a pre-attenuator ahead of a monitoring receiver or spectrum analyzer preamp in order to properly position the dynamic range of the monitoring system when monitoring bands with large signals.

During every sweep of this type of spectrum measurement from all measuring points (e. g. 1 000 points) the received signal strength is stored. These steps can be considered as 1 000 single channels. From every channel the received data can be processed.

Distribution plots of the measured values to get a good indication of the number of base stations, received signal strength over time (mostly 24 h), information about average speech length etc. can be obtained rather easily.

Because the size of the resolution bandwidth (RBW) filter normally is bigger than the size of the steps not all of the "channels" can be used. For instance the band to be examined is 7.5 MHz. As an example this is done in 1 000 steps so the step size is 7.5 kHz. The RBW filter can be 10 kHz.

Now from every third step the information can be processed which will result in occupancy information every 25 kHz, which could be the existing channel spacing in the measured band. In case 12.5 kHz as frequency step is used one can process every second step.

Another solution could to be change the filter size (if possible) to 10 kHz and the problem is solved. This can only be applied for FCO because in every step a small portion of the spectrum is skipped (not measured). For every channel -5 and + 5 kHz is observed.

The occupancy will not differ if measured with a 15 kHz filter. It should be understood that the sweep time, which is comparable with the re-visit time of the frequency channel occupancy measurements, in this case is about 10 s and cannot be reduced infinitely.

It is of importance to note that extended tests have shown that the accuracy will not dramatically change in case the re-visit time increases from 1 to 10 s. (See § 4.10.2)

4.10.6 Presentation and analysis of collected data

When occupancy data has been collected there is a requirement to analyse the results and present them in a useful format. Data needs to be turned into information and ultimately knowledge.

The monitoring system may already have presentational and analytical functions built into the software supplied. Irrespective of whether these functions are included within the measurement gathering software, or supplied as a separate application, the processes are similar.

The complete process is described in 3 steps:

1. Measuring and collecting data.
2. Processing and converting data into information (plots, graphs etc.).
3. Presenting the result for reports or display on websites, etc.

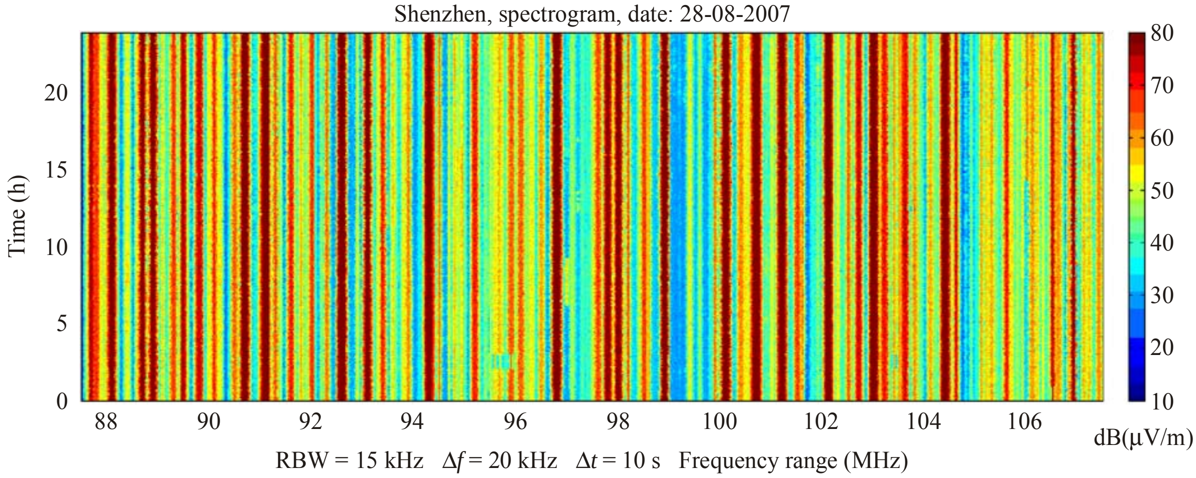
From the collection of raw data it is possible to generate the following presentational options:

– tables;
– textual graphs;
– graphs;
– maps.

Some examples of frequency band measurements are presented below:

FIGURE 4.10-8

Spectrogram

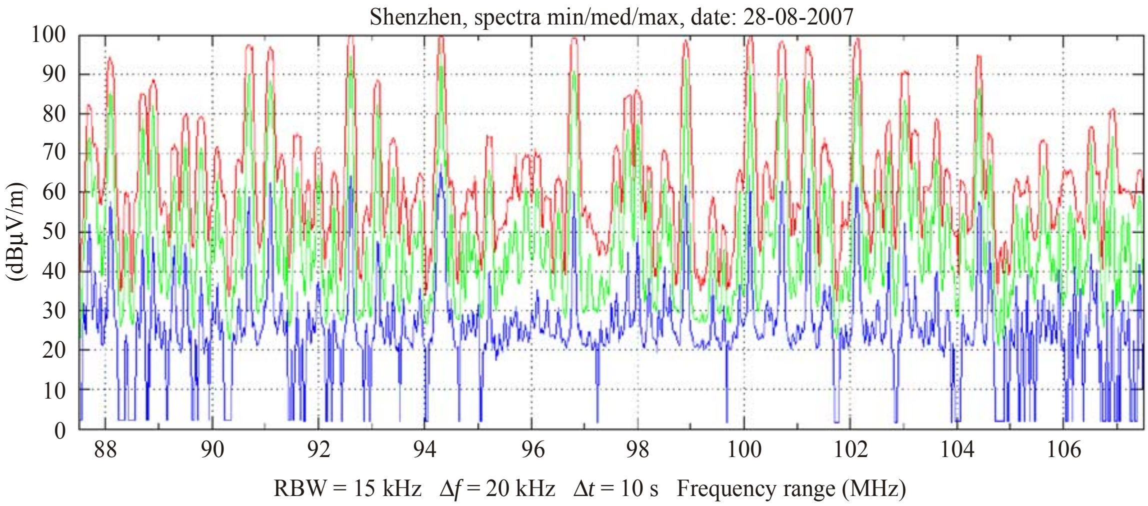


Spectrum-4.10-08

FIGURE 4.10-9

Minimum, Maximum, Median curves

(from same measurement database as spectrogram above)



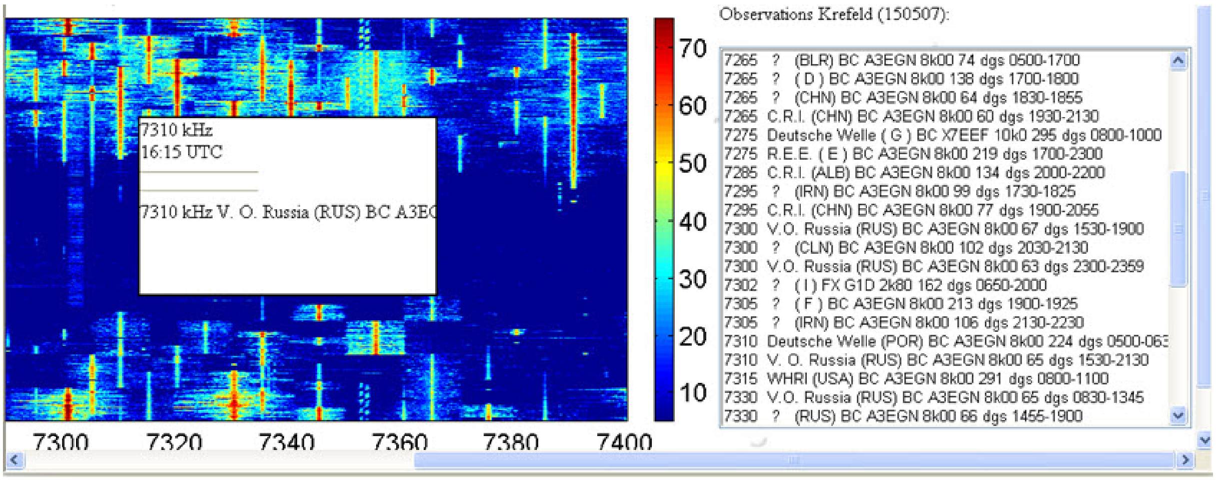
Spectrum-4.10-09

The presentation, in case of frequency channel occupancy measurements, should as a minimum contain the following information:

– location of monitoring;
– date and period of measurement;
– frequency;
– type of user(s);
– occupancy in the busy hour.

FIGURE 4.10-10

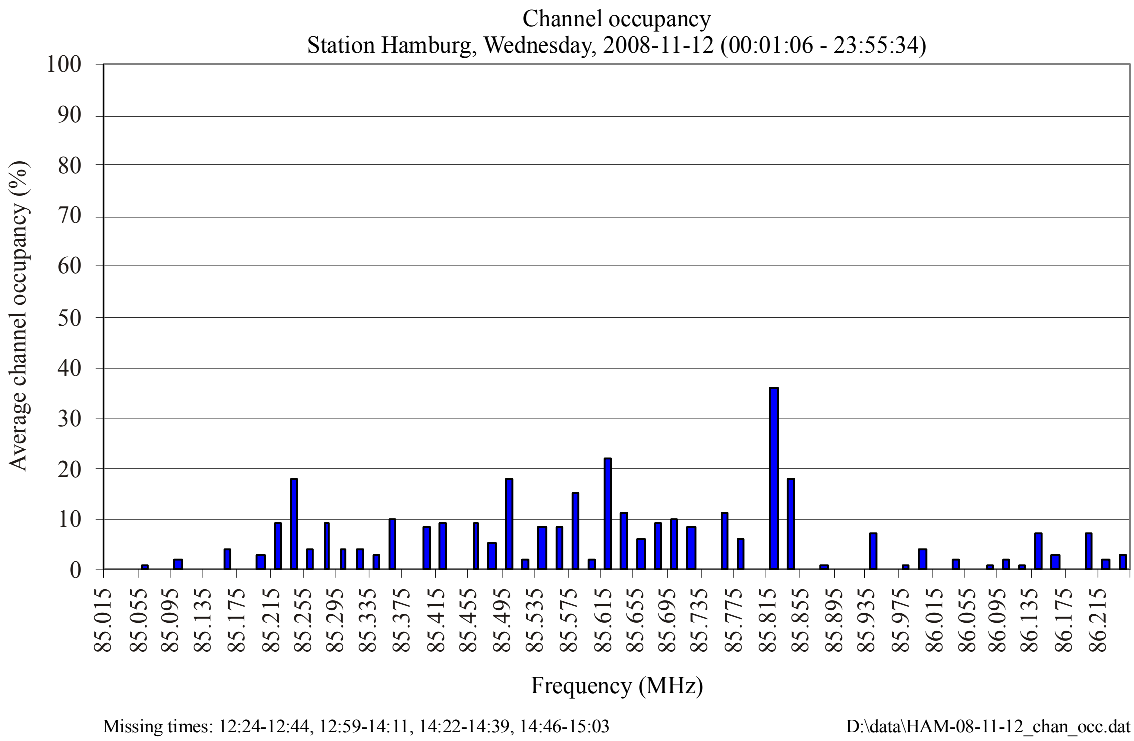
Screenshot from HF measurements combined with results from manual monitoring



Spectrum-4.10-10

FIGURE 4.10-11

Example of a channel occupancy measurement



Spectrum-4.10-11

For many of a regulator's decisions a quick overview of the channel occupancy may suffice. Such an overview may be produced from the occupancy data with the help of a spreadsheet program (Open Office, Excel). With two buttons for the limits the evaluation can always be adapted to current conditions.

FIGURE 4.10-12

Example of a quick overview of channel occupancy measurements

Short overview
Channel occupancy over time

Hours	0..1	1..2	2..3	3..4	4..5	5..6	6..7	7..8	8..9	9..10	10..11	11..12	12..13	13..14	14..15	15..16	16..17	17..18	18..19	19..20	20..21	21..22	22..23	23..24
Channel 01	15%	16%	17%	18%	19%	21%	22%	24%	25%	27%	29%	31%	33%	36%	38%	41%	44%	47%	51%	27%	23%	21%	18%	19%
Channel 02	8%	9%	8%	5%	9%	9%	19%	5%	13%	12%	4%	12%	14%	5%	6%	19%	38%	24%	16%	18%	5%	25%	11%	7%
Channel 03	10%	11%	12%	17%	17%	18%	2%	5%	17%	25%	14%	22%	12%	24%	18%	24%	21%	4%	12%	1%	2%	15%	25%	10%
Channel 04	4%	10%	10%	13%	5%	15%	6%	2%	9%	6%	11%	1%	11%	29%	34%	10%	41%	7%	7%	24%	6%	26%	23%	11%
Channel 05	14%	12%	6%	4%	5%	5%	18%	4%	16%	1%	4%	12%	27%	15%	8%	9%	27%	2%	4%	24%	17%	30%	24%	19%
Channel 06	9%	9%	9%	1%	3%	1%	6%	7%	13%	11%	14%	8%	27%	26%	8%	12%	25%	39%	39%	11%	28%	17%	10%	8%
Channel 07	10%	1%	1%	8%	6%	2%	7%	14%	15%	2%	25%	16%	34%	10%	15%	21%	46%	26%	21%	8%	15%	33%	21%	12%
Channel 08	4%	15%	8%	15%	1%	3%	15%	11%	2%	19%	27%	21%	10%	30%	32%	9%	30%	9%	50%	9%	23%	21%	22%	23%
Channel 09	4%	14%	2%	5%	17%	2%	2%	20%	1%	8%	9%	23%	24%	10%	9%	12%	15%	3%	7%	23%	22%	4%	4%	35%
Channel 10	0%	8%	16%	15%	5%	11%	4%	19%	7%	15%	17%	15%	14%	20%	24%	37%	38%	44%	7%	19%	25%	7%	31%	16%
Channel 11	12%	1%	15%	16%	1%	1%	6%	9%	22%	20%	12%	24%	12%	32%	18%	14%	5%	11%	9%	15%	14%	19%	32%	12%
Channel 12	10%	13%	13%	3%	4%	9%	1%	3%	6%	27%	18%	21%	3%	2%	36%	5%	37%	11%	20%	23%	15%	9%	29%	16%
Channel 13	8%	2%	1%	12%	17%	10%	8%	16%	24%	26%	16%	25%	24%	24%	6%	37%	14%	20%	6%	9%	24%	24%	30%	20%
Channel 14	13%	8%	1%	8%	4%	3%	7%	14%	25%	10%	26%	24%	8%	23%	20%	2%	30%	46%	22%	24%	17%	3%	23%	22%
Channel 15	2%	14%	0%	15%	10%	19%	15%	16%	24%	27%	18%	19%	20%	30%	37%	8%	43%	29%	37%	20%	28%	20%	31%	1%
Channel 16	3%	12%	11%	4%	2%	17%	8%	7%	15%	12%	26%	11%	19%	17%	17%	30%	34%	20%	49%	8%	6%	7%	3%	5%
Channel 17	14%	0%	4%	1%	8%	3%	7%	7%	23%	7%	13%	7%	24%	4%	3%	9%	2%	14%	5%	23%	5%	15%	28%	10%
Channel 18	10%	3%	1%	10%	17%	16%	12%	12%	17%	25%	23%	24%	28%	4%	36%	37%	18%	10%	12%	10%	18%	25%	33%	25%
Channel 19	3%	7%	15%	13%	7%	10%	16%	6%	1%	5%	13%	7%	27%	22%	13%	23%	39%	11%	21%	10%	26%	4%	28%	4%
Channel 20	3%	1%	6%	2%	12%	14%	1%	12%	1%	23%	2%	23%	4%	17%	19%	20%	13%	18%	12%	3%	28%	14%	11%	9%

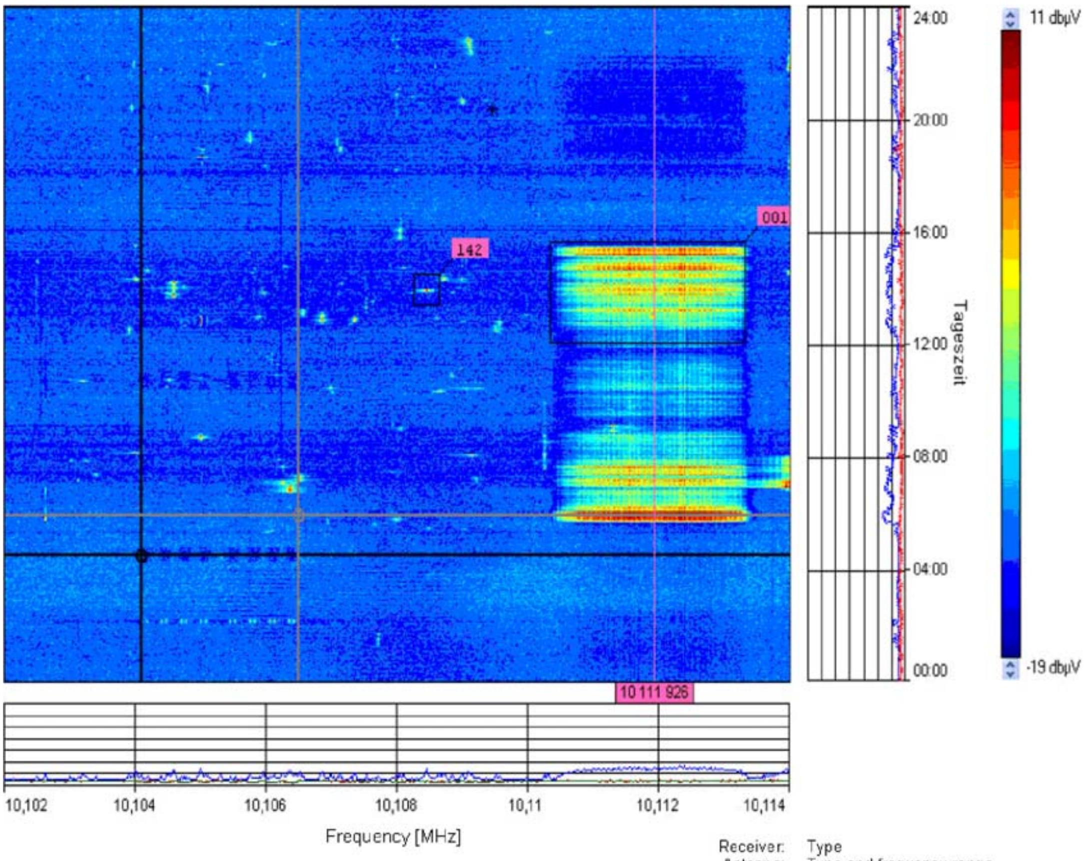
< 10%   10% <-> 20%   > 20%

Spectrum-4.10-12

FIGURE 4.10-13

Example of a frequency band measurement

BÜ B1 271-00020-08 - 10108 kHz/KON/KONMST/0001_MAX



	Level	Frequency	Time [UTC]
Marker1 ------	-12.3 dBµV	10.104 093 MHz	04:30:12 h
Marker2 ------	-12.5 dBµV	10.106 493 MHz	05:55:52 h
Delta	-0.2 dBµV	2.400 kHz	01:25:40 h
Mouse pointer	-13.5 dBµV	10.109 450 MHz	20:22:31 h

Receiver:	Type		
Antenna:	Type and frequency range		
Date:	16.12.2008		
Period of Observation:	03.12.2008 – 16.12.2008		
Frequency range:	start	stop	resolution
	10.102 MHz	10.114 MHz	10 Hz
Averaging period:	1 second		
001, 142	Markers, manually set as a reference for a report		

Spectrum-4.10-13

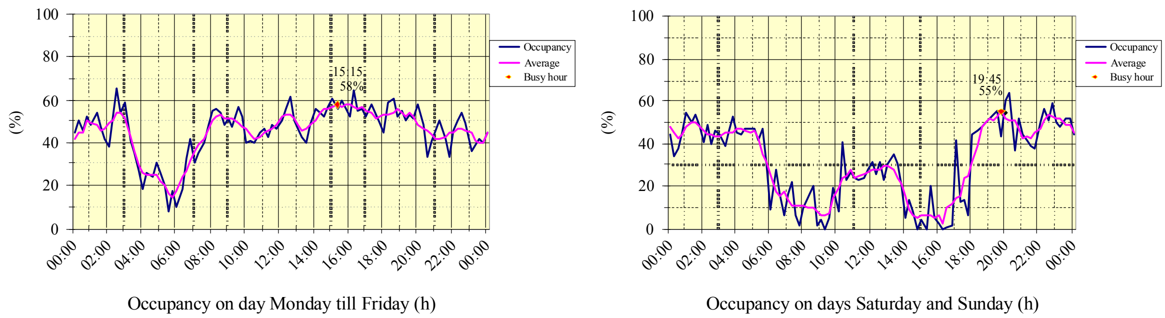
The next example of a presentation shows the processing of data of a system that only indicates that a signal observed was above the pre-set threshold level.

The receiver may monitor a bundle of 50 channels continuously during measurements on 14 consecutive days. The collected data may be divided into two batches. One batch contains workday data, the other weekend data.

Each batch is then processed in the following way as depicted in Fig. 4.10-14.

FIGURE 4.10-14

Report of occupancy on a single channel



Spectrum-4.10-14

Samples of 15 min are averaged, resulting in 96 samples per day.

Each 15 min occupancy-value then is used to form a so-called sliding 1-h average. That is, 4 pieces of 15-min samples are averaged 96 times a day to build an one hour average-value.

All values are now plotted in a graph, showing maximum and running average occupancy during workdays and a graph of the same nature giving the occupancy during the weekend.

The moment on the running average line where the occupancy is the highest is named the busy hour. For interference problems a daily presentation (graph) and review of occupancy is desirable.

These daily presentation graphs can help solve interference problems. They show the difference in occupancy on one specific channel typical for taxi. The left side of Fig. 4.10-14 shows the graph on days Monday till Friday, the right side shows the occupancy on Saturday and Sunday. The upper line in the graph is the maximum occupancy, the second the running average. The X-axis is time and Y-axis is percentage of occupancy. The measuring period is 14 days. Sample frequency is 0.54 Hz. Busy hour is noted as red dots in Fig. 4.10-14 at 15.15 h (left diagram) and at 20.45 h (right diagram).

4.10.7 Exchange of data

Neighbouring Administrations may be interested in exchanging occupancy data, especially concerning regions near the country borders, to assist in frequency assignments. In such cases it is important to use a unique and unambiguous format that allows correct interpretation of the data the cooperating parties deliver to each other.

As an example of that, Recommendation ECC/REC(05)01 "Harmonisation of automatic measuring methods and data transfer for frequency band registrations" recommends to use the comma separated value (CSV) file format for this purpose. Most database and spreadsheet programs can read this format.

A header section describes the location from which the measurements are carried out, frequency range and a number of other technical parameters.

The header section is separated from the real data by a blank line. Each line (scan) of the data section starts with the time followed by the level (or field strength) value for each frequency step e.g. 1 000. If the scan or sweep time is 10 s, the data file contains > 8 630 lines.

```
FileType          Bandscan
LocationName      Shenzhen
Latitude          2W23.00
Longitude         5N35.00
FreqStart         87500
FreqStop          107500
AntennaType       HK-014
FilterBandwidth   15
LevelUnits        dBuV/m
Date              2007-08-30
DataPoints        1001
ScanTime          10.0
Detector          Average
Note              Receiver:

00:01:40,19,2.3,19.1,44.5,34,39.9,43.9,63.5,65,66.2,75.1,74.6,63.6,etc
00:01:50,21.5,22,21.8,34.7,32.8,46.5,43.2,62.9,62.4,75.9,76.4,67.4,etc
00:02:00,27.7,22.8,23.2,41.7,35.1,36.4,53.5,51.4,61.6,64.8,64.3,64.5,etc
00:02:10,2.3,19.2,22.1,41.4,33.1,36.4,53.8,47.6,66.4,66.2,76.4,64.1,etc
00:02:20,22.5,20.8,32,32.7,37.8,47.2,49.3,61.1,71,75.1,73.4,73.9,59.2,etc
00:02:30,22.3,22.1,26.6,30.3,39.2,41.9,51.2,44,61.2,67.7,64.8,77.5,59,etc
00:02:40,22.8,28.3,19.3,30.6,40.1,45.4,47.8,52.5,66.7,70.4,74.8,66.5,etc
00:02:50,20.9,20.6,28,29.3,43.4,43.8,47.1,63,64.5,74,72.5,65.4,62.6,etc
00:03:00,22,23.4,23.5,24.3,37.2,46.2,42.3,59.4,65.7,64,73.4,78,62.9,etc
00:03:10,20.8,20.3,2.3,32.7,34.7,45.8,51.7,45.4,63.2,78.1,65.9,62,etc
.......
.......
.......
23:58:50,20.7,20.6,28.9,31.9,38.1,42.8,51,53.5,48.1,81.7,66.5,79.6,etc
23:59:00,23.4,2.3,35.2,24.6,43.4,43.2,49.8,48.8,59.7,72.6,73.2,73.1,etc
23:59:10,22,24.3,2.3,27.1,37.7,43.8,33.6,51.7,58,66.4,78.4,64.3,51.6,etc
23:59:20,21.8,2.3,22.2,30.2,48.3,34.8,57.9,58.5,71.7,73.2,66.8,72.9,etc
23:59:30,20.7,20.9,32,33.3,41.2,46.5,41.7,37.9,72.2,66.9,74.6,61.8,etc
23:59:40,2.3,22.1,20.5,43.2,34.1,42.2,42.2,53.4,58,71.1,78.3,74.9,etc
23:59:50,2.3,20.5,20.2,33,40.5,40.6,51.9,55.2,66.5,50.4,65.3,72.6,etc
```

Another possibility to exchange or even to publish data is to use the hyper text mark-up language (HTML).

Bibliography

SPAULDING, A. D. & HAGN, G. H. [1977] *On the Definition and Estimation of Spectrum Occupation* IEEE, Vol. EMC-19, No. 3, Aug 1977

ITU-R Recommendations

NOTE – In every case the latest edition of the Recommendation is encouraged to be used.

Recommendation ITU-R SM.182* – Automatic monitoring of occupancy of the radio-frequency spectrum.

Recommendation ITU-R SM.1536* – Frequency channel occupancy measurements.

Recommendation ITU-R SM.1753 – Method for measurements of radio noise.

Recommendation ITU-R SM.1793* – Measuring frequency channel occupancy using the technique used for frequency band measurement.

Recommendation ITU-R SM.1809 – Standard data exchange format for frequency band registrations and measurements at monitoring stations.

**Note by the Secretariat*: This Recommendation has been suppressed and replaced by Recommendation ITU-R SM.1880 – Spectrum occupancy measurements.

4.11 Coverage measurements

4.11.1 Introduction

Monitoring services have to measure the coverage of radio transmitters and networks for different purposes:

- To verify predictions of computerised tools used for the planning of the network.
- To verify compliance with license conditions if part of the license is that a certain area, percentage of an area or percentage of the population is covered by the radio service.
- To verify the quality of service in a given area.
- To assess the receiving conditions at certain locations where interference is reported.

In analogue modulated systems it may be sufficient to measure the field strength. Due to certain circumstances and principles inherent in the reception of digitally modulated systems, the coverage of digital terrestrial networks has to be measured differently from analogue networks.

This text describes the measurement principles, procedure and necessary equipment for fixed and mobile coverage measurements of radio transmitters and networks. However, it may be necessary to adapt the information provided to the requirements of the individual system or to the individual license conditions.

4.11.2 Coverage prediction

Coverage prediction is a procedure to calculate the geographical area inside which reception of the service is possible. It is based on transmitter parameters, terrain and propagation models and is done with computerised tools. The result represents a defined location and time probability.

For example, a certain area is regarded as being "covered" by DVB-T, when the median field strength for the particular receiving situation in a specified height above ground (often 10 m) and the protection ratio reach or exceed the values given in the relevant planning documents (e.g. the GE06 Agreement).

The assumption of a certain area to be covered or not is a result of the calculation process done with a coverage prediction tool that takes into consideration defined conditions and/or values for:

- the receiving condition (e.g. fixed or portable reception);
- the field-strength loss with distance due to topography and morphology;

– the receiver model (e.g. sensitivity and selectivity);
– the receiving antenna (height, gain and directivity);
– the reception channel (Gaussian, Rice or Rayleigh).

Attached to the attribute “covered” is also a certain probability in time and location. Using planning tools, the coverage area is calculated for this probability (e.g. 50% of the time and 50% of the locations). It can therefore not be assumed that reception with a standard receiver is possible at every single location inside the area defined as being covered.

It is important to define coverage of a certain network comprehensively and unambiguously before issuing the license. Otherwise unpleasant discussions may follow if no agreement about the actual coverage is found between the network operator and the regulatory authority.

4.11.3 Basic measurement principle

Usually it is not possible to measure the field strength or other relevant parameters at all points of the area of interest. Actually the conformity of the prediction with the actual coverage is measured rather than the coverage itself.

Normally in analogue systems the field strength is measured at a statistically sufficient number of fixed locations or travelling along routes. The limiting factors are the accessibility of the measurement points and the available time and working hours. The measured values of the field strength are then compared with predicted field strength values.

The same principle is applicable for system specific parameters or quality of service parameters in digital systems. It should be noted that complex coverage definitions result in complex measurement and evaluation procedures.

Recommendation ITU-R SM.1875 on DVB-T coverage measurements and verification of planning criteria adapted from the GE06 Agreement can be cited as an example of complexity.

Before the measurements can be carried out, reference areas or reference routes have to be defined allowing the extrapolation of the measurement results obtained in the reference area to the coverage throughout the whole area of interest.

In other words, if the predictions closely match the actual coverage in the reference areas, it can be assumed that the coverage predictions claimed by the network operator are also sufficiently accurate outside of the reference routes and areas.

There are several options how the measurement routes can be planned. One option would be to follow radials starting in the centre of the service area and until the signal is consistently degraded beyond specified parameters in terms of field strength or other relevant parameters.

Another option would be to check regions which represent specific types of areas as high densely populated urban, suburban, industrial or rural areas.

Finally, for the verification of the coverage it is important that the measurements include areas at the borders between covered and uncovered regions.

Figure 4.11-1 is an example of results obtained from those measurements.

Green indicates coverage and red indicates no coverage. The grey area should be covered according to the prediction tool, whereas the white areas were predicted as not covered.

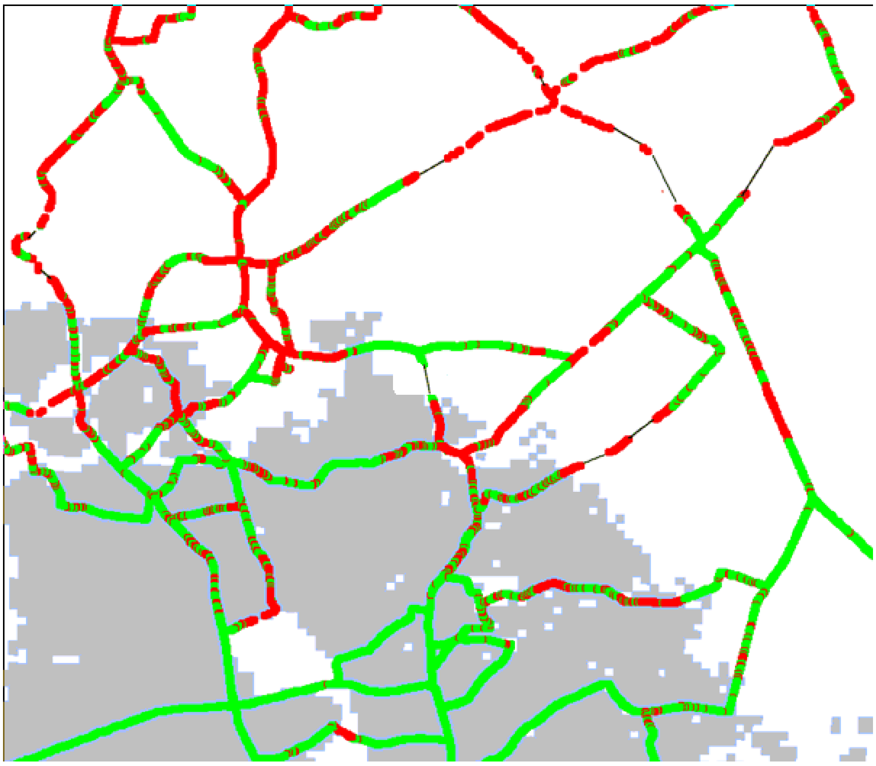
For special purposes affecting coverage, measurements may be carried out on bridges, in tunnels, near power distribution infrastructure or even in buildings.

4.11.4 Measurement setup

The measurement setup usually consists of an antenna, a receiver, a positioning system and a computer. The computer is used to assist the measurements by controlling the measurement receivers and by recording the measurement data and positioning data together with additional system specific data as appropriate.

FIGURE 4.11-1

Sample measurement along a route inside a reference area



Spectrum-4.11-01

There are two basic alternatives for the measurement setup. The first option would be to use reference terminal equipment and the other option would be using standard monitoring equipment.

The use of reference terminals might provide only limited results since they merely indicate the behaviour of that very piece of equipment in the given environment. Parameters as the sensitivity of the receiver may not be known and therefore different from parameters assumed by the prediction tool.

On the other hand, such results might provide valuable information about network characteristics and quality of service by representing the user's perception of the network.

Simultaneous use of more than one terminal including different models may be considered to improve the reliability of such measurements or in order to investigate the coverage for different type of terminals such as automotive receivers, handheld and portable devices.

The other alternative, the use of standard monitoring equipment, can be used to evaluate technical parameters such as field strength. This should preferably be done under the same receiving conditions as assumed in the planning tool allowing further comparison between measurements and predictions.

The antenna is normally mounted on the roof of smaller vehicles for the coverage measurement of mobile reception whereas measurements in 10 m height may be appropriate for the determination of the coverage of broadcasting transmitters.

A receiver or spectrum analyzer is used to provide field strength values for measurements in analogue networks. They are further used to identify any interference that could impede correct measurements.

The positioning system consists of a GPS receiver or a dead reckoning system. Such systems are used to track the vehicle's movement based on an odometer and compass when the GPS signal is lost, e.g. in a tunnel.

For coverage measurements in digital system, specific receivers have to be used. They provide specific parameters such as Bit Error Rate (BER) and other quality parameters like dropped calls as an example.

4.11.5 Parameters to be recorded for coverage measurements

The parameters that have to be recorded very much depend on the purpose of the measurements. The formal verification of license parameters may require other parameters to be measured and recorded compared to the network evaluation from a user's perspective.

In the framework of spectrum monitoring, it is desirable that intrinsic parameters of the signal and its impact on the spectrum are measured. These parameters may be:

– field strength;

– signal to noise ratio;

– adjacent channel noise level.

Additionally to these parameters, the context (e.g. environment) of the measurement should also be recorded and some information like co-ordinates and time stamps of the measurements or specific events like interference and environmental information (rural areas, tunnels, high buildings nearby etc.) should be reported.

As explained in the § 4.11.4, coverage measurement on specific services may require the measurement of some additional parameters in order to assess the quality of service.

As an example, the following parameters could be measured in the case of measurement done on a mobile communication network:

– bit, block and/or modulation error rates;

– start time and duration of a call;

– times of network access and disconnection;

– overstepping and shortfall of a specified data rate;

– number of dropped calls;

– number of blocked calls.

Moreover each network has its specific parameters to assess the coverage. For example, RxQual and RxLev are important parameters of a GSM networks and for UMTS networks different parameters in the code domain as the RSCP (Received Signal Code Power) and the RSSI (Received Signal Strength Information) are important.

4.11.6 Verification of coverage

Special software including a GIS (Geographic Information System) is required to present the measured values together with the geographical coordinates of the measurement vehicle in a map and to compare them with the coverage prediction.

Coverage results obtained along routes may be extrapolated to forecast the coverage of an area. They may also be combined with data from other sources, e.g. resulting in a statement of the coverage expressed in percentage of the population.

References

GE06 Agreement – The Final Acts of the Regional Radiocommunication Conference for planning of the digital terrestrial broadcasting service in parts of Regions 1 and 3, in the frequency bands 174-230 MHz and 470-862 MHz (RRC-06), contain the Regional Agreement GE06, adopted by RRC-06, which governs the use of frequencies by the broadcasting service and other primary terrestrial services in the frequency bands 174-230 MHz and 470-862 MHz. They also contain frequency assignment and frequency allotment plans for the digital broadcasting service (television and sound), the analogue

television plan applicable in the transition period, the coordinated list of assignments to other terrestrial primary services in these bands, and the Resolutions adopted by RRC-06. The GE06 Agreement is provisionally applicable as from 17 June 2006.

See at: http://www.itu.int/publ/R-ACT-RRC.14-2006/en.

ITU-R Recommendations

NOTE – In every case the latest edition of the Recommendation is encouraged to be used.

Recommendation ITU-R SM.1875 – DVB-T coverage measurements and verification of planning criteria.

4.12 Unwanted emission measurements

4.12.1 Introduction

The measurement of unwanted emission is a common task for monitoring services. On the one hand, the goal of such measurements may be to check the conformity of an emission compared to an emission mask provided in a standard or a recommendation. On the other hand, such measurements could be required in the case of an interference caused by an unwanted emission.

Unwanted emissions are emissions out of the necessary bandwidth of a signal which include out of band emissions and spurious emissions.

Measurements of unwanted emissions may be difficult to carry out due to the fact that they require measurement equipment with extremely high dynamic range. According to the system to measure, ITU-R Recommendations and relevant system standards describe requirements for the optimum setup of the measurement.

4.12.2 Definitions and terminology

The following terms and definitions are extracted from the RR Edition 2008.

"1.144 *out-of-band emission:* Emission on a frequency or frequencies immediately outside the necessary bandwidth which results from the modulation process, but excluding spurious emissions."

"1.145 *spurious emission:* Emission on a frequency or frequencies which are outside the necessary bandwidth and the level of which may be reduced without affecting the corresponding transmission of information. Spurious emissions include harmonic emissions, parasitic emissions, intermodulation products and frequency conversion products, but exclude out-of-band emissions."

"1.146 *unwanted emissions:* Unwanted emissions consist of spurious emissions and out-of-band emissions."

"1.146A *out-of-band domain (of an emission):* The out-of-band domain is the frequency range, immediately outside the necessary bandwidth but excluding the spurious domain, in which out-of-band emissions generally predominate. Out-of-band emissions, defined based on their source, occur in the out-of-band domain and, to a lesser extent, in the spurious domain. Spurious emissions likewise may occur in the out-of-band domain as well as in the spurious domain."

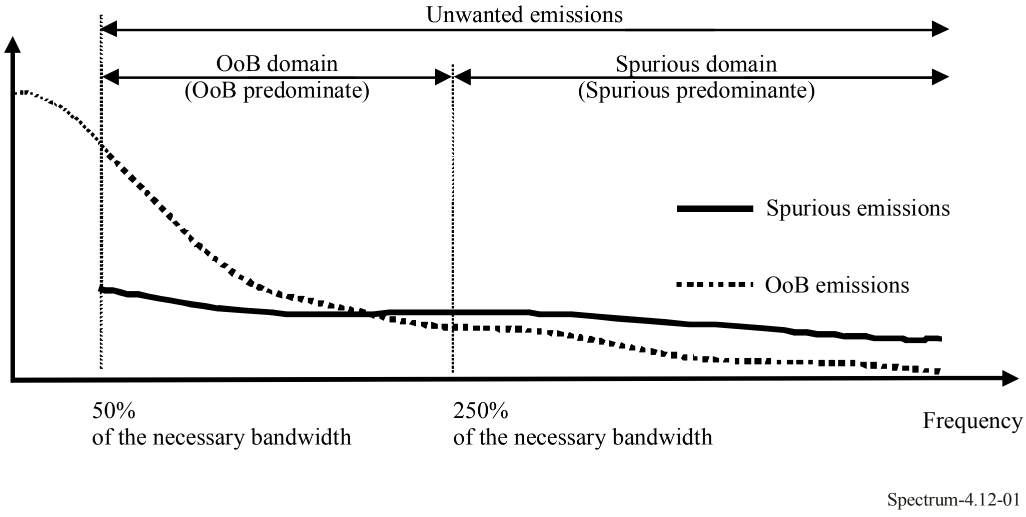
"1.146B *spurious domain (of an emission):* The spurious domain is the frequency range beyond the out-of-band domain in which spurious emissions generally predominate."

"1.152 *necessary bandwidth:* For a given class of emission, the width of the frequency band which is just sufficient to ensure the transmission of information at the rate and with the quality required under specified conditions" is the necessary bandwidth."

Figure 4.12-1 illustrates those definitions. The boundary between the out-of-band and the spurious domain is provided for information (250% is commonly used for radar systems for example).

FIGURE 4.12-1

Illustration of the OoB and spurious domain



4.12.3 Frequency ranges of unwanted emissions

Unwanted emissions are divided into two domains:

– Out-of-band domain;

– Spurious domain.

To distinguish the two domains, the boundary between them should be defined. Some guidelines are provided in Recommendation ITU-R SM.1539: Tables 1 and 2 of Annex 1 provide values to assess the frequency separation between the centre frequency of the signal and the boundary between out-of-band and spurious domain. This frequency separation is defined by two thresholds which depend on the nature of the signal (narrowband (B_L) and wideband (B_U) emission). Practically, for very narrowband emissions, the out-of-band domain is relatively wider compared to the necessary bandwidth (where the boundary to the spurious domain starts at an offset of 2.5 times the necessary bandwidth). Inversely, if the emission is very wide, the out-of-band domain is also narrower compared to the necessary bandwidth.

When the boundary between OoB and spurious domain is determined, the frequency range of the measurement should be defined. Measurements of unwanted emissions have to be carried out covering a wide frequency range. The following table is extracted from Recommendation ITU-R SM.329 and provides the frequency range to analyse according to the frequency of the fundamental of the signal.

TABLE 4.12-1

Frequency range for measurement of unwanted emissions

Fundamental frequency	**Frequency range for measurements**	
	Lower limit	**Upper limit**
9 kHz-100 MHz	9 kHz	1 GHz
100 MHz-300 MHz	9 kHz	10th harmonic
300 MHz-600 MHz	30 MHz	3 GHz
600 MHz-5.2 GHz	30 MHz	5th harmonic
5.2 GHz-13 GHz	30 MHz	26 GHz
13 GHz-150 GHz	30 MHz	2nd harmonic
150 GHz-300 GHz	30 MHz	300 GHz

Note that the measurement should include the entire harmonic band and not be truncated at the precise upper frequency limit stated

4.12.4 Measurements in the spurious domain

Usually spurious emissions are weak signals and equipment has to fulfil stringent requirements to measure them. The general approach is to attenuate the main signal with the use of filters as much as possible and scan the required frequency range (see Table 4.12-1) with the measurement bandwidth stated in the relevant Standard or Recommendation. Usually this frequency range is far too wide to record it in one single step (e. g. one sweep with an analyzer). Modern spectrum analyzers display the spectrum using a raster scan LCD. Characteristic for these displays is that the number of pixels in the level axis as well as in the frequency axis is limited. This leads to limited resolution for both level and frequency. The limited frequency resolution may cause a loss of signals on screen, when measuring wide frequency ranges with narrow resolution bandwidths (narrower than one pixel). Some equipment allows that the number of sweep points may be specified by the user. The higher the displayed point number the higher is the frequency resolution of the measurement.

However, a number of points higher than the screen resolution do not show all results on the built-in screen. The increased frequency resolution is only usable if the trace data is exported and post-processed by software.

In most cases, multiple measurements have to be performed, each one covering a certain part of the total frequency range.

4.12.5 Measurements in the out-of-band domain

For most of the services, the result of the measurement of unwanted emissions is either expressed as the mean power (r.m.s.) emitted in channels other than the assigned channel, or in spectrum power density (or the power of discrete components) at frequencies above and below the limits of the necessary bandwidth. To determine the conformance of a signal regarding the out-of-band emissions, two different types of measurement could be defined:

– the adjacent channel and alternate adjacent channel power method;

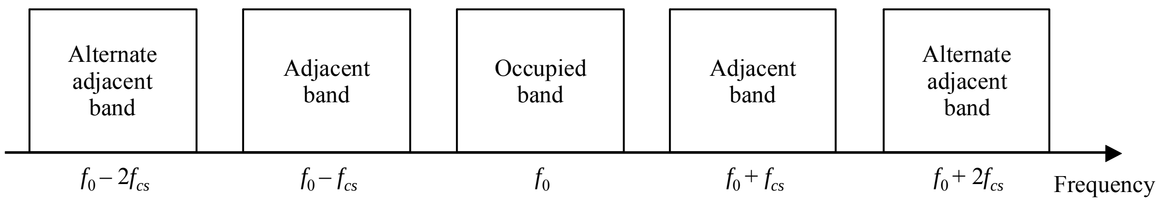
– the spectrum mask method.

4.12.5.1 Adjacent channel power measurements

This method consists in measuring the mean power of a signal in bands illustrated in Fig. 4.12-2.

FIGURE 4.12-2

Power measurements bands



f_{cs}: Spacing between assigned frequencies.

Spectrum-4.12-02

This measurement is most commonly performed using a spectrum analyzer. Most modern analyzers have a built-in measurement function that measures the in-band power and the power in neighbouring channels at the same time. The channel bandwidth and channel spacing has to be entered manually. Their values can be taken from the relevant standard, national or international channelling plans, whichever is applicable to the service. In some systems, the channel spacing is wider than the channel bandwidth (guard bands), but most analyzers allow to enter them separately.

The mean powers of the requested channels are measured by integrating the spectral power density in each channel separately after the total spectrum has been recorded with a relatively narrow resolution bandwidth (RBW). As a rule of thumb, the optimum RBW is about 1/100 to 1/500 of the total span. Care must be taken not to use the peak detector for this measurement.

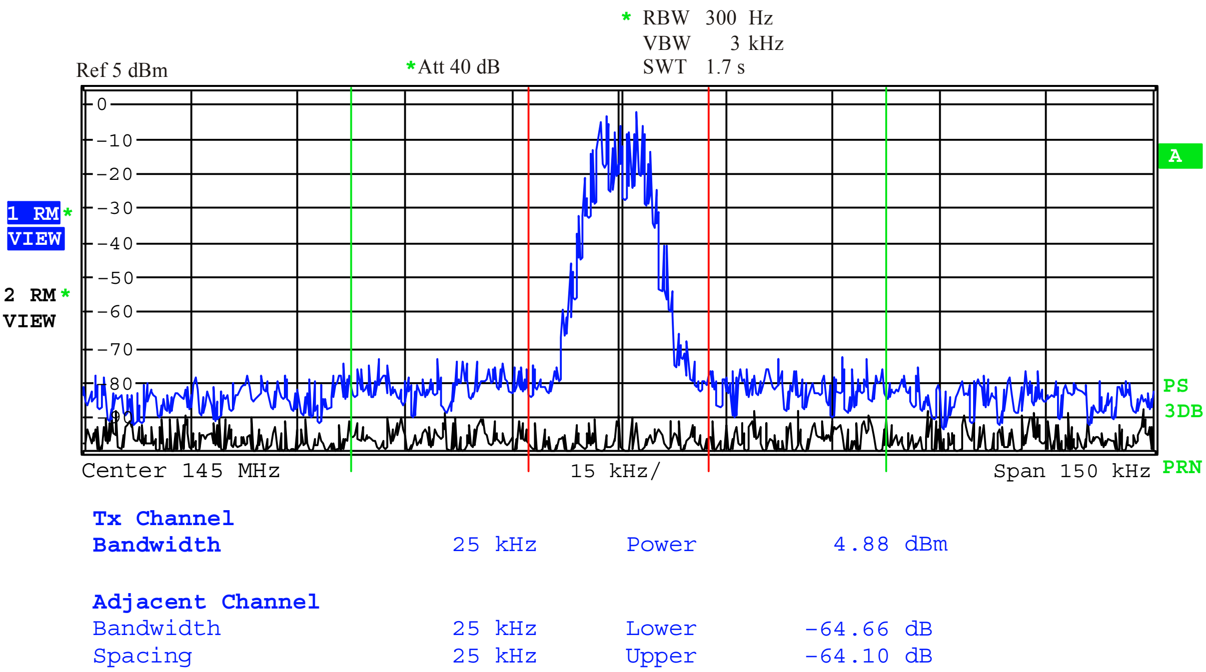
In most of the services, depending on the measurement equipment, the sample or RMS detector has to be used and the trace mode must be clear/write. Without additional functions such as a "gated trigger", this measurement can therefore only be used with continuous emissions and is not possible with TDMA systems. However, it should be noted that some systems (as radars for example) require that the measurement is performed with a peak detector and the maxhold trace.

The most common practical problem occurring in this measurement is that the power in the adjacent or alternate channels is below or close to the noise floor of the measurement receiver/analyzer. To ensure that the result is valid, a preliminary measurement with the transmitter switched off should be made, using the same equipment settings as for the actual measurement. The displayed adjacent and alternate channel powers are noted. The actual measurement is valid if the adjacent and alternate channel powers with the transmitter switched on are at least 10 dB above the values of the preliminary measurement.

Figure 4.12-3 gives an example of the adjacent channel power measurement of an Amateur station. The lower trace is the system noise level (DANL) when the transmitter under test is switched off.

FIGURE 4.12-3

Adjacent channel power measurement example



Spectrum-4.12-03

4.12.5.2 Spectrum mask measurements

This method may be applied for OoB or spurious emissions. It is based on the comparison of the spectrum power density of an emission in a certain measurement bandwidth with a spectrum mask provided in recommendations or standards.

Strictly taken, this method only works if a continuous relative spectrum mask using the same reference bandwidth is defined. In many standards, however, the out-of-band limits are given as a mixture of absolute and relative levels. This is to ensure that the maximum radiated power in adjacent bands does not exceed certain values, regardless of the total power radiated by the transmitter. In these cases, a mask used to compare the measured spectrum with has to be calculated first (using relative levels). This mask, however, is then only valid for a certain output power of the transmitter.

Many standards apply different reference bandwidths for different parts of the OoB spectrum. In these cases, the spectrum mask method will not produce accurate results according to the standard. However, because emissions in the out-of-band domain usually have a continuous spectral density distribution (i. e. no distinct frequencies), the method can still be applied with reasonable accuracy if the calculation of the relative spectrum mask includes the necessary bandwidth correction.

Example:

The ETSI Standard EN 125 101 for UMTS user equipment (UE) may serve as an example to illustrate the calculation of a spectrum mask. In this standard, the mask requirements are a mixture of absolute and relative levels. Furthermore, two different reference bandwidths are defined. Table 4.12-2 contains the relevant table from this Standard.

TABLE 4.12-2

Spectrum emission mask requirements for UMTS user equipment

Δf (MHz) (Note 1)	**Minimum requirement (Note 2) Band I, II, III, IV, V, VI**		**Additional requirements Band II, Band IV and Band V (Note 3) (dBm)**	**Measurement bandwidth (Note 6)**
	Relative requirement (dBc)	**Absolute requirement (dBm)**		
2.5-3.5	$\left\{-35-15\cdot\left(\frac{\Delta f}{\text{MHz}}-2.5\right)\right\}$	–71.1	–15	30 kHz (Note 4)
3.5-7.5	$\left\{-35-1\cdot\left(\frac{\Delta f}{\text{MHz}}-3.5\right)\right\}$	–55.8	–13	1 MHz (Note 5)
7.5-8.5	$\left\{-39-10\cdot\left(\frac{\Delta f}{\text{MHz}}-7.5\right)\right\}$	–55.8	–13	1 MHz (Note 5)
8.5-12.5	–49 dBc	–55.8	–13	1 MHz (Note 5)

NOTE 1 – Δf is the separation between the carrier frequency and the centre of the measurment bandwidth.

NOTE 2 – The minimum requirement for bands I, II, III, IV, V and VI is calculated from the relative requirement or the absolute requirement, whichever is the higher power.

NOTE 3 – For operation in band II, Band IV and Band V only, the minimum requirement is calculated from the minimum requirement in Note 2 or the additional requirement for Band II, whichever is the lower power.

NOTE 4 – The first and last measurement positon with a 30 kHz filter is at Δf equals to 2.515 MHz and 3.485 MHz.

NOTE 5 – The first and last measurement positon with a 1 MHz filter is at Δf equals to 4 MHz and 12 MHz.

NOTE 6 – As a general rule, the resolution bandwidth of the mesauring equipment should be equal to the measurement bandwidth. However, to improve measurement accuracy, sensitivity and efficiency, the resolution bandwidth may be smaller than the measurement bandwidth. When the resoluton bandwidth is smaller than the measurement bandwidth, the result should be integrated over the measurement bandwidth in order to obtain the equivalent noise bandwidth of the measurement bandwidth.

Using the information in the Table above, the spectrum mask for a UE with a maximum power of +24 dBm in the UHF band I is to be calculated. The bandwidth of the UMTS emission is 3.84 MHz. The power reference for the spectrum mask is the total r.m.s. level (+24 dBm), but the break points at the boundary of the out-of-band domain (fc +/–2.5 MHz) are referenced to a measurement bandwidth of 30 kHz, which means the mask starts at a an absolute level of:

24 dBm +10*log(30 kHz/3.84 MHz) = +3 dBm

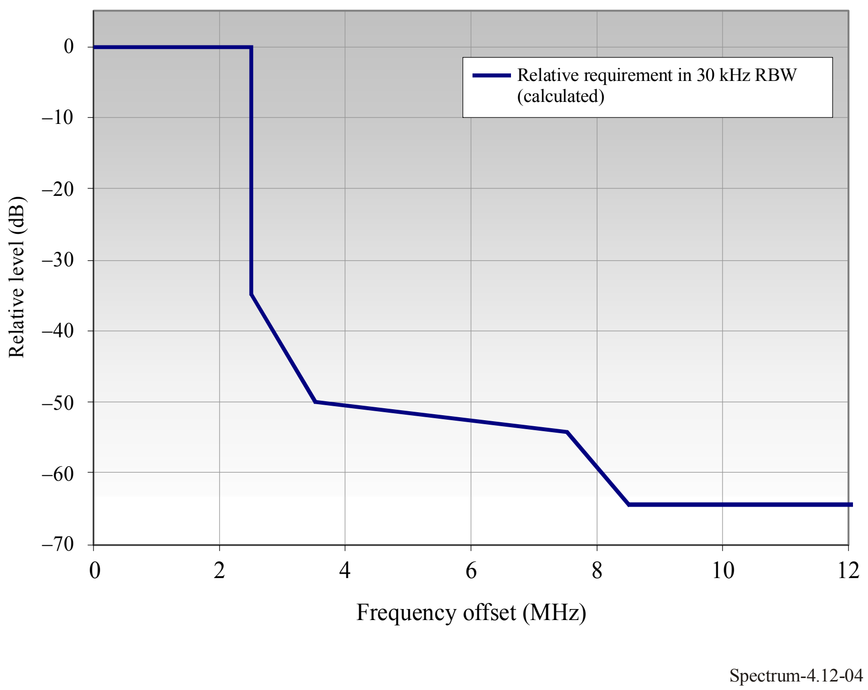
This value marks the 0 dB reference level for the whole spectrum mask. At 2.5 MHz, the mask drops by 35 dB as this is the result of the equation in the column "relative requirement" for 2.5 MHz. Between 2.5 and 3.5 MHz, the mask falls at a rate of 15 dB/MHz down to –50 dBc. At 3.5 MHz offset, the reference bandwidth changes from 30 kHz to 1 MHz. With a measured spectrum, however, the following part of the mask has to be recalculated to 30 kHz bandwidth which means all levels have to be corrected by 10*log(30/1 000) = 15 dB.

So the relative level of the resulting mask at 3.5 MHz offset is –35 dBc –15 dB = –50 dBc, providing a seamless transition from the previous part. The mask then drops with a slope of 1 dB/MHz down to –39 dBc at 7.5 MHz offset and so on. The final level of the column "relative requirement" is –49 dBc at offsets higher than 8.5 MHz. In absolute levels (or spectral power densities), this would relate to +3 dBm –49 dB = –46 dBm in 30 kHz bandwidth.

Part of the absolute limits stated in the next column also has to be bandwidth corrected, so that the results for 30 kHz measurement bandwidth are at a constant –71 dBm for all frequency offsets. However, Note 2 says that if the relative level is higher, the absolute level can be disregarded and vice versa. The additional requirement for band IV calculates up to –28 dBm which in any case is higher than the relative values. Figure 4.12-4 illustrates the resulting spectrum mask which can directly be compared to a spectrum, measured with an RBW of 30 kHz.

FIGURE 4.12-4

Example spectrum mask for UMTS UE

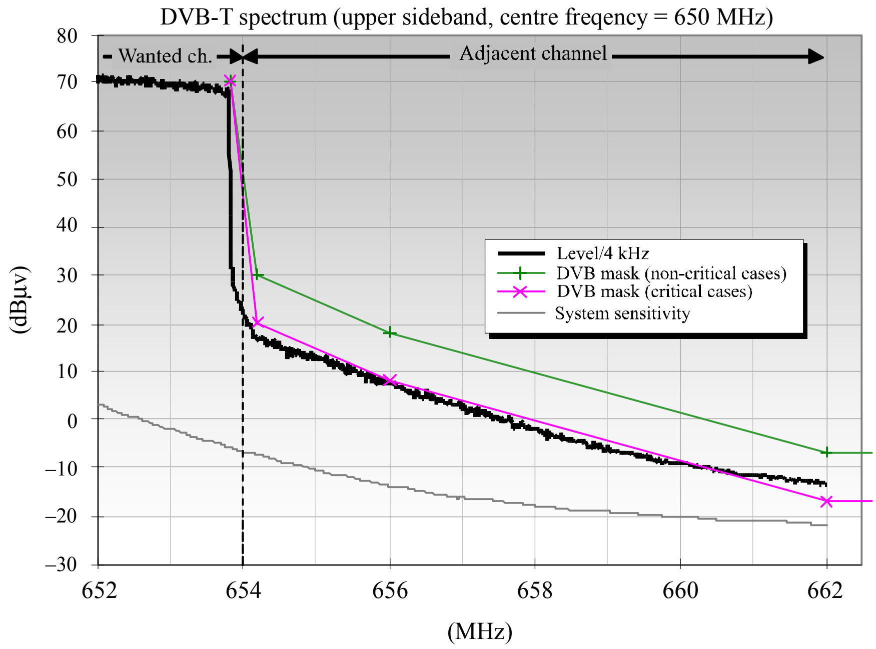


The results of the spectrum mask measurement should be presented in terms of dBsd, dBc or dBpp (see Recommendations ITU-R SM.329 and ITU-R SM.1541).

Figure 4.12-5 shows an example result of an out-of-band emission measurement of a DVB-T transmitter using the spectrum mask method.

FIGURE 4.12-5

Out-of-band emission measurement of a DVB-T transmitter



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4.12.6 Equipment requirements, setup and measurement limitations

The measurements of unwanted emissions require a high dynamic range which might be out of equipment specifications for a given measurement setup. So, to perform such measurement special care should be taken to optimise the measurement setup.

4.12.7 Optimizing the dynamic range of the measurement setup

In order to obtain the maximum dynamic range for unwanted emission measurements, the measurement receiver or spectrum analyzer has to be loaded with the maximum possible level at the input mixer, without compressing the transmit signal. The RF attenuation has to be set to the minimum possible value that does not result in compression of the signal path.

The equipment noise floor is a limitation. The noise floor of a spectrum analyzer or receiver is usually specified as the Displayed Average Noise Level (DANL) in 10 Hz or 1 Hz resolution bandwidth. This characteristic represents the capacity of an analyzer to measure a weak signal and the value of this characteristic limits the minimum of discernible signal on the equipment. The inherent noise power of a spectrum analyzer or receiver is dependent on the resolution bandwidth setting and the reference level setting. The lower the RBW, the lower is the inherent noise power of the analyzer. Nevertheless, the RBW is usually fixed in the relevant Recommendation or standard, in accordance with the type of signal to measure.

4.12.8 Required equipment

The general approach to measure unwanted emissions is the use of a spectrum analyzer. However, measurement receivers may also be used. One practical way, especially for spectrum mask measurements in the out-of-band domain, is a computer controlled scan over the frequency range of interest, using a measurement receiver. The preselection filters usually employed in measurement receivers often provide a higher dynamic range than the use of spectrum analyzers.

To lower the inherent noise power in the unwanted emission measurement, internal or external low noise amplifiers (LNA) may be used. However, the maximum measurable level without overloading the equipment then depends on the capabilities of the LNA rather than the spectrum analyzer or receiver itself. Care must be taken not to overload any component of the measurement system.

If the measurement setup allows a direct measurement with a sufficient dynamic range then the measurement may be carried out directly and the result may be processed without any post-treatment.

In many cases (like in the example of DVB-T in Fig. 4.12-5), the spectrum mask spans a level range of 100 dB or more, or the spurious emissions should be suppressed by 100 dB. Measurements in these domains are only valid when the receiver noise is still at least 10 dB below the weakest signal component to measure. This would require a measurement dynamics of at least 110 dB which is beyond the specification of any spectrum analyzer or receiver. As the input of the spectrum analyzer is loaded with high level of the signal to measure, signal distortion might be observed due to non-linearity in the spectrum analyzer signal path. In particular, well-known spurious products are third order intermodulation products and harmonic distortion products. In these cases, the main signal in the wanted channel has to be suppressed by filters. For frequencies above 1 GHz, YIG filters are most appropriate as they can be tuned electrically and only pass the frequency range currently measured. The unwanted emissions are then measured through the filter and the results are corrected by the (measured) filter attenuation. This is usually done by post-processing software.

Moreover, for any desired signal, where the output amplitude changes with time (e.g. non constant envelope modulation), ten or more averaged measurements may be used for consistency.

4.12.9 Practical aspects of the measurement

Usually the relevant standard or recommendation requires a conducted measurement at the transmitter output. However, if the measurement is performed off air, the results have to be measured as field strength values. This means that different measurement antennas with different correction factors may have to be used. Care should be taken that measurement antennas are only used inside their defined operational range.

One of the main practical problems, especially when performing these measurements off air, is that signals from other transmitters, that cannot be fully suppressed, will be seen in the result. To minimise their influence, two consecutive measurements of each part of the frequency range may be done: during the first measurement the investigated transmitter is switched off, during the second one it is switched on. Emissions showing up in both scans are due to external signals, emissions showing only in the second scan may be due to spurious emissions from the transmitter under test. Considering that even external emissions are not always active, this approach delivers better results if there is less time difference between scan one and two. If the emission from the transmitter under test is pulsed, the pauses can be evaluated to detect external signals. This approach, however, requires that the measurement equipment is time-synchronized with the transmitter under test.

Spectrum mask measurements in the OoB domain are covered in detail in Annex 1 of Recommendation ITU-R SM.1541.

A further example of unwanted emission measurements of radar systems is described in § 5.5.

The measurement of unwanted emissions in the spurious domain is largely covered in Annex 2 of Recommendation ITU-R SM.329.

Bibliography

Application note 1EF45_0E, Rohde and Schwarz, “spurious emission measurements on 3GPP Base Station Transmitters”, 2002

Recommendation CEPT, REC(02)05, “unwanted emissions”.

ITU-R Recommendations

NOTE – In every case the latest edition of the Recommendation is encouraged to be used.

Recommendation ITU-R SM.328 – Spectra and bandwidth of emissions.

Recommendation ITU-R SM.329 – Unwanted emissions in the spurious domain.

Recommendation ITU-R SM.1541 – Unwanted emissions in the out-of-band domain.

Recommendation ITU-R SM.1792 – Measuring sideband emissions of TDAB and DVB-T transmitters for monitoring purposes.

CHAPTER 5

SPECIFIC MONITORING SYSTEMS AND PROCEDURES

Page

5.1 Monitoring of spacecraft emissions

5.1.1 Tasks and measurements to be performed

A monitoring service responsible for the enforcement of domestic laws and regulations and engaged in international monitoring, pursuant to RR Article 16, would normally participate in the monitoring of emissions from space stations as a normal and necessary extension of regular monitoring facilities, techniques and operations.

In general, the tasks carried out by a radio monitoring station for space services do not differ from those of a radio monitoring station for terrestrial services. However, radio monitoring for space services requires the use of relatively more complex measuring equipment, such as more complex antenna systems, as well as differing monitoring and measurement procedures. This is primarily because space stations are located aboard satellites whose positions are time dependent, except for those in tightly controlled geostationary (GSO) orbits. Basic knowledge of the orbits of such objects is an important precondition for any kind of observations and measurements of them.

Because space monitoring differs from terrestrial monitoring in both measurement techniques and terminology, that which provides the space function is known as a “monitoring station for space radio services”. The functions of such a station can be outlined as follows:

– regular and systematic observation of the radio frequency spectrum with the aim of detecting and identifying space station emissions;
– determination of occupancy and percentage use of transponders or space station transmitters;
– measurement and recording of the characteristics of space station emissions;
– investigation and elimination of harmful interference caused by space station emissions, if appropriate, in cooperation with terrestrial and other monitoring stations for space services;
– investigation and elimination of harmful interference to the frequencies used by a space station caused by the emissions of terrestrial stations, unknown earth stations, or other satellites, e.g. by observing and measuring a transponder, interfering signal in a similar manner as for legitimate space station emissions; (see § 5.1.1.1);
– measurements and recordings for technical and scientific projects;
– detection of illicit use of transponders and identification of its source(s);
– using special satellite techniques to locate emitters on Earth;
– pre-launch monitoring, during the pre-phase of the launch of a satellite, to monitor the frequencies used for telemetry, telecommand and tracking with respect to the orbit position. This pre-launch monitoring will facilitate a saver launch and early orbit phase, including position.

If all types of spacecraft have to be observed, the antenna system must be capable of tracking low orbiting and highly elliptical orbiting satellites as well as being able to point accurately at GSO satellites.

Satellite communication is divided in the following radio services:

– *Fixed-Satellite Service (FSS)*

  The FSS comprises all satellite communication services based on fixed infrastructure via private or public networks providing telephony, fax, Internet, video and data services.

– *Broadcasting Satellite Service (BSS)*

  This radio service is mainly used for the distribution of TV and video signals.

– *Mobile Satellite Service (MSS)*

  The MSS services are mainly used for mobile telephony and data services and for navigation and satellite fleet management.

Overall system cost must be balanced against design choices made for the provision of the above-mentioned capabilities: frequency coverage, system sensitivity, antenna slewing rate, antenna pointing accuracy, ease of changing antenna feed hardware if necessary, receiving bandwidth capability, degree of sophistication of signal analysis instrumentation and degree of automation of measurements. A highly automated and sophisticated spacecraft monitoring system, fully steerable, with continuous frequency coverage across the 1-30 GHz spectrum, for example, and sensitive enough to give carrier-to-noise ratios of at least 26 dB on all signals of interest would be ideal. However, as a practical matter in this example, incremental improvements in sensitivity come at costs that rise almost exponentially. Each administration must, therefore, analyze its own priorities and internal needs with regard to spectrum management and decide priorities for monitoring of space services.

Table 5.1-1 provides an overview of factors to consider when conducting monitoring activities involving satellite signals. The table is organized by satellite type and signal path (uplink to satellite, downlink from satellite).

TABLE 5.1-1

Factors to be considered when conducting monitoring activities involving satellite signal

Satellite type	Satellite spacecraft emissions (downlinks)	Satellite earth station emissions (uplinks)
GSO	Monitoring tasks are usually conducted from fixed monitoring stations, due to their superior antenna performance and system sensitivity. The antenna positioning required for GSO satellites is along the equatorial arc only.	Monitoring of emissions from satellite earth stations to GSO satellites, including very small aperture terminals (VSATs) found on many businesses, are accomplished by mobile vehicles operating in the appropriate frequency range. The high directivity of typical satellite earth station antennas requires the measuring equipment to be near the transmitting antenna or somewhere in the main beam.
Non-GSO	Monitoring tasks are usually conducted from fixed monitoring stations with antenna tracking capability (though mobile systems with tracking capability could be used). The monitoring station antenna must continuously track the satellite position based on one of several methods of satellite tracking covered later in the chapter.	Monitoring of emissions from satellite earth stations to non-GSO satellites are accomplished by mobile vehicles. As with the GSO case, the antenna directivity requires the measuring equipment to be near the transmitting antenna or somewhere in the main beam. An additional factor is that the transmitting antenna will be moving to follow the satellite orbit, complicating measurements of amplitude related parameters.

5.1.1.1 Types of measurements

For the satellite monitoring, the following main measurements and determinations are to be carried out:

– Frequency.

– Doppler frequency.

– Power flux-density in reference bandwidth and total.

– e.i.r.p, channel e.i.r.p and carrier e.i.r.p.

– Carrier C/N_0.

– Bandwidth and carrier bandwidth.

– Out-of-band spectrum measurements.

– Transmission characterization.

– Identification of modulation type.

– Spectrum observations recording.
– Fast spectrograms to visualize fast slots drifts and sweeping signals.
– Polarization measurements.
– Satellite orbit position (orbital position accuracy of at least 0.1°).
– Base band characteristics of received signals i.e. BPSK, QPSK, QAM, FDM/FM.
– Received signal-to-noise ratio.

5.1.1.2 Types of interference caused by satellite systems

– Adjacent channel interference.
– Co-channel interference.
– Cross-channel (cross-polarization) interference.
– Adjacent system interference.

These types of interference are produced at the input of the receiving earth station by carriers transmitted by either the satellite of the considered system (consisting of a earth station and satellite) or by a satellite of another system.

Adjacent channel interference

This type of interference is produced by carriers transmitted from the satellite to earth stations in the same system, located in the same spot beam as the earth station under consideration, which is further below in the text referred to as the victim earth station, transmitted at different frequencies but at the same polarization.

In FDMA and TDMA access schemes, these carriers interfere with the victim carrier because of the non-ideal performance of the filter of the transmitted earth station.

Co-channel (co-polarization) interference

Co-channel interference is produced by carriers, transmitted by the satellite to earth stations of the same system, at the same frequency and at the same polarization as the victim carrier.

These interfering carriers are sent to earth stations, located in a different spot beam from the victim earth station in FDMA and TDMA, but they are located in the same spot beam as the victim earth station in CDMA.

In FDMA and TDMA, this interference is limited by the satellite antenna roll of the adjacent spot beam in the direction of the victim earth station where as in CDMA it is limited by code correlation properties.

Cross-channel interference

This type of interference is produced by carriers, transmitted by the satellite to earth stations of the same system, at the same frequency and at the orthogonal polarization as the victim earth station carrier.

These interfering carriers are sent to earth stations located in a different spot beam as the victim earth station if single polarization is used, but to earth stations located in the same spot beam as the victim earth station for dual polarization systems.

For systems with single polarization this interference is limited by the satellite roll of the adjacent spot beam in the direction of the victim earth station and by the isolation in polarization of the satellite antenna. In case of polarization re-use, it is limited by the polarization isolation of both satellite and earth station antennas only.

Adjacent system interference

This inference is produced by carriers transmitted by another satellite to earth stations of another satellite communication system, transmitting at the same frequency and polarization as the victim earth station carrier.

This interference is limited by angular separation of the two satellites from the victim earth position.

5.1.2 Measurement techniques

5.1.2.1 General

The main factors which necessitate different techniques for the monitoring, observation and measurement of emissions from space stations as compared to emissions from fixed or mobile radio stations on or near the Earth are:

– the difference between the received and the transmitted frequency, and the varying nature of the received frequency, caused by the Doppler shift effect, particularly for satellites not in GSO orbit;

– the weak pfd at the Earth receiving point, due to distance and generally low transmitter power;

– the relatively short time that a signal from a near-Earth orbiting satellite is receivable at a fixed monitoring point;

– the continual direction changes that have to be made to highly directional earth station antennas used to receive emissions from space stations not in GSO orbit.

5.1.2.2 Frequency measurements

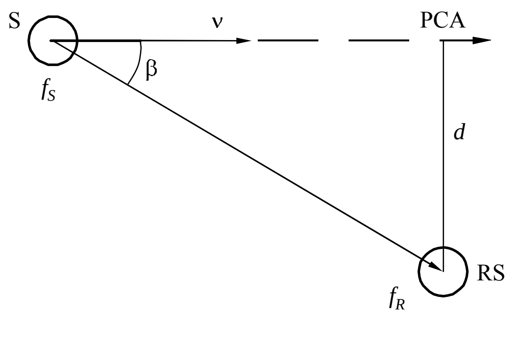
In the case of GSO space stations, the same frequency measurement methods can be applied as are used for terrestrial stations. These methods are discussed in detail in § 4.2.

5.1.2.2.1 The Doppler shift effect

When there is a relative velocity between the transmitting space station and the monitoring station, a difference of frequency proportional to the relative velocity arises between the transmitted and received signal owing to the Doppler shift effect. Equations (5.1-1) and (5.1-2) are derived from Fig. 5.1-1.

FIGURE 5.1-1

Principle relations in case of Doppler shift effect



$$f_R = \frac{c f_S}{c - (v \cos \beta)} \tag{5.1-1}$$

$$\left(\frac{df_R}{dt}\right)_{max} = \frac{f_S}{c} \cdot \frac{v^2}{d} \tag{5.1-2}$$

where:

S: satellite

RS: receiving station

PCA: position of closest approach

f_S: transmitting frequency

f_R: receiving frequency

v: velocity of satellite

d: minimum distance at pass over

c: propagation velocity of electromagnetic waves

β: angle between flight direction and line of sight direction to receive station.

The equations lead to the following findings:

– the received frequency is higher than the source frequency when the satellite is approaching the monitoring station;

– a measured frequency is equal to the correct satellite source frequency only at the time of closest approach (TCA) which coincides with the position of closest approach (PCA);

– during the TCA the maximum rate of change of frequency (MRCF) is to be observed, which gives the slope of the inflectional tangent$(\mathrm{d}f_R/\mathrm{d}t)_{max}$;

– the received frequency is lower than the source frequency when the satellite is receding from the monitoring station;

– the Doppler shift effect is proportional to the satellite's source frequency and depends on the relative velocity between the source and the monitoring station.

5.1.2.2.2 Measurement method

The achievable accuracy of a determined frequency emitted by a satellite depends on satellite orbital parameter, the propagation path, the measuring equipment and the method of evaluation. The measurement of the frequency of a non-GSO orbiting satellite is an indirect procedure, which first requires the registration of the Doppler shift, followed by the evaluation of the Doppler curve.

To obtain adequate measurement an automated measuring method is preferred. See § 5.1.6.1 for details of a possible technical solution.

5.1.2.2.3 Frequency calculation procedure and measurement accuracy

By using graphical methods it is possible to determine the satellite frequency, the TCA and the MRCF (Fig. 5.1-2). The achievable frequency measurement accuracy is $\pm 1 \times 10^{-7}$ Hz.

A modified method enables the degree of accuracy to be improved. By a single differentiation of the Doppler frequency curve with respect to time, a parabola is obtained, the vertex of which indicates the TCA and also the transmitter source frequency of the satellite.

For the construction of the parabola, it is sufficient to utilize the individual measured values within 30 s of the TCA. The time interval between the measured values must be chosen so that the shape of the curve is clearly defined, for example, at least in intervals of 5 s.

With this method and graphical evaluation methods an accuracy of $\pm 5 \times 10^{-9}$ Hz can be obtained if a Caesium type of reference oscillator, or better, is used.

Figure 5.1-3 shows the results of frequency determination performed in this manner.

Instead of time-consuming graphical evaluation methods, a software solution, which can directly process the single frequency measurement results of a frequency counter, would be best.

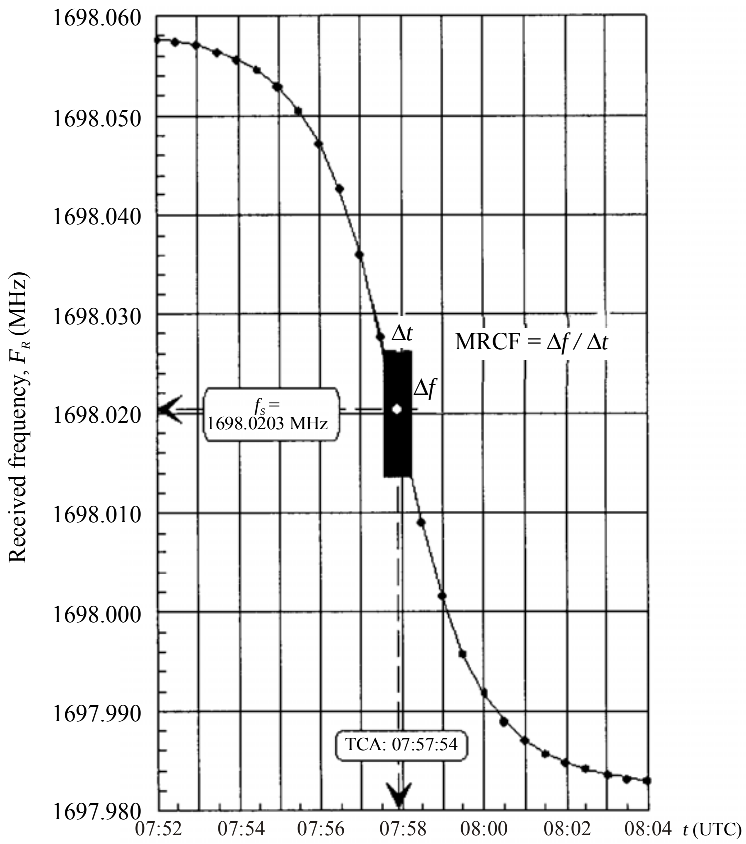
It is obvious that reliable frequency measurements can only be performed if the spectrum contains a characteristic frequency component to which the receiver can be synchronized. This, of course, also applies to the measurement of the frequencies of terrestrial stations.

5.1.2.3 Bandwidth measurements

For bandwidth measurements of GSO satellite emissions the same methods can be applied, in principle, as for measurements of terrestrial emissions. A description of these methods may be found in § 4.5.

FIGURE 5.1-2

Calculation of satellite frequency from Doppler-curve



Spectrum-5.1-02

In cases where there is a relative velocity between the space station and the monitoring station, the apparent transmitted bandwidth as measured at the monitoring station varies because of the Doppler shift effect in the same manner as described for the carrier frequency.

Two factors have to be taken into consideration:

– the entire frequency spectrum drifts during the time necessary for the bandwidth measurement;

– the frequency shift is slightly greater for signal components near the upper edge of the spectrum of the emission than for those near the lower edge. This difference could amount to hundreds of hertz for wide bandwidths. The effect causes the apparent bandwidth, as observed at the monitoring station, to vary slightly.

Automatic frequency control at the monitoring receiver can compensate for Doppler frequency shift of an emission. In this case, the normal measuring methods used to determine the bandwidth at terrestrial monitoring stations can be applied without radical changes.

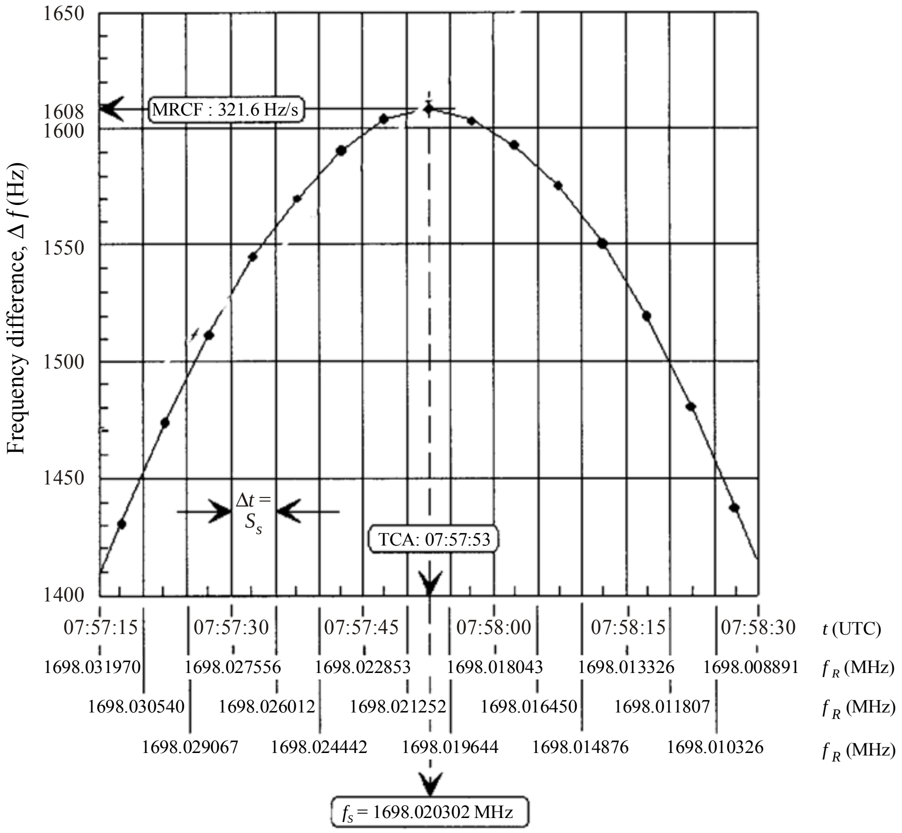
If the received signal is very weak, it is possible to ensure automatic correction of the receiver oscillator's frequency by using, as a reference signal, a carrier or pilot frequency emitted by the space station which is filtered by an extremely narrow bandpass filter.

If the monitoring station for space services does not possess appropriate receivers with automatic frequency control, account must be taken of the frequency shift of the space station during the measurement, if necessary, by making a simultaneous Doppler frequency measurement when determining the bandwidth.

It may also be necessary to make a simultaneous recording of the PFD so that the effect of PFD variations occurring during the analysis of the spectrum may be eliminated from the calculations.

FIGURE 5.1-3

Calculation of satellite frequency by differentiation of the Doppler-curve



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5.1.2.4 Power flux-density measurements

5.1.2.4.1 Measurements in a reference bandwidth

The coordination and successful operation of space stations requires that given maximum values of pfd be not exceeded on the surface of the Earth by emissions from a space station, including emissions from a reflecting satellite.

The values for individual frequency bands, space services, angles of arrival, and sharing conditions are given in RR Article 21, Section V which should be available at the space monitoring facility.

The pfd in dB(W/m^2) is related to a particular bandwidth, in general to 4 kHz, 1 MHz, or 1.5 MHz, depending on the frequency of the fundamental emission.

The indication of the reference bandwidth (RBW) is essential because the radiated power is normally not concentrated at a single frequency but is distributed within a band of frequencies.

5.1.2.4.2 Measurement of total pfd

In this case, the pfd is fully determined on the basis of the bandwidth occupied by an emission.

The bandwidth of the measurement filter should be selected accordingly. Such measurements are significant if, for example, the e.i.r.p. of a space station is to be calculated.

For frequency bands below 13 GHz, and provided that clear-sky conditions prevail, the total atmospheric loss may be taken as 0.1-0.2 dB for the calculations.

5.1.2.4.3 Measurement procedure

Whether the power flux-density in the reference bandwidth or the total power flux-density is to be measured, it is preferable to determine the pfd by a direct power measurement, especially at frequencies above about 1 GHz.

When this method is used, the pfd can be determined by equations (5.1-3a) and (5.1-3b):

$$pfd_{RBW} = P_{SYS} - 30 - A_e - K_{BW} + K_{POL} \tag{5.1-3a}$$

$$pfd_{TOT} = P_{SYS} - 30 - A_e + K_{POL} \tag{5.1-3b}$$

where:

- pfd_{RBW}: pfd in reference bandwidth (RBW) (dB(W/m^2))
- pfd_{TOT}: pfd in bandwidth occupied by emission (dB(W/m^2))
- P_{SYS}: system input power (dBm)
- 30: factor for converting dBm to dBW
- A_e: effective antenna area (see Note 2) (dBm^2)
- K_{BW}: correction factor for measuring bandwidth (see Note 3) (dB)
- K_{POL}: polarization correction factor (see Note 4) (dB).

The pfd value derived from equations (5.1-3a) and (5.1-3b) may be used to calculate the e.i.r.p of the space station by using equation (5.1-4). Knowledge of the slant range to the object at the time of measurement is required for the calculation.

$$\text{e.i.r.p.} = \text{pfd} + 10\log(4\pi d^2) + L_{ATM} \tag{5.1-4}$$

where:

- e.i.r.p.: equivalent isotropically radiated power of space station (dBW)
- pfd: measured pfd (dB(W/m^2))
- d: distance between space station and receiving station (m)
- L_{ATM}: atmospheric loss relative to free space (dB).

NOTE 1 – Input power is measured with a thermal power meter, normally connected to the IF output of the receiver and preceded by a bandpass filter of known effective bandwidth (r.m.s. measurement). The input signal is then substituted by a signal from a calibrated signal generator. Compensation for a possible Doppler shift of the incoming satellite signal should precede the IF output.

NOTE 2 – Effective antenna area (A_e) can be calculated from antenna aperture or gain by using equation (5.1-5):

$$A_e = 10\log(A\eta) = 10\log\left(\frac{\lambda^2}{4\pi}\right) + \ Gi \tag{5.1-5}$$

where:

- A_e: effective antenna area (dBm^2)
- A: antenna aperture (m^2)
- η: efficiency expressed as a decimal
- λ: wavelength (m)
- G_i: isotropic antenna gain (dBi).

NOTE 3 – The bandwidth used for the measurement can be larger than the reference bandwidth, as long as the power is uniformly distributed in the measurement bandwidth. This condition can be checked by spectrum analysis. The measurement bandwidth is the effective bandwidth of the filter, which does not necessarily correspond to its 3 dB or 6 dB bandwidth. The correction factor is calculated by equation (5.1-6):

$$K_{BW} = 10 \log\left(\frac{B_M}{RBW}\right) \tag{5.1-6}$$

where:

K_{BW}: bandwidth correction factor (dB)

B_M: measurement bandwidth

RBW: reference bandwidth with same units as B_M.

NOTE 4 – In the case of matched polarization between the receiving antenna and the received signal, the polarization correction factor, K_{POL} = 0 dB. For linearly polarized reception of a circularly polarized emission or vice versa, K_{POL} = 3 dB.

Since the pfd normally varies not only with frequency but also with time, its maximum value has to be determined. This can be done by recording the output signal of the power meter over a period of time at the frequency of interest. The time constant of the power sensor used will determine the rate of power variation that can be detected. Additional information on the e.i.r.p. calculation may be found in the existing monitoring Handbook

5.1.2.4.4 Measurement uncertainty

The degree of uncertainty for pfd measurements is essentially influenced by three factors:

– antenna gain uncertainty of the receiving antenna;

– uncertainty of the reference signal (power reference generator) for calibrating the measuring receiver/spectrum analyzer;

– precision of antenna pointing/tracking.

Whereas the uncertainty of the reference source may, to a large extent, be controlled and minimized, the actual problem lies in the exact calibration of the antenna gain of the receiving antenna. Larger parabolic reflector systems may only be calibrated after assembly at the place of installation. Accordingly, satisfactory calculation of the antenna gain must account for the specific conditions at the installation site. [Newell *et al.*, 1986] [Newell *et al.*, 1973]; [Satoh and Ogawa, 1982].

The expanded measurement uncertainty (coverage factor 2) should not exceed 2 dB. A reduction in the measurement uncertainty in all frequency bands should be sought.

5.1.2.5 Polarization measurements

Knowledge of the polarization of the satellite signal is essential because the determination of this basic signal characteristic can assist in the identification of unknown emissions. Consequently, a competent antenna system should be capable of distinguishing between different types of polarization.

The technical implementation of polarization measurements has to take into account the widespread use of the dual polarization technique in the frequency bands above 1 GHz which are used by the fixed-satellite service and the broadcasting-satellite service.

To obtain optimized receiving and measurement conditions for the satellite signal in terms of:

– maximum C/N;

– maximum C/I by sufficient polarization discrimination between orthogonally polarized signals.

It should be possible to match the polarization of the receiving antenna at the monitoring station to that of the incoming signal. In the case of dual linear polarization, full steerability of the polarization plane is required. A polarization discrimination of at least 20 dB should be provided.

5.1.2.6 Determination of orbital positions and orbital elements

The determination of orbital positions concerns GSO satellites and the determination of orbital elements concerns non-GSO satellites.

5.1.2.6.1 GSO satellites

A GSO satellite is subject to disturbances which tend to change its position in orbit. These disturbances lead to spurious orbital plane rotation and semi-major axis and eccentricity errors. This resulted in the fact that, as viewed by an observer on Earth, the satellite displays an oscillatory movement with a period of 24 h. This motion (the so-called “figure of eight”) is composed of a North-South component and an in-plane component.

Space stations on board GSO satellites using frequencies allocated to the fixed-satellite or broadcasting-satellite service have to be kept within ± 0.1° of the longitude of their nominal position (see RR Article 22, Section III), except for experimental stations on board GSO satellites which should be kept within ±0.5° longitude, and for the broadcasting-satellite service stations operating in the band 11.7-12.75 GHz which should be kept within the limits specified in RR Appendix 30. Space stations need not comply with these limits as long as the satellite network does not cause unacceptable interference to any other satellite network whose space station complies with these limits. Position determination of GSO satellites is therefore a required task of a monitoring station for space services. The orbital position is usually computed from angle measurements in the azimuth and elevation planes of the receiving antenna. Section 5.1.7.4 illustrates one example of such a measurement.

5.1.2.6.2 Non-GSO satellites

The calculation of orbital elements of a non-GSO satellite (ephemeris data) from measurements of sufficient accuracy is a basic requirement for the:

– identification of an unknown space station (see § 5.1.5);
– investigation of possible reception times;
– predetermination of azimuth and elevation as a function of time, e.g., for computer-controlled antenna steering in cases where officially published data is not available.

A monitoring station for space services making use of passive mode measurements can provide the following timed measurement data:

– azimuth;
– elevation;
– Doppler shift.

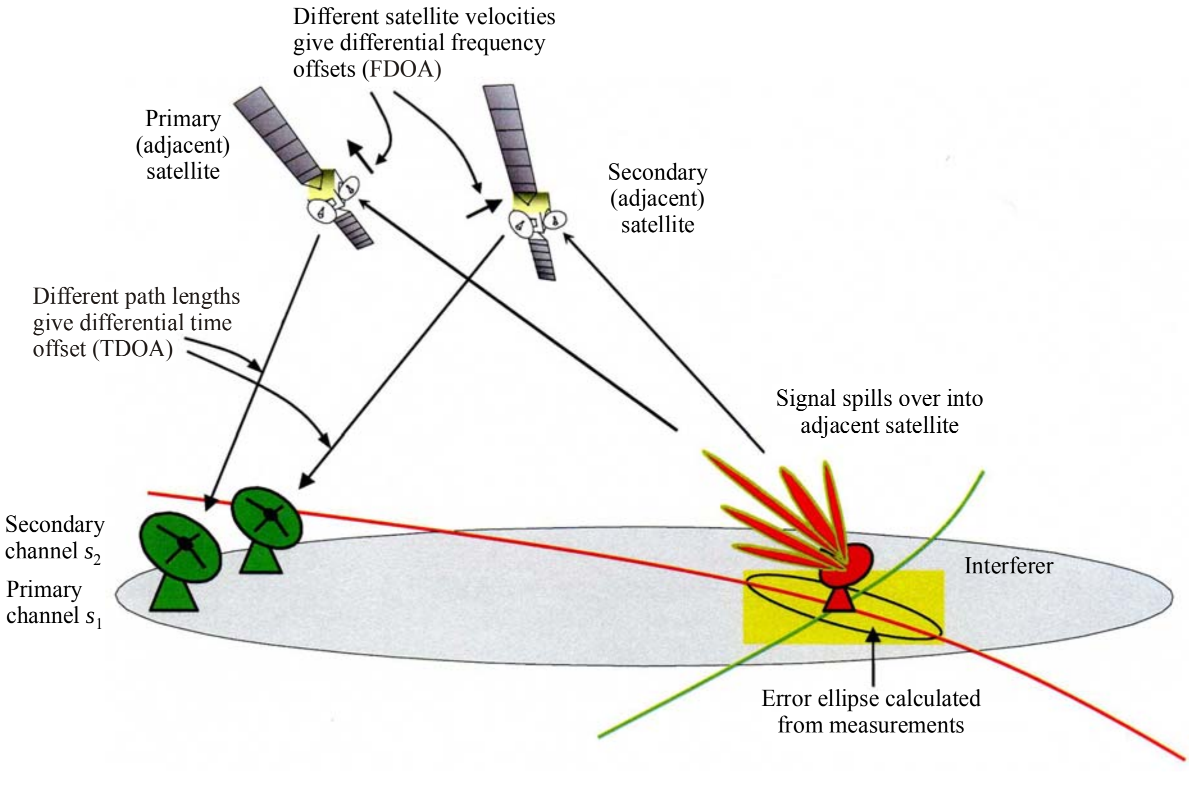
Since orbit determination requires the solving for at least six (e.g. Keplerian orbital elements), multiple measurements of the above-mentioned quantities are necessary. Typically, orbit determinations are the result of a statistical procedure in which the greater the volume of input data leads to improved accuracy of the orbital elements. When monitoring higher frequencies, i.e. above 1 GHz, methods based on the evaluation of angle measurements in the azimuth and elevation planes are preferred due to the narrower beamwidth of the receiving antenna at these frequencies.

5.1.2.7 Geolocation of transmitters on Earth using time and frequency difference measurements from two GSO satellites

Sources of interference located on Earth can affect the up-link signal received at the satellite. The receiver of the wanted signal perceives the interference as an interference of the downlink. Geolocation of radio transmitters affecting communication satellites in GSO orbit is a challenging task which is usually accomplished through analysis of time difference of arrival (TDOA) and frequency difference of arrival (FDOA) compound measurements. Both of these measurement types require that the transmissions be monitored through a second GSO satellite that lies within the transmitter beam. The GSO satellite carrying the unknown signal is usually referred to as the “primary satellite” and the above mentioned second GSO satellite as “adjacent satellite”. A TDOA measurement yields the difference in the time the same signal arrives at one ground-based receiver through the primary satellite and another ground-based receiver through the adjacent satellite. An FDOA measurement yields the difference in frequency measured between the signal which separately arrives at the two receivers. Usually, the two receivers are co-located at the same geographic site, but this is not a requirement (see Fig. 5.1-4). In "distributed mode", the two receivers used for geolocation are separated from one another, but are constrained to be within the downlink beam of each space station, respectively. Distributed mode must be used when the downlink footprints are nonintersecting; indeed, these downlinks may be received on different continents. When operating in distributed mode, the raw signal measurements must be transferred to a common location for further geolocation processing.

FIGURE 5.1-4

Geolocation of transmitters on Earth using TDOA and FDOA from two GSO satellites



The arrival time varies because the transmitted signal travels different distances as it passes through the two different satellites to each receiver. The received frequency differs because, generally, there is relative motion between the two satellites causing different Doppler frequency shifts on the transmissions. Although the positions of GSO satellites are loosely described as being fixed at specific positions over the Earth's equator, they actually do move about these nominal positions within certain limits. It is these movements that induce a measurable Doppler shift in the received signals. The received frequencies can also differ as the result of drifts in the oscillators which set the retransmission frequency on the downlink of each satellite.

Single TDOA or FDOA measurements combined with the satellite and ground station configuration each describe different surfaces on which the unknown transmitter must be located. The figure of the Earth (where nearly all transmitters of interest occur) provides a third surface that constrains the unknown's location. The intersection of these three surfaces provides an estimate of the unknown signal from a single pair of TDOA and FDOA measurements. Since measurement or modelling errors can lead to errors in the geolocation, additional TDOA and FDOA measurements combined in a statistical solution can serve to reduce such errors.

5.1.2.7.1 Measuring time and frequency differences

The two time series of the transmitter signal downlinked from each of the two GSO satellites are recorded and analyzed to obtain time and frequency differences between them (i.e., TDOA and FDOA). This is done through the calculation of the cross ambiguity function (CAF) or correlation map in two dimensions. The value of CAF for a given time and frequency difference is the cross-correlation of the two recorded signals. In the special case of continuous wave (CW) emitters, no TDOA measurement can be generated since the two signals correlate for all delay time differences.

The CAF can be visualized in three dimensions where the value of the CAF is a function of both TDOA and FDOA. For the case of a single interference signal in the selected frequency range, the maximum value of CAF with respect to TDOA and FDOA selects those shifts as the TDOA and FDOA values that are presented to the geolocation algorithm that calculates the location of a single transmitter. For a CW emitter, a ridge along a line of constant FDOA is the result. Alternatively, several broadband transmitters from multiple locations will produce multiple CAF peaks. A detailed discussion of algorithms used to calculate and analyze the CAF is given by Stein [1981].

5.1.2.7.2 Geolocation algorithm

The geolocation algorithm often uses TDOA and/or FDOA measurements in an iterative least squares procedure to estimate the location where the transmitted signal originates. In its simplest form, an initial guess of the transmitter location and the given orbits of the two satellites are combined with the physical laws of satellite motion to generate predicted TDOA and FDOA measurements. The difference between the actual and predicted TDOA and FDOA measurement values (the residuals) are used to generate adjustments to the transmitter position. This adjusted transmitter location is used to generate a second set of predicted TDOA and FDOA measurements which imply further adjustments to the transmitter position and so forth. An iterative solution is required because the problem is inherently nonlinear.

Iterations continue until the adjustments in the transmitter position are sufficiently small at which point the geolocation solution is said to have converged.

TDOA and FDOA measurements made over time converge on the transmitter location based on the laws of physics. Additional geolocation solutions are also available for other combinations of measurement types. For example, geolocations of CW emitters are possible from a series of FDOA measurements alone with reduced accuracy over what would have been available with the corresponding TDOA measurements that are accessible from a broadbanded signal. Alternatively, use of a third satellite to generate a second set of TDOA and/or FDOA measurements can also provide improved solutions, however, this comes at the expense of greater use of receiver antenna resources. TDOA-only solutions are possible by the use of a third satellite, but the surfaces of constant TDOA derived from the two satellite pairs are nearly parallel making their practical use more dependent on TDOA measurement precision or more time for gathering measurements.

In practice, the accuracy of the satellite ephemeris of each of the two satellites limits the accuracy of the geolocation solution. Improved geolocation performance is achieved through TDOA and FDOA measurements of separate transmitter signals, sometimes referred to as reference locators, which originate from known locations and pass through the same pair of satellites as the signal of interest. These reference locators are used to refine the orbital ephemeris of one or both of the satellites which, in turn, improves the accuracy of the estimate of the location of the transmitter of the signal of interest.

5.1.2.7.3 Uncertainty analysis

The goal of uncertainty analysis of a geolocation problem is to provide a realistic appraisal of the accuracy of a geolocation solution.

Providing accurate uncertainty analyzes can sometimes be complex and difficult. The precision of the individual TDOA and FDOA measurements are both proportional to the square root of the signal-to-noise ratio obtained in the correlation solution. The precision of TDOA and FDOA measurements are also proportional to the signal bandwidth and measurement time, respectively. The least squares geolocation solution provides formal error estimates and confidence intervals of the location of the transmitter of interest that are based on the uncertainties assigned to the TDOA and FDOA measurements. The reliability of these

TDOA and FDOA uncertainties can be checked statistically against their corresponding measurement residuals. Alternatively, if a sufficient number of TDOA and FDOA measurements are available, the uncertainties in the TDOA and FDOA measurements can be estimated by the same solutions procedure. An example error analysis is given by Bardelli *et al.* [1995].

Two caveats must also be given. First, the uncertainties in the TDOA and FDOA measurements may be large enough so as to invalidate the assumption that the solution is linear in the spanned region of parameter space.

This means that the formal errors generated by the geolocation algorithm that are based on linearized statistical analysis are less accurate. Monte Carlo techniques may be employed to generate better uncertainty estimates in these cases.

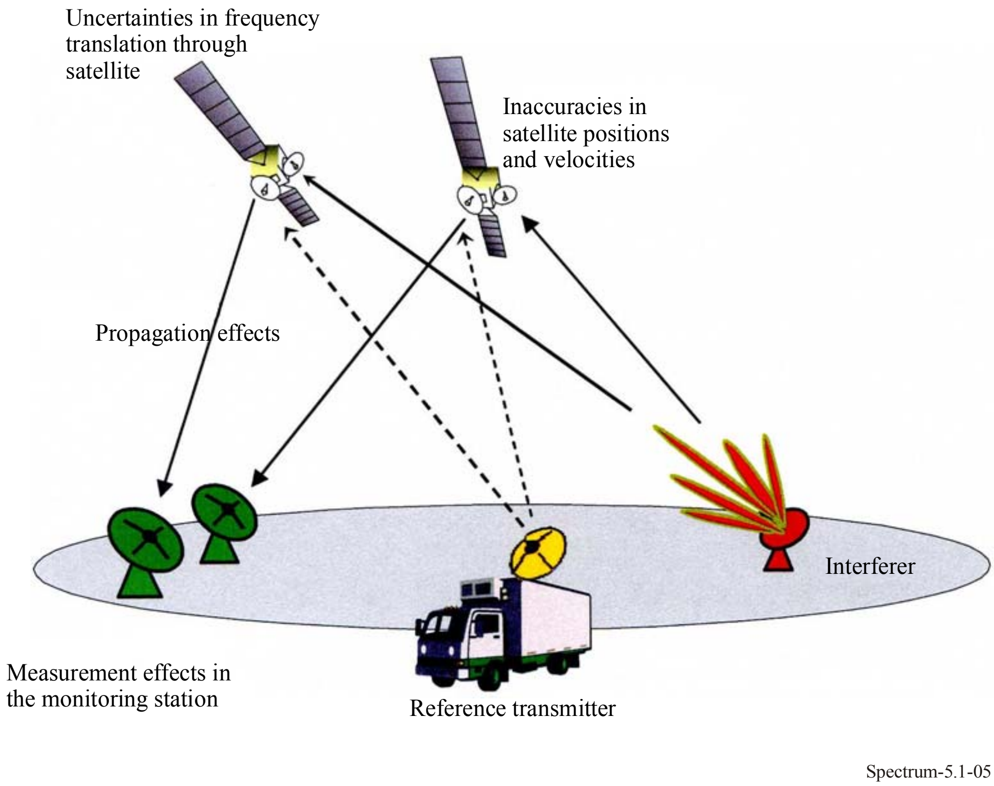
Second, the formal uncertainties account for random error and only partially for any systematic errors. Systematic errors can arise, for example, through incomplete modelling of the physics of the TDOA and FDOA measurements or in the force model used to produce the satellite ephemeris.

The impact of systematic errors can be assessed by very thorough simulation of the geolocation technique and all of its systematic error sources.

There are several potential inaccuracies resulting in a location error. The error can be substantially reduced by using reference transmitters whose geographical coordinates are exactly known (see Fig. 5.1-5).

FIGURE 5.1-5

Geolocation of transmitters on Earth using TDOA and FDOA from two GSO satellites using a reference transmitter



Reference stations deployed over a huge area can eliminate errors due to ephemeris inaccuracies whereas the use of reference stations located in the vicinity of the interferer can minimize the location error. See §§ 5.1.5.4.5 and 5.1.5.4.6.

5.1.2.8 Geolocation of transmitters on Earth using a single GSO satellite and inverse Doppler shift

The location of a transmitter (or interference) on the surface of the Earth may be determined under certain conditions using the transmitted signals relayed through a single GSO communications satellite. The small Doppler shift on the signal carrier frequency, which is induced by the slight motion of the satellite relative to the Earth during an orbit can be exploited to estimate the location of the transmitter to the point (within tens of km) that mobile units may be deployed to pinpoint transmitter or interference location. The technique utilizes measurements of the carrier frequency of infrequent, short transmissions distributed over several hours. Super resolution techniques and signal processing are used to estimate the small Doppler shift in the transmitted signals with the needed degree of accuracy. Predictions of the position and velocity of a satellite can be refined using a reference transmitter [Koets, Bentley, 1999].

Non-zero inclination and eccentricity of a GSO orbit induces some motion in the satellite relative to the surface of the Earth. This motion induces a small Doppler shift, which can be exploited to estimate the location of the transmitter. The technique even makes use of observations of infrequent and short transmissions scattered over a period of several hours. The carrier frequencies of the transmissions must be measured with very high precision in order to use this method. A non-linear iterative estimation technique is then applied. See § 5.1.2.8.3 and Fig. 5.1-6 for discussion of GSO satellite excursions.

For all these reasons the implementation of the geolocation method using one satellite is very difficult. Moreover it imposes assumptions on the transmitter itself that are generally not met, such as:

– an ultra stable local oscillator of the transmitter during a long period of time;

– an emission of the transmitter during a long period of time.

5.1.2.8.1 Geolocation algorithm

The geolocation algorithm utilizes a mathematical expression (f_R) to predict the carrier frequency of a signal that is relayed through a GSO satellite. The expression incorporates the known position and velocity of the satellite and the location of the receiver, as well as the unknown location of the sought transmitter. The effects of uplink Doppler shift, frequency translation within the satellite transponder, and downlink Doppler shift must be taken into account.

All vector quantities are expressed in the three-dimensional Earth-centred Earth-fixed Cartesian coordinate system:

$$f_R = \left[f_T \cdot \left(1 + \frac{\vec{v}_S \cdot (\vec{r} - \vec{r}_S)}{c \cdot \|\vec{r} - \vec{r}_S\|} \right) + \Delta_f \right] \cdot \left(1 + \frac{v_D}{c} \right) \tag{5.1-7}$$

where:

f_R: carrier frequency of the received signal

f_T: carrier frequency of the transmitted signal

v_S: velocity vector of the satellite at the observation time

r_S: position vector of the satellite at the observation time

r: position vector of the transmitter

Δ_f: frequency translation in the satellite transponder

v_D: scalar range rate between the satellite and the receiver

c: propagation velocity of the signal.

Equation (5.1-7) is a function of known and unknown parameters. The known parameters consist of the position and velocity of the satellite, frequency translation, and the range rate between the satellite and receiver. The satellite position and velocity and range rate are dependent on time. The unknown parameter set consists of the location and carrier frequency of the transmitter. Measurements of the actual carrier frequency of the signal at the receiver are made at several observation times. The geolocation algorithm estimates a set of unknown parameters such that the sum of square errors between the measured carrier frequency and the carrier frequency predicted from the expression is a minimum.

The geolocation algorithm uses a linearized version of the received frequency expression, which is a first order multi-dimensional Taylor series expansion of equation (5.1-7). A set of linear equations can be formed using this expression and assembled as the matrix equation:

$$E = A\Delta \tag{5.1-8}$$

where E is the column vector of measurements of the carrier frequency of the received signal at each of the observations times, and $A = [A_f A_x A_y A_Z]$ where each column vector A_i is the derivative of the expression with respect to the parameter *i*, computed at each observation time, and Δ is the vector of errors between the true parameter values and their initial estimates. The matrix equation is solved for the vector Δ in a linear least squares sense and this error vector is used to iterate and refine the initial parameter estimates. Since the linear equation used is only an approximation to the model, several iterations of the process are performed, using the most recently obtained parameter estimates for each step. The parameter values converge to the final frequency and location estimates.

5.1.2.8.2 Frequency (Doppler) measurement

Since a GSO satellite moves slowly relative to a fixed point of the Earth, the Doppler shifts observed in a communications link are small, on the order of tens of Hertz. Accurate geolocation is therefore dependent on very accurate carrier frequency estimation (rubidium standard is sufficient).

The multiple signal classification (MUSIC) algorithm may be used for frequency estimation. The resolution of the frequency estimator is limited only by machine precision and not by the length of the data set. The accuracy of the estimates is constrained by the signal-to-noise ratio. The MUSIC algorithm produces a much more precise frequency estimate than fast-Fourier-transform-based algorithms.

5.1.2.8.3 Position and velocity correction

Accurate geolocation results are dependent upon accurate knowledge of the position and velocity vectors of the satellite at every time of observation. These vectors are typically computed using an orbit propagation model and a set of six orbital elements that describe the orbit of the satellite. These elements are periodically updated based on observations of the satellite and the updated element sets available. Orbit propagation algorithms model the gravitational effects of the Earth, sun, and moon to predict the position and velocity of the satellite for times later than the time at which the elements are computed. There are forces that affect the motion of a satellite that are not modelled. Therefore, the resulting position and velocity estimates become less accurate as the time difference between the prediction time and the time the element set was updated becomes large. The frequency translation within the satellite transponder is also imperfectly known.

It is necessary to refine the satellite position and velocity predictions and the translation frequency to improve the accuracy of location estimates. A reference transmitter at a known location and with a known carrier frequency can be used to refine these values. The reference transmitter should relay signals through the satellite during the same period that signals of interest are observed. The carrier frequency of each of the reference signals observed at the receiver is computed in the same manner as a target signal. These observed reference frequencies are then compared to frequencies that are predicted by evaluating the expression with the known location of the reference transmitter and initial estimates of the set of orbital elements and the translation frequency to refine the results. Figure 5.1-6 illustrates the improvement in frequency predictions obtained with the refined orbital elements and the refined translation frequency.

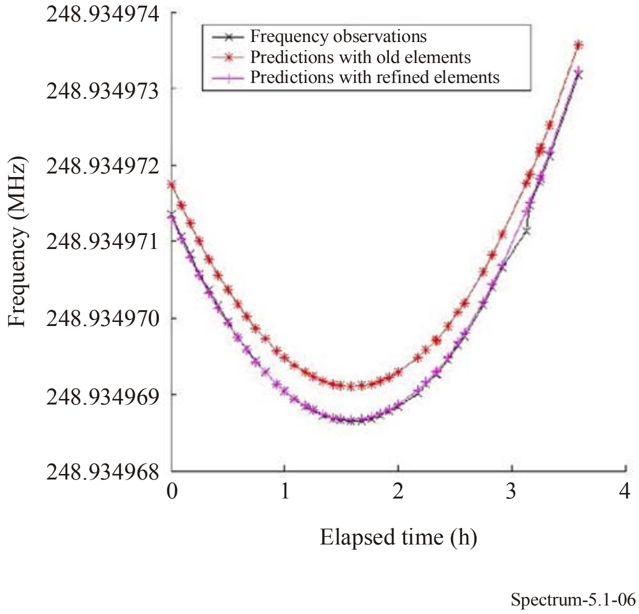
5.1.2.9 Frequency occupancy measurements and GSO orbit position occupancy measurements

Preparations in the planning of new satellite systems should include specific investigations into the occupancy of the downlink frequencies by other satellite systems. This applies in general, since it cannot always be assumed that utilization of frequencies has been subject to coordination or notification. Such occupancy measurements are therefore valuable in order to avoid unexpected interference.

Automatic radio frequency spectrum recording equipment has proved to be very useful for monitoring low orbiting satellite emissions. Using non-directional or hemispheric-shaped beam antennas, the results obtained over a period of several days permit the determination of the occupancy of the frequency band by satellite emissions. In addition, the approximate determination of the satellite frequencies is possible, as are the expected times of reception and the computation of the period of revolution with a good degree of accuracy. One example of a frequency spectrum record is given in § 5.1.7.1.

FIGURE 5.1-6

Improved frequency predictions with orbital element refinement



General frequency occupancy monitoring methods using low-gain antennas are as a rule, not suitable for frequency bands above about 3 GHz. For low pfd signals, directional antennas with adequate antenna gain are required. In the case of GSO space stations, however, occupancy measurements are possible which:

– determine the positions occupied by space stations;
– provide frequency and time-related data regarding the occupancy of frequency bands at occupied positions.

In order to identify occupied positions, an inter-active process is recommended to steer the directional antenna used for reception along the GSO orbit within its half-power beamwidth, during which measurements are continuously taken from the analyzer used for the signal processing to monitor crossing of the threshold values. After scanning the orbit segment visible to the radio monitoring station, the analyzer is switched to the next frequency sub-band and the whole process is repeated.

The time and frequency-related occupancy measurements for a pre-determined position allow for variations, which should be coordinated precisely with the target selected. One example is illustrated in § 5.1.7.3.

5.1.2.10 Measurements below the noise floor

Often there is a need to analyze weak radio signals or parts of signals which are hidden below the noise floor. Especially space radio emissions suffer from this situation. Recommendation ITU-R SM.1681 – Measuring of low-level emissions from space stations at monitoring earth stations using noise reduction techniques, was developed to solve this problem. Figure 5.1-7 shows the typical block diagram for such measurements.

The measurement of low-level emissions below the noise floor is based on an integration method which subtracts the noise spectrum from the signal.

The IF signal is sampled by an analogue/digital converter and stored on a hard disc. This measurement is repeated typically 10 000 times in order to acquire 10 000 recorded samples. Immediately thereafter the antenna is pointed to an adjacent orbit position with the satellite outside the antenna beam thus receiving the noise only under the same environmental conditions.

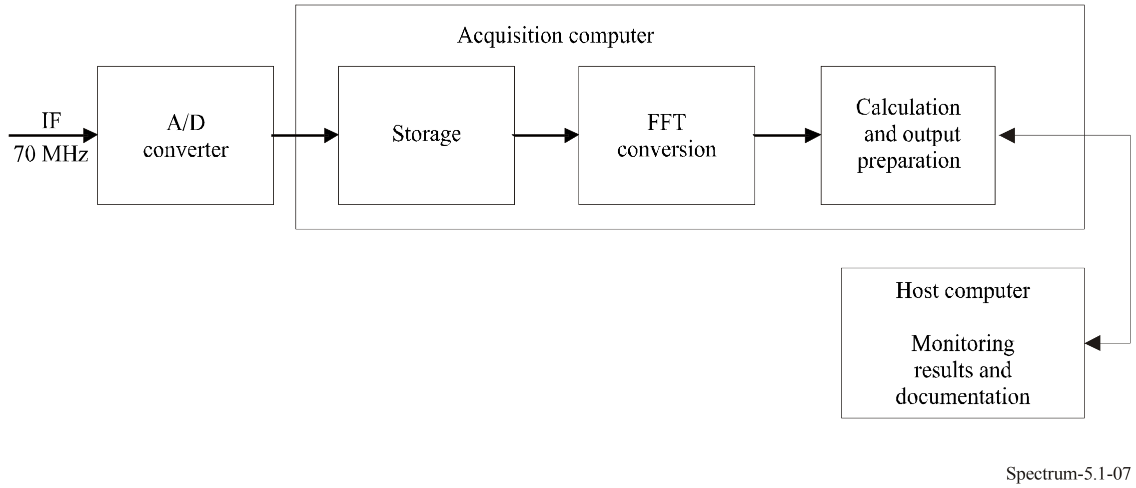
Another 10 000 samples are taken and stored on the hard disk. Both 10 000 sample lines are linearly averaged and subtracted from each other. This results in a noise reduction of typically 10 to 20 dB.

It should be noted that an excellent frequency stability of the whole receiving path is necessary.

Also any noticeable satellite Doppler frequency shift must be eliminated or deducted.

FIGURE 5.1-7

Block diagram for monitoring below the noise floor



5.1.3 Equipment and facility requirements

The purpose of the following paragraphs is to highlight some system characteristics.

Further details regarding figure of merit, antenna systems, antenna steering and auto-tracking are contained in the Handbook on Satellite communications (FSS), and in the publications listed in the Bibliography.

5.1.3.1 General

The technical concept of a radio monitoring station for space services is essentially determined by the tasks to be performed in accordance with the specific needs of the administration.

New developments in the field of space services should be taken into consideration during the planning of the concept. Some important aspects are listed in Table 5.1-2.

The required measurement accuracies, e.g. for frequency and pfd measurements and in particular for angle measurements for the determination of the position of GSO space stations or the orbital elements of non-GSO satellites, are of special importance.

In general, as in more conventional monitoring stations, equipment for monitoring signals from space stations must have adequate flexibility to tune over a wide range of frequencies, in contrast to the spot frequency coverage that suffices for the needs of a research or operational space agency.

TABLE 5.1-2

Tasks and their sphere of influence with respect to the technical concept of the monitoring station for space services

No.	Tasks	Sphere of influence
1	Which part of the frequency spectrum should be able to be monitored?	Number and kind of antenna systems
2	Which satellite systems should be included in the monitoring? Which power flux-densities do these systems produce at the locality of reception? What carrier-to-noise ratio should be achieved?	Figure of merit of the receiving system (antenna gain, system noise temperature)
3	Should position determination of GSO satellites be possible?	Pointing accuracy, kind of antenna steering, receiver concept
4	Should determination of orbital elements of non-GSO satellites be possible?	Pointing accuracy, kind of antenna steering, acceleration and antenna steering velocity, receiver concept
5	Should determination of polarization characteristics and measurements in case of dual polarization systems be possible?	Antenna feed system

5.1.3.2 Figure of merit of a space monitoring system

The achievable C/N on reception of an emission from space depends on the following factors:

– the pfd of the signal at the reception site;

– the gain of the receiving antenna;

– the system noise temperature of the receive system.

The figure of merit, G/T, of a receiving system is the ratio between the gain of the receiving antenna in the direction of the received signal and the receiving system noise temperature as set out in equation (5.1-9).

$$\left(\frac{G}{T}\right) = G - T_{RS} \tag{5.1-9}$$

$$\left(\frac{G}{T}\right) = \left(\frac{C}{N}\right) - pfd - 10\log\left(\frac{\lambda^2}{4\pi}\right) + 10\log\,(kB) \tag{5.1-10}$$

where:

G/T: figure of merit (dB/K)

G: antenna gain (dBi)

T_{RS}: system noise temperature of receiving system (dB(K))

C/N: wanted carrier-to-noise ratio in measurement bandwidth, B (dB)

pfd: pfd in measurement bandwidth, B (dB(W/m^2))

$\lambda^2/4\pi$: effective area of an isotropic antenna (m^2)

k: Boltzmann's constant (1.38×10^{-23} J/K)

B: measurement bandwidth (Hz).

In the case of the fixed-satellite service, the link conditions for a planned system are known exactly. The required G/T for a given C/N can be calculated by using equation (5.1-10). The measurement bandwidth is equivalent to the receiving bandwidth. It is up to the system developer to decide whether a required *G*/*T* should be achieved by means of an increase in the antenna gain, or a reduction in the noise temperature.

Such clarity of conditions cannot be expected for the space monitoring activity. The method used is, however, similar. The desired *G*/*T* is calculated on the basis of the lowest pfd values of those space stations for which the technical analysis of their emission characteristics is regarded as necessary for the monitoring station.

Direct measurement of *G*/*T* of a space monitoring system is preferred to taking the ratio of separately measured *G* and *T*, because the opportunity for error is reduced. Separate measurements of *G* and *T* also require the use of a signal generator, which unnecessarily introduces an additional factor of uncertainty. The sun, rather than a radio star, is often used for *G*/*T* measurements for pfd calibration purposes at monitoring stations because of its much stronger signal. Should, however, the receiving system be sufficiently sensitive, use of radio stars would be better.

5.1.3.2.1 Terms defining *G*/*T*

The figure of merit is usually determined at 5° elevation and expressed in (dB/K) units i.e., *G*/*T* (dB/K) = 10 log (*G*/*T* numeric).

$$G/T \text{ (dB/K)} = \text{antenna gain (dBi)} - 10 \log \text{(system noise temperature (K))} \tag{5.1-11}$$

or

$$G/T \text{ (numeric)} = \frac{8\pi k r_1 r_2 f^2 (y_{sun} - 1)}{s c^2 y_x} \tag{5.1-12}$$

where:

k: Boltzmann's constant (1.38×10^{-23} J/K)

r_1: correction factor for atmospheric attenuation; for angles ≥ 5°

where:

$$r_1 = \text{antilog} \frac{\frac{A}{\sin\theta} \text{(dB)}}{10}$$

A: the one-way atmospheric absorption in decibels for a vertical path and θ is the Sun's elevation angle at the time of measurement

r_2: correction factor for receiving antenna half power beamwidth relative to the angular diameter of the Sun where:

$r_2 = 1 + \frac{401.4}{\vartheta_h^2}$ and ϑ_h^2 is the antenna half power beamwidth (min)

f: frequency (Hz)

y_{sun}: measured values, expressed in numeric units, where:

$$y_{sun} = \text{antilog} = \frac{Y_{sun}\text{(dB)}}{10}$$

s: Sun flux-density obtained from a national standards laboratory; if the Sun flux-density, s, at the frequency (f) of direct interest is not available, the following interpolation equation should be used, instead of linear interpolation, to obtain greater accuracy:

$$s = \left(\frac{s_1}{s_2}\right)^{R_2}$$

where:

s_1: flux at lower frequency (f_1), (J/m^2)

s_2: flux at higher frequency (f_2), (J/m^2)

$$R_2 = \frac{\log\,(f\;/\,f_2)}{\log\,(f_1\,/\,f_2)}$$

c: velocity of light (3×10^8 m/s)

y_x: measured values, expressed in numeric units, where:

$$y_x = \text{antilog}\,\frac{Y_x\,(\text{dB})}{10}$$

5.1.3.2.2 *G/T* measurement procedures

A receiver of the type usually found at monitoring stations, having an IF output voltage indicator, e.g., voltmeter or oscilloscope, is required. It is highly desirable that the indicator has a voltage resolution of 0.1 dB (1%) or better. The receiver must be stable and have no significant gain changes during the measurement period.

For the measurements:

– the receiver automatic gain circuit should be switched off;

– the antenna should be pointed towards the Sun and maximum signal obtained. The Sun should have an elevation angle greater than about 30° to avoid atmospheric effects and to ensure that the correction factors r_1 and r_2 are minimally affected;

– the antenna should then be slewed, in azimuth only, away from the Sun, e.g., more than a few degrees. The IF voltage level should be noted. This voltage corresponds to the cold sky reference value;

– the antenna should then be returned in azimuth towards the sun and the voltage noted. The difference in readings equals Y_{sun} (dB);

– the antenna should then be slewed, in elevation coordinate only, down from the Sun to 5° elevation and the voltage noted. The difference between this voltage level and the cold sky level is Y_x (dB) for x° of elevation. It should be noted that 5° of elevation (x°) is a common reference standard.

The *G/T* can then be evaluated using the measured values of y_{sun} and y_x and applying the correction values r_1 and r_2. The Sun flux-density, s, can be obtained from a national standard laboratory.

Using the equation for *G/T*, the root-sum-square uncertainty of the measurement is of the order of < 0.5 dB.

It is necessary that the measurement procedures be carried out on a bright, sunny day.

5.1.3.3 Antenna systems

The antenna gain should be as high as possible in order to provide a good minimum sensitivity limit for the measuring equipment.

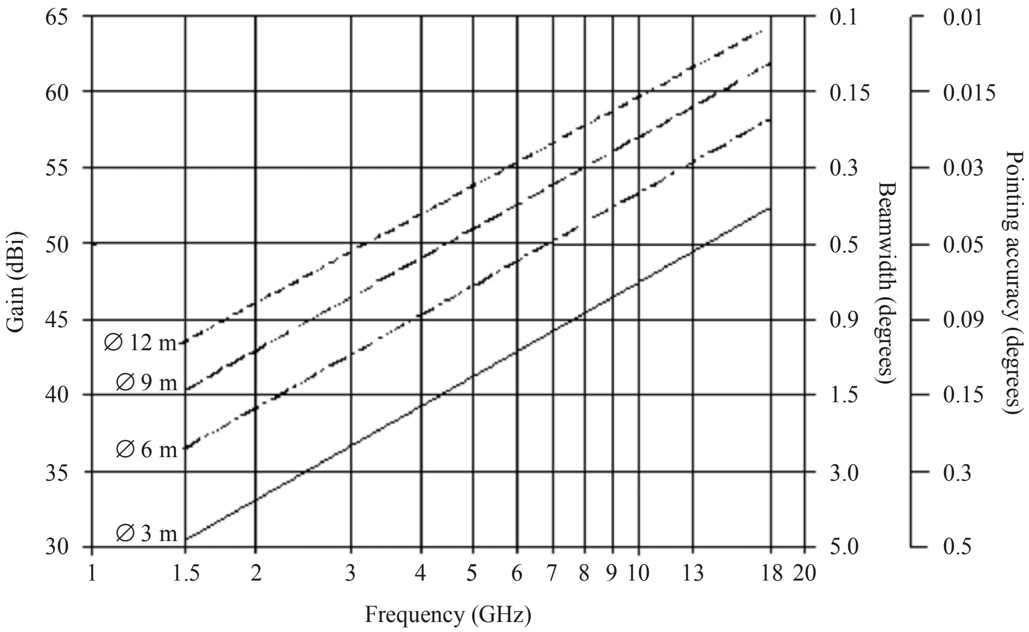
Helical antennas or dipole antenna arrays are suitable for the 100-1 000 MHz frequency range. As individual antennas, they provide a gain of about 12 to 16 dBi.

For the frequency range from 1 to 26.5 GHz, one parabolic reflector with one broadband feed at the prime focus is adequate. If optimised polarization and directivity characteristics are required, a design, which uses interchangeable feed system, is preferred. Examples for such technical solutions are given in § 5.1.6.1.

Figure 5.1-8 illustrates the antenna gain as a function of frequency for the different diameters of the parabolic reflector, assuming a typical antenna efficiency of 55%. The diameter of the reflector should be a minimum of 3 m. In this case, antenna gains ranging from 31 dBi at 1.5 GHz to 53 dBi at 18 GHz may be obtained. Extrapolation to higher frequencies is applicable. Generally, antennas with a diameter ranging from 6 m to 12 m are used.

FIGURE 5.1-8

Antenna gain, 3 dB beamwidth and pointing accuracy as a function of frequency for the different diameters of the parabolic reflector and an antenna efficiency of 55%



Spectrum-5.1-08

In some cases the use of log-periodic antennas may be of advantage. Antennas of this type provide good general coverage over a 10 to 1 frequency range and have been used for satellite monitoring on frequencies between 50 and 5 000 MHz. The disadvantage in this case is a frequency-independent and near-constant antenna gain, generally ranging below 10 dBi.

5.1.3.4 Antenna steering

The antenna drive system should allow either manual or computer-controlled adjustment. If accurate position determination of GSO satellites is required or if the calculation of orbital elements of a space station based on angle measurements is seen as a required task, then autotracking is necessary. Step-track or monopulse tracking are the two possible solutions.

The step-track technique is based on measurements of the strength of the received signal in positions around the expected satellite position. By computation the optimum is found stepwise. The monopulse technique is based on the analysis of the wave type arriving in the tracking receiver. Only when the antenna is pointed directly towards the satellite, the expected wave type (waveguide mode) is produced. Other wave types produce the tracking information for proper pointing. The monopulse tracking is usable for GSO and non-GSO satellites and have no impact on the power measurements.

5.1.3.5 Antenna beamwidth necessary for angle measurements

The intention in this sub-section is to establish a relationship between the half-power (3 dB) beamwidth of an antenna and the achievable pointing accuracy. This is of interest with respect to auto-tracking techniques in those cases where the monitoring of the station-keeping of GSO space stations or the calculation of the orbital elements of non-GSO satellites are seen as a required task of a radio monitoring station (see § 5.1.2.6).

Pointing accuracy is a measure of how well an antenna system determines the look angles (azimuth, elevation) of an object. In this respect there is a difference between space monitoring, and earth stations of the fixed-satellite service, since in the case of the latter, even a smallest possible relative alignment error (relative to the space station) is significant.

A relationship between the half-power beamwidth of an antenna and the maximum achievable pointing accuracy can be established:

$$R = n \cdot \theta_0 \qquad (5.1\text{-}13)$$

where:

R: angle measurement error (degrees)

n: improvement factor

θ_0: half-power beamwidth (degrees).

For optimised narrow-band antennas, $n = 0.01$. For a broadband antenna of the kind generally used by a radio monitoring station for space services, a factor of 0.1 seems to be realistic if a monopulse system is used and 0.15 if a step-track system is used. The remaining variable, the half-power beamwidth is a function of the diameter of the reflector.

The suitable half-power beamwidth should be selected by taking into account the smallest longitudinal position tolerance of $\pm 0.1°$ as defined in the RR. A tolerance of $\pm 0.1°$ of the longitude defines an angular segment of the equatorial orbital plane. In the restrictive case where a monitoring station is operated on the equator, position keeping would have to be checked by angle measurements in only the elevation plane of the antenna. When the monitoring station is shifted to the South or North, a rotation takes place in the azimuth plane of the monitoring antenna. In the case of 50° latitude, for example, this means that the longitudinal station-keeping tolerance of a GSO space station is predominantly measured as angular difference in the azimuth plane of the antenna. It reaches the value $\pm 0.13°$ for a longitudinal difference of 0° between monitoring station and sub-satellite point and drops to $\pm 0.085°$ for a longitudinal difference of 60°. The corresponding measurement error in this example is $\pm 0.01°$, i.e. smaller by a factor of 10 compared to the allowable tolerance.

Figure 5.1-8 contains values for the half-power beamwidth and the pointing accuracy of an antenna as a function of frequency and reflector diameter. It is clear that full implementation of position monitoring as a monitoring task is subject to restrictions, especially in the case of lower frequency bands. Less stringent requirements allowing the use of smaller antenna systems are permissible in such cases where only greater divergences or deviations in position-keeping, for example in investigations of harmful interference, are to be identified.

5.1.3.6 System polarization

For polarization measurements (§ 5.1.2.5) the characteristics of the antenna system should be carefully considered. As circular and linear polarizations are used in the frequency bands above 1 GHz and use of dual polarizations in the frequency bands of the fixed-satellite service is a standard technique, it is necessary that the polarization of the receiving system can be adapted to that of the received signal and that a sufficient polarization discrimination is achieved.

Apart from enabling the polarization characteristics of the received signal to be obtained, such a system will also provide for maximum antenna gain and maximum reduction in the crosstalk signals between the two orthogonal polarization planes, which is a requirement for most of the measurements indicated in § 5.1.2.

5.1.3.7 Receivers

For economic reasons and because general coverage is required at monitoring stations, the extremely low noise figures of the fixed-frequency receivers used for space research and operational purposes are not reached by tuneable monitoring receivers. Nevertheless, the noise figure of the receiving system for a monitoring station for space services affects the total system noise figure. Its reduction to the lowest possible value is an important goal during the design phase of a monitoring station for space services. This is true even though it is possible in nearly all cases to improve the signal-to-noise ratio by narrow band filtering of a part of the emission spectrum.

For frequencies below about 3 GHz, standard monitoring receivers may be used. Above about 3 GHz a microwave receiver system of modular design should be used to meet the various requirements. The conventional concept, where the receiver comes as a self-contained unit, cannot be used, as, due to the high cable losses in the microwave range, the front end of the receiver must be situated close to the antenna, whereas the low-frequency modules and the control facilities can be located in the operating room. An example of receiving system specifications for C and Ku bands is given in Table 5.1-3.

TABLE 5.1-3

Example of receiving system characteristics

Tuner and synthesizer	
Frequency range	1-18 GHz with several overlapping tuners
Receiving frequency bandwidth	Centre frequency $\pm$50 MHz
Frequency error	$< \pm 2.5 \times 10^{-8}$
IM-free dynamic range	> 66 dB (1 MHz bandwidth)
Oscillator phase noise	<–90 dBc (Hz) (10 kHz from carrier)
Broadband receiver	
Minimum tuning step	1 kHz
IF filter bandwidth	0.05/0.3/1.25/2.5/5/10/20/40 MHz

In the case of automatic methods for Doppler shift measurements, where a frequency counter is required, the receiver has to deliver a noise-free output signal, which accurately represents the satellite carrier frequency. For this purpose the receiver must provide phase-locked synchronization to the satellite carrier frequency.

The bandwidth of the loop should be able to be switched between a few hertz and a few hundred hertz. The output frequency of such a phase-locked circuit may also be used as a pilot frequency for the adjustment of the frequency of a second receiver during bandwidth measurements, as outlined in § 5.1.2.3.

For more general purposes, if a satellite signal without a carrier has to be received, and if the pfd of this signal is sufficient, an automatic frequency tuning device may be used to avoid distortion of bandwidth and pfd measurements due to Doppler shift in the received signal frequency.

The following receiver outputs should be provided to facilitate the taking of measurements: wideband and narrow-band intermediate frequency outputs, video frequency, audio frequency and baseband (AM/FM) outputs. The intermediate frequency should be the same for all the receivers of a measuring installation so that the same auxiliary equipment may be used with all the receivers.

5.1.3.8 Peripheral equipment

5.1.3.8.1 General equipment

Table 5.1-4 contains a list of some peripheral equipment, which is necessary for the above-mentioned measurements, and other useful equipment, which can be added to the receiving system.

5.1.3.8.2 Analyzer

The spectrum analyzer has proven to be one of the most powerful instruments not only for general monitoring, but also for space monitoring purposes. To enable it to be used for monitoring tasks, the spectrum analyzer should be able to work interactively with other equipment under computer control.

To perform real time spectrum display and power measurements, a digital FFT or vector analyzer can be used. The bandwidths and the appropriate filter curves for the different modulations (FM, QPSK, etc.) can be chosen by programming digital filters. FFT analyzes show a real-time spectrum and do not need a significant period of time to sweep over the signal bandwidth like conventional spectrum analyzers.

TABLE 5.1-4

Peripheral equipment

Necessary peripheral equipment		Additional peripheral equipment	
Type of equipment	**Function**	**Type of equipment**	**Function**
Frequency/time standard	Central reference	TV demodulator	Demodulation of FM- and digitally-modulated TV carriers
Frequency counter	Doppler shift frequency measurements	TV decoder	Decoding of TV baseband signals (NTSC, PAL, SECAM, HDTV)
Time divider	Timing pulse for frequency counter		
Signal analyzer	Spectrum analysis, bandwidth measurements	Sound carrier demodulator	Demodulation of TV sound subcarriers, tunable
Power meter	PFD measurements		
Signal generator	Reference PFD measurements	Modulation analyzer	Identification of types of modulations, modulation measurements
Recorder	General purpose		
Digital oscilloscope	General purpose		

5.1.3.9 Broadband RF or IF monitoring channel

It is recommended for the technical design of the receiving system of a monitoring station for space services to allow for the broadband monitoring of the radio frequency spectrum. Simultaneous analysis of a minimum bandwidth of 500 MHz should be provided for.

5.1.3.10 Radio-frequency spectrum recording equipment

The technical characteristics of the recording equipment for space monitoring (see § 5.1.2.9 for reference) correspond to those required for terrestrial monitoring purposes. Since non-directional antennas of preferably linear polarization have to be used, the loss in antenna gain has to be compensated for by a selecting a small bandwidth for the recording equipment. As a general rule, and particularly for graphical recording units, the total analyzed spectrum bandwidth should not exceed 2 MHz.

5.1.3.11 Computer requirements

Computer requirements should be seen as an integral part of a monitoring station for space services. They can be used, for example, for:

– calculation of orbital elements;
– calculation of antenna pointing angles from orbital elements;
– antenna steering;
– storage of measurement results;
– evaluation of measurement results.

5.1.4 Documentation and database support to space monitoring

5.1.4.1 General considerations of documentation and database

Successful operation of a monitoring station for space services depends on the continual update of paper or electronic documentation. Preferably these would take the form of a database system containing not only the data officially published by the ITU, i.e.:

– BR International Frequency Information Circular (BR IFIC) on CD-ROM;

– Space Network List (Online or on CD-ROM);
– Space Radiocommunication Stations on DVD-ROM;
– Radio Regulations, paper or CD-ROM;

but also a survey of all satellites in orbit, together with some of their most important orbital elements (time of revolution, inclination, apogee, perigee). The data of earth stations licensed by the administration are valuable in earth station geolocation, especially in identifying the unauthorized users of the spectrum.

To facilitate monitoring operation, it is necessary to establish a database in order to record two kinds of information. One is general information of all satellites of interest, and the other is the characteristics of the satellites that will be obtained by monitoring.

5.1.4.2 General information database of existing satellites

The database of general information of an existing satellite mainly describes the characteristics and the licensed space service of a satellite within the monitoring capacity of the station. The most important information includes:

– satellite orbital information, including nominal longitude of a GSO satellite, longitude tolerance, ephemeris information of a non-GSO satellite etc.;
– transponder information, including number of transponders, bandwidth of transponders, frequency range, beacon frequency, maximum antenna gain;
– satellite beam information, including beam coverage, service area, maximum power(dBW/m^2).

Additionally, the following satellite information is useful in the geolocation of earth stations:

– geographic information, including longitude, latitude and altitude etc.;
– antenna information, including antenna size, gain, antenna pattern etc.;
– other information, including frequency assignment, bandwidth, polarization, transmitting power, service type, modulation type, work time etc.

Sources for the above information can be satellite operator(s), the administration(s), and public media.

5.1.4.3 Monitoring information database

The monitoring information database is used to record the measurement result of space monitoring station. The measurement result should include some key parameters, such as frequency, polarization, bandwidth, power flux-density, modulation type etc. A long term occupancy analysis of spectrum can facilitate the spectrum planning.

To facilitate the data exchange between monitoring stations, the parameters of monitoring itself, such as position of antenna, antenna parameters, measurement time and weather etc., should be recorded in the database.

5.1.4.4 Using documentation and database to facilitate monitoring

In monitoring, documentation and database support the following purposes:

Identifying space stations

Space stations can be identified through a comparison between the general information database and monitoring data. The detail introduction to the process of identifying space stations will be given in the following section.

Identifying illegal emissions

Monitoring engineers can identify illegal emissions through comparison of corresponding entry in the general information database which has been approved by the administration. This can be achieved automatically by monitoring systems.

This is only applicable when the approved data of the carriers is available to the administration.

Facilitating the geolocation of emissions

Database systems can remarkably improve the efficiency of geolocation missions. Analysis can be performed based on the information in the database, including:

– adjacent satellite analysis;

– reference signal selection;

– potential interferer analysis.

In addition, geographic information systems (GIS) plays an important role in space monitoring, a joint system of station database and GIS database can give the monitoring engineer an overview of the use of the spectrum. Such a joint system can be used in analysis of potential interferers to space stations.

5.1.5 Identification of space stations and geolocation of earth stations

The identification of a space station is generally based on the comparison of the measured emission and orbital characteristics with those found in the reference database and documentation. Reference characteristics consist of a list of the emission and orbital characteristics of all space stations, which have been published or made available to the monitoring service. The unknown station is identified by the iterative elimination of those stations, which do not correspond to the measured characteristics. Reference characteristics are given in Table 5.1-5.

TABLE 5.1-5

Reference characteristics

Emission characteristics	Orbital characteristics
Frequency	Ephemeris data, or, if not available:
Bandwidth	– period of revolution
Type of modulation	– angle of inclination of orbit
Polarization	– perigee and apogee distances
e.i.r.p.	– equator crossing time and longitude of crossing

With the wide use of GSO satellites, it is necessary for administrations to be able to identify earth stations transmitting toward GSO satellites. This is done to acquire complete information of the use of earth stations and eliminating harmful or illegal emissions. When using the geolocation method described in § 5.1.2.7, positional inaccuracies typically can be tens of kilometres. This accuracy may be sufficient for identifying emissions from legitimate users, As for the illegal emissions, other terrestrial monitoring means may be required to finally pinpoint and eliminate the interference.

5.1.5.1 Monitoring results to be used for identification

5.1.5.1.1 Evaluation of frequency band recordings

With reference to § 5.1.2.9 and to the example given in § 5.1.7.1, approximate values for the following space station characteristics can be obtained from frequency band recordings:

– frequency;

– expected time of reception for non-GSO satellites;

– period of revolution.

5.1.5.1.2 Calculation of period of revolution

For the calculation of the period of revolution with an accuracy level of several seconds, it is possible to obtain an initial approximate value by measuring the times of TCA of two successive paths. A refined result is then based on additional TCA measurements over a period of one or two days.

5.1.5.1.3 Direction-finding

To complement the determination of the exact TCA of a satellite to a monitoring station, a curve can be plotted to show the change in direction of arrival of the signal with time, as determined by Direction-finding (DF) bearings or orientation of a highly directional receiving antenna. The maximum angular rate of change will occur when the satellite is nearest to the monitoring station during a particular pass, and the information obtained by this method should agree with the information obtained from the Doppler shift curve.

DF measurements are well suited for the determination of the TCA in cases where a carrier frequency does not exist within the spectrum. However, DF measurements require a sufficient pfd at the receiving point.

5.1.5.1.4 Calculation of ephemeris data from antenna angle measurements

If a monitoring station is equipped with an auto tracking antenna system, angle measurements in the azimuth and elevation planes may be used to calculate the ephemeris data of the unknown satellite [Montenbruck, 1989] and [Montenbruck and Pfleger, 1991]. Software to carry out the calculations is commercially available.

The accuracy in determining the ephemeris data depends on:

– overall angle measurement accuracy (§ 5.1.3.5);

– orbit segment used for angle measurements;

– type of orbit of the satellite.

A significant operational problem is the need to point the antenna quickly at a non-GSO satellite soon after its entry into the visibility range of the monitoring station. While the need to obtain accurate angle measurement requires highly directional antennas, their use increases the difficulty of searching for and finding a LEO satellite since the portion of the orbit that can be used for measurements is less than the total visible orbit. One example illustrating the calculation of orbital elements on the basis of angle measurements is found in § 5.1.7.2.

5.1.5.1.5 Emission characteristics

Measurements of the emission characteristics as outlined in the sections above may be sufficient for the identification of a space station. This is particularly the case for those space stations which are operated in accordance with the RR and whose emission characteristics are notified or published.

5.1.5.2 Identification procedure

If the measured emission characteristics do not result in the identification of a space station, the measured ephemeris data, or parts thereof, may be of help.

When comparing the measured ephemeris data with the published reference data, the orbiting objects with the most similar data are selected first. Subsequent step-by-step comparison of the data should result in a significant reduction in the number of objects to be considered. Finally, by calculating the visibility times and the TCA for the remaining objects and by comparing them with the monitored results, it should be possible to achieve correct identification.

5.1.5.3 Other possibilities for identifying space stations

The procedures that have been discussed so far for the identification of space stations have been based on comparing the measured and observed signal characteristics with published information, and by comparing the measured ephemeris data or parts thereof (time of revolution, inclination angle, TCA) with published ephemeris data. This procedure is, however, time consuming and requires access to the ephemeris data of the objects in orbit.

In some cases, particularly when non-compliance with the RR or where cases of harmful interference are observed, an additional procedure may be useful. In these cases, the monitoring station for space services could log all possible information concerning frequency and bandwidth measurements and other emission characteristics, together with ephemeris data, or parts thereof, and request identification based on this data from identification and tracking centres or from satellite network operators.

5.1.5.4 Operational considerations regarding the geolocation of uplinking earth stations toward GSO satellites

At present, there are commercial geolocation systems from different manufacturers available, these systems use the principles described in § 5.1.2.7 to geolocate uplinking earth stations toward GSO satellites, and are adopted by some satellite operators and administrations. Certain operational considerations of these systems are presented here in this section.

At the outset, the operator of the geolocation system should first determine the nature of the unknown signal. This can be done in two ways: by means of other monitoring facilities, or getting information from the satellite operator. Then an adjacent satellite is required for the test. The operator may have multiple choices when evaluating the candidate adjacent satellites. He should also input other required information into the geolocation system. Usually a number of reference signals are required to either cancel the drifts in the oscillators on board the two satellites, or be used in the geolocation algorithm to correct the position fix inaccuracy as a result of ephemeris errors.

5.1.5.4.1 Acquisition of necessary information

The operator should know some useful information regarding the signal under test. For example, the satellite carrying the unknown signal, the frequency plans of its transponders, the centre frequency, bandwidth, duty cycles (for intermittent signals) and the frequency mobility characteristics of the unknown signal. Based on this information the operator will select the appropriate observing parameters to optimize the likelihood of successful geolocation.

The above information can be acquired by other monitoring means, or, if the unknown signal being harmful interference, provided by the victim.

It is also helpful to record the interfered transponder of the satellite with a spectrum recorder as soon as possible after the interference is reported to the monitoring station. That allows seeing the activities of the interferer and the transponder occupancy.

5.1.5.4.2 Adjacent satellite selection

There may be more than one suitable satellite that can be used as an adjacent satellite. The primary consideration in doing this is to assure that the selected adjacent satellite has the proper uplink and downlink connectivity.

From the known downlink frequency and polarization for the unknown signal, the operator may infer the corresponding uplink frequency and polarization for the unknown signal. In the case where either hemispherical or spot uplink beams are employed, the uplink beam pattern may limit the geographical region from which the unknown signal is likely to originate. The operator should keep in mind, however, that large uplink antennas residing outside of the main beam pattern of the satellite uplink beam interference may cause interference as well.

From a consideration of the unknown signals uplink frequency and polarization and the beam coverage of the primary satellite's uplink antenna, the candidate adjacent satellite(s) can be found. These criteria for selecting the adjacent satellite are:

– same uplink frequency coverage as the primary satellite;
– same uplink polarization as the primary satellite;
– similar uplink beam coverage as the primary;
– angular separation from the primary satellite along the geostationary arc;
– transponder does not use on board processing.

The primary selection criteria listed above are ordered roughly according to their relative importance. The first two criteria, uplink frequency, uplink polarization and downlink beam coverage, are absolute prerequisites to successful measurements.

Once the operator has identified one or more candidate adjacent satellites based on the above mentioned criteria, the secondary criteria can be used to help guide the final selection.

These secondary criteria include:

– availability of adequate reference signals for the primary/adjacent satellite pair;

– quality of the ephemeris data available for the adjacent satellite;

– presence/absence of signals in the transponder of the adjacent satellite corresponding to the frequency of the interferer signal.

In making the final choice of adjacent satellite, the operator should keep in mind that the optimum geometric solution will be obtained for satellites with good quality current ephemeris data and an adequate selection of reference signals for the satellite pair to be used.

Reference signals may appear on either the primary or adjacent satellite. If adequate reference signals are available on the primary satellite, this criterion need not drive the selection of the adjacent satellite. Dedicated reference transmitters, fixed or transportable, can also be used to improve the geolocation result.

An additional factor that may influence the selection of adjacent satellite is orientation of the FDOA lines for the chosen satellite pair at the time of measurement. Unlike the TDOA lines, the orientation of the FDOA lines for a given satellite pair can vary significantly over the course of an orbital period (1 day).

The best choice is to find an adjacent satellite without signals around the interferer signal and the reference signals. To observe the actual transponder activities it is recommended to record the transponder of the adjacent satellite with a frequency spectrum recorder facility.

If the measurements are taken when the FDOA lines are nearly parallel to the TDOA lines, the result area will be highly elongated along the lines of constant TDOA. In such circumstances the operator should consider either choosing a different adjacent satellite or scheduling additional measurements at a time when the FDOA line orientation is more favourable.

5.1.5.4.3 Reference signals

An ideal reference signal is a full time broad-banded signal uplinked from a precisely known geographic location that produces strong correlation on the two satellites being used. This precise location can be obtained from the database of earth stations, but preferably double-checked with a portable GPS receiver. In such case that reference signals are abundant, the operator should try to use reference signals:

– uplinked from a relatively small antenna;

– which are well distributed geographically;

– with suitable modulation;

– whose frequency is unused transponder sections on the adjacent satellites.

5.1.5.4.4 Ephemeris data

The quality of the ephemeris data for both the primary and adjacent satellite will directly impact the quality of the result. In most cases, the error in the ephemeris can be eliminated to a large extend by using 2 or more reference signals (see § 5.1.2.7.2 for detailed information). If the ephemeris data is particularly bad, as may be the case immediately following manoeuvres or when the epoch of the ephemeris data is several days prior to the date of the measurements, position uncertainties as large as several hundred kilometres may result. In this case the operator should strive to either obtain better ephemeris data or use an alternate adjacent satellite.

The operator of the geolocation system can acquire ephemeris data in the following way:

– request data from the satellite operator(s);

– download the published data from websites.

Check the ephemeris data with a geolocation measurement of a known (e.g. reference) station. If the quality of the result is not sufficient, an ephemeris error compensation can be applied. This is a capability to compensate satellite ephemeris errors.

With 3 or more reference stations a geolocation measurements are carried out. The ephemeris error compensation corrects the ephemeris data with an inverse calculation of the geolocation measurements.

5.1.5.4.5 Establishment of dedicated supplementary reference transmitters

The operator of the geolocation system may find the number and the geographic distribution of reference signals not sufficient to yield accurate result in some circumstances. On some satellites, most of its users are located in one or two major cities, which significantly limit the number of reference signals available for geolocation. Therefore, it is necessary for administrations to establish a number of dedicated supplementary reference transmitters to provide the operator of a geolocation system more choices in terms of reference signals. These transmitters should:

– meet the technical requirements of satellite operators;

– be able to point to any visible GSO satellites along the geostationary arc;

– be well distributed geographically;

– have relatively small antenna sizes;

– use suitable modulation type(s).

It is advisable for administrations to cooperate in establishing dedicated supplementary reference transmitters at different locations, and use them as a reference when necessary.

Before using the dedicated supplementary reference transmitters to transmit toward a certain satellite, prior consent of the satellite operator is required. And certain technical test may also be required before transmitting.

5.1.5.4.6 Transportable reference transmitter

Generally it is very hard to search for a transmitter uplinking to a GSO satellite, especially in an urban area. Two major factors lead to these difficulties, one being the blockage of radio-waves by buildings, the other the normally high directivities of antennas which produces very week side lobes in the terrestrial direction. Therefore is would be useful to use the TDOA and FDOA measurement with the help of transportable transmitters to help pinpoint the transmitter, typically a harmful interference.

As mentioned in the previous section, before transmitting toward a certain satellite, prior consent of the satellite operator is required. And certain technical test may also be required before transmitting.

Theoretically, given a satellite pair, two earth stations transmitting at different frequencies produces the same TDOA value and two FDOA value with a very small difference. The closer the reference transmitter is to the unknown interferer, the better accuracy the geolocation algorithm will yield.

Before using the transportable reference transmitter, the operator should make full advantage of all fixed reference transmitters to minimize the inaccuracy of the result and the size of the resulting area. After that prior consent should be obtained from the satellite operator to transmit with regard to the technical parameters of the transmission. Then the following two steps should be taken:

Step 1: move the transportable reference to the centre of the result area, and transmit the reference signal as agreed by the satellite operator. Then the operator of the geolocation system should be notified to perform the geolocation measurement. He should also be notified the accurate position of the vehicle.

Step 2: The geolocation measurement yields a new result using the transportable reference transmitter.

The result will be refined after the second step, and these steps can be repeated to get even better result.

The operator of the transportable transmitter should keep close contact with the operator of the geolocation system. In practice, the selection of route and the transmission will be affected by many other factors such as traffic regulations and the operator should take note of these factors.

5.1.6 Technical solutions by examples

5.1.6.1 Example for a space radio monitoring station

This section describes the principle composition of a space radio monitoring station. In principle it is made up of 4 technical main parts:

Part 1: Antenna system (see § 5.1.6.1.1)

One or more different antennas for all the telecommunication and space radio frequency bands of interest. (directional and omnidirectional antennas).

Part 2: Receiving facilities (see § 5.1.6.1.2)

Feed systems, polarization unit, down-converters, calibration system, reference frequency source.

Part 3: Monitoring equipment (see § 5.1.6.1.3)

Both automatic measurement systems and manual measurement and analytic facilities like signal analyzers, receivers, spectrum recording systems and modulation analyzers are part of the monitoring equipment.

Part 4: Control facilities (see § 5.1.6.1.4)

The control facilities comprising the hard- and software for the control of the antenna positioning, the settings of the receiving system and the settings of the monitoring equipment facilitate automatic measurement procedures.

General

Location of the monitoring station:

The monitoring station should be as far away as possible from urban and industrial areas with man made noise, cell phones and RLANs. Fixed links should not cross the location of the site. A protected area around the monitoring station should be declared and kept free from terrestrial transmitters and fixed links.

The landscape around the monitoring station should be flat without blocking the line of sight due to hills and buildings.

Site configuration:

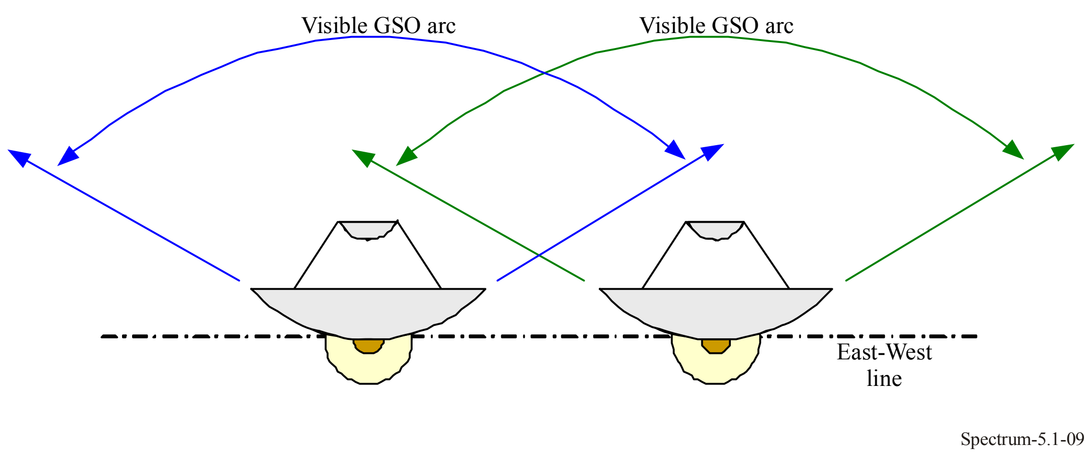
The location of the antennas and the buildings depends mainly on the target of monitoring (GSO or non-GSO satellite) and which part of the geostationary orbit that will be of interest. Future expansions should be taken into account.

For even and open conditions the antennas can be arranged on a line, e.g. East-West-Line.

The distance between antennas directed toward GSO satellites only, the visible angle of the geostationary arc has to be free of obstacles (see Fig. 5.1-9).

FIGURE 5.1-9

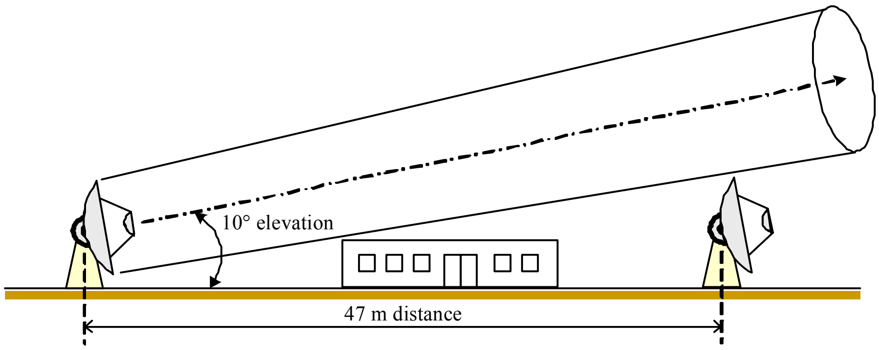
Separation of GSO satellite monitoring antennas



For the unhindered receiving of non-GSO satellites the area around the antenna must be free of obstacles (antennas, buildings) in all directions at least up to the lowest required elevation (see Fig. 5.1-10).

FIGURE 5.1-10

Elevation of non-GSO satellite monitoring antennas



Spectrum-5.1-10

Table 5.1-6 shows the ideal distance between two antennas (9 m diameter each) for clear line of sight to the satellites. The elevation angle is the lowest angle for an unblocked view to the satellite.

In order to optimize the number of antennas needed, combination of receiving bands shall be preferred, without significant deterioration of the antenna performances. A geolocation measurement system requires two antennas each covering the desired frequency band.

For example a combination of 3 antennas (1 C/Ku, 1 L/S and 1 Ka) offer the possibility to receive applications like broadcast links, networks and satellite control and test signals optionally. It is also possible to combine 4 or 5 frequency bands in only one antenna. This can be achieved by using a Cassegrain antenna with a beam waveguide system and two cabins or by using a revolving feed system.

The disadvantage of such a multi-band antenna is that only one frequency band can be used at the same time.

TABLE 5.1-6

Distance between two antennas (of the same size) for clear line of sight to the satellites

Elevation (degrees)	**Distance (m)**
5	99
10	47
15	30
20	22
25	18
30	16

5.1.6.1.1 Antenna system

Antenna concepts in principle

– Limited motion antenna
– Turning head antenna with continuous azimuth travel range of >180°
– Full motion antenna with elevation axis above azimuth axis
– Full motion antenna with elevation axis above azimuth axis above tilt axis

– Full motion antenna with slant axis above azimuth above tilt axis
– Full motion antenna with X-Y mounting
– Hexapod.

Monitoring GSO or non-GSO satellites require different types of antennas.

The most common antenna types are described below.

Antennas for GSO satellite monitoring

When monitoring GSO satellites, antennas with slow azimuth and elevation velocity can be used.

Usable tracking systems:

– Computer tracking with two line elements (TLE)
– Step track
– Monopulse tracking.

Antennas for non-GSO satellite monitoring

Full motion antennas with a faster velocity and a tracking system must be used.

Depending on the antenna pedestal type (elevation above azimuth or X-Y-mounting) the needed velocity and acceleration are different.

Usable tracking systems:

– Computer tracking with two line elements (TLE).
– Monopulse tracking.

Antenna with elevation axis above azimuth axis

This type of antenna can be used for all kinds of satellites with satellite orbits up to 85° elevation. In the zenith, this antenna type has a keyhole. It provides different options for the mounting of the receiving equipment e.g. a cabin direct at the dish.

Tracking satellite orbits up to 85° elevation with this type of antenna requires an azimuth speed of around 15°/s depending on the satellite altitude.

Particularly for low orbiting satellites with high elevation angles there is a risk to lose the contact with the satellite if the azimuth speed is not sufficient.

The diagram in Fig. 5.1-13 shows the relation between the satellite orbit, the azimuth speed and the attainable elevation angle.

To be able to reduce the azimuth speed, antennas can be used with a so-called tilt axis. Tilt axis systems shift the whole antenna pedestal slantwise.

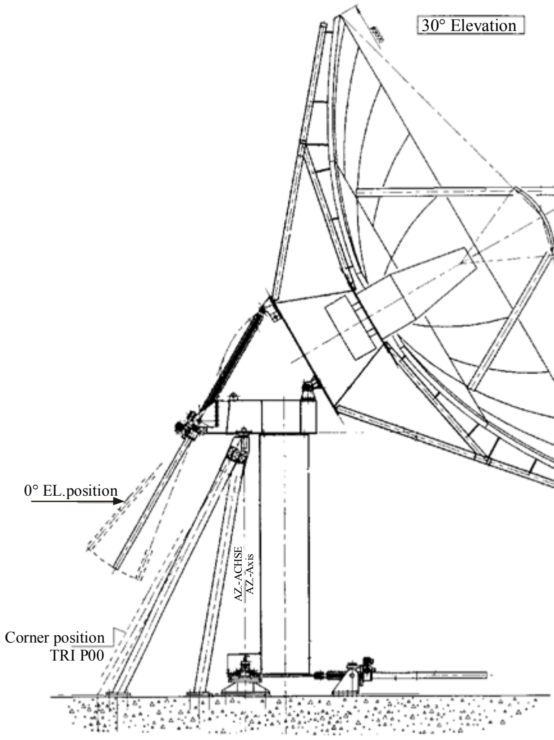
This enables satellite tracking without interruption even at lower azimuth velocity.

The satellite orbit must be well-known (e.g., two line elements) for the advanced calculation of the tilt angle. Tilting cannot be used for satellites with unknown orbit data.

These satellites can for example be tracked by means of monopulse tracking.

FIGURE 5.1-11

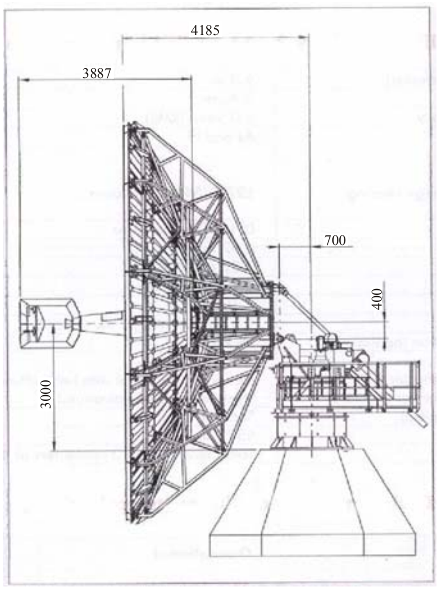
9 m limited motion antenna with Kingpost Pedestal and motorized jackscrews in azimuth and elevation



Spectrum-5.1-11

FIGURE 5.1-12

Example: 9.3 m turning head antenna

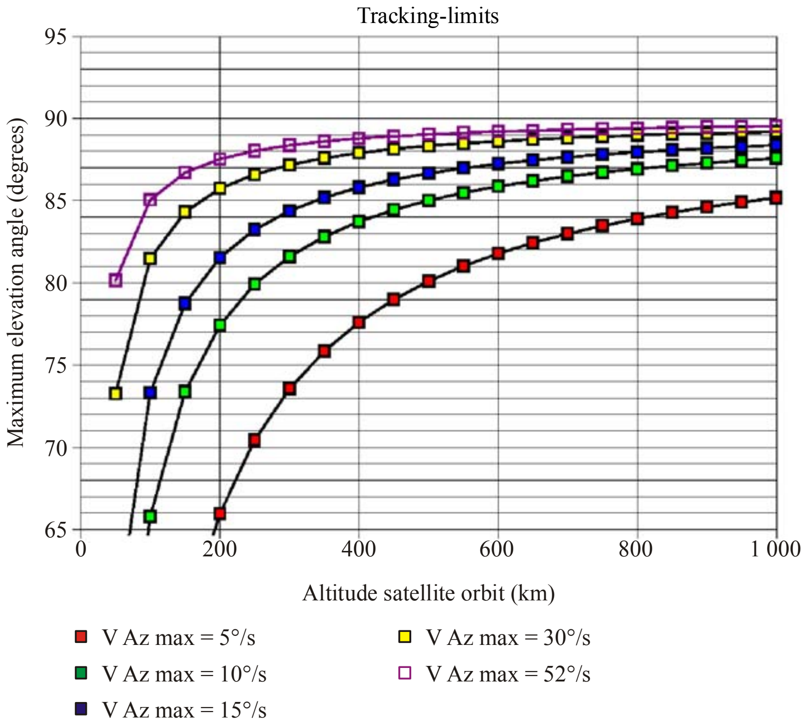


9.3 m antenna roof top version (0° elevation)

Spectrum-5.1-12

FIGURE 5.1-13

Relationship between satellite orbit, elevation angle and azimuth velocity for the antenna type elevation axis above azimuth axis



Spectrum-5.1-13

FIGURE 5.1-14

12 m Cassegrain beam waveguide antenna with an elevation above azimuth pedestal and 2 cabins for the receiving facilities at the rear side of the dish

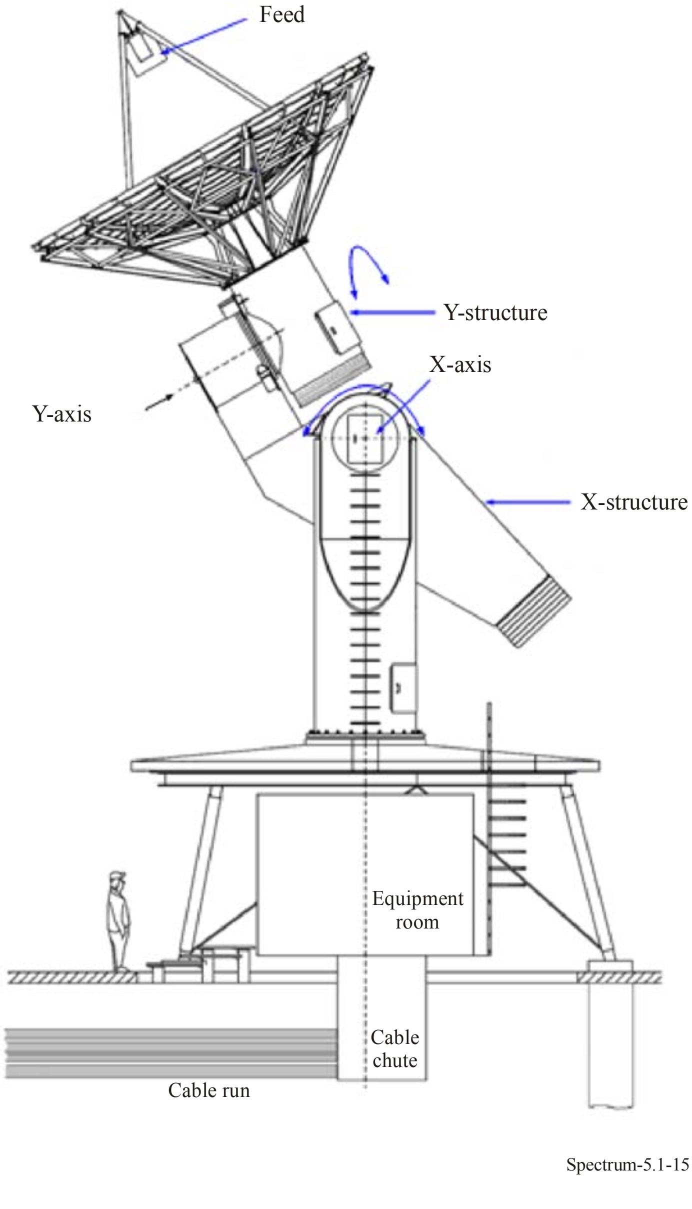
Spectrum-5.1-14

X-Y antenna

This type of antenna has the advantage that any type of orbit can be tracked without keyholes in the zenith. The special axis construction needs only slow velocity and acceleration (≤ 3°/s). The disadvantage is that the reverse side of the antenna provides only limited space for receiving equipment.

FIGURE 5.1-15

7 m X-Y prime focus antenna



Spectrum-5.1-15

Antennas specification

Table 5.1-7 provides technical specifications of practical satellite monitoring antennas. As the requirements depend on the station, the figures in the table should be regarded as typical minimum specifications. The actual parameters, however, should be determined by the specific measurement requirements.

TABLE 5.1-7

Technical specifications of practical satellite monitoring antennas

Parameter		Performance		
		L/S/C-Band	**Ku-Band**	**Ka-Band**
Frequency range		L band: 1 452-1 492 and 1 530-1 800 MHz S band: 2 100-2 300 MHz 2 500-2 690 MHz C band: 3 400-4 200 and 4 500-4 800 MHz	10.70-12.75 GHz	17.30-21.20 GHz
Maximum signal level at the input of Low noise amplifier (LNA) (dBm)		≤ –30	≤ –30	≤ –30
Power flux density (pfd) measurement performance (*C/N* at least 23 dB)		–155 dBW/m^2 in 4 kHz bandwidth	–165 dBW/m^2 in 4 kHz bandwidth	–160 dBW/m^2 in 4 kHz bandwidth
pfd measurement accuracy (dB)		±1	± 1	± 1
Figure of Merit (*G*/*T*) (dB/K)		L = 20 S = 23 C = 28	37	33
Reference frequency accuracy		Aging: one part in 10^{10} per day, Temperature: one part in 10^9 0° to 50° total change		
Polarization		X, Y, left-hand circular, right-hand circular		
Frequency resolution (kHz)		1		
Dynamic range (dB)		≥ 60		
Antenna	Dish diameter (m)	≥ 9	≥ 9	≥ 4.5
	Pointing accuracy (degrees)	0.15-0.04	0.02-0.017	0.025-0.02
	Beam width (degrees)	1.6-0.5	0.22-0.18	0.27-0.22
	Step-track speed for GSO satellites (degrees)	0.02-2/ s, manual drive and auto step track (depending of the antennas location longitude and latitude)		
	Coverage for GSO satellites (degrees)	EL: 0 to 90, AZ: ± 60		
	Coverage for non-GSO satellites (degrees)	EL: 0 to 85, AZ: ± 270°(total azimuth coverage 360), store at 90		

NOTE 1 – The frequency ranges in this table and other sections in § 5.1, such as L, S, C bands, are not defined in the ITU RR, but are widely used in the satellite communication community. These frequency ranges may be defined slightly differently depending on the source.

NOTE 2 – For the measurement of out-of-band emissions, the mentioned commercial frequency bands must be enlarged. Strong terrestrial emissions have to be blocked with filters.

5.1.6.1.2 Receiving facilities

The advantage of a beam waveguide system is that the beam can be directed to different locations with low insertion loss.

The feeds can be accommodated in equipment cabins providing sufficient space for the installation and maintenance of equipment and air condition.

The feed systems for satellite monitoring antennas are relatively unique, since these antennas are used for receiving only, and generally cover a wide frequency range.

FIGURE 5.1-16

Example: Separated feeds with a moveable feed and a select reflector layout for 3 frequency bands into a 12 m beam waveguide antenna

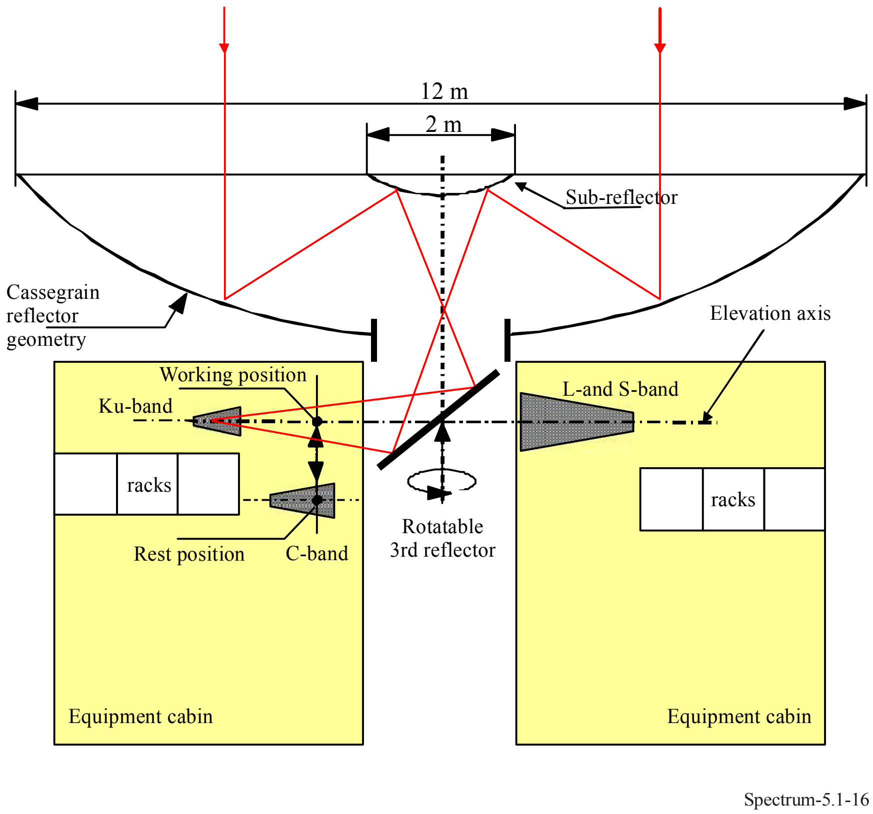
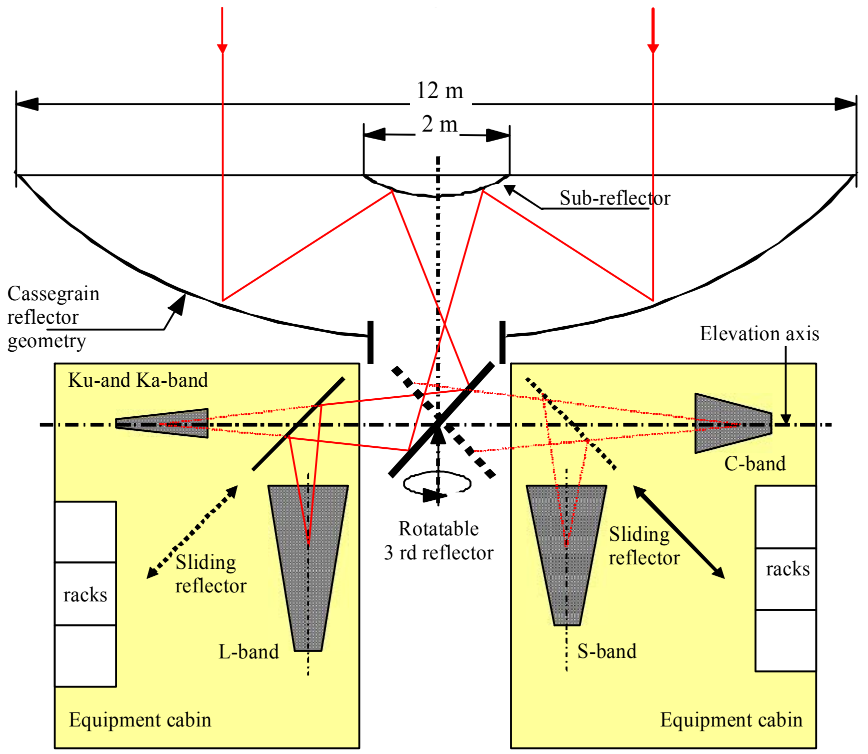


FIGURE 5.1-17

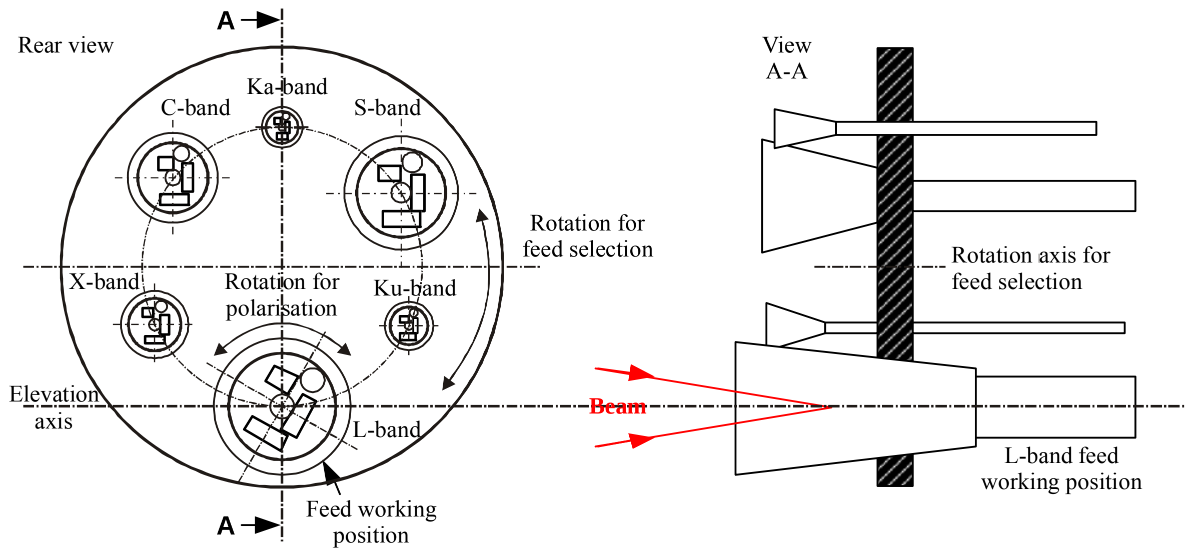
Example: Fixed feeds with moveable select reflectors layout for 5 frequency bands into a 12 m antenna



Spectrum-5.1-17

FIGURE 5.1-18

Example: Multi feed revolver system with 6 feeds for a beam waveguide antenna



Spectrum-5.1-18

Example: Multi feed revolver system with 8 feeds for a prime focus antenna

Frequency range: 1-26.5 GHz without frequency gaps.

Feed 1 up to 6 (frequency range 1 GHz-12.75 GHz) are crossed dipoles with cavity design.

Feed 7 and 8 (frequency range 12.5 GHz-26.5 GHz) are horn antennas.

Outdoor case dimension: around 700 x 700 x 500 mm [*W* x *D* x *H*]

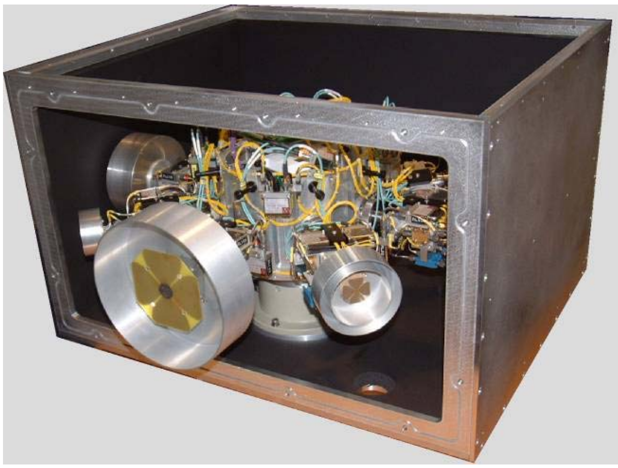
FIGURE 5.1-19

Multi feed mounted in prime focus

Spectrum-5.1-19

FIGURE 5.1-20

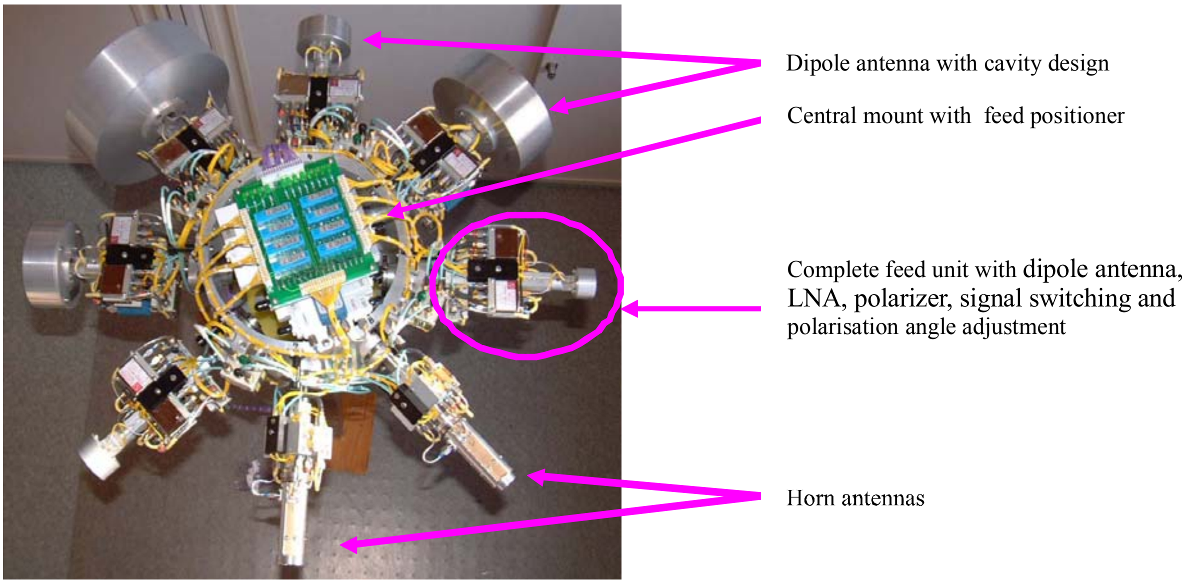
Multi feed in the open outdoor case



Spectrum-5.1-20

FIGURE 5.1-21

Feed without outdoor case mounted around the feed positioner



Spectrum-5.1-21

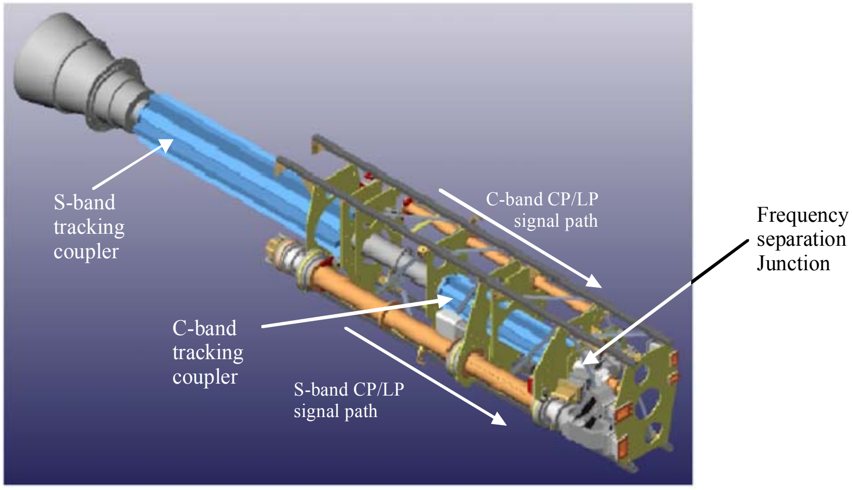
All feeds designed in coax technique for linear and circular polarization and polarization angle adjustment of ± 95°.

FIGURE 5.1-22

Example: Combination of 3 frequency bands into a 12 m antenna

Feed system for Cassegrain antenna configurations 11 m and larger. CP/LP switching, independent LP polarization adjustment and monopulse tracking in both bands.

S-band: 2.1-2.7 GHz
C-band: 3.4-4.8 GHz



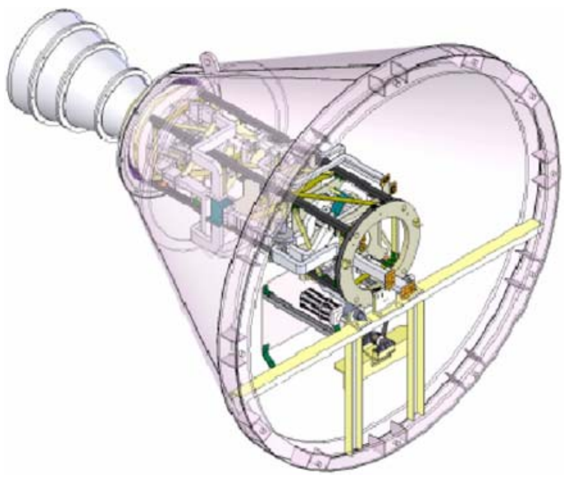
Spectrum-5.1-22

FIGURE 5.1-23

Example of feed with 2 closely spaced frequency bands

Feed system for Cassegrain antenna configurations 9 m and larger.

C-band: 3.4-4.2 GHz, CP/LP
X-band: 7.25-8.4 GHz, CP
Ku-band: 10.9-12.75 GHz, CP/LP



Spectrum-5.1-23

Receiving equipment

The receiving equipment comprises the following items in Table 5.1-8:

TABLE 5.1-8

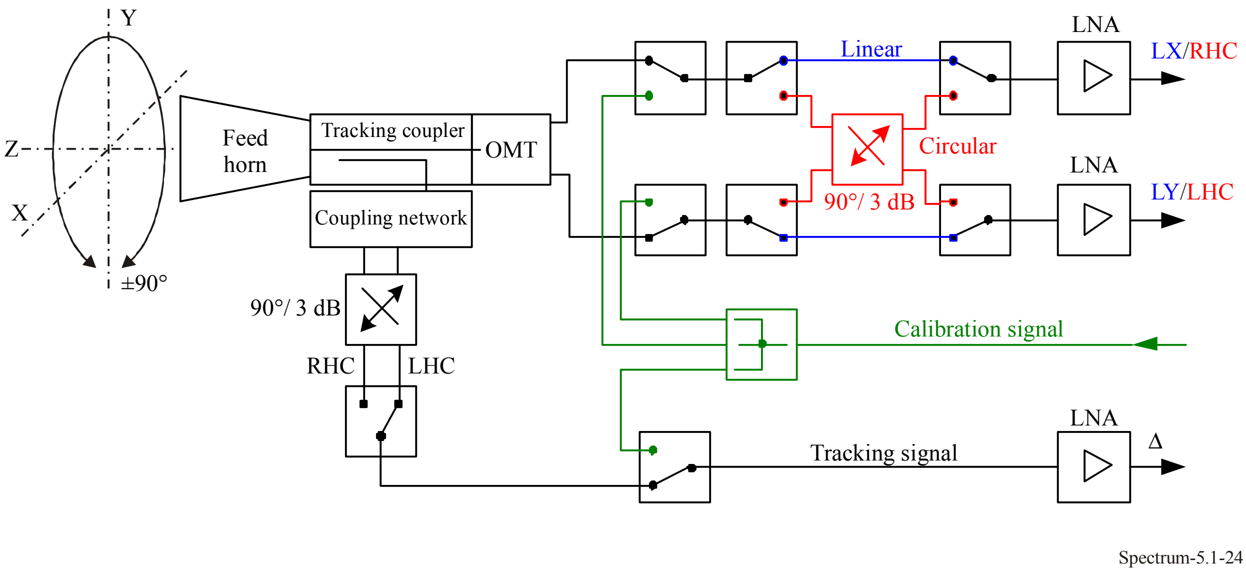
Receiving equipment of an antenna system

Feed	Horn-, dipole- or cross dipole-antenna and the coupling network
Tracking coupler	Coupling out the TE21 mode for the monopulse antenna tracking
Polarization adjustment	Rotator for the adjustment of the polarization angle
Orthomode transducer (OMT)	Separation of the polarization planes X and Y in two channels
Low noise amplifier (LNA)	First amplifier with a noise figure as low as possible
Polarizer	Combine the X and Y channels into RHC and LHC polarization in the case of circular polarization
Down-converter	Converts the RF signal into a broadband IF and/or a narrowband IF e.g., 70 MHz IF
Switching and post amplifying	Switches the different signal paths and amplifies the IF for the transmission to the main building

Depending on the type of antenna these components may be spatially separated.

FIGURE 5.1-24

Block diagram: Example of a feed system with tracking coupler and polarizer

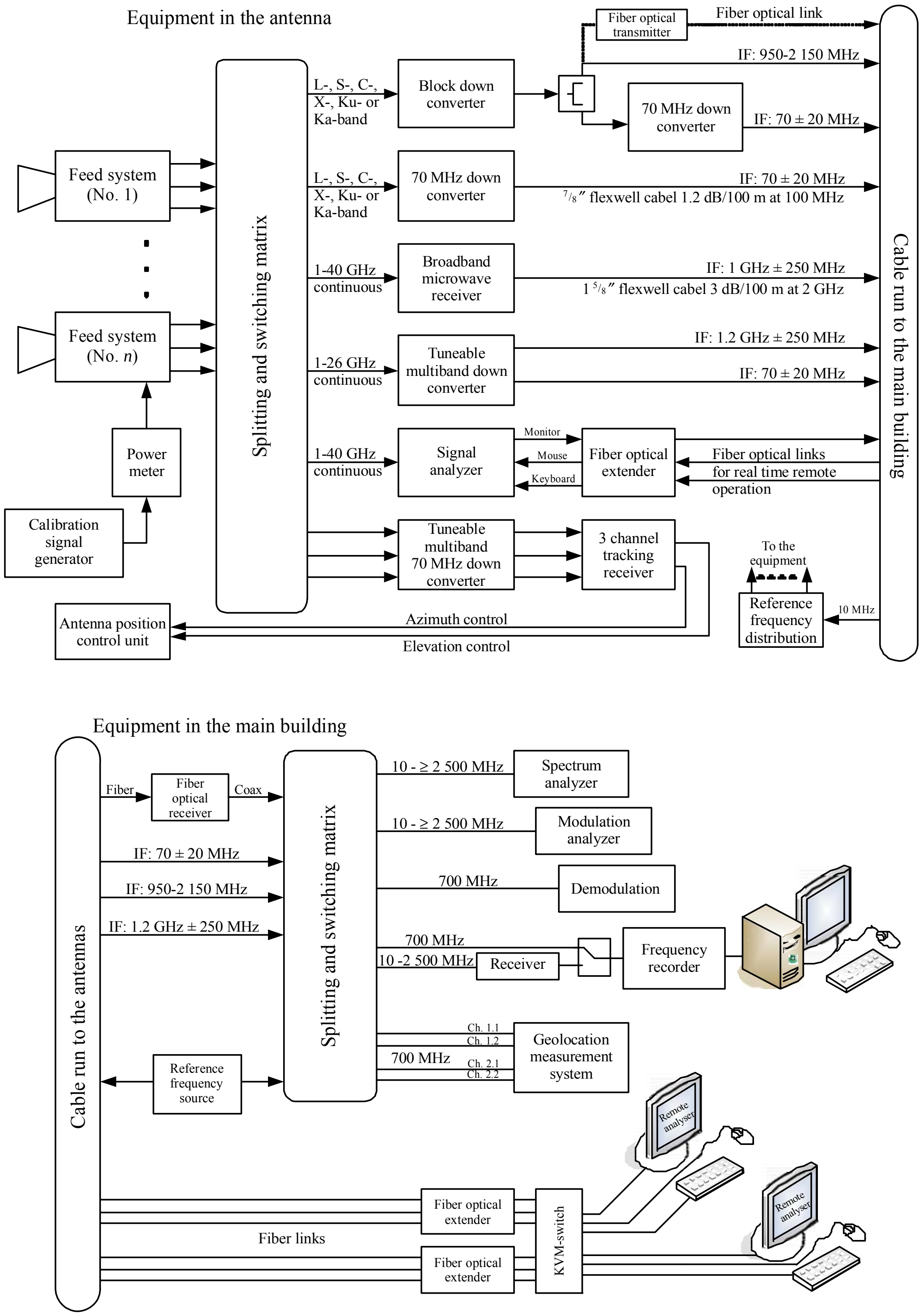


5.1.6.1.3 Monitoring equipment

The following diagrams as in Fig. 5.1-25 show examples for the integration of monitoring equipment.

FIGURE 5.1-25

Integration of monitoring equipment



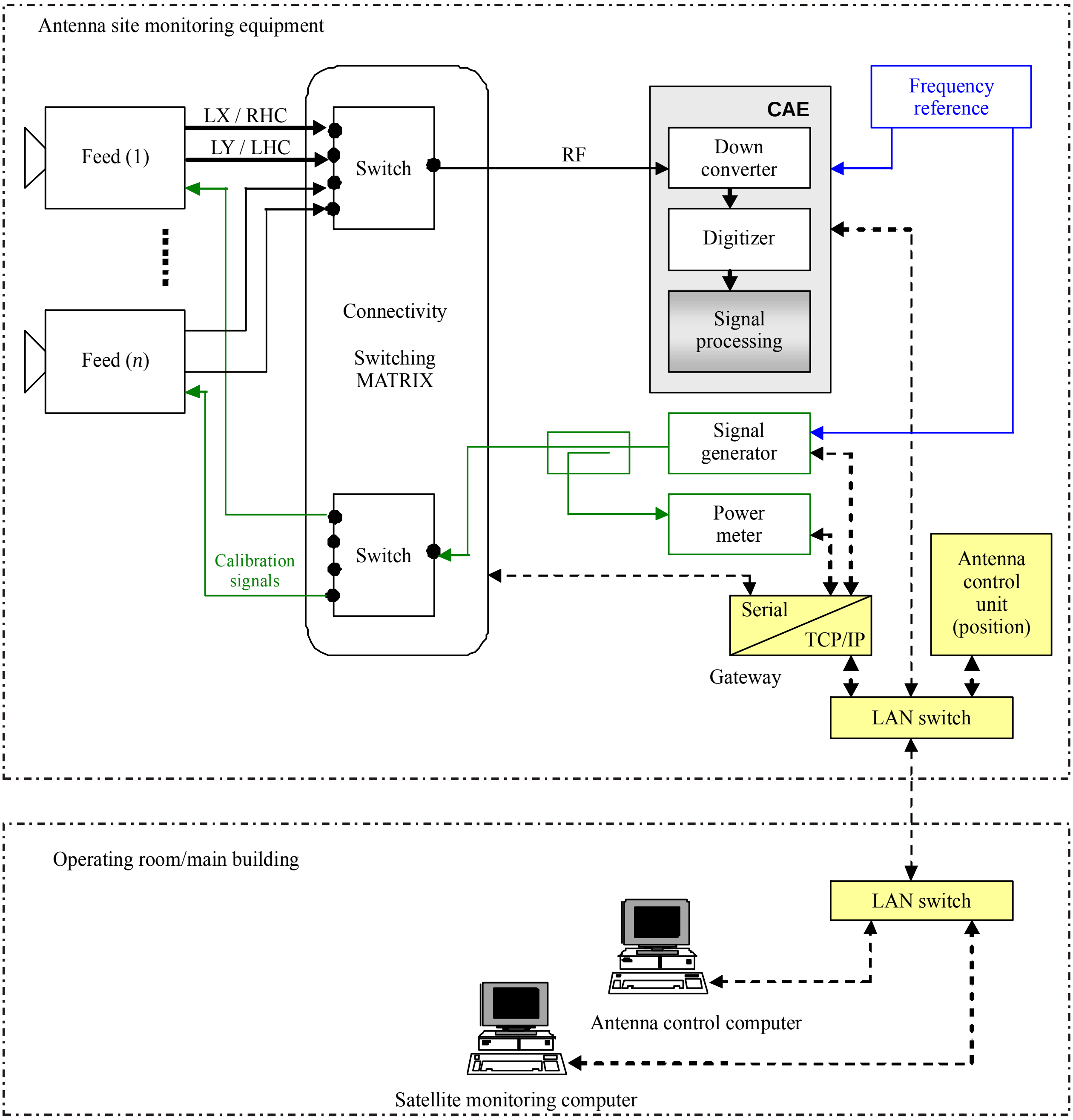
Spectrum-5.1-25

Automated satellite monitoring system

The following figure as in Fig. 5.1-26 shows an automated monitoring system for carrier acquisition. The carrier acquisition equipment (CAE) hardware architecture for satellite monitoring uses a calibration system and injection points which are shown in the figure. The power meter controls the calibration signal from the signal generator.

FIGURE 5.1-26

Example of an automated satellite monitoring equipment



Spectrum-5.1-26

The CAE is capable of:

– Acquiring satellite frequency in L, S, C, Ku and Ka bands.
– Detecting all carriers above noise floor (typical 6 to 10 dB above noise floor).
– Getting RF parameters for each carrier.
– Giving a full carrier classification including all digital parameters used by the modulator and the standard that is used.

The CAE shall be able to analyze and classify carriers of up to 80 MHz bandwidth which covers most of the civilian transponders.

When satellite traffic is known, the CAE detects unwanted carriers and optionally localizes the transmitters using FDOA and TDOA methods.

For the automated satellite monitoring, the following measurements should be carried out:

– RF measurements:
  – Carrier power at equipment level.
  – Carrier e.i.r.p. at satellite level.
  – Carrier C/N_0.
  – Carrier frequency by barycentre, recovery, carrier shape, peak search methods.
  – Carrier bandwidth: *x*-dB method, ß% of total power method, derived from symbol rate calculation.
  – Spectrum observations and analysis tools (markers, zoom, spectrogram, selectors).
  – Transponder e.i.r.p. at satellite level.
– Digital measurements:
  – Carrier characterization.
  – Modulation type.
  – Bit rate (transmission rate).
  – FEC rate.
  – Reed Solomon rate.
  – Standard used.
  – Carrier demodulation diagram.
– Carrier detection based on power density detection (typical 6 to 10 dB above noise floor):
  – Subsequent database update.
  – Inside defined carrier detection (carrier rejection capability shall be better than 13 dB).
– Spectrum observations, virtual spectrum observations by simulating end-user G/T.
– Fast spectrograms to visualize fast slots drifts (e.g., MF TDMA access).
– Orbital parameters (orbital position accuracy of at least ±0.1°).
– Calibration should be is used to determine the gain of the reception chain.

The software system on the satellite monitoring computer should perform both interactive and automated measurements.

Interactive measurements allow the operator to investigate signals rapidly. Interactive measurements include observation of multiple bands in multiple formats, hand off signals to carrier measurements and control of the spectrum analyzer and optionally receiver, tape recorder, printer and plotter.

Automated measurements should be triggered under event occurrence (see Note 1) or scheduled in background without an operator present. A task scheduling shall allow coordinating signal presence, carrier measurements, spectral occupancy and statistical measurements.

NOTE 1 – For example an automated target signal and reference signal recording may be started immediately after unwanted signal detection. This allows paving the way for the geolocation module.

The monitoring screenshot in Fig. 5.1-27 showing spectrum and spectrogram information is given hereafter as an example:

FIGURE 5.1-27

Example of spectrum monitoring screen on the satellite monitoring computer

Spectrum-5.1-27

5.1.6.1.4 Control facilities

Operation modes of antenna control system

For the space radio monitoring an efficient control of the antennas simply to be operated is necessary. The quantity of the different operation modes should be various to point the antenna just at difficult satellites constellations efficient.

The most common antenna control functions are listed in Table 5.1-9.

TABLE 5.1-9

Operation modes of antenna control system

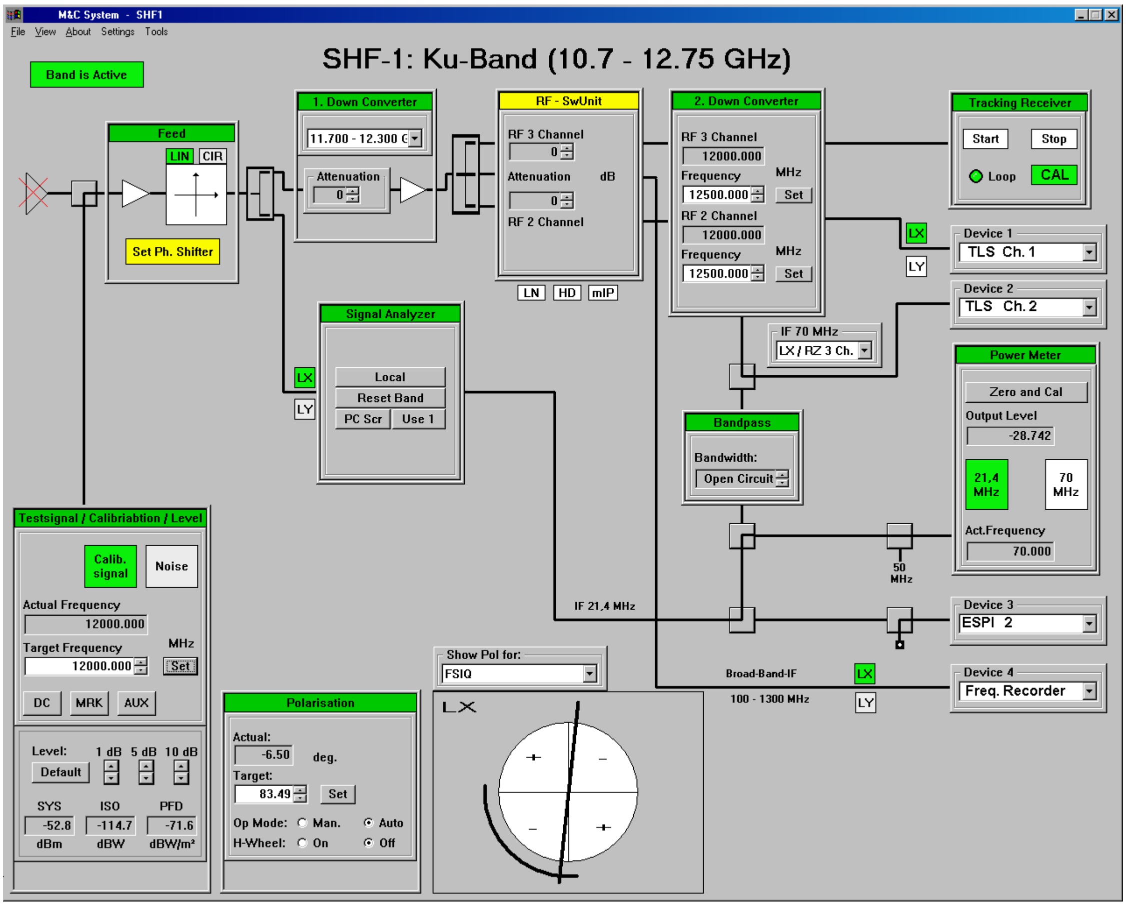
Modes	Description	Comment
PRESET	Movement to predefined position Input: Az and El values	
GEO PRESET	Movement to pre-defined position Input: Satellite position e.g., E19.2°	Set the antenna to a GSO orbit position without user calculation of Az and El values
POSITION	Movement at user-defined angle around the actual antenna position	Moves the antenna in Az and El with 4 arrow buttons or with knobs for manual antenna adjustment
RATE	Movement at user-defined constant velocity	Most for calibration and test measurements
PROGRAM TRACK	Tracking of an object along a pre-defined path with Az, El, Data and Time data records	
TLE TRACK	Tracking of an object along a pre-defined path with TLE orbital data sets from NORAD	
STAR TRACK	Tracking of astronomical targets	Option for calibration and test measurements
AUTO TRACK	Tracking of an object using tracking error signals (monopulse tracking)	Needs a monopulse tracking coupler in the feed system and a monopulse tracking receiver
STEP TRACK	Tracking of an object using step track receiver	Needs a step track receiver but without additional components at the feed system
ORBIT PREDICTION TRACKING	Intelligent step track	Option to improve the step tracking pointing accuracy
MEMORY TRACK	Tracking using last stored satellite position data	
SECTOR SCAN	User defined sector is scanned horizontally/ vertically	Helpful to find a satellite e.g., a high inclination satellite
SEARCH SPIRAL	Pulsating spiral around last actual position	Helpful to find a satellite e.g., a high inclination satellite
GEOSYNC	Pointing to a pre-defined geo-synchronous orbit and movement on the geo arc	Manuel movement with east/west buttons along the geo arc

Monitoring and control system

The monitoring and control system (M&C) is a central computer based system for the control of all facilities in the monitoring station. A graphical user interface (GUI) represents an abstracted clearly arranged overview of the equipment and switching status on every operator’s place (see Fig. 5.1-28 for example). For the prevention of access collisions on equipment, the system should have an assignment and locking mode. The measurement units can depend the M&C development state and the requirements completely controlled or only for the manually use connected at the signal path of the M&C. To make an efficient workflow possible, the operation of the antenna positioning and the device control should be divided up on two monitors.

FIGURE 5.1-28

Example: GUI screen of a monitoring and control system (M&C)



Spectrum-5.1-28

Following equipment is controlled and inspected:

– Antenna control system for the pointing and searching functions.
– Antenna tracking system with the monopulse or the step track receivers.
– Feed system with polarization switching and polarization angle adjustment.
– Down-converters, filters and post-amplifiers.
– All switching units for connection and distribution of the RF an IF signals.
– The connection and the settings of the measurement and analytic units.
– Launching automated measurement software.

Signal 1.1 and 1.2 received by the antenna 1 from the interfered satellite. Signal 2.1 and 2.2 received by antenna 2 from the adjacent satellite.

Signal 1.1 and 2.1 is the interferer signal, 1.2 and 2.2 is the reference signal.

FIGURE 5.1-29

Principle: Geolocation measurement system

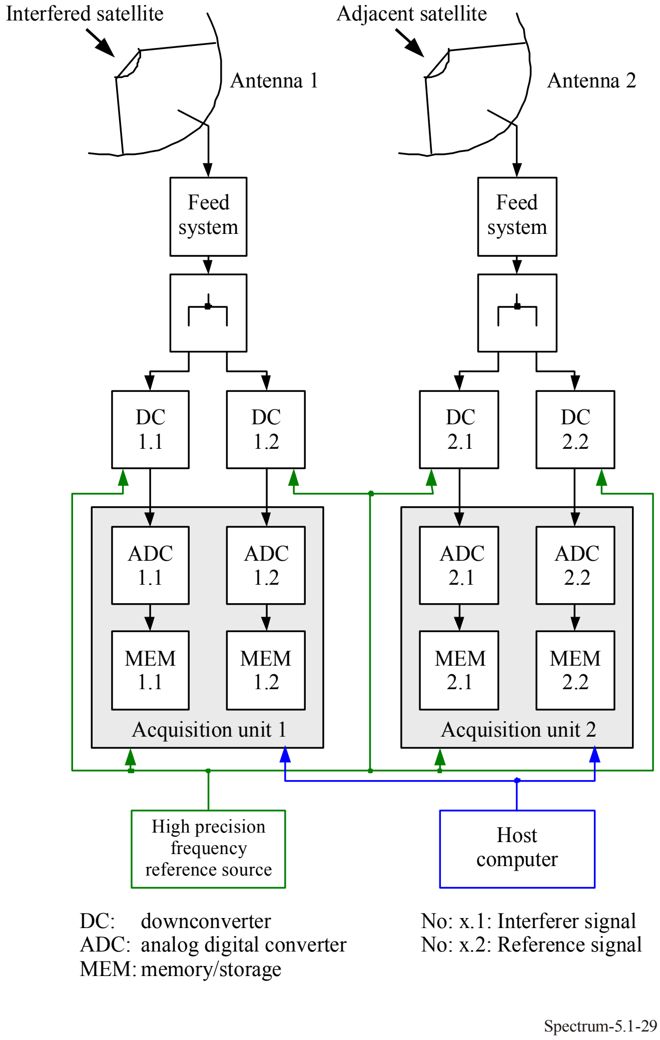
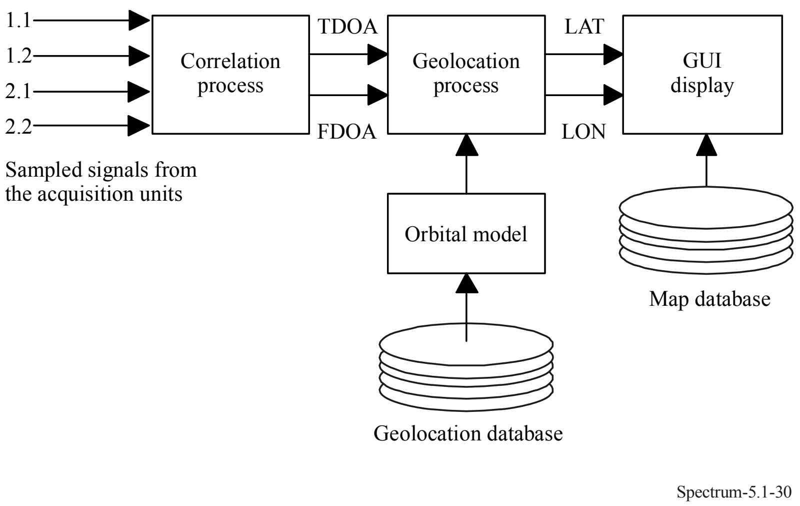


FIGURE 5.1-30

Principle of geolocation calculation procedure in the host computer



5.1.6.2 Process for radio monitoring of GSO satellites

An automated system for radio monitoring of GSO satellites is described below. It attempts to minimize the number of operators in its task of measuring the orbit and radio wave quality using various techniques.

The automated monitoring system is equipped with a computer program which has the following managing functions:

– Control, for the establishment of operation priority.

– Registration, for the scheduling of a single measurement.

– Error detection of the system software with a reporting function to operators.

– Searching and measuring.

– Calibration of the system and inspection to check whether the monitoring facility operates properly.

– Reporting for measurement result to the operators.

– Storing of the registered satellites and the measurement results in the database.

Operators of the space radio monitoring station should construct the monitoring schedule so that monitoring tasks are routinely performed according to the monitoring plan.

For detecting harmful interference sources, monitoring new satellites and measuring the frequency spectrum occupancy in detail, the semi-automatic and manual modes may well operate simultaneously.

The specified items in the monitoring schedule include such items as monitoring time, automatic or semi-automatic mode selection, satellite name, number of times for monitoring, task priority etc.

Figure 5.1-31 shows the example of the sequential process of monitoring.

Measurement items of the scheduling process include satellite orbital position, polarization, centre frequency, power flux-density, occupied bandwidth and so on. It is important for space radio monitoring facilities to have techniques for fast tracking, choosing polarization by means of comparison algorithms, locating centre frequencies for measuring occupied bandwidth, and measuring carrier power.

The polarization is determined by repeatedly checking incoming measurements against the polarization criteria.

Usually, the mono-pulse tracking method is chosen but other methods such as step tracking are also used.

Satellite identification is verified by comparing measurement result with the satellite database.

Repetition of measurement and corrections are required in order to improve the accuracy and reliability of the measurement results.

Such a measurement task should be performed with high reliability considering the propagation characteristics at the high frequency and the weak signal of the satellite received on the Earth. The monitoring stations verify whether the satellite is operated following the technical standards and regulations.

Moreover, operators register or renew the operation schedule for any new monitoring request and special task. Storing of the standard procedures which are often used will simplify the registration process.

5.1.6.3 Precise orbital longitude monitoring (radio interferometry)

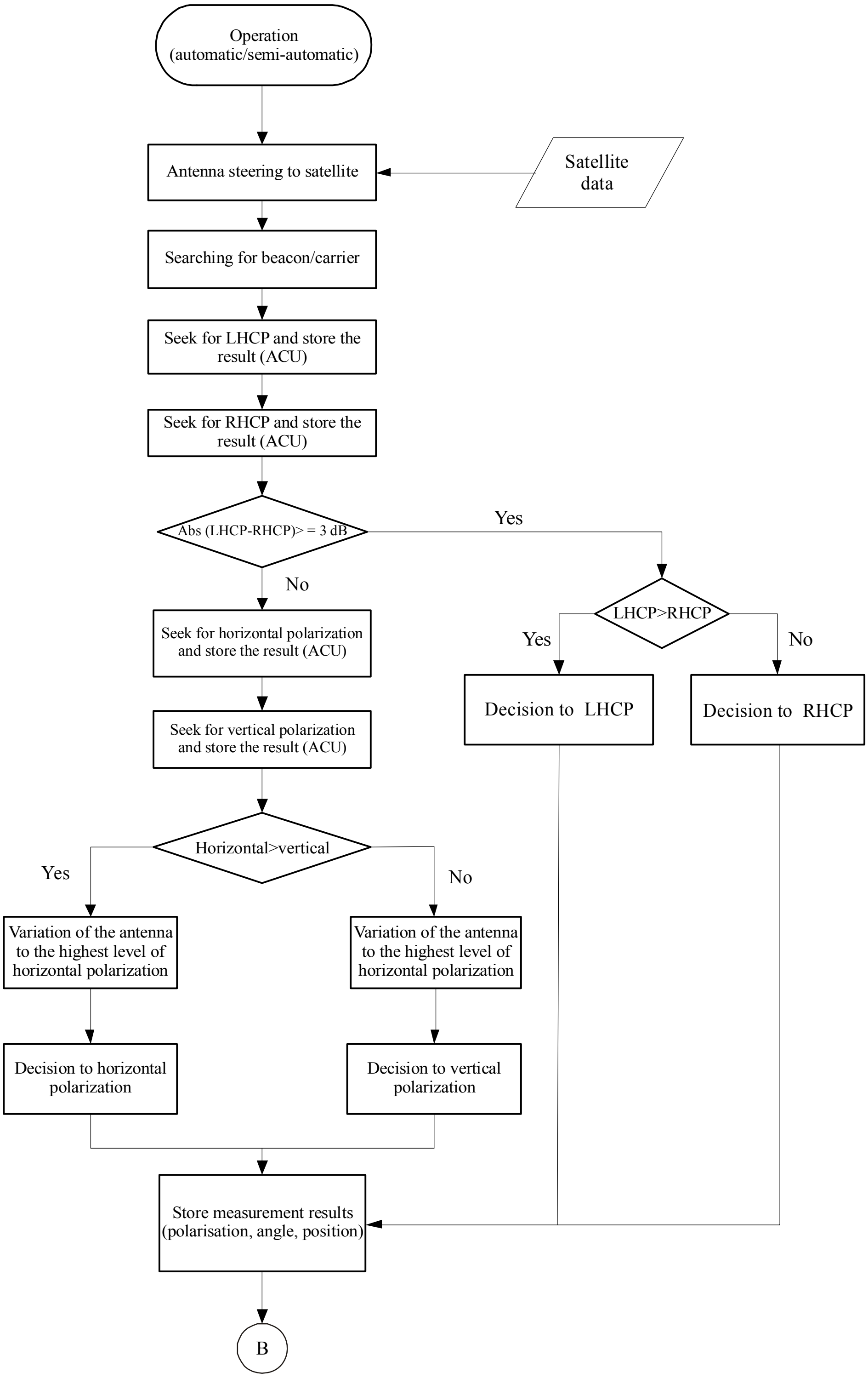
5.1.6.3.1 Purposes of precise orbit monitoring

There is a growing demand for precise orbit monitoring owing to the ever increasing number of satellites in geosynchronous orbits. Strict station-keeping is necessary for satellites located at orbital longitudes that are close to each other, without which the satellites may come too close to one another. Accordingly, the precision in orbit monitoring must be more than the conventional ±0.1°.

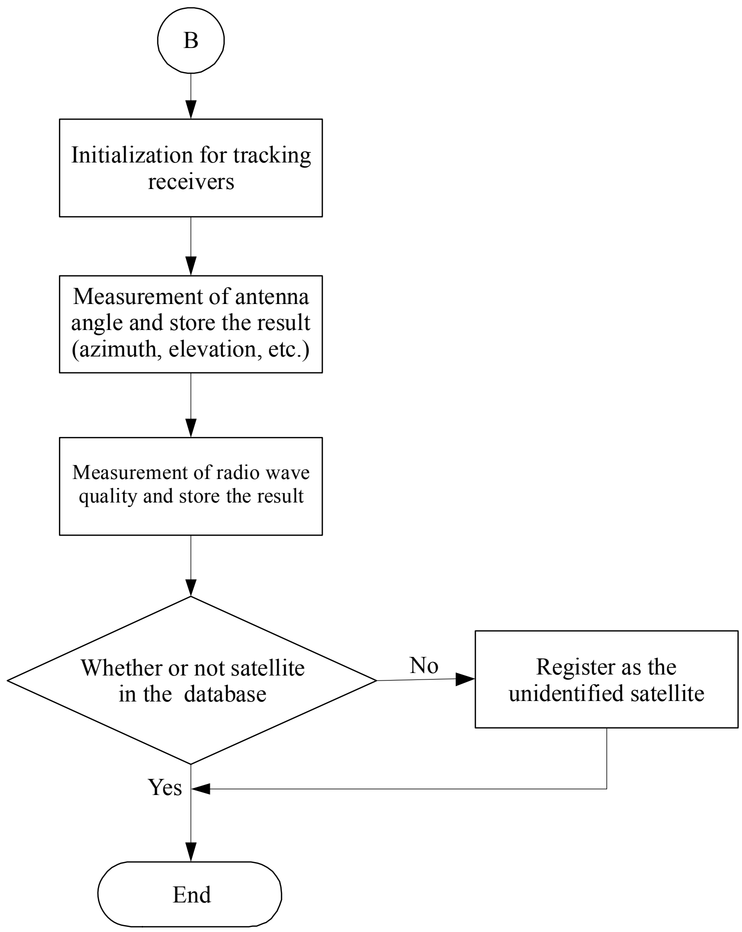
In some cases, two or more satellites are located at the same orbital longitude. In such a case, the orbital slot of ±0.1° is divided into sub-slots, and each satellite is allotted a unique sub-slot. Monitoring in such cases must be even more precise.

FIGURE 5.1-31

Sequential process of monitoring



Spectrum-5.1-31



Spectrum-5.1-31-cont

Precise orbit monitoring is also essential in the geolocation of transmitters, since geolocation relies on accurate information regarding the six orbital elements of satellites. A monitoring station that operates transmitter geolocation should preferably be capable of generating orbital information by receiving satellite down-links.

There is thus a growing need for precise orbit monitoring of geosynchronous satellites. A promising technique that can be used for this purpose is radio interferometry. An example of a radio interferometer with its technical specifications and operation procedure is presented in the following sections.

5.1.6.3.2 Interferometer hardware

An interferometer is basically a system comprising two receiving antennas for measuring phase differences, while an actual orbit-monitoring interferometer takes the form shown in Fig. 5.1-32. The down-link microwave from a target satellite is first reflected by mirror A and then by mirror B, before being received by antenna C. The mirrors are planar. Similarly, the microwave is reflected by mirrors D and E, before being received by antenna F.

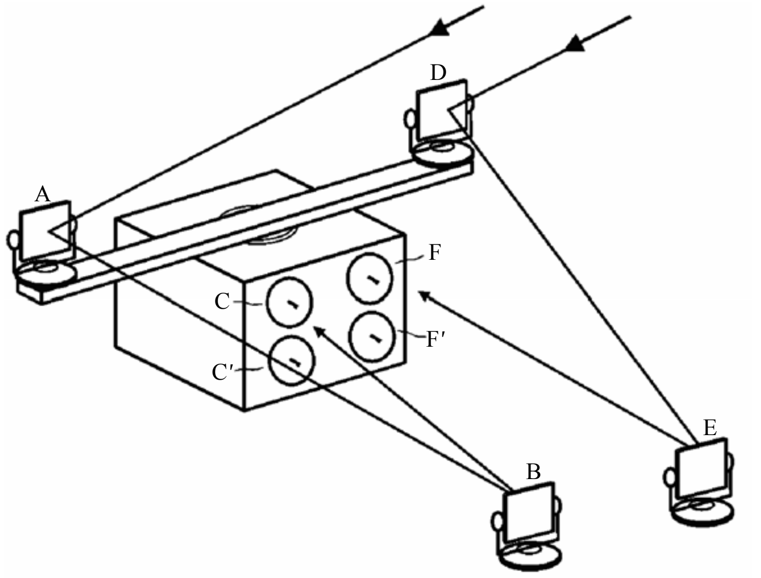
The phase differences between antennas C and F are measured. After correcting for the phase delays over paths A-B-C and D-E-F, one can assume that the receiving antennas are at A and D. Line AD then becomes the DF baseline of the interferometer.

Mirrors A and D are positioned on a horizontal rotary arm, for reasons shown later. As the arm changes its orientation, the mirrors are repointed so that the microwaves are accurately guided to the receiving antennas. The two pairs of antennas (C, F and C′, F′) are used for two different frequency bands. Mirrors B and E are tilted to choose the desired pair of antennas.

FIGURE 5.1-32

Radio-interferometer for geosynchronous orbit monitoring

A, B, D, E: planar mirrors; C, F, C′, F′: fixed antennas



Spectrum-5.1-32

Figure 5.1-33 illustrates the measurement of phase difference between the antennas for a given frequency band. In each receiving route, signals are down-converted before being input to FFT. The down converters are phase-synchronized by using local signals from a common oscillator (LO). The Fourier-transformed data are then cross-multiplied and time-integrated; this process is referred to as correlation processing. Since noises are suppressed by time-integration, the phases are measured with an improved *S*/*N*, and this is equivalent to improving the receiving antenna's *G*/*T*.

The correlation processor has a bandwidth of 20 MHz, and any signal within this bandwidth – beacon or band-pass communication signals – can be chosen as the measuring target. Reference signals from a common oscillator (RO) are coupled into the low-noise amplifiers, in order to compensate for phase variations that can occur in the receiving routes.

The specifications of the interferometer are listed in Table 5.1-10. The fixed antennas and rotary arm with mirrors appear as in Fig. 5.1-34. Other mirrors, which appear as in Fig. 5.1-35, are 16m away from the fixed antennas. Presently, the interferometer has two frequency bands, and a new band can be added by placing another pair of receiving antennas and down-converters.

The receiving equipment shown in Fig. 5.1-33 uses conventional earth-station antennas and components, while the correlation processor is specific to this interferometer.

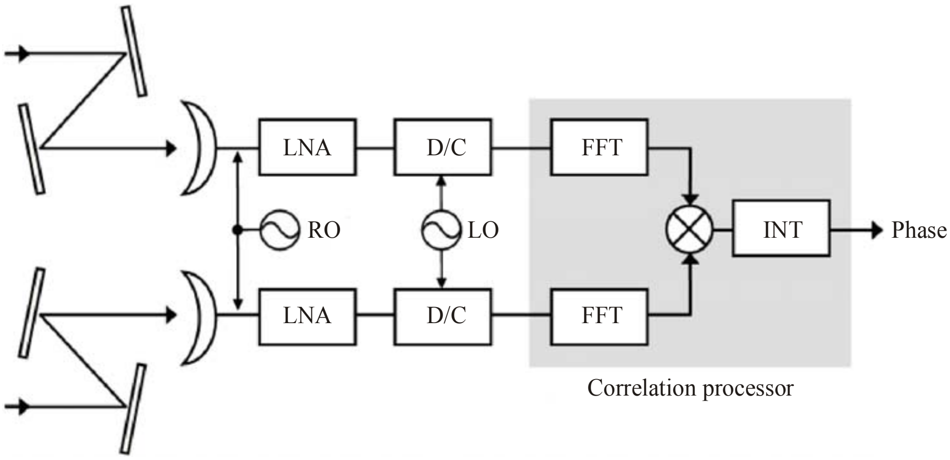
If the interferometer were designed so as to mount the receiving antennas on the arm at A and D in Fig. 5.1-32, the cables between the antennas and the in-house units would twist as the arm rotates, thus causing phase errors.

The use of guiding mirrors enables the placement of antennas C and F (and C′ and F′) side by side; hence, the lengths of the cables can be sufficiently shortened to ensure phase stability when the surrounding temperature changes. In addition, mirrors B and E are useful for band switching. The arm and the mirrors can balance weights around their rotary pivots owing to their symmetric forms. So, small motors can drive them smoothly.

FIGURE 5.1-33

Block diagram for phase-difference measurement

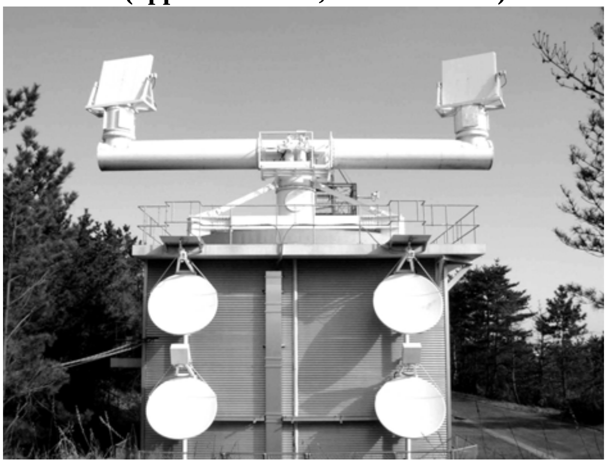
LNA: low-noise amplifier; D/C: down-converter; FFT: fast Fourier transform
RO: reference oscillator; local oscillator; INT: time-integration



Spectrum-5.1-33

FIGURE 5.1-34

Rotary arm, planar mirrors and fixed antennas (upper: Ku-band, lower: C-band)



Spectrum-5.1-34

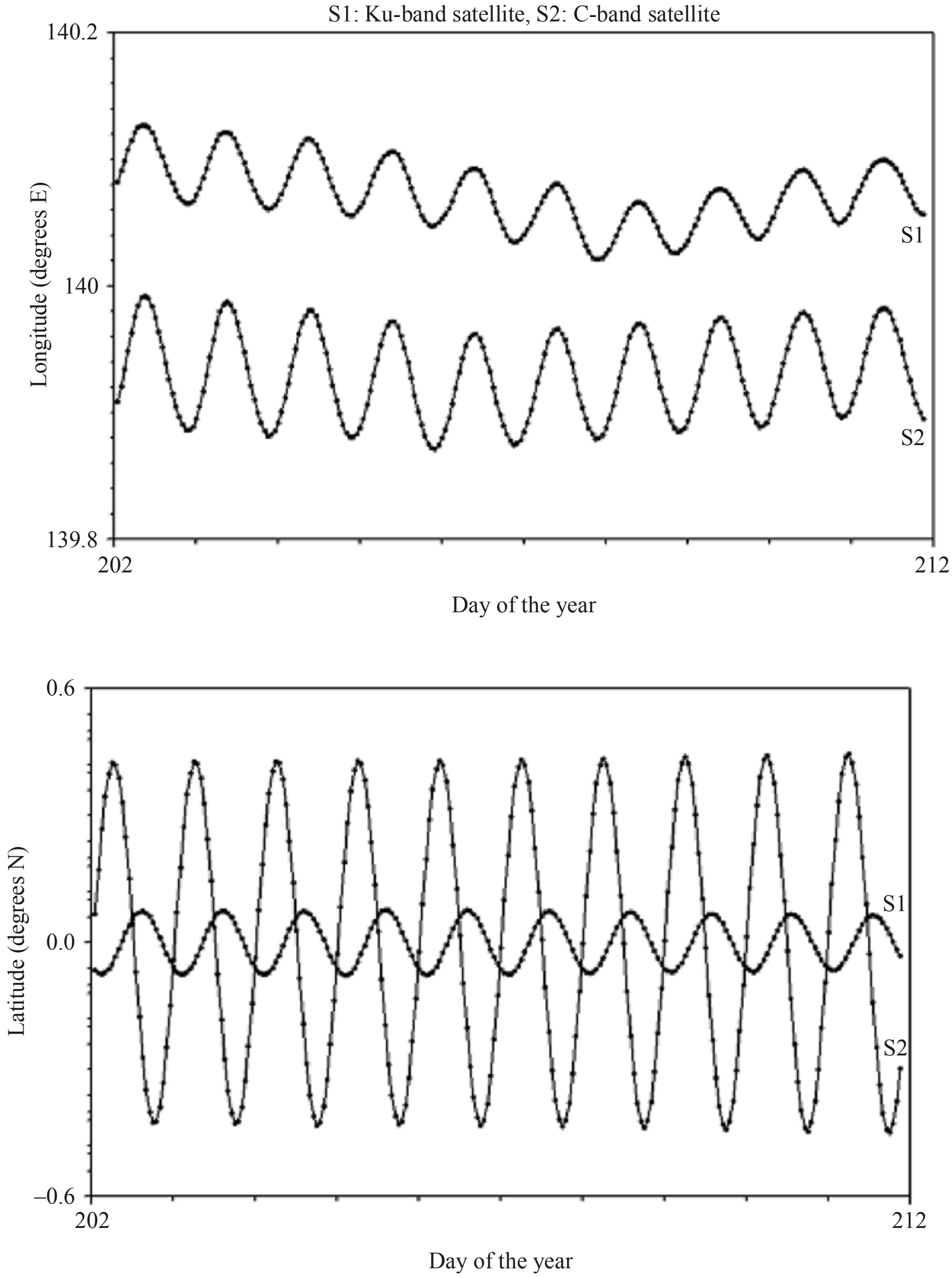
FIGURE 5.1-35

Planar mirrors for band switching

Spectrum-5.1-35

FIGURE 5.1-36

Example of satellite position monitoring



Spectrum-5.1-36

5.1.6.3.3 Interferometer operations

The interferometer operates in different modes for different monitoring purposes, as listed in Table 5.1-11.

The rotary mode is a start-up procedure for monitoring an unknown satellite. The arm goes through one revolution while stopping at every 15° of the orientation angle. Each time when the arm is at rest, phase data are collected. One round of data collection takes 15 min for one satellite. The phase data are then processed, to determine the satellite direction in azimuth and elevation. The rotary mode is essential for resolving phase ambiguity. If x is a phase measured in degrees, then it may also be equivalent to $x \pm 360$, $x \pm 720$, etc. Collecting phase data at different arm angles allows unambiguous determination of the satellite direction.

At the end of the rotary mode, monitoring of the same satellite can be continued in the quick mode. Phase data are collected, every hour, at two different arm orientation angles that differ by 90°. The data are recurrently input to an orbit estimation program from which satellite positions in longitude and latitude are output.

An example of this type of position monitoring is shown in Fig. 5.1-36, where two satellites operate in adjoining longitudes. Parallel monitoring of three or even more satellites is also possible, since one set of data collection for one satellite finishes in a few minutes. Six orbital elements can be also output if input data are sufficient. Data collection must be carried out at least for half a day, while it must be for one day for obtaining good orbital elements.

The fixed mode is used for monitoring satellite longitudes. The arm is oriented east-west and fixed at this position, while its precise angle depends on the location of the target satellite. Phase data are converted to satellite longitudes through a linear mapping function.

Prior to the fixed mode, the rotary mode must be carried out for starting up. The fixed mode is useful for monitoring long-term longitude occupancy of satellites.

5.1.6.3.4 Error calibration

Since the interferometer has movable components, mechanical positioning errors are inevitable. Major errors are modelled by the following parameters:

– Effective length of the arm.

– Bias in the arm orientation angle.

– Off-horizontal tilt of the arm for east-west orientation.

– Off-horizontal tilt of the arm for north-south orientation.

To calibrate the error parameters, five satellites at different orbital locations are chosen as references. The azimuth and elevation of the reference satellites are assumed to be known. The error parameters are then adjusted, so that the azimuth/elevation data from the interferometer agree with the reference data.

The errors are calibrated annually to maintain the accuracy according to the level specified in Table 5.1-10.

TABLE 5.1-10

Interferometer specifications

Frequency band	C: 3 400-4 200 MHz Ku: 11 700-12 750 MHz
Fixed antennas	Diameter: 1.8 m *G/T*: 16.8 dB/K (C) *G/T*: 23.2 dB/K (Ku)
Rotary arm	Length: 13 m Pointing precision: 0.001°
Planar mirrors	Square with a side of 2 m Pointing precision: 0.01°
Correlation processor	Bandwidth: 20 MHz Target signal: beacon or band-pass *S/N* improvement: 23 dB (1s-integration)
Direction-finding accuracy	0.005°

TABLE 5.1-11

Interferometer operation modes

Rotary mode	Arm rotates through one revolution Determines azimuth-elevation direction Starting up for quick mode/fixed mode
Quick mode	Arm rotates between two orientation angles Outputs longitude-latitude position Outputs six orbital elements
Fixed mode	Arm is fixed at east-west Outputs satellite longitude

5.1.7 Monitoring results by examples

5.1.7.1 Frequency band recording in the VHF band

Radio frequency spectrum recording systems are especially suitable for the monitoring of frequency bands for occupancy by emissions from low orbiting space stations in frequency bands below 1 000 MHz with an omni-directional antenna.

The structure of the occupancy pattern (Doppler curve) depends on the orbital elements of the satellite and is of fingerprint quality.

In addition to the receive frequency, the period of revolution (PERIOD raw), taken as the average of several consecutive revolutions, and the expected times of reception may be different. In order to determine the period of revolution with a satisfactory degree of accuracy (PERIOD fine) an iterative method is recommended using registrations taken over a period of several days on the basis of equations:

$$PERIOD\text{ raw} = T2 - T1 \tag{5.1-14}$$

$$PERIOD\text{ fine} = (Tx - T1)/n \tag{5.1-15}$$

Tx is the centre point of the receiving window one day or several days later. The divisor, *n*, is a fictitious number of revolutions in the case of equation (5.1-15).

It is systematically altered until the minimum divergence between the desired result for the *PERIOD* fine and *PERIOD* raw is achieved. In this way, the measurement error of the time of revolution may be reduced after a period of only 24 h to some tenths of a minute. The time of revolution and the characteristics of the recording pattern are reliable for the identification of a satellite.

Another method is the use of an adjustable time line grid as an overlay in the spectrogram of the recorded satellite emissions over a period of two or more days. If the time lines match the satellite emissions the PERIOD raw is found. In the example as shown in Fig. 5.1-37, the PERIOD raw is 112 min.

To find out the exact period time, the search in the NASA database is necessary as a second step.

With the result of 112 min it can search for satellites with a revolution period close to 112 min. Figure 5.1-38 illustrates the NASA-SSR database with marked satellites close to 112 minute-periods.

With the related two-line-elements the visibility time for these satellites for the location of the monitoring station have to calculate.

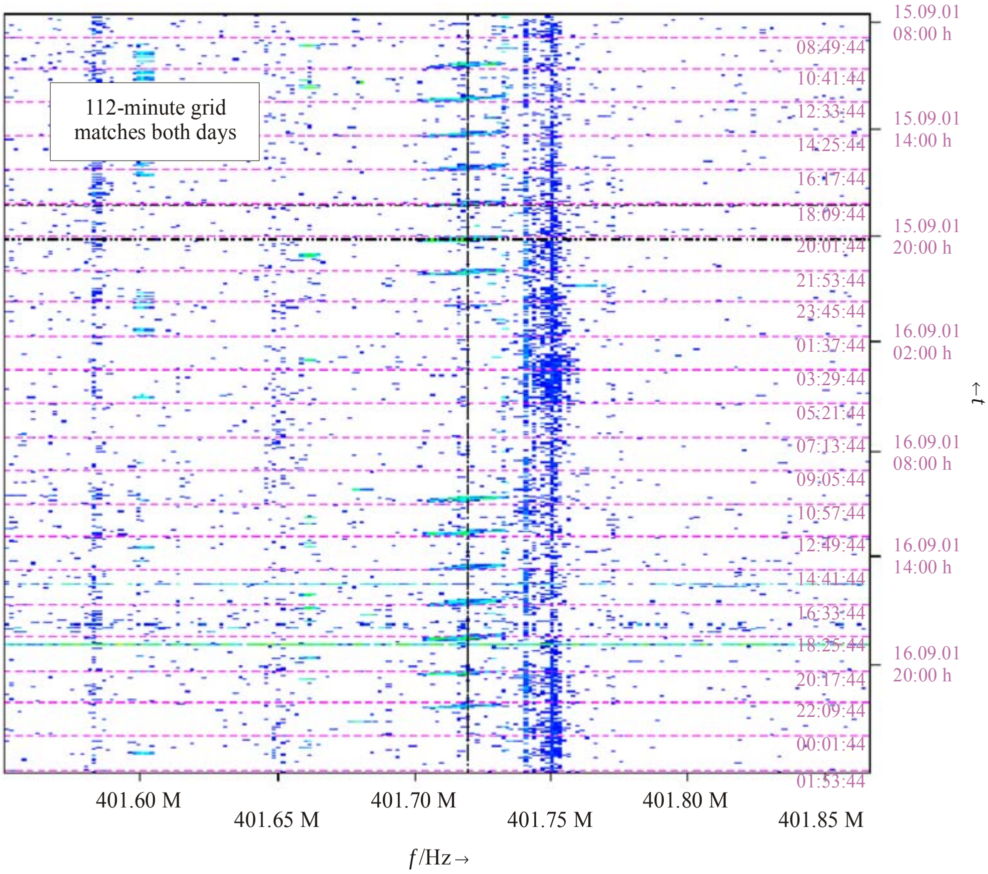
The frequency recorder system can display these visibility windows as an overlay in the spectrogram of the received satellite emission.

If the visibility windows match all the recorded satellite emissions the satellite is identified. Figure 5.1-39 illustrates the visibility windows for the S80/T satellite with a revolution period of 111.9 min.

After the orbit data are known now, with these data a directional antenna can track the satellite for further measurements.

FIGURE 5.1-37

Frequency occupancy registration, approximated determination of time of revolution



Spectrum-5.1-37

FIGURE 5.1-38

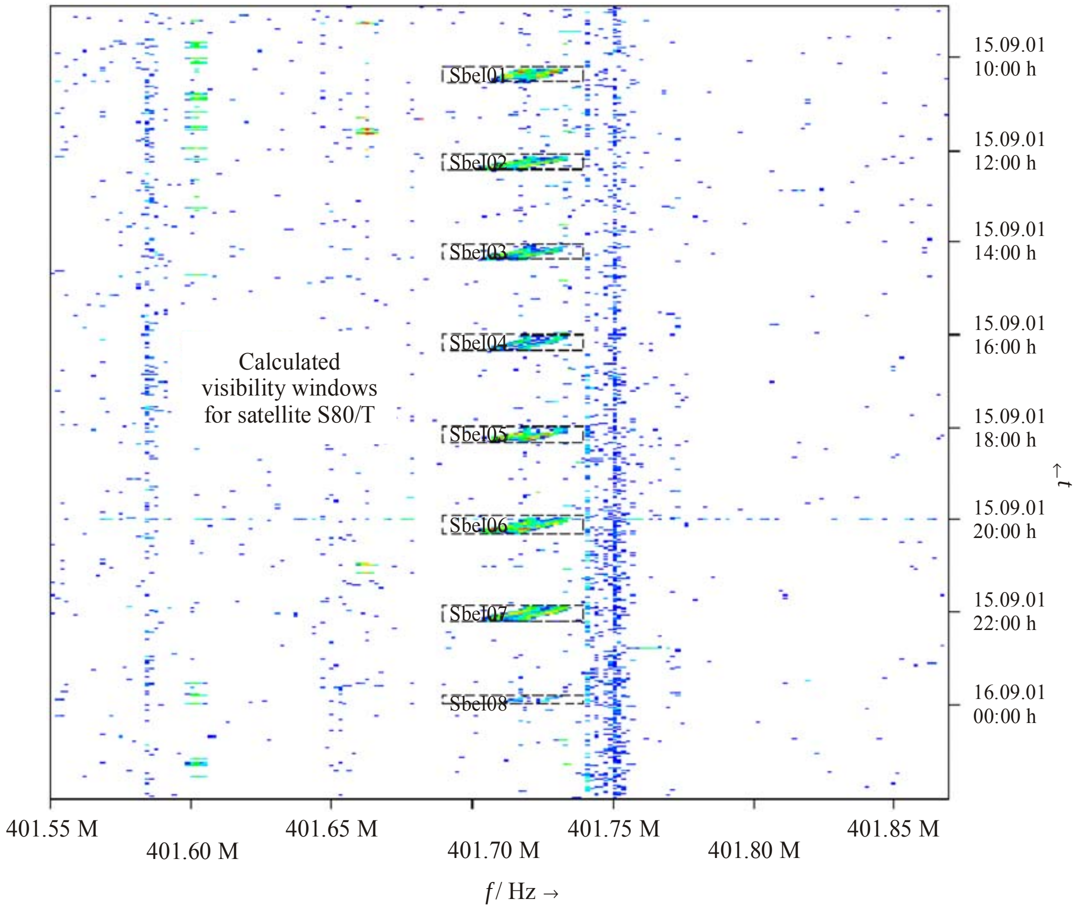
Search in NASA-SSR

INT-ID	CAT	SRC	PERIOD	INCL	APOG.	PERIG.	RCS	NAME	DATE
1990-114F	21033	CIS	113,7	82,6	1410	1386	2,2032	COSMOS 2119	22.12.90
1989-074B	20233	CIS	113,7	82,6	1410	1386	1,7514	COSMOS 2039	14.09.89
1988-002F	18793	CIS	113,7	82,6	1411	1384	1,9042	COSMOS 1914	15.01.88
1987-074A	18334	CIS	113,7	82,6	1409	1387	2,1058	COSMOS 1875	07.09.87
1987-026B	17583	CIS	113,7	82,6	1411	1385	2,2787	COSMOS 1828	13.03.87
1985-003C	15471	CIS	113,7	82,6	1413	1383	1,3662	COSMOS 1619	15.01.85
1992-052A	22076	US	112,4	66	1344	1332	10,6361	TOPEX/POSEIDON	10.08.92
1990-013C	20480	JPN	112,2	99,1	1744	912	0,3319	JAS 1B (FUJI 2)	07.02.90
1990-013B	20479	JPN	112,2	99,1	1743	912	0,4893	DEBUT (ORIZURU)	07.02.90
1992-052C	22078	FR	111,9	66,1	1325	1305	0,4416	S80/T	10.08.92
1992-052B	22077	KOR	111,9	66,1	1325	1307	0,2912	OSCAR 23 (KITSAT 1)	10.08.92
1994-046A	23191	US	110,6	70	2156	355	3,8606	APEX	03.08.94
2000-075C	26621	SWED	110,5	95,4	1799	701	0,1528	MUNIN	21.11.00
1989-086A	20305	CIS	110,4	82,6	1251	1238	11,6301	METEOR 3-3	24.10.89
1995-059B	23711	US	109,7	100,5	1493	934	13,2018	SURFSAT	04.11.95
1994-003B	22970	GER	109,4	82,6	1208	1185	7,6481	TUBSAT B	25.01.94
1994-003A	22969	CIS	109,4	82,6	1208	1186	41,1628	METEOR 3-6	25.01.94
1991-030A	21232	CIS	109,4	82,6	1208	1188	9,5992	METEOR 3-4	24.04.91
1991-056A	21655	CIS	109,3	82,6	1206	1187	7,8738	METEOR 3-5	15.08.91
1988-064A	19336	CIS	109,3	82,5	1208	1184	8,0195	METEOR 3-2	26.07.88

Spectrum-5.1-38

FIGURE 5.1-39

Visibility windows in the frequency occupancy registration



Spectrum-5.1-39

5.1.7.2 Calculation of orbital elements from antenna angle measurements

The identification of a satellite is made easier, and in some cases only possible, by the use of orbital elements calculated from antenna angle measurements. The question of whether or not a sufficiently accurate determination may be obtained depends largely on the angle measurement accuracy of the antenna available and the length and type of the tracked orbit arc. The following example should allow specific conclusions to be drawn regarding the achievable calculation accuracy, which may not at the same time be universally applicable. It is based on a comparison between the ephemeris data of the space station NOAA10, published with a good degree of accuracy and therefore used as reference data, with the ephemeris data obtained from antenna angle measurements and on a comparison between the visibility times and the azimuth and elevation calculated on the basis of both sets of ephemeris data for a path approximately 24 h later.

The antenna angle measurement accuracy of the available 12 m parabolic reflector antenna using the monopulse technique is approximately 0.12° in the 1 700 MHz frequency band used (see also § 5.1.3.5). The maximum elevation angle of the tracked orbit above the horizontal plane was approximately 60°.

Three sets of antenna angle measurement data (azimuth/elevation/time) are used for an initial mathematical determination of the orbit, followed by calculation of the orbital elements. In order to improve the results, a parametric calculation is then made, with the aim of obtaining a solution, which corresponds as closely as possible to the antenna angle measurement values for the series of measurements. [Montenbruck, 1989]; [Montenbruck and Pfleger, 1991].

Table 5.1-12 and Fig. 5.1-40 illustrate the results of these comparisons. When used as an identification aid, the elements in Table 5.1-12 can considerably facilitate the identification of a satellite. However, when the ephemeris data as a whole are used for the predetermination of azimuth and elevation as a function of time, deviations growing with interval to the epoch are observed. Limitations in accuracy when computing the orbital elements from the angle measurements of a single satellite path only are the reason for this. The satellite pick up during the following paths however is remarkably improved. The divergence of azimuth and elevation for a satellite path 24 h later (after 14 revolutions) and based on initial orbit determination is presented in Fig. 5.1-40. The calculated curves are shifted by –1 min for compensation of time delay.

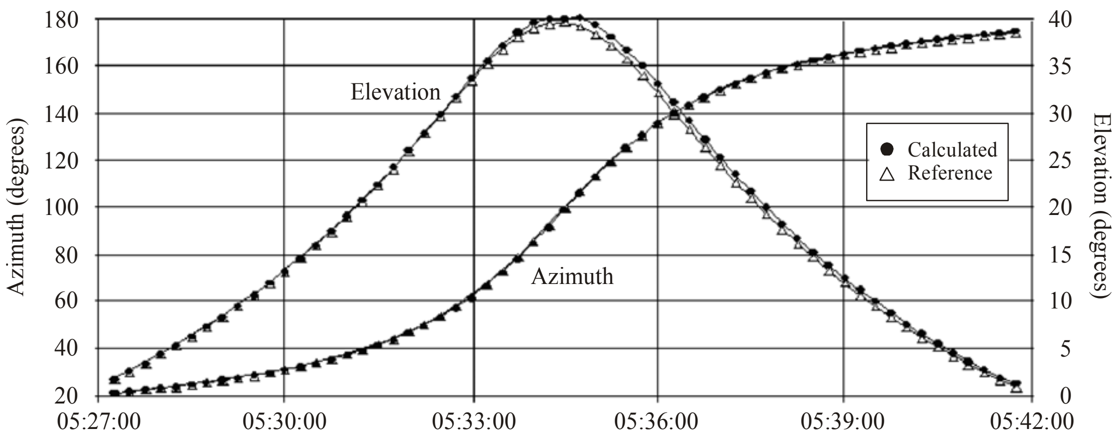
TABLE 5.1-12

Comparison between reference orbital elements and computed orbital elements (initial orbit determination)

Orbital elements NOAA10	Reference elements	Computed elements
Perigee (km)	807	808
Apogee (km)	825	830
Semi-major axis (km)	7 187	7 190
Eccentricity	0.0012156	0.0015
Inclination (degrees)	98.5121	98.78
Time of revolution (min)	100.781	100.85

FIGURE 5.1-40

Comparisons between antenna angles computed from reference orbital elements and from measured orbital elements



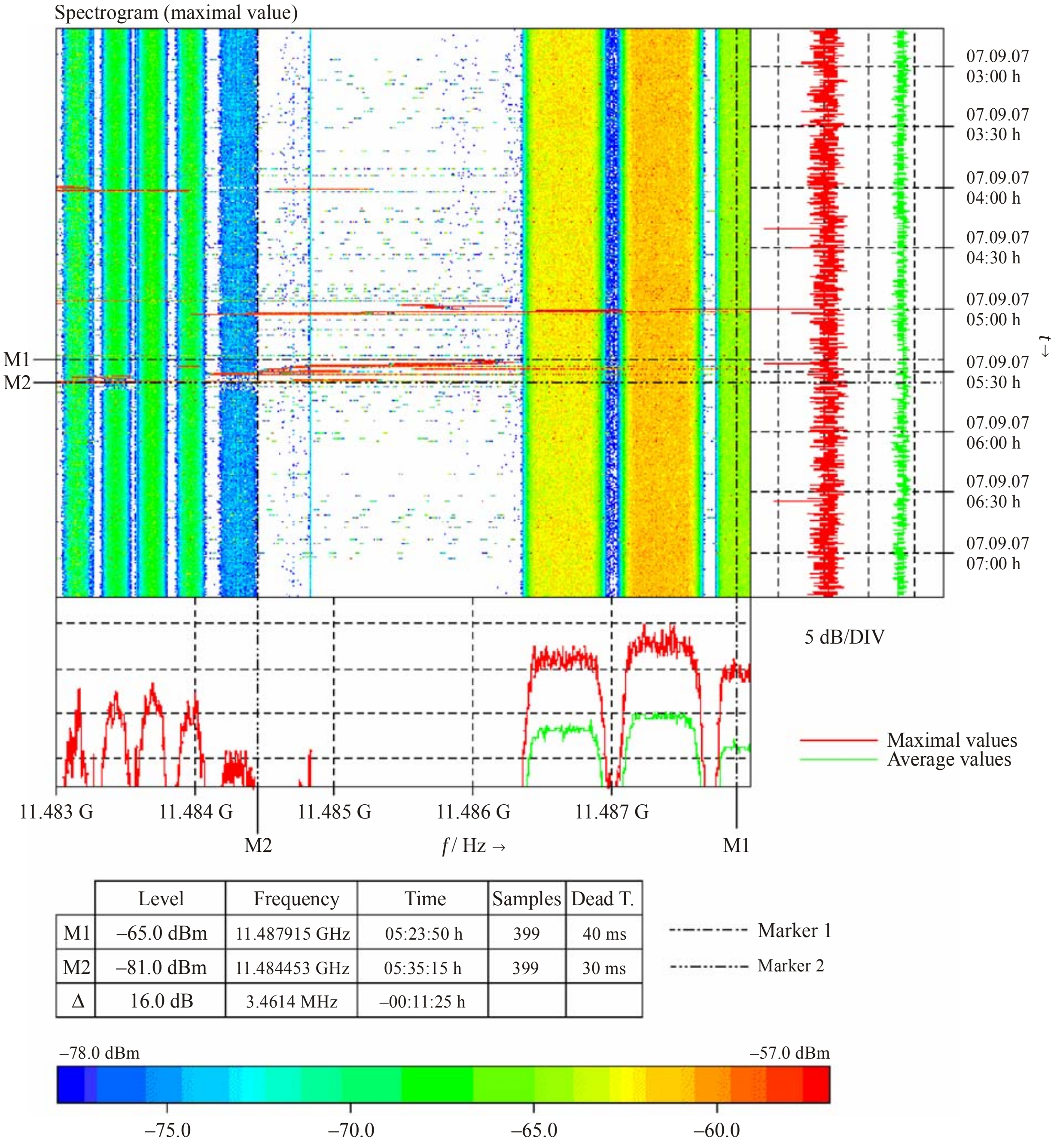
Spectrum-5.1-40

5.1.7.3 Transponder occupancy measurements

Figure 5.1-41 illustrates the result obtained from a transponder occupancy measurement with a frequency recording system. The spectrogram shows a satellite transponder occupancy with an unused transponder section in the middle of the displayed frequency range and a temporarily appearing high power interfering signal. The interferer is crossing the whole transponder fast up and down. The signal, received with a directional antenna, is connected to the frequency recorder in the IF range. The signal is digitized and online represented with a FFT transformation as a spectrogram in the frequency recorder. The spectra are stored continuously on a hard disk and are available for the further offline processing. The different colours represent the power level in the spectrogram. The displayed power level range is adjustable by the colour range settings. The spectrogram can be changed in the frequency range and in the recorded time range by zooming in so that a short observation period can be represented very in detail or zooming out for a long observation period provides a general view. To the position of the frequency marker line and the time marker line is on the right side and below the spectrogram displayed the respectively spectrum.

FIGURE 5.1-41

Transponder occupancy measurements



	Level	Frequency	Time	Samples	Dead T.
M1	–65.0 dBm	11.487915 GHz	05:23:50 h	399	40 ms
M2	–81.0 dBm	11.484453 GHz	05:35:15 h	399	30 ms
Δ	16.0 dB	3.4614 MHz	–00:11:25 h		

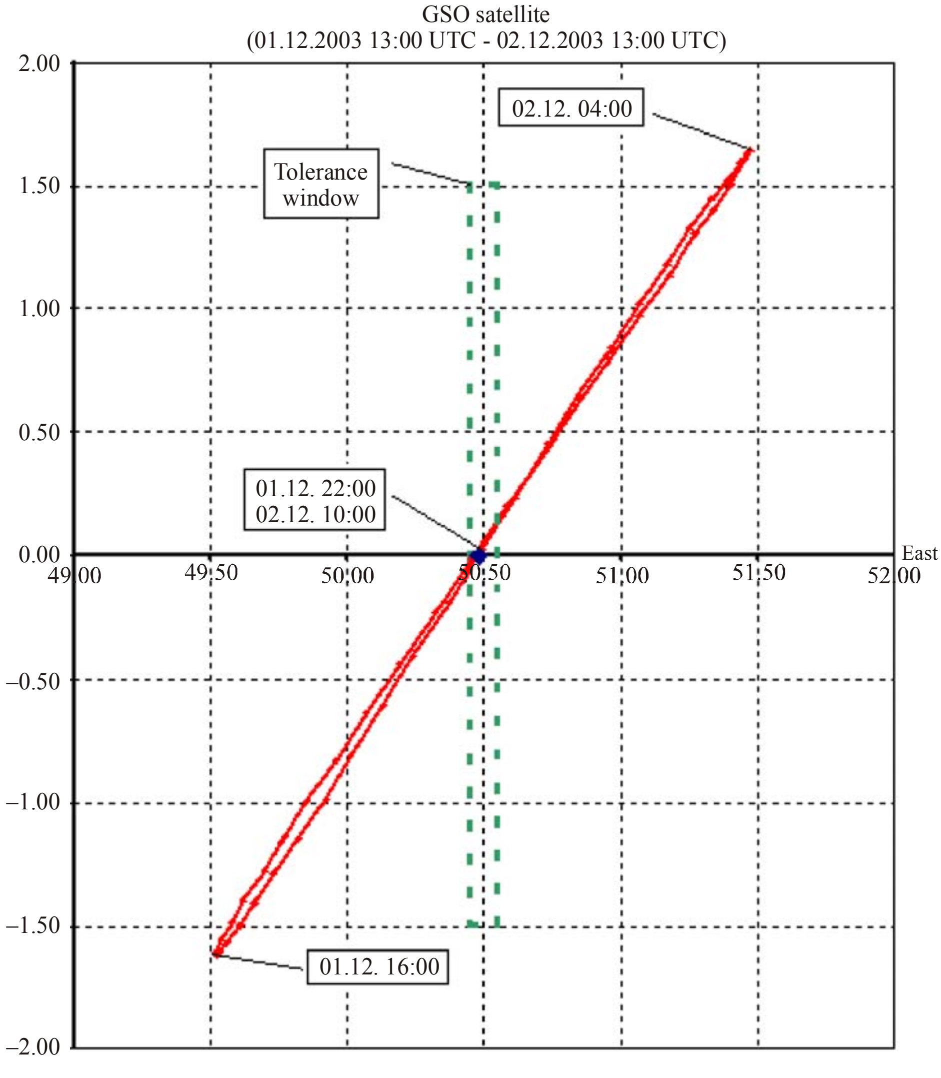
Spectrum-5.1-41

5.1.7.4 Inclination of GSO satellites

The plot in Fig. 5.1-42 was obtained by observing the position of a GSO satellite at 30 min intervals by using a 12 m parabolic antenna with a half-power beamwidth of 0.15°. Based on a monopulse tracking procedure the antenna pointing data are acquired automatically by initially manually locating the satellite. The satellite positions are recorded over a 24 h period and the results are calculated to produce the Fig. "8". The information obtained shows the satellite's excursion from its nominal orbital position and provides a reference for future observations.

FIGURE 5.1-42

Inclination of geostationary satellites (Figure "8")



Spectrum-5.1-42

5.1.7.5 Result and presentation of a geolocation measurement

Figure 5.1-43 presents the results obtained from a TDOA and FDOA geolocation measurement of an unknown uplinking earth station. The result is usually presented in the form of an elliptical area, which can be overlaid on a digital map application for better understanding. The shape and the orientation of the ellipse may vary significantly due to the number of measurement made, the measurement time of the day, modulation type of the signal under test, the correlation SNR etc.

The factors to define the ellipse include:

– The length of the semi-major axis.

– The length of the semi-minor axis.

– Angle of semi-major axis (or semi-minor axis) with respect to a reference direction.

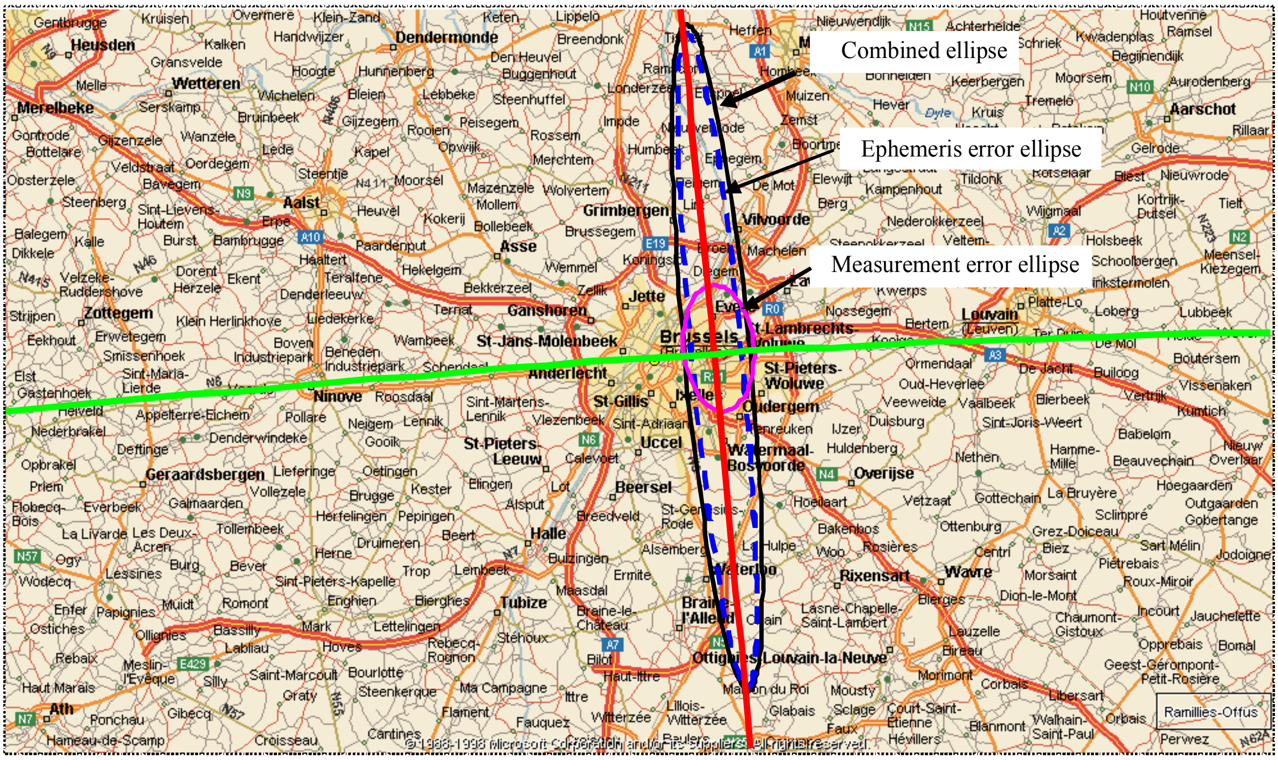
– Coordination of the centre.

– Confidence level.

Shown below is the representation of a geolocation measurement on map with the error ellipse. The huge ellipse for the ephemeris error shows inaccuracies in satellite position and velocities. In this case an ephemeris error compensation measurement should be carried out.

FIGURE 5.1-43

Geolocation result of earth station transmitting to GSO satellite



Spectrum-5.1-43

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ITU-R Recommendations

NOTE – In every case the latest edition of the Recommendation is encouraged to be used.

Recommendation ITU-R S.446 – Carrier energy dispersal for systems employing angle modulation by analogue signals or digital modulation in the fixed-satellite service.

Recommendation ITU-R S.484 – Station-keeping in longitude of geostationary satellites in the fixed-satellite service.

Recommendation ITU-R BO.650 – Standards for conventional television systems for satellite broadcasting in the channels defined by Appendix 30 of the Radio Regulations.

Recommendation ITU-R S.673 – Terms and definitions relating to space radiocommunications.

Recommendation ITU-R SM.1681 – Measuring of low-level emissions from space stations at monitoring earth stations using noise reduction techniques.

5.2 Broadcast monitoring

5.2.1 Introduction

At first glance, one could consider that broadcast services, radio and TV, are adequately covered by the standard monitoring procedures. In fact, these procedures discussed in the previous chapters cover most of the basic measurements to be performed on broadcast services. However due to the importance of these services as means for mass communication, and, as such, as a tool for education and to promote regional and national cultural values, several countries apply especial regulations to these services, usually including parameters such as coverage, quality of service, content restrictions such as time limitations on commercials, minimum amount of cultural, educational or news programs, etc.

These regulatory constrains will demand specific monitoring procedures and equipments. Although standard monitoring receivers usually have demodulation capabilities that allow the reception and recording of broadcast programs, the use of expensive measurement instruments in such a menial task is economically inefficient and inadequate since the reception characteristics might not be suitable in terms of quality. For example, monitoring receivers are usually unable to record stereo channels or present the decoded picture itself. Most of the time, measurement instruments will not provide a good correlation in terms of performance, selectivity and quality to consumer products specifically designed to be used to access these services.

Based on these concepts, this chapter will present general guidelines to expand the monitoring facilities by implementing additional monitoring channels adequate to content monitoring. These subsystems usually are essential to perform activities such as coverage and quality of service evaluation, providing receiving characteristics closer to the final user experience, and also may prove invaluable to provide ability to simultaneously monitor multiple channels at relatively low cost.

Considering the spectrum usage, is also important to notice that broadcast services, especially FM audio broadcast and TV broadcast, usually applies extremely high transmission power over large segments of the spectrum at VHF and low UHF, very close to critical applications such as aeronautical navigation and communication frequencies, increasing the importance of a tight control over harmonics and spurious emissions, and as such the importance of monitoring activities as a means to prevent interference to other services. On this subject, this chapter will briefly present the characteristics of main broadcast standards in use, providing a reference for the analysis of these systems.

5.2.1.1 Quality of service

In the psychology field, quality of service is generally defined as the difference between perceptions and expectations [Llosa, *et al.*, 1998]. Although still disagreements exist about the implementation of these concepts, especially its formula elements, several methods have been produced to quantitatively define the quality of products and services.

In general, one can consider three methods of quality evaluation applicable for broadcasting and telecommunications in general:

1. *Intrinsic quality*, where technical parameters of the service are considered, for example, (SNR), signal to interference ratio (SIR), signal to interference + noise ratio (SINR), total harmonic distortion (THD), relative baseband signal levels, bit error rate (BER), modulation error rate (MER), frame error rate (FER), etc.

   Generally the evaluation of intrinsic quality is directly relevant to the radio environment and to the proper system operation, and it is thus strongly related to the broadcast standard, to the engineering of the broadcast network, and in some case to the technology used within TV receivers and decoders.

   Note that intrinsic quality is a drastic condition for a system operation, but it has usually lower correlation with actual user's perception, especially on modern systems and codecs that strive on the limitation of human perception to improve quality with reduced bandwidth, using non-linear and non-stationary transformations.

2. *Perceived quality by subjective methods*, where psychological and statistical instruments are used to evaluate user's perception on a media segment, based on the actual opinion of users, rated under controlled environment conditions and instruments. This procedures are technology independent, they can be seamlessly applied from narrow-band analogue radios to high definition digital TV systems and will provide a reliable result if properly used, being, as such, the primary reference to which all other quality evaluations are referenced, but with the major drawback of been expensive and time consuming.

3. *Perceived quality by objective methods*, where algorithms are created to combine several parametric quality indicators to provide a single quality grade that better correlates with a subjective evaluation. This is a later development on the issue of quality evaluation and intends to combine the technology independent benefits of the subjective analysis with the easiness of use from the parametric evaluation procedures.

All three procedures usually are based on the concept of inputting a test signal or pattern to the transmission/reception system and taking the output to the analysis. The analysis itself can be made with or without the knowledge or measurement of the input signal.

Objective measurements of perceived quality usually will demand a comparison with the reference signal. Subjective methods might or might not use the reference, considering the alternatives when the evaluation is based on intelligibility and on the subjective perception of the listening test group. Intrinsic evaluation may be based on specific characteristics of the signal, such as cyclic redundancy codes (CRC), or r.m.s. power, and, as such, does not demand the input signal to produce a result, or may need reference test patterns to provide specific results.

The perceived quality, especially when performing subjective assessment, may also be divided into two classes: "quality assessment", when the target is to evaluate the system under optimum condition; and "impairment assessment", when the target is to evaluate the influence of coding or transmission or emission over the signal quality.

The following sections will further describe the quality parameters for audio and video, focusing on subjective and objective quality evaluation procedures described within ITU, since these are the most relevant in this area and parametric evaluation was described when the standards in use were presented on the previous section.

Usually, a comprehensive performance analysis can be obtained by combining both intrinsic and perceived quality evaluations with traditional field strength and carrier to noise ratios for analogue standards, with additional radio propagation parameters such as signal to interference ratios, propagation delay spread, synchronisation delay spread, etc. for digital standards. Such evaluation is especially critical when considering the present migration from analogue to digital systems that has been carried out in several countries.

A common mistake on this subject is the misunderstanding that quality means users satisfaction. In fact, it can be considered a scientific fact that the user's satisfaction is only proportional to the quality whenever this quality correlates with the expectations and desires of the consumer in a broader sense, i.e., one might be happy in having a relatively bad quality in a phone call if the price is much lower than other alternatives, such as on internet voice messaging applications, or alternatively, one might not give importance to an excellent video quality, if the information presented is irrelevant.

Whenever a regulatory effort on quality is performed, the associated costs on monitoring should be considered and the final balance on the expected benefits to the user should be clear.

a. Perceived audio quality

Subjective audio quality measurements has been an issue in broadcast and telecommunication applications for some time and, as such, produced several different ITU-R and ITU-T Recommendations.

Considering audio in sound broadcast, an excellent starting point is Recommendation ITU-R BS.1283 that summarizes several other Recommendations on sound quality subjective assessment, which can be considered the most reliable basis for quality evaluation.

Generally speaking subjective evaluation applies scales with 5 or 7 grades that may vary from excellent to bad quality, from imperceptible impairment to very annoying impairment or from much better to much worse, when comparing pairs of recordings.

Using these scale, selected test groups perform listening sessions at especially designed environments and register their opinion on evaluation of each recording or comparison of pair of recordings. The evaluation results are statistically processed in order provide the final score, or grade, that is free from individual tendencies and with high correlation with the final user's opinion. Usually the processing takes both reference and "distorted" recordings for evaluation, The difference in grades between the reference input and the resulting output of the system under test is called: "subjective difference grade" (SDG), which scale from 0 (imperceptible impairment) to –4 (very annoying impairment).

Recommendation ITU-R BS.1116 is the basic reference within ITU for designing experiments on subjective assessment, stating stringent experimental conditions that are especially important on the determination of small impairments on the audio quality. To reduce the costs on the use of this Recommendation, Recommendation ITU-R BS.1285 might be used to coordinate pre-selection procedures on the recordings, reducing the amount of media to be evaluated.

Recommendation ITU-R BS.1284 was defined taking Recommendation ITU-R BS.1116 as a main reference, but considering more flexible parameters, being as such, more recommended for general applications, where the impairment in audio is of greater magnitude, but still consider a high quality audio system.

For intermediate quality systems, such as internet audio streaming, solid state players, and digital broadcast systems, Recommendation ITU-R BS.1534 was developed that might be more effective when evaluating audio quality that would fall on the lower half of the grade of Recommendation ITU-R BS.1116.

For low quality, narrow band systems as mainly used in voice communication, ITU-T Recommendations P.800, P.810 and P.830 might also be used. These Recommendations describe the methodology for mean opinion score (MOS) tests, the subjective standard reference used for telecommunication services such as telephony.

Finally, Recommendation ITU-R BS.1286 can be used in complement to the previously discussed Recommendations whenever the sound is presented with an accompanying picture, merging the principles of sound quality evaluation to an environment where image is also presented, such as observed in TV. Studies demonstrate that the human perception of sound is affected by the vision associated. Therefore TV and multimedia program evaluation cannot consider separately the audio and video contents associated whenever a full system evaluation is to be performed.

More recently, several algorithms and computer programs have been developed, trying to mimic the results and procedures from subjective evaluations, with the expected benefits of cost reductions and flexibility for application on continuous monitoring activities as discussed in this Handbook.

For high quality systems, a basic reference for objective quality evaluation is Recommendation ITU-R BS.1387. This Recommendation was created by the validation and consolidation of six previously existing methods: disturbance index (DIX), noise-to-mask ratio (NMR), perceptual audio quality measure (PAQM), perceptual evaluation (PERCEVAL), perceptual objective measure (POM) and The toolbox approach.

The validation process used several natural sound recordings with 10 to 20 s of duration, either from musical instruments and human voices. The SDG was correlated to the objective difference grade in order to optimize the algorithms described in the Recommendation. The algorithms itself might be used with these test signals or any other sequence, like a jingle, that can easily be placed within the normal program, allowing tests to be performed without any interruption of the standard station operation.

ITU-T Recommendation P.862 presents another objective method called "perceptual evaluation of speech quality" (PESQ). It is used for speech quality assessment of narrow-band (3.1 kHz) telephone networks and speech codecs. PESQ works in a very similar fashion as described for other methods, comparing the input and output signals from a system under test. The validation process of PESQ followed a similar procedure that was used in Recommendation ITU-R BS.1387, but applying only narrow band voice sequences and using MOS measurements as reference.

Alternatively, ITU-T Recommendation P.563 presents a method that does not require the input signal for processing. The algorithm involves sophisticated speech analysis that reconstructs an estimated reference signal based on the distorted signal and from this, provides an estimate MOS equivalent grade.

The user of these objective methods should be aware of its limitations. Most of these are defined in the Recommendations.

For example, Recommendation ITU-R BS.1387 demands synchronized samples, and, as such, is unable to evaluate any delay on the transmission. ITU-T Recommendations P.563 and P.862, on the other hand, not only are unable to evaluate delays, but also level distortions, since the first stages of the algorithms process and remove such distortions. Even some distortions caused by limitations on the frequency response of the system might pass unnoticed.

In general, objective algorithms may still be unable to mimic every facet of human perception, and, it is recommended to apply these methods with caution, whenever possible crosschecking the results with more reliable methods, or, at least, with a quick evaluation from the operator when the results presented by the system are incompatible with the experience, considering the propagation and system characteristics under evaluation.

b. Perceived video quality

The main reference for subjective perceived video quality evaluation within ITU is Recommendation ITU-R BT.500. This Recommendation describes several methods that can be applied for the quality assessment. Basically they vary in the form of stimuli presentation, the type of scale and the type of image media used. These tests consist, in general, of presenting still images or video sequences to a group of no less than 15 volunteers, in this Recommendation usually called assessor, who will annotate their perception on scales during sections of about half-an-hour. The scores registered are later statistically processed. All steps of these procedures are thoroughly described.

In terms of stimuli, these methods can be divided into single stimuli and double stimuli. For single stimuli, the assessor is asked to evaluate an image, an image sequence or a video segment, describing his impression after each segment. For double stimuli, the assessor is asked to evaluate pairs of images or video sequences, that are presented alternately or side by side, one with impairment and another produced directly from the source. For this type of stimuli, the scale might be defined in terms of impairment, comparing both pictures on a relative scale, or in terms of quality using a standard scale. The double stimuli method usually provides lower variance in the response, but also demands greater care and might not be applicable under specific conditions or for certain systems, for example, such as discussed on ITU-T Recommendations J.140 and J.245, that apply single stimuli methods based on the understanding that these methods better approximate the real observers condition at home using a standard TV set or a computer.

In terms of scale, mainly four types of evaluation are described in the ITU Recommendations mentioned in this section:

– Firstly the use of numerical scales, with five, seven or even eleven grades, varying from excellent to bad on single stimuli methods or from much better to much worse on double stimuli methods.
– Secondly, some methods might simply apply adjectival category judgment, without the numerical association, where the assessor simply chooses the more adequate adjective from a provided set.
– Thirdly, a graphical scale might be used, this scale, usually defined as a line or segmented line, connecting an adjective such as excellent on the upper side to another such as bad on the lower side. The assessor is then requested to draw a mark at the point in the scale that corresponds to its perception.
– Fourthly, the use of a slider, an electronic device that register the subjective perception in much similar fashion as the graphical scale but with the benefit of being able to do so on a continuous basis, registering this impression over time, something especially important on the evaluation of moving pictures.

In terms of media, Recommendation ITU-R BT.500 describes both static and moving picture evaluation procedures. Static pictures were traditionally more valuable when evaluating analogue systems and its impairments, since these effects where not scene-dependent and time-varying in the same fashion that is observed with modern digital video compression algorithms that demanded the creation of the so called continuous evaluation procedures.

Considering these variations, Recommendation ITU-R BT.500 defined the following methods:

– The double-stimulus impairment scale, or EBU method;
– The double-stimulus continuous quality-scale;
– Single-stimulus adjectival categorical judgement; Single-stimulus numerical categorical scale (SSNCS);
– Single-stimuli Non-categorical judgement with continuous scaling;
– Single-stimuli Non-categorical judgement with numerical scaling;
– Single stimulus continuous quality evaluation (SSCQE);
– Simultaneous double stimulus for continuous evaluation (SDSCE).

Apart from all these methods, several others may be found on the literature and even within ITU. For instance, Recommendation ITU-R BT.710 presents additional information, such as viewing conditions and choice of assessment alternatives concerning the use of Recommendation ITU-R BT.500 test methods for

HDTV. Recommendation ITU-R BT.1128 provides similar information concerning conventional television systems and Recommendation ITU-R BT.1129 for digital systems, mainly considering studio applications.

Also within ITU it is possible to obtain test materials that may be used for quality assessment or for demonstrations, such as presented in Recommendation ITU-R BT.1210. These standard materials are also used in many references to provide a common base of comparison between alternative methods.

The large number of tests available may look confusing. In fact, this is a consequence of the great variety of possible types of media and impairments to be addressed. Each test method has its strengths and weaknesses, and might be more suitable for a certain type of evaluation. The aid of experienced personal, careful planning, and often the use of several different methods are essential to obtain and interpret the evaluation results. An interesting discussion on the available test methods is presented in the Report ITU-R BT.1082 that, although being a bit out-of-date, still is a useful reference to better understand the classical methods described in Recommendation ITU-R BT.500.

Considering objective perceived quality measurement techniques a main reference within ITU is the video quality expert group (VQEG), created in 1997 joining experts from ITU-T and ITU-R from various affiliations. This ad-hoc group has produced Recommendations such as:

– ITU-T Recommendation J.144 – Objective perceptual video quality measurement techniques for digital cable television in the presence of a full reference.
– ITU-T Recommendation J.149 – Method for specifying accuracy and cross-calibration of video quality metrics (VQM).
– Recommendation ITU-R BT.1683 – Objective perceptual video quality measurement techniques for standard definition digital broadcast television in the presence of a full reference.

A comprehensive tutorial on this subject, "Objective perceptual assessment of video quality: Full reference television", was published in 2004 by ITU-T and is available on the ITU Website for download free of charge.

5.2.2 Broadcast standards and measurements

In this section the characteristics of the main standards in use worldwide for broadcast systems are presented. This description is focused on the spectrum occupancy features and main intrinsic quality parameters that can be used in each standard, being as such, focused on the spectrum monitoring applications.

5.2.2.1 Analogue AM sound broadcast

Analogue amplitude modulated sound broadcast is the most traditional broadcast service, being around since the beginning of broadcast transmissions, almost a hundred years from now.

AM Sound broadcast usually applies basic amplitude modulation with double sideband and carrier, allowing the use of very simple receivers, a key feature when these systems were implemented. The signal characteristics and measurement techniques are generically described in § 4.6.3.1 of this Handbook.

As described in Recommendation ITU-R BS.706, a data system similar to radio data system (RDS) implemented on the VHF band (Recommendation ITU-R BS.643) was also developed for the AM sound broadcast services in the bands below 30 MHz. This system called AMDS was implemented in some countries, especially in Western Europe, using phase modulation over the main sound carrier and allowing transmission of data with up to 200 bit/s. The use of AMDS does not interfere with the standard spectrum occupancy characteristics of the AM sound broadcast service.

5.2.2.2 Analogue FM sound broadcast

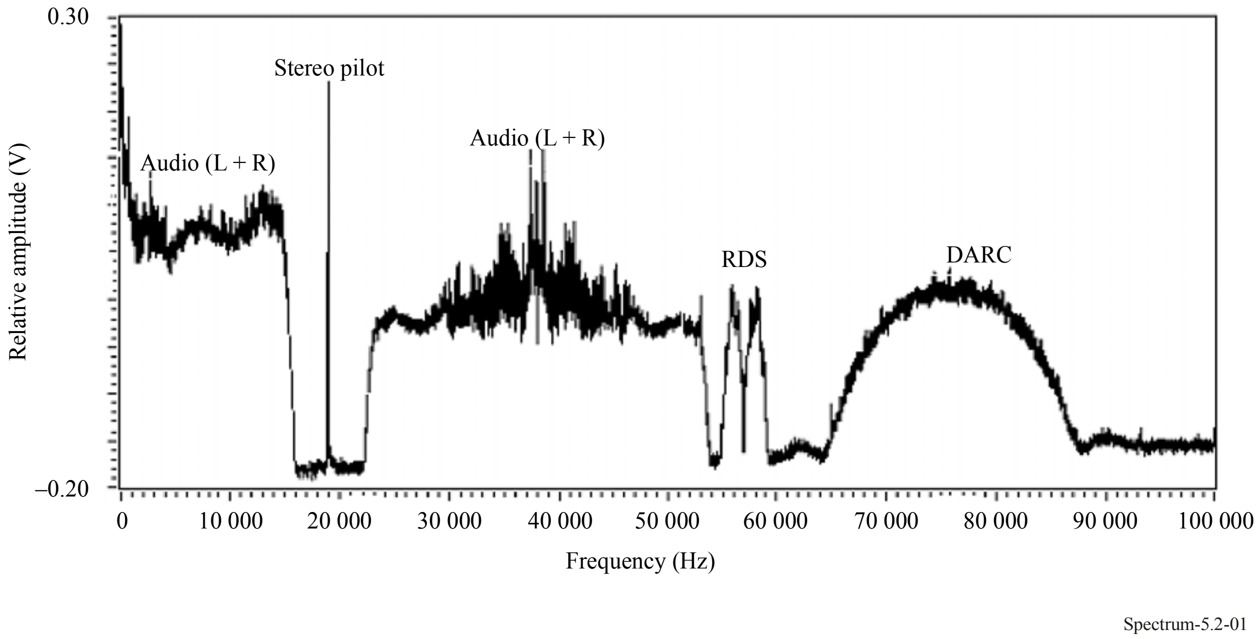
Analogue frequency modulated sound broadcast has been a relatively late development in radio history. Milestone arrangements about the use of the VHF band for FM broadcast has been decided within ITU during the sixties and the number of FM listeners superseded the AM only in the seventies.

A key reference for FM broadcast standards in use worldwide is Recommendation ITU-R BS.450. This Recommendation presents the standards for FM broadcast in the VHF band, including radio frequency in use, pre-emphasis and general system characteristics for various countries.

FM stereo is composed mainly by a set of multiplexed carriers in the baseband signal, namely the mono audio (Left + Right channels), Pilot Tone, Stereo Audio (Left – Right), digital radio system (RDS, RBDS), SCA (auxiliary channel – subsidiary communication authority) and high speed data systems (e.g., HSDS, DARC, C2R, FMeXtra). The complete multiplex signal can consist of the mono signal from 0 to 15 kHz, the pilot tone at 19 kHz, stereo signal from 23 to 53 kHz, RDS at 57 KHz and for instance DARC from 76 to 86 kHz.

FIGURE 5.2-1

Baseband spectrum of the FM multiplexed signal



Radio data system (RDS) was developed within the European Broadcast Union in 1984, later adopted with enhancements by the EU in 1990, as the standard EN 50067 and by ITU in Recommendation ITU-R BS.643.

RDS uses an AM modulation with suppressed carrier by a shaped bi-phase data signal on a sub-carrier frequency of 57 kHz, locked in phase or in quadrature with the third harmonic of the pilot tone at 19 kHz. The result of this modulated signal is equivalent to a PSK transmission with data rates of about 1187.5 bit/s.

Radio broadcast data system (RBDS) was implemented in the United States of America based on the RDS but with modifications by NRSC in 1992. The modulation characteristics of RBDS are the same as the ones of RDS, and receivers designed for RDS will generally work with RDBS. The differences are mainly in the program type tables and other functionalities, not affecting the modulation and transmission layers.

Other data systems, intended for higher data rates (16 to 30 kbits/s) were also developed, one can mention the following: HSDS, DARC, C2R, FMExtra. These systems have limited success and will not be discussed in this chapter.

In order to minimize interferences between neighbouring FM sound broadcasting channels, Recommendation ITU-R BS.412 limits the maximum frequency deviation to ± 75 kHz and the power of the multiplex signal (MPX power), to the AF level of a sinusoidal tone with 19 kHz deviation.

This reference MPX power of 0 dB, averaged over a period of 60 s, must not be exceeded.

One of the most critical problems connected to analogue FM sound broadcasting is the intermodulation created in aeronautical navigation receivers (ILS and VOR) due to multiple high power signals on frequencies close to 108 MHz. Recommendation ITU-R SM.1009 describes the mechanisms and calculation procedures involved in all details.

Because the spectrum of analogue sound broadcast signals is much wider than the bandwidth of an ILS or VOR receiver, more than just one aeronautical radionavigation channel can be affected by this so-called

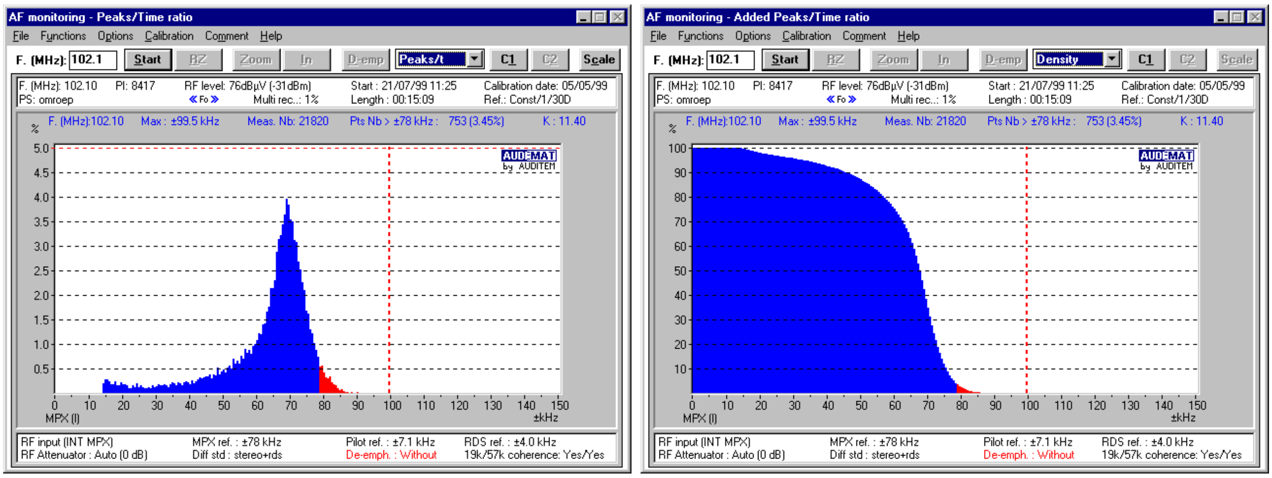
"B1" interference. Apart from the input power to the receiver, how severe is this interference and the number of ILS or VOR channels affected depend on the maximum and average spectrum width of the FM sound broadcast transmitters involved.

The maximum deviation determines the broadest RF spectrum and the MPX power determines the average spectrum. To avoid unnecessary interference, especially to the safety of life services such as VOR and ILS, both deviation and MPX power have to be measured by the monitoring service. In order to achieve accurate results, the equipment used for these measurements has to fulfil especial requirements that are described in Recommendation ITU-R SM.1268, together with detailed information about the measurement itself.

In Recommendation ITU-R SM.1268 is stated that FM BC emission should be observed over a period of 15 min. All the measured values, the peak values of the deviation in 50 ms, should be processed and a distribution plot and a complementary cumulative distribution function (CCDF) plot can be presented similar to those shown in the following figures. Note: the display of the statistical distribution curves depend on the measuring equipment used. It is necessary that this equipment should conform to Recommendation ITU-R SM.1268.

FIGURE 5.2-2

(a) Distribution plot and (b) complementary distribution function plot of the frequency deviation on FM broadcast



a) b)

Spectrum-5.2-02

Multipath propagation is a general problem for FM signals in the VHF bands and at higher frequencies. The result of multipath propagation in FM systems is unacceptable distortion of the modulated signal, such as that the indicated value on the FM modulation meter can be changed as much as by a factor of 2.

Due to multipath propagation, FM is converted into a certain percentage of AM by vectorial addition at the receive antenna. Therefore multipath propagation can be found by measuring the AM of a frequency-modulated carrier. For this purpose the modulation meter has to measure AM and PM/FM simultaneously.

For this purpose, instruments are in use, which offers parallel measurements of deviation and modulation depth with immediate calculation of the conversion factor, expressed in % modulation depth over kHz FM deviation.

Recommendation ITU-R SM.1268 defines maximum values for the amount of AM as well as other prerequisites for an accurate measurement.

5.2.2.3 Analogue TV broadcast

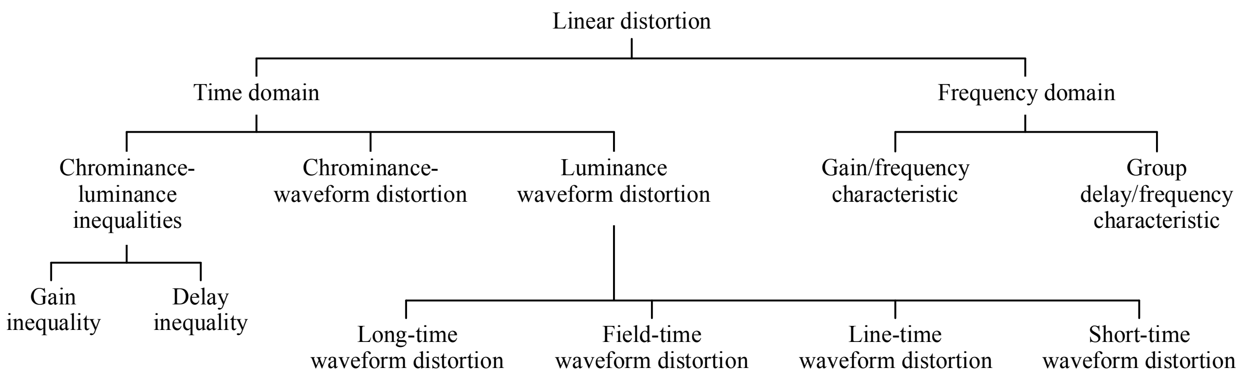
Analogue TV broadcast main standards defined within ITU are NTSC, PAL and SECAM, which baseband signals are defined by Recommendation ITU-R BT.1700. These baseband characteristics define parameters that might be used by specialized instruments when performing objective video quality analysis.

Recommendation ITU-R BT.1439 describes measurement methods of intrinsic quality parameters applicable in the analogue television system, including also specific studio measurements. In this Recommendation, measurement procedures are presented for insertion gain, more applicable to studio, noise (continuous, low frequency, periodic noise, impulsive noise), linear and non-linear distortion.

The following diagrams, extracted from the Recommendation ITU-R BT.1439 with edition, provide a brief resume of the parameters that can be measured in analogue television broadcast, classified in accordance with the effects observed.

FIGURE 5.2-3

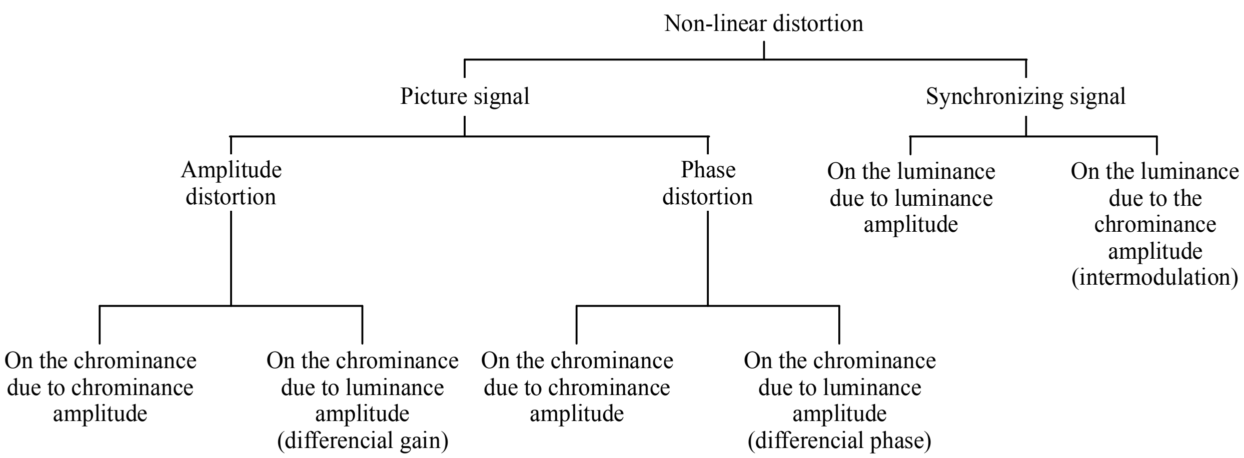
Linear distortion classification of analogue video signals



Spectrum-5.2-03

FIGURE 5.2-4

Non-linear distortion classification of analogue video signals



Spectrum-5.2-04

To measure these effects concisely as described by Fisher 2008, it is usually necessary to use test signal patterns. These tests can also be described in terms of the pattern in use (i.e. white bar amplitude; sync amplitude; burst amplitude; tilt of the white bar; 2T pulse amplitude; 2T K factor; luminance-chrominance amplitude and delay in the 20T pulse; static nonlinearity on the greyscale; differential gain and phase on the greyscale with colour subcarrier; weighted and unweighted luminance signal/noise ratio and hum).

Analogue test receivers can provide information on the vision carrier level, sound carrier level, deviation of the sound carriers, frequencies of vision and sound carriers, residual picture carrier, incidental phase modulation (ICPM). Most of these measurements can also be performed by standard spectrum monitoring equipment that can usually provide basic information on the characteristics of the signal, mainly evaluating level, frequency and the differential relations of these parameters. Other information, such as incidental phase modulation, demands a system with vector analysis capabilities.

The spectrum characteristics, considering several variants of these main standards in use in different countries are presented in Recommendation ITU-R BT.1701 for bandwidths from 6 to 8MHz.

5.2.2.4 Digital sound broadcast

Digital sound broadcast has been under development since the eighties, but its implementation has been slower than for digital TV broadcast.

Although this slower diffusion, the use of digital technologies is expected to provide several benefits, as presented in Recommendation ITU-R BS.774, including the improvement of the audio itself, allowing mobile reception at “CD quality”, an improvement in spectrum efficiency, better performance under multipath environment, ability to create single frequency networks and more sophisticated services such as data communication, including pictures, content metadata, traffic information, paging, etc.

Recommendation ITU-R BS.1114 presents three standards to be used in the VHF and UHF bands. In this Recommendation these systems are referred to as Digital Systems A, F and C, respectively, known commercially as Eureka 147 – DAB, ISDB-T_{SB}, and IBOC DSB. All three systems operate with OFDM modulation in the channel coding, with the addition of convolution error correcting coding in the case of DAB. These are capable of providing “FM quality” reception with less than 200 kHz bandwidth per encoded audio programme, improving the spectrum efficiency.

Recommendation ITU-R BS.1615 presents two standards to be used in the HF, MF and LF bands, DRM and again IBOC DSB. Although this recommendation is focused on the frequencies below 30 MHz, DRM operates with COFDM and, under the name of DRM+, extended the operational bands into the lower VHF band up to 120 MHz using channel bandwidths of 100 kHz. Both systems improve the quality of sound reception keeping the same bandwidth limits of the original analogue services that they are intended to replace.

The intrinsic quality evaluation for these systems usually is performed by measuring the BER (bit error ratio) and the SNR for systems A, F and DRM, and BLER and the S/N for system C. While the measurement of SNR is possible using standard monitoring equipment, the theoretical correlation of this ratio with the error rate might be extrapolated from laboratory studies, such as presented in Recommendation ITU-R BS.1114 for systems above 30 MHz and Recommendation ITU-R BS.1615 for systems below 30 MHz. The proper measurement of error rate should be performed using specialized equipment integrated in the respective decoder.

The measurement of the SNR is in fact troublesome, since the presence of the signal makes it impossible to evaluate the real noise level. One alternative is to temporarily turn off the emitter, an impossible task in most monitoring cases, except for experimental and initial trial purposes. Another alternative would be to extrapolate the noise level considering measurements performed on adjacent empty channels, far enough to avoid the spurious emissions from the carrier under evaluation but close enough to keep a reasonable correlation with the original channel noise value. Some automated measurement systems for digital systems might designate as SNR another error measurement, more correctly designated as modulation error rate (MER).

MER is computed as the ratio between the power of an IQ signal and the power of the error vector, where this error is computed as the difference between the signal received and the expected IQ values, considering the ideal constellation as estimated by the receiver. MER measurements should be identical to the SNR when the only noise affecting the signal is a White Gaussian Noise, a situation not really found in the real world, where multipath and non linear distortion effects are commonly seen.

The following items and tables present the main characteristics for setup of monitoring equipment to perform evaluation of spectrum characteristics of the main digital sound broadcast standards.

The specific channel assignment depends on regional regulations in force.

When evaluating hybrid systems, which simultaneous broadcast (simulcast) analogue and digital signals such as proposed in HD radio and DRM, a simple objective measurement of quality can be achieved by recording the moments when the switching between analogue and digital demodulation takes place.

In these systems, the receiver switches automatically from analogue to digital as the error rate increases above a pre-defined threshold.

The use of such alternative should, although providing some benefits in terms of simplification of the system and procedures, must be carefully planned and used, since the obtained results might be restricted to the specific conditions of the receivers used, making it harder to compare this results with others that presents different performance characteristics.

In any case, it’s highly recommended that the characteristics of the receiver, such as sensitivity and maximum acceptable error rate are well known.

a) Recommendation ITU-R BS.1114 System A – Eureka 147 – DAB

Modulation	COFDM with π/4 DQPSK
Frequency bands	VHF and UHF
Channel bandwidth	1.54 MHz
Carriers per channel	
Mode I	1 536 with 1 kHz spacing
Mode II	384 with 4 kHz spacing
Mode III	192 with 8 kHz spacing
Mode IV	768 with 2 kHz spacing
Critical BER under AWGN	1×10^{-4}
SPAN for single channel view	2 MHz
RBW or filter per BIN	4 kHz
Sweep speed/integration time	Slow (2 s)

Using a measurement bandwidth of 4 kHz, the following spectrum mask applies:

	Frequency relative to the channel centre (kHz)	**Level difference in relation to in-channel peak level (dB)**
Transmitters operating in uncritical cases or in the 1.5 GHz band	± 970	–0
	± 970	–30
	± 3 000	–80
Transmitters operating in critical cases	± 770	–0
	± 970	–45
	± 1 750	–80
	± 3 000	–80
Transmitters operating in certain areas where frequency block 12D is used	± 770	–0
	± 970	–52
	± 2 200	–101
	± 3 000	–101

b) Recommendation ITU-R BS.1114 System F – ISDB-TSB

Modulation	OFDM with DQPSK,QPSK, 16-QAM, 64-QAM
Frequency bands	VHF and UHF
Channel bandwidth	429 kHz, 500 kHz or 572 kHz, depending on the reference channel raster size (6, 7 or 8 MHz)
Carriers per channel	Depending on the number of segments used per channel, single or triple
Mode 1	109 or 325
Mode 2	217 or 649
Mode 3	433 or 1297
Critical BER under AWGN	1×10^{-4}
SPAN for single channel view	6 MHz
RBW or filter per BIN	10 kHz
Sweep speed/integration time	Slow (2 s)

Using a measurement bandwidth of 10 kHz, the following spectrum mask applies:

	Frequency relative to the channel centre (kHz)	**Level difference in relation to in-channel peak level (dB)**
Single segment of 429 kHz channel. (Channel raster 6 MHz)	± 220	0
	± 290	–20
	± 360	–30
	± 1 790	–50
Triple segment of 429 kHz channel. (Channel raster 6 MHz)	± 650	0
	± 720	–20
	± 790	–30
	± 2 220	–50
Single segment of 500 kHz channel. (Channel raster 7 MHz)	± 255.5	0
	± 325.5	–20
	± 395.5	–30
	± 1 825.5	–50
Triple segment of 500 kHz channel. (Channel raster 7 MHz)	± 756.5	0
	± 826.5	–20
	± 896.5	–30
	± 2 326.5	–50
Single segment of 572 kHz channel. (Channel raster 8 MHz)	± 291.5	0
	± 361.5	–20
	± 431.5	–30
	± 1 861.5	–50
Triple segment of 572 kHz channel. (Channel raster 8 MHz)	± 864.5	0
	± 934.5	–20
	± 1 004.5	–30
	± 2 434.5	–50

c) Recommendation ITU-R BS.1114 System C – IBOC DSB

Modulation	OFDM with QPSK
Frequency bands	VHF
Channel bandwidth	400 kHz
Carriers per channel	
MP1 (Hybrid)	380 divided into 20 frequency partitions.
MP2 through MP3 (Extended hybrid)	up to 530 divided into 28 frequency partitions
MP5, MP6, MS1 through MS4 (All digital)	up to 1093 divided into 58 frequency partitions
Critical BLER under AWGN	0.16
SPAN for single channel view	1.3 MHz
RBW or filter per BIN	1 kHz
Sweep speed/integration time	Slow (2 s)

Using a measurement bandwidth of 1 kHz, the following spectrum mask applies:

	Frequency relative to the channel centre (kHz)	**Level difference in relation to in-channel peak level (dB)**
Digital signal on hybrid mode	0 to ± 50	–83.39
	± 50 to ± 95	{–83.39 + (|frequency (kHz)| – 50 kHz) × 0.2}
	± 95 to ± 100	{–61.39 + (|frequency (kHz)| – 100 kHz) × 2.6}
	± 200 to ± 205	{–61.39 – (|frequency (kHz)| – 200 kHz) × 2.6}
	± 205 to ± 250	{–74.39 – (|frequency (kHz)| – 205 kHz) × 0.2}
Signal on all–digital	± 200 to ± 207.5	{–51.39 – (|frequency (kHz)| – 200 kHz) × 1.733}
	± 207.5 to ± 250	{–64.39 – (|frequency (kHz)| – 207.5 kHz) × 0.2118}
	± 250 to ± 300	{–73.39 – (|frequency (kHz)| – 250 kHz) × 0.56}
	± 300 to ± 600	–101.39
	> 600	–111.39

d) Recommendation ITU-R BS.1615 – DRM below 30 MHz

Modulation	COFDM with 64QAM, 16QAM or 4QAM
Frequency ands	LF, MF, HF and Low VHF (120MHz)
Channel bandwidth	4.5; 5.0; 9.0, 10.0; 18.0 or 20.0 kHz depending on the selected occupancy type.
Carriers per channel	Maximum values for channel BW from 4.5 to 20 kHz respectively
Mode A	98; 110; 202; 226; 410; 458
Mode B	90; 102; 182; 206; 366; 410
Mode C	- ; - ; - ; 138; - ; 280
Mode D	- ; - ; - ; 88; - ; 178
Critical BER under AWGN	1×10^{-4}
SPAN for single channel view	40 kHz
RBW or FILTER per BIN	300 Hz
Sweep speed/integration time	Slow (2 s)

Using these parameters, the following spectrum mask should be applicable:

	Frequency relative to the channel centre (kHz)	**Level difference in relation to in-channel peak level (dB)**
Spectrum occupancy 0 (4.5 kHz on the upper or lower half of traditional analogue AM channel)	< ± 2.385	0
	± 2.385	–30
	> ± 2.385	–12 dB/octave to –60 dB
	~ 13.49	–60 dB
Spectrum occupancy 1 (5 kHz on the upper or lower half of traditional analogue AM channel)	< ± 2.65	0
	± 2.65	–30
	> ± 2.65	–12 dB/octave to –60 dB
	~ 14.99	–60 dB
Spectrum occupancy 2 (9 kHz on the traditional analogue AM channel)	< ± 4.77	0
	± 4.77	–30
	> ± 4.77	–12 dB/octave to –60 dB
	~ 26.98	–60 dB
Spectrum occupancy 3 (10 kHz on the traditional analogue AM channel)	< ± 5.3	0
	± 5.3	–30
	> ± 5.3	–12 dB/octave to –60 dB
	~ 29.98	–60 dB

	Frequency relative to the channel centre (kHz)	Level difference in relation to in-channel peak level (dB)
Spectrum occupancy 4 (18 kHz using two of the traditional analogue AM channel)	< ± 9.54	0
	± 9.54	–30
	> ± 9.54	–12 dB/octave to –60 dB
	~ 53.97	–60 dB
Spectrum occupancy 5 (20 kHz using two of the traditional analogue AM channel)	< ± 10.6	0
	± 10.6	–30
	> ± 10.6	–12 dB/octave to –60 dB
	~ 59.96	–60 dB

e) Recommendation ITU-R BS.1615 – IBOC DSB

Modulation	OFDM with QPSK
Frequency bands	VHF
Channel bandwidth	400 kHz
Carriers per channel	
MP1 (Hybrid)	380 divided into 20 frequency partitions
MP2 through MP3 (Extended hybrid)	Up to 530 divided into 28 frequency partitions
MP5, MP6, MS1 through MS4 (All digital)	Up to 1 093 divided into 58 frequency partitions
Critical BLER under AWGN	0.16
SPAN for single channel view	1.3 MHz
RBW or filter per BIN	1 kHz
Sweep speed/integration time	Slow (2 s)

Using these parameters, the following spectrum mask should be applicable:

	Frequency relative to the channel centre (kHz)	Level difference in relation to in-channel peak level (dB)
Digital signal on hybrid mode	0 to ± 50	–83.39
	± 50 to ± 95	{–83.39 + (|frequency (kHz)| – 50 kHz) × 0.2}
	± 95 to ± 100	{–61.39 + (|frequency (kHz)| – 100 kHz) × 2.6}
	± 200 to ± 205	{–61.39 – (|frequency (kHz)| – 200 kHz) × 2.6}
	± 205 to ± 250	{–74.39 – (|frequency (kHz)| – 205 kHz) × 0.2}

	Frequency relative to the channel centre (kHz)	Level difference in relation to in-channel peak level (dB)
Signal on all–digital	± 200 to ± 207.5	{–51.39 – (|frequency (kHz)| – 200 kHz) × 1.733}
	± 207.5 to ± 250	{–64.39 – (|frequency (kHz)| – 207.5 kHz) × 0.2118}
	± 250 to ± 300	{–73.39 – (|frequency (kHz)| – 250 kHz) × 0.56}
	± 300 to ± 600	–101.39
	> 600	–111.39

5.2.2.5 Digital terrestrial TV broadcast

Digital terrestrial TV broadcast also produced several standards around the globe. These standards share the same band and channels used for analogue television. For this reason, the spectrum occupancy follows the same definitions as for the legacy systems. This concern has been stated in Recommendation ITU-R BT.798, and later explicitly defined in the form of protection masks in Recommendation ITU-R BT.1206. Due to this definition, all standards discussed are provided with alternatives for channel bandwidths of 6 MHz, 7 MHz or 8 MHz, in order to match the previously existing TV broadcast bandwidth in use.

At this section are described the standards discussed in more detail within ITU, namely ATSC, DVB-T and ISDB-T, considering Recommendation ITU-R BT.1368 as a reference, which defines planning criteria for digital terrestrial television services, and Recommendation ITU-R BT.1306, which defines error-correction, data framing, modulation and emission methods for these systems. Another reference used for the following description was the book by Fischer [2008].

Another standard that is not presented in the above-mentioned Recommendations and will not be thoroughly discussed on this Handbook is the DTMB (digital terrestrial multimedia broadcast) also known previously as DMB-T/H. It uses TDS-OFDM (time domain synchronous-orthogonal frequency-division multiplexing), providing two modes of multicarrier operation for fixed and mobile applications. Further details on this system can be obtained on the Chinese Standardization Administration.

Considering intrinsic quality parameters for digital television broadcast standards due to the various topologies and engineering options of transmitter networks, and additionally, the numerous analogue to digital migration and frequency sharing scenarios among broadcast networks, advanced intrinsic quality diagnostics might be essential to allow the proper application of spectrum monitoring resources, especially to solve interferences and promote the spectrum usage efficiency.

One especial feature of some of the digital modulation standards is the possibility of creation of single frequency networks (SFN), a condition where several transmitters are operating at the same frequency on the vicinity of each other, transmitting the same content. The basic objective of such network is to provide better coverage over an area using lower power transmitters, solving propagation limitations such as posed by terrain features and/or distance and thus providing better spectrum efficiency.

This possibility is created taking advantage of ability of digital transmission systems to provide multi-path cancelation and considering the multiple transmitters as a severe case of multi-path propagation. i.e., as long as the symbols transmitted are the same; the frequency is the same; and the time difference between transmitters are within acceptable limits, the receivers should be able to decode the signal with no error. This technique is somewhat similar to the CDMA soft handoff feature on mobile communication networks.

In fact, the ability to operate on a SFN mode is inherent to any digital transmission scheme that provides fairly robust features against multi-path propagation and as such, can be easily used also for most OFDM transmission systems either for TV or sound broadcast, although is more commonly applied to TV.

Whenever an SFN is in operation, the use of specialized equipment able to perform detailed system analysis is required in order to properly evaluate the network performance, mainly because simple signal level measurements will not be able to determine if such network is operating within it’s modulation requirements and /determine if interference affected areas are a product of SFN engineering restrictions or from other cause.

An example of interference studies on DVB-T systems can be observed at the Project IST-2000-26222 ANTIUM "DVB-T field trial report".

a) ATSC – Advanced television systems committee

Modulation	Eight-level trellis-coded vestigial sideband (8-VSB)
Intrinsic quality measurements	– BER (3 types: Before Viterbi; after Viterbi and after Reed-Solomon) – MER (Modulation error ratio) – Shoulder attenuation – Amplitude frequency response – Pilot carrier amplitude – Harmonics – Group-delay – Phase response
Frequency bands	VHF and UHF
Carriers per channel	1
Critical BLER under AWGN	1×10^{-6} after Reed-Solomon decoding
Carrier-to-noise ratio in an AWGN channel	Depending on modulation and channel code. 3.1-20.1 dB. Obtained from simulation with perfect channel estimation at critical BLER
SPAN for single channel view	10 MHz
RBW or filter per BIN	10 kHz
Sweep speed/integration time	Average (300 ms)

Using a measurement bandwidth of 500 kHz, the following spectrum mask should be applicable. See also IEEE P1631/D3 for additional measurement information about this system:

	Frequency difference relative channel edge Δf (MHz)	**Level difference in relation to in-channel total average power (dB)**
Full service transmitters (FCC 47CFR § 73.622(h))	Up to 0.5	–47
	Between 0.5 and 3.0	$-11.5 \times (\Delta f + 3.6)$
	> 3.0	–110
Stringent emissions, according to FCC 47CFR § 74.794(a)	Up to 0.5	–47
	Between 0.5 and 3.0	$-\{[11.5 \times (\Delta f - 0.5)] + 47\}$
	> 3.0	–76
Simple emissions, according to FCC 47CFR § 74.794(a)	Up to ± 3.0	$-[(\Delta f^2 \div 1.44) + 46]$
	> ± 6.0	–71

b) DVB-T/H – Digital video broadcast – Terrestrial and handheld

Modulation	OFDM with QPSK, 16-QAM, 64-QAM, MR-16-QAM, MR-64-QAM
Intrinsic quality measurements	– BER (3 types: Before Viterbi; after Viterbi and after Reed-Solomon) – MER (Modulation error ratio) – Signal noise ratio – AWGN (Additive white gaussian noise) – Phase Jitter – I/Q amplitude imbalance – I/Q phase error – Crest factor – Amplitude, phase and group delay – Impulse response – Shoulder attenuation
Frequency bands	VHF and UHF
Carriers per Channel	1 705 (2k mode – T/H) 3 409 (4k mode – H) 6 817 (8k mode – T/H)
Critical BLER under AWGN	1×10^{-4} before Reed-Solomon decoding
Carrier-to-noise ratio in an AWGN channel	Depending on modulation and channel code 5.0-23 dB. Obtained by test with prototype system at critical BLER
SPAN for single channel view	10 MHz
RBW or filter per BIN	10 kHz
Sweep speed/integration time	Average (300 ms)

Using a measurement bandwidth of 4 kHz, the following spectrum mask should be applicable, as per GE06 Final Acts, Annex 2. See also Recommendation ITU-R SM.1792, for additional information:

	Frequency relative to the channel centre (MHz)	**Level difference in relation to in-channel peak level (dB)**
Transmitters operating with 7 MHz channel spacing in uncritical cases	± 3.35	0
	± 3.7	–40
	± 5.25	–52
	± 10.5	–77
Transmitters operating with 7 MHz channel spacing in critical cases	± 3.35	0
	± 3.7	–50
	± 5.25	–62
	± 10.5	–87

	Frequency relative to the channel centre (MHz)	Level difference in relation to in-channel peak level (dB)
Transmitters operating with 8 MHz channel spacing in uncritical cases	± 3.9	0
	± 4.2	–40
	± 6.0	–52
	± 12.0	–77
Transmitters operating with 8 MHz channel spacing in critical cases	± 3.9	0
	± 4.2	–50
	± 6.0	–62
	± 12.0	–87

c) ISDB-T – Integrated services digital broadcasting – Terrestrial

Modulation	OFDM with DQPSK, QPSK, 16-QAM, 64-QAM
Intrinsic quality measurements	– BER (3 types: Before Viterbi; after Viterbi and after Reed-Solomon), may be presented for each transmission mode – MER (Modulation error ratio) – Signal noise ratio – AWGN (Additive white gaussian noise) – Phase jitter – I/Q amplitude imbalance – I/Q phase error – Crest factor – Amplitude, phase and group delay – Impulse response – Shoulder attenuation
Frequency bands	VHF and UHF
Carriers per channel	1 405 (Mode 1) 2 809 (Mode 2) 5 617 (Mode 3)
Critical BLER under AWGN	2×10^{-4} before Reed-Solomon decoding
Carrier-to-noise ratio in an AWGN channel	Depending on modulation and channel code 5.0-23 dB. Obtained by test with prototype system at critical BLER
SPAN for single channel view	10 MHz
RBW or filter per BIN	10 kHz
Sweep speed/integration time	Average (300 ms)

On the following table are presented spectrum masks for ISDB-T operating with 6 MHz (5.7 MHz) bandwidth. For other bandwidths, simplified masks are presented at Recommendation ITU-R BT.1206.

	Frequency relative to the channel centre (MHz)	**Level difference in relation to in-channel peak level (dB)**
Transmitter below 0.25 W (ARIB STD-B31 Version 1.6)	± 2.79	0
	± 2.86	–20
	± 3.00	–27
	± 4.36	–44
Transmitter power between 0.25 W and 2.5 W (ARIB STD-B31 Version 1.6)	± 2.79	0
	± 2.86	–20
	± 3.00	–27
	± 4.36	–50
Sub-critical mask (ABNT NBR 15601:2007)	± 2.79	0
	± 2.86	–20
	± 3.00	–27
	± 3.15	–36
	± 4.5	–53
	± 9	–83
Non-critical mask (ABNT NBR 15601:2007)	± 2.79	0
	± 2.86	–20
	± 3.00	–27
	± 3.15	–36
	± 4.5	–53
	± 9	–83
Critical mask (ABNT NBR 15601:2007)	± 2.79	0
	± 2.86	–20
	± 3.00	–34
	± 3.15	–50
	± 4.5	–67
	± 9	–97

5.2.3 Specific instruments used on broadcast monitoring

As discussed on the introductory notes of § 5.2, in this sub-section are described general guidelines to expand the monitoring facilities by implementing additional monitoring channels adequate to radio signal monitoring and adequate to content monitoring.

Information recorded by the additional channels can be used to help identifying transmitters, ascertain compliance with specific content regulations, such as commercial use of non-commercial licensed channels, and even evaluation of transmission characteristics, such as operating time and spectrum occupancy, night time power reduction for HF broadcast or objective image and sound quality parameters.

According to national needs, a network of such stations can provide auditing capabilities to several different organizations evaluating different obligations of broadcast service providers, including taxation over media production, copyright protection or even civil rights.

Much like for standard spectrum monitoring facilities, the regulator can implement content monitoring stations of different types. Most of the time, considering the small size of such stations, it might be of interest to implement this content monitoring channel as an additional resource of standard spectrum monitoring stations. For example, once a transmission is detected, a secondary recorder is activated, freeing the monitoring receiver to proceed with the scan over a wider frequency span.

5.2.3.1 General topology

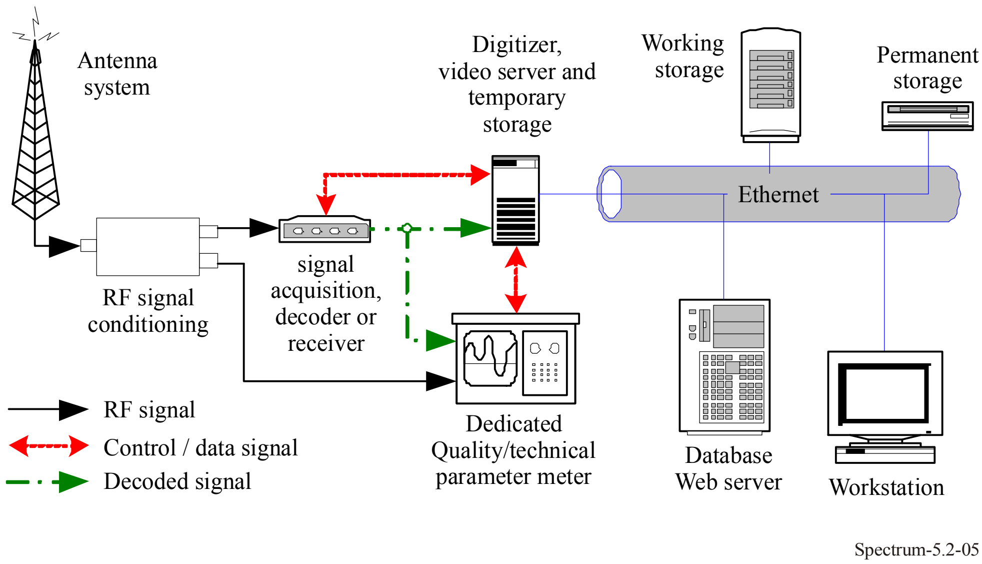
Modern monitoring systems can largely benefit from the state-of-art software design practices, including the use of scalable and reusable software components, such as API, Browser components and commercial communication standards such as TCP/IP, HTML and Web services to provide a more flexible and easy to integrate platform.

The use of analogue recording and distribution systems as support for monitoring activities, although possible, is not reasonable on the modern days due to its limitations in terms of operation and maintenance, and, as such will not be further considered on this chapter.

The following diagram presents a simplified platform architecture for content monitoring. From this diagram, the following sections are defined, providing more detailed information on each element.

FIGURE 5.2-5

Simplified platform architecture for content monitoring



Such platform can be implemented either as a fixed station, or integrated on mobile or transportable stations. Several of the above functions might be integrated into a single device.

5.2.3.2 Antenna system

The number, size and type of antennas should be chosen in such way to accommodate specific signal characteristics and installation conditions.

Recommendation ITU R BS.599 proposes the use of directive antennas on fixed FM sound broadcast monitoring installations, this kind of antenna will significantly reduce the probability of interference and increase the sensitivity. The directivity mask for sound broadcast presented on this recommendation, either in vertical and horizontal polarizations is presented on Fig. 5.2-7.

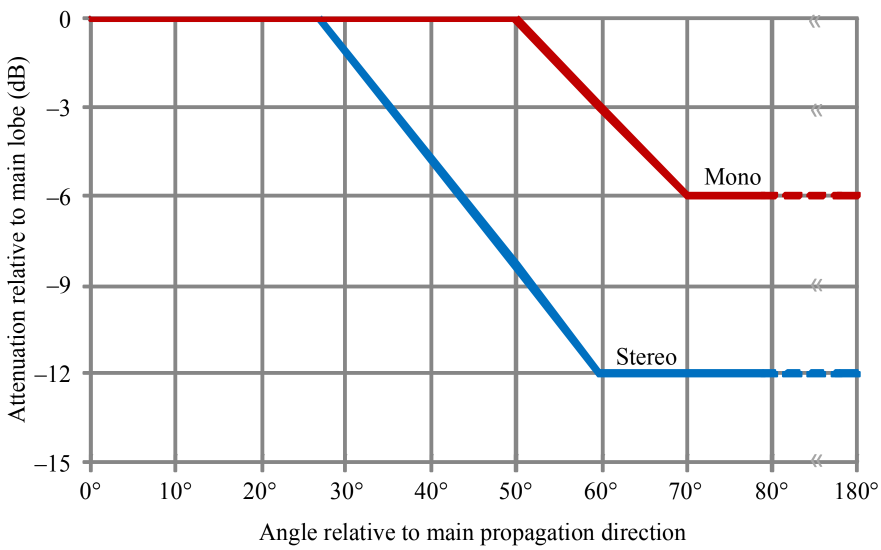
Although there is no clear recommendation on the type of antenna and on the amount of directivity recommended for other services, especially for specific radio interface signal measurements the concept still applies and the use of directive antennas is recommended in order to reduce the influence of undesirable propagation effects.

Mobile content monitoring devices should give preference to non directional antennas or antenna arrays, at least on the horizontal plane. This usually is performed by monopoles or arrays of antennas. Monopoles, dipoles and discone antennas might be good alternatives as passive antennas for the VHF bands.

For more specialized mobile systems, aimed for example to perform interference analysis on SFN networks, or to be used on network optimization tasks, the use of antenna arrays and of adaptive spatial processing with interference mitigation capabilities is desirable since it may provide better flexibility and performance in terms of signal-interferer rejection, including in cases of correlated signals over the same frequency, such as observed over SFN.

FIGURE 5.2-6

Directivity of receiving antenna for fixed monitoring site



Spectrum-5.2-06

Considering gain specification for fixed installations, Recommendation ITU-R BT.804, proposes the following values for use on the television bands:

Band	**Frequency (MHz)**	**Antenna gain (dB)**
I	41-68	3.5
III	162-230	7.5
IV	470-582	10
V	582-960	12

As stated on the referred Recommendations, these values are generally used as reference for planning, and, as such might be used to integrate a reference station that is in accordance with the general user.

For digital television systems, Recommendation ITU-R BT.1368 proposes similar values, sometimes with slightly higher gain over lower frequency bands. The reader should refer to the tables presented later on this section in order to properly select the antenna system considering the sensitivity requirements of the receiver and the available RF conditioning devices.

RF Conditioning:

The RF conditioning devices include switching, distribution, cabling, low noise amplifiers and filters to promote optimum receiving quality while maintaining realistic user's conditions.

As a reference, the sensitivity levels discussed below should be considered when designing such a subsystem.

5.2.3.3 Reception and decoding

In the simplest cases the signal reception and decoding is usually performed by standard commercial video and audio receivers/tuners and decoders.

When deeper analyzes are required as described above, the signal reception and decoding may include adaptive spatial filters in order upgrade the demodulation and the decoding performances.

Ideally the system should be flexible enough to be easily integrated with standard commercial receivers/decoders, enabling the easy monitoring of digital broadcast on different standards, and coded pay-TV services operating over cable, satellite or terrestrial.

According to Recommendations ITU-R BS.703 (analogue AM broadcast), ITU-R BS.1615 (digital sound broadcast below 30 MHz), ITU-R BS.704 (FM broadcast), the signal acquisition, considering receivers, RF conditioning and antenna systems, should provide sensitivity in accordance with the Table 5.2-1:

TABLE 5.2-1

Receiver sensitivity for sound broadcast

System	Frequency Band	Filter BW	Minimum Field Strength (dB(μV/m))
AM DSB sound	30 kHz-300 kHz	10 kHz	66.0
Digital sound	30 kHz-300 kHz	9 kHz	39.1 (1)
AM DSB sound	300 kHz-3 MHz	10 kHz	60.0 (2)
Digital sound	300 kHz-3 MHz	10 kHz	33.1 (3)
AM DSB sound	3 MHz-30 MHz	10 kHz	40.0 (4)
Digital sound	3 MHz-30 MHz	10 kHz	19.1 (5)
FM sound – mono	66 MHz-108 MHz	150 kHz or 100 kHz (6)	30.0
FM sound – stereo	66 MHz-108 MHz	150 kHz or 100 kHz	50.0

(1) Lower estimated value for DRM (most robust operation mode), values up to 49.2 dB(μV/m) might be used to increase the transmission quality. For narrower spectrum occupancy mode, minimum usable field strengths are slightly higher. See Recommendation ITU-R BS.1615 for a detailed description.

(2) Values of 54 dB(μV/m) and 40 dB(μV/m) are also supported.

(3) Lower estimated value for DRM (most robust operation mode) considering ground waves only. Values up to 46.5 dB(μV/m) might be used to increase the transmission quality using also sky waves. For narrower spectrum occupancy mode, minimum usable field strengths are slightly higher. See Recommendation ITU-R BS.1615 for a detailed description.

(4) The WARC (HFBC-87) [1987, Geneva] adopted this value for DSB and SSB reception.

(5) Lower estimated value for DRM (most robust operation mode), values up to 29.9 dB(μV/m) might be used to increase the transmission quality. For narrower spectrum occupancy mode, minimum usable field strengths are slightly higher. See Recommendation ITU-R BS.1615 for a detailed description.

(6) 150 kHz for pilot tone system or 100 kHz for polar-modulation system, according to local system in use.

According to Recommendations ITU-R BT.804 (analogue TV broadcast) and ITU-R BT.1368 (digital TV broadcast) the signal acquisition, considering receivers, RF conditioning and antenna systems, should provide sensitivity in accordance with Table 5.2-2:

TABLE 5.2-2

Receiver sensitivity for television broadcast

System	Frequency band (MHz)	Filter BW (MHz)	Minimum field strength (dB(μV/m))
Analogue TV	41-68	6, 7 or 8	47
Analogue TV	162-230	6, 7 or 8 (1)	53
Analogue TV	470-582	6, 7 or 8	62(2)
Analogue TV	582-960	6, 7 or 8	67
Digital TV – ATSC	54-88	6	35(3)
Digital TV – ATSC	174-216	6	33(3)
Digital TV – ATSC	470-806	6	39(3)
Digital TV – DVB-T QPSK	200	8	27(4)
Digital TV – DVB-T QPSK	550	8	33
Digital TV – DVB-T QPSK	700	8	35
Digital TV – DVB-T 16-QAM	200	8	33
Digital TV – DVB-T 16-QAM	550	8	39(5)
Digital TV – DVB-T 16-QAM	700	8	41
Digital TV – DVB-T 64-QAM	200	8	39
Digital TV – DVB-T 64-QAM	550	8	45
Digital TV – DVB-T 64-QAM	700	8	47
Digital TV – ISDB-T DQPSK	100	6	20.7(6)
Digital TV – ISDB-T QPSK	100	6	23.4
Digital TV – ISDB-T 16-QAM	100	6	29.1
Digital TV – ISDB-T 64-QAM	100	6	36.1
Digital TV – ISDB-T DQPSK	200	6	24.7
Digital TV – ISDB-T QPSK	200	6	23.4
Digital TV – ISDB-T 16-QAM	200	6	33.1
Digital TV – ISDB-T 64-QAM	200	6	40.5
Digital TV – ISDB-T DQPSK	600	6	30.2
Digital TV – ISDB-T QPSK	600	6	28.9
Digital TV – ISDB-T 16-QAM	600	6	38.6
Digital TV – ISDB-T 64-QAM	600	6	46.0

(1) The bandwidth should be considered between 6, 7 or 8 MHz, according to local system in use.

(2) The limit values in bands IV and V should be increased by 2 dB for system K.

(3) The limit values are computed according to expressions presented on Recommendation ITU-R BT.1368. The presented values are computed for 6 MHz channel bandwidth and frequencies of 69, 194 and 615 MHz, respectively.

(4) The limit values are computed according to expressions presented on Recommendation ITU-R BT.1368. The presented values are computed for 8 MHz channel bandwidth.

Notes relating to table 5.2-2 (end)

(5) The limit values are computed according to expressions presented on Recommendation ITU-R BT.1368. The presented values are computed for 8 MHz channel bandwidth at selected representative frequencies.

(6) The limit values are computed according to expressions presented on Recommendation ITU-R BT.1368. The presented values are computed for 6 MHz channel bandwidth at selected representative frequencies.

The implementation of the additional content monitoring channel may also be done by the integration of radio scanners, such as the ones used by amateur radio. Compared to commercial broadcast receivers, such scanners might lack the proper decoding capabilities but might provide benefits such as larger operational frequency range and automation resources, enabling the provision of a transparent user interface for a mixed monitoring system, composed by the standard measuring channels, such as described on Chapter 3, and additional content monitoring channels.

5.2.3.4 Dedicated quality/technical parameter meter

On most cases, basic service evaluation such as coverage and spectrum mask can be performed by standard monitoring equipment combined with standard commercial video and audio receivers/tuners and decoders. For digital broadcasting, even can be found some more sophisticated commercial receivers that perform some basic intrinsic quality measurements, such as BER, but to fully evaluate the characteristics of broadcasting networks, more specialized equipment might be needed, especially to solve complex interference cases, such as may be observed on SFN.

Experimental studies, such as Project IST-2000-26222 ANTIUM "DVB-T multi-channel processing report", indicate that such system, including receiver, decoder and antennas, should provide from 10 to 20 dB of interference rejection capability more than regular terminals, so that reliable interference diagnosis and signal measurements can be achieved, including proper decoding of the signalling channel, allowing the identification of essential parameters such as guard time modulation and coding schemes.

5.2.3.5 Digitizing and compression

Whenever choosing a digitizing system, one should be aware of its intrinsic noise characteristics, choosing higher grade systems for applications such as media quality evaluation, i.e. with larger bits/sample ratio and with better input filter characteristics, or lower grade systems for standard content monitoring and media classification. Considering modern systems, alternatives with less than 8 bits per sample should be avoided, and more than 10 bits per sample could be considered an unnecessary effort for most applications.

In terms of resolution and scale based on the analogue systems is the common intermediate format (CIF) that defines an image frame of 352 × 288 pixels. A standard definition television would be defined around 4CIF, 704 × 576 pixels and a high definition television around 16CIF, 1408 × 1152 pixels. Other lower resolutions are also defined, as QCIF, a quarter of CIF with 176 × 144 pixels and SQCIF, sub-quarter CIF, with 128 × 96 pixels.

Considering a basic calculation, taking 8 bits per colour component, making 24 bits per pixel, multiplying these 24 bits times the 101.376 pixels on a CIF frame, would give us 2.433.024 bits per frame, or 72.990.720 bits/s on a 30 fps moving picture sequence. With this numbers in mind, one comes easily to the conclusion about the importance of video compression algorithms.

Compression algorithms take advantage on the natural redundancy of the information in order to reduce its size. This redundancies may be only in terms of the digital representation chosen, from which can be derived the lossless compression algorithms, or may include redundancy on the information itself, such as invariant frame segments over time, the difference between luminance resolution and chrominance resolution needed to represent a certain scene, the spectrum characteristics of the information in relation to the human perception limitations. The suppression or reduction of such redundancies wields to loss compression algorithms. Usually, video and audio compression algorithms combine both methods to achieve greater compression.

Within ITU, video compression was subject of some Recommendations. ITU-T Recommendation H.120 (Edition 1 – 1988), focusing on videoconferencing, was the first on a series of video CODEC standards within ITU-T. Followed by ITU-T Recommendation H.261 (Edition 1 – 1990). This Recommendation focused on transmissions over SDH channels (n × 64 kbit/s rate) and application such as video conferencing.

Later ITU-T Recommendation H.262, jointly developed with ISO/IEC and more commonly known as MPEG-2, was issued in 1995 and tried to address the need for a generic CODEC with higher quality, more suitable for applications such as broadcasting and digital media storage.

ITU-T Recommendation H.263 (Edition 1 – 1996), improved the CODEC specifications from ITU-T Recommendation H.261, including better transformations and inter-picture prediction to decrease spatial and temporal redundancies compression.

The last and most notable Recommendation on this series within ITU is ITU-T Recommendation H.264, approved in 2003 and with later corrigendum issued in 2009. This Recommendation was a joint development from ITU-T video coding expert group (VCEG) and ISO/IEC moving picture experts group (MPEG) in the form of the Joint Video Team (JVT). The ISO/IEC standard, identical to the ITU-T Recommendation H.264 is the ISO/IEC 14496, also known as MPEG-4.

This later standard provide higher performance than the previous, file size reduction may be as high as 64% when comparing with ITU-T Recommendation H.262 and 49% when comparing with ITU-T Recommendation H.263. The distortion, when measured in terms of peak signal-to-noise ratio (PSNR) for a video sequence coded at approximately 768 kbit/s, is about 4 dB higher than ITU-T Recommendation H.262 and 3 dB higher than ITU-T Recommendation H.263.

The discussion on this section focused on video, because of its higher demands in terms of processing, transmission and storage of information. Audio signals suffer from the same problems in terms of sampling and quantizing but the transmission and storage of raw digital data is feasible, and might be considered for high-end applications. On computer systems, for example, the WAV file standard corresponds to such raw digital format.

Usually, the video standards described above include also a compression layer for audio and the same algorithms are used for audio compression, even when not accompanied by the video. This is the case of commonly known formats, such as MP3, acronym for MPEG Layer 3, which corresponds to the audio layer for compression standard from MPEG.

As a conclusion, probably is clear by now the importance of the compression for the implementation of content monitoring and recording. On the other hand, considering that most compression algorithms will also introduce noise and distortion, one have to keep in mind the specific objectives of the intended system.

The most recommended approach is to consider a solution that integrates several options and maybe even several codec, allowing the choice of the proper codec and bit rate in accordance to the later intend use of the media.

Experience with such system has demonstrated that for applications such as media browsing, streaming, content identification and classification, compression rates as high as 16 kbits/s for audio and 180 kbits/s for video using ITU-T Recommendation H.264 codec may provide acceptable results. This may provide video and audio quality similar to the experienced on videoconferencing applications.

For quality assessment on video, one could consider a much higher bit rate, above 4 Mbits/s, using codecs such as ITU-T Recommendations H.264 and H.262 that shall provide quality similar to digital television or a DVD. For quality assessment of sound broadcast, the use of raw digital format might be considered.

It is recommended also to have additional alternatives for intermediate quality, between the high end needs for quality assessment and basic needs for browsing and classifications, providing the system user with the ability to better suit his needs.

An interesting alternative is that such parameter to be configurable during the scheduling process.

5.2.3.6 Preliminary media analysis and metadata

Preliminary media analysis of the audio and/or video collected comprehends the creation of metadata fields that are essential to improve the performance of media search algorithms and further classification and annotation of the collected information by a human operator, whenever this task might be necessary.

Nowadays, the metadata information can include not only basic information directly provided by the receivers and accessory systems, such as: original timestamp, frequency, signal level, RDS information, closed caption, error rate, but also more complex information derived from specialized analysis algorithms, such as: key frame detection, reference image detection, reference sound sequence detection (jingle), quality evaluation, speaker identification, rhythmic classification, etc.

The real time generation of advanced metadata might be useful or even mandatory when, for example, one is analyzing video quality parameters or trying to identify or classify especial features (frame identification), since the further compression and storage might affect the original information characteristics, for example, reducing the number of frames per second on a video sequence and increasing the error rate of the automatic annotation of frame detection.

The system design should make a compromise between the cost of real time processing required to perform the preliminary media analysis and the benefits of metadata gathered as an aid for further processing. No specific study has been known up to this moment to address this issue, but the fact is that the constant evolution on algorithms and computer power will constantly bend this balance to increase the systems ability to perform real time media classifications.

There are several ways to store the metadata collected or produced, traditionally they would simply be stored on a database system that allows its easy recovery through the use of query algorithms embedded on such systems. This concept still useful and might be applied to implement an integrated media portal to enable access to the media to several users.

The main drawback of simple database systems is that, once the media is retrieved, it may lose its link to the metadata, also, the distribution and permanent storage of this media, outside the database system, may be a problem. To overcome this, the use of multimedia description standards, such as MPEG-7 is encouraged.

MPEG-7 is described on the standard ISO/IEC 15398, and provide a large set of tools for metadata core description and also system tools for handling the media associated information. With MPEG-7, the metadata may be stored in a XML structure within the data stream itself, allowing easy and secure transmission and storage of this information.

5.2.3.7 Data distribution and processing

As discussed at the beginning of this section, to take advantage from the digital recorded media data, the systems should consider network resources for distribution and processing of the collected information.

Although the network transmission capacity is constantly increasing, when considering the implementation of a content monitoring system, the network usage should be carefully considered, especially in terms of costs in the short and long term. Whenever possible, higher compression rates should be used, allowing more efficient use of these resources.

In terms of processing, an example of workflow expected for such system, considering full automation of basic tasks, is presented on the following figure. This scheme presents the interaction between automated and manual tasks for media processing.

The tasks on the diagram presented on Fig. 5.2-7 could be summarized as follows:

Step 1: A supervisor organizes the task schedule. This schedule can be defined with different levels of priority and different recording characteristics in order to accommodate different mission objectives and accomplish higher usability of the system. The signal is recorded by the automated acquisition system and stored on a temporary database for further analysis.

Step 2: Supervisors superficial analysis of the recorded media in order to establish it’s relevance for further studies and/or storage.

Step 3: Media processing for specialized analysts and applications.

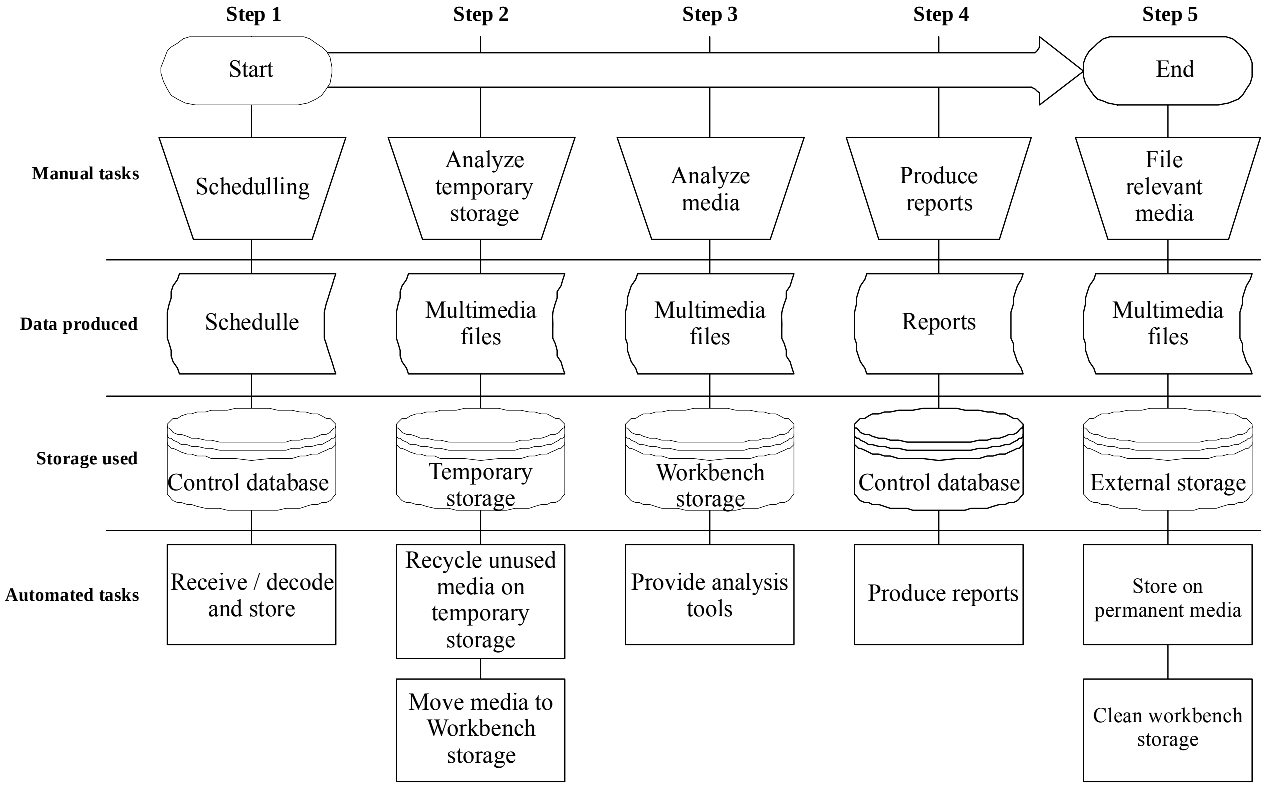
Step 4: Automated reported generation.

Step 5: Permanent storage on higher capacity media in order to open space on the working databases for future missions.

One should consider that, with the evolution of new algorithms and techniques for automated media evaluation and classification, the volume of media to be analyzed should be reduced but there is no perspective even on mean term, to completely suppress the manual tasks.

FIGURE 5.2-7

Data processing workflow example



Spectrum-5.2-07

5.2.3.8 Data storage

As described on the diagram presented on the previous section, one can conceive at least 3 main storage units on a content monitoring system: a temporary, where media is storage during and immediately after being capture; a workbench, where the media is storage for further processing; and a permanent, where media is storage after all processing has been performed.

The size and type of storage to be used may vary greatly depending on the solution designed. In general, one should compute the size of the storage taking into consideration the bit rate consumption in accordance with the compression algorithms used and the desired amount of media time to be available on each step of the media processing.

No matter how much time is considered for media availability, the storage capacity is bound to run out in relatively short period. Thus, the project implementation should seriously consider the alternatives for permanent media storage, such as tapes, DVDs and media robots for very large, low speed, storage.

Whenever implementing this type of storages, one should also consider on the implementation the means for indexing and accessing this information, complementing the storage data system with a proper database for indexing the media storage.

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Technical Instruction [1982] No. 5R4, [07.1982], issued by ARD and ZDF, available from Institut für Rundfunktechnik GmbH, Floriansmühlstraße 60, D-80939 München (in German).

ITU-R Recommendations and Reports

NOTE– In every case the latest edition of the Recommendation should be used.

Recommendation ITU-R BS.412 – Planning standards for terrestrial FM sound broadcasting at VHF.

Recommendation ITU-R BS.599 – Directivity of antennas for the reception of sound broadcasting in band 8 (VHF).

Recommendation ITU-R BS.643 – System for automatic tuning and other applications in FM radio receivers for use with the pilot-tone system.

Recommendation ITU-R BS.703 – Characteristics of AM sound broadcasting reference receivers for planning purposes.

Recommendation ITU-R BS.704 – Characteristics of FM sound broadcasting reference receivers for planning purposes.

Recommendation ITU-R BS.706 – Data system in monophonic AM sound broadcasting (AMDS).

Recommendation ITU-R BS.774 – Service requirements for digital sound broadcasting to vehicular, portable and fixed receivers using terrestrial transmitters in the VHF/UHF bands.

Recommendation ITU-R BS.1114 – Systems for terrestrial digital sound broadcasting to vehicular, portable and fixed receivers in the frequency range 30-3 000 MHz.

Recommendation ITU-R BS.1116 – Methods for the subjective assessment of small impairments in audio systems including multichannel sound systems.

Recommendation ITU-R BS.1283 – A guide to ITU-R Recommendations for subjective assessment of sound quality.

Recommendation ITU-R BS.1284 – General methods for the subjective assessment of sound quality.

Recommendation ITU-R BS.1285 – Pre-selection methods for the subjective assessment of small impairments in audio systems.

Recommendation ITU-R BS.1286 – Methods for the subjective assessment of audio systems with accompanying picture.

Recommendation ITU-R BS.1387 – Method for objective measurements of perceived audio quality.

Recommendation ITU-R BS.1534 – Method for the subjective assessment of intermediate quality levels of coding systems.

Recommendation ITU-R BS.1615 – "Planning parameters" for digital sound broadcasting at frequencies below 30 MHz.

Recommendation ITU-R BT.500 – Methodology for the subjective assessment of the quality of television pictures.

Recommendation ITU-R BT.710 – Subjective assessment methods for image quality in high-definition television.

Recommendation ITU-R BT.798 – Digital television terrestrial broadcasting in the VHF/UHF bands.

Recommendation ITU-R BT.804 – Characteristics of TV receivers essential for frequency planning with PAL/SECAM/NTSC television systems.

Recommendation ITU-R BT.1128 – Subjective assessment of conventional television systems.

Recommendation ITU-R BT.1129 – Subjective assessment of standard definition digital television (SDTV) systems.

Recommendation ITU-R BT.1206 – Spectrum shaping limits for digital terrestrial television broadcasting.

Recommendation ITU-R BT.1210 – Test materials to be used in subjective assessment.

Recommendation ITU-R BT.1306 – Error correction, data framing, modulation and emission methods for digital terrestrial television broadcasting.

Recommendation ITU-R BT.1368 – Planning criteria for digital terrestrial television services in the VHF/UHF bands.

Recommendation ITU-R BT.1439 – Measurement methods applicable in the analogue television studio and the overall analogue television system.

Recommendation ITU-R BT.1700 – Characteristics of composite video signals for conventional analogue television systems.

Recommendation ITU-R BT.1701 – Characteristics of radiated signals of conventional analogue television systems.

Recommendation ITU-R SM.1009 – Compatibility between the sound-broadcasting service in the band of about 87-108 MHz and the aeronautical services in the band 108-137 MHz.

Recommendation ITU-R SM.1268 – Method of measuring the maximum frequency deviation of FM broadcast emissions at monitoring stations.

Recommendation ITU-R SM.1792 – Measuring sideband emissions of T-DAB and DVB-T transmitters for monitoring purposes.

Report ITU-R BT.1082 – Studies toward the unification of picture assessment methodology.

ITU-T Recommendations and Tutorial

ITU-T Recommendation H.120 – Codecs for videoconferencing using primary digital group transmission.

ITU-T Recommendation H.261 – Video codec for audiovisual services at p x 64 kbit/s.

ITU-T Recommendation H.262 – Information technology – Generic coding of moving pictures and associated audio information: Video.

ITU-T Recommendation H.263 – Video coding for low bit rate communication.

ITU-T Recommendation H.264 – Advanced video coding for generic audiovisual services.

ITU-T Recommendation P.563 – Single-ended method for objective speech quality assessment in narrow-band telephony applications.

ITU-T Recommendation P.800 – Methods for subjective determination of transmission quality.

ITU-T Recommendation P.810 – Modulated noise reference unit (MNRU).

ITU-T Recommendation P.830 – Subjective performance assessment of telephone-band and wideband digital codecs.

ITU-T Recommendation P.862 – Perceptual evaluation of speech quality (PESQ): An objective method for end-to-end speech quality assessment of narrow-band telephone networks and speech codecs.

Tutorial ITU-T [2004] Objective perceptual assessment of video quality: Full reference television.

5.3 Monitoring of cellular systems

5.3.1 Introduction

In the context of this section, the term "cellular systems" is used to comprise all mobile radio systems providing direct or indirect access to public telecommunication networks such as public telephone networks or the internet. Considering differences in network architecture and degree of mobility which have consequences for radio monitoring tasks and procedures, cellular systems are divided in the following categories:

– Cellular radio systems.
– Personal communication systems (PCS).
– Mobile satellite systems (MSS).
– Broadband wireless access (BWA).

5.3.2 Cellular radio systems and standards

Cellular radio systems provide mobile access to other mobile users as well as to the public switched telecommunication network (PSTN). There are many different standards for cellular radio systems in operation today throughout the world. Improved new systems will continue to be installed as demand for high quality mobile voice and data service increases. These new systems, however, place additional challenges on telecommunication administrations charged with spectrum monitoring and regulatory compliance enforcement. Radio monitoring stations equipped with conventional, universal technology may have difficulties in detecting and monitoring cellular radio systems. New equipment must be installed in radio monitoring stations and new techniques employed in order to keep up with advances in cellular radio system design.

Cellular radio systems are different from other land mobile radio systems in several ways. They offer:

– increased call capacity to accommodate larger numbers of users;
– improved quality of service over larger geographic areas;
– better utilization of radio frequency spectrum.

Cellular radio systems utilizing analogue standards have been in operation in the past around many parts of the world. However, such systems are almost universally replaced or upgraded to digital cellular radio systems. Analogue standards were known as the first generation of cellular radio systems. Monitoring of these systems is not covered in detail in this section.

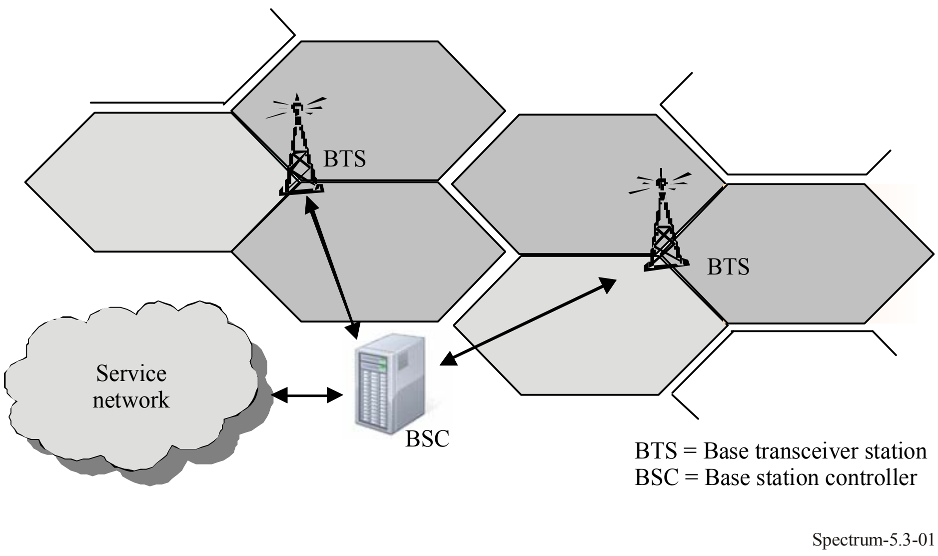
A major limitation of any cellular radio system is the availability of radio frequency spectrum. All cellular radio systems utilize frequency (channel) re-use and most of them enable controlled handovers between defined geographical areas known as cells. The size of a cell is determined by the geographical coverage area of a given signal strength from a base station transmitter operating within that cell.

Figure 5.3-1 shows the simplified architecture of a digital cellular radio system using the example of GSM.

To minimize the number of base stations, they are usually placed at the intersection of three hexagonal shaped cells that are served individually by directional sector antennas with an opening angle of 120°.

FIGURE 5.3-1

GSM network architecture



A so-called handover process automatically switches control of the mobile terminal (handset, or other mobile user equipment) and connection to the adjacent cell when it moves into a new geographic area covered by a different base station transceiver (BTS) usually operating with one or more of the following techniques:

– on a different RF channel for frequency-division multiple access (FDMA);

– on a different time slot for time-division multiple access (TDMA);

– with different orthogonal spreading codes on the same RF channel for code-division multiple access (CDMA).

In CDMA networks it is possible to serve a mobile unit from more than one base station simultaneously. So-called "soft handovers" seamlessly spread the user data stream over two or three base stations depending on their receiving situation at the location of the mobile.

For a more detailed description of the above mentioned multiplex methods see § 6.6.

There are six major standards for digital cellular radio systems that have been deployed prior to the year 2000.

These are known as 2nd generation (2G) systems:

– the European Telecommunications Standards Institute (ETSI) defined standard – known as GSM (Global System for Mobile communication);

– the North American Telecommunication Industry Association/Electronic Industry Association standard for TDMA – commonly known as IS-54 (superseded by the new standard TIA/EIA-136);

– the Japan Research and Development Center for Radio Systems (RCR) TDMA standard RCR STD-27 – known as PDC (personal digital cellular) communication system;
– the North American Telecommunication Industry Association/Electronic Industry Association standard for CDMA – commonly known as IS-95 (superseded by TIA/EIA-95);
– the Japan Association of Radio Industries and Businesses (ARIB) CDMA standard ARIB T-53;
– the Korea Telecommunications Technology Association (TTA) CDMA standard TTA.KO-.06.0003.

The European standard GSM replaces the many incompatible analogue cellular systems previously in use throughout Europe with a single digital network, which allows roaming across international boundaries.

GSM has also been deployed in Europe in the 1 800 MHz band and in the Americas in the 1 900 MHz and 850 MHz band.

The North American Interim Standards IS-54 and IS-95 (now superseded by TIA/EIA-136-A and TIA/EIA-95-C) initially required digital cellular networks to operate in the same frequency bands as analogue cellular.

Service providers have gradually replaced existing analogue equipment with digital services as required to meet demand in individual cell sites.

The PDC standard is similar to IS-54, although it has been implemented in a dedicated 1 500 MHz band in addition to an 800 MHz digital band.

Since year 2000, several 2G extensions and 3G development have built new standards for IMT such as:

– Global Packet Radio Service (GPRS) and Enhanced Data rates for GSM Evolution (EDGE): these 2.5G systems are middle to high rate extensions of the GSM standard.
– UMTS (universal mobile transmission system), is a European 3G standard, based on several CDMA wave forms (FDD mode) and mixed TDMA/CDMA wave forms (TDD mode), that is standardized by ETSI and 3GPP organizations. Terrestrial UMTS operates mainly at 2 000-2 100 MHz, with several extensions in the 900 MHz and in the 450 MHz frequency ranges.
– UMTS supports numerous mobile radio services (voice over IP, mobile video, etc.). Recent extensions for high speed data modes, such as high speed–downlink packet access (HSDPA) and high speed-uplink packet access (HSUPA), and current evolutions towards terrestrial 4G (long term evolution (LTE) increase available data rates and system flexibility.
– CDMA–2000, is a U.S. 3G standard, based on several CDMA wave forms (mainly FDD mode), including the second generation IS 95 A and B CDMA standards, that is standardized by TIA/EIA and 3GPP2 organizations. CDMA 2000 includes multiple radio configurations covering most of the mobile radio services, including high speed packet modes. Convergence of 3GPP2 standards with 3GPP standards is discussed nowadays.

Table 5.3-1 provides some information affecting the air interface and spectra of digital cellular radio systems.

TABLE 5.3-1

Air interface characteristics of digital cellular radio systems

Standard	**GSM 850**	**GSM 900**	**GSM 1 800 (DCS-1 800)** **GSM 1 900 (PCS-1 900)**	**TIA/EIA-136** **(was IS-54)**	**PDC**	**TIA/EIA-95** **(IS-95)**	**UMTS** **CDMA2000**	**LTE**
Access method	TDMA/FDMA (FHSS)			TDMA/FDMA	TDMA/FDMA	CDMA/FDMA (DSSS)	CDMA/FDMA (DSSS)	OFDMA/SC-FDMA
Frequency band (MHz) – Base to mobile – Mobile to base	 869.2-893.8 824.2-848.8	 935-960 std 925-960 extd 890-915 std 880-985 extd	 DCS: 1 805-1 880 PCS: 1 930-1 990 DCS: 1 710-1 785 PCS: 1 850-1 910	 869-894 1 930-1 990 824-849 1 850-1 910	 810-888 1 477-1 501 893-958 1 429-1 453	 869-894 1 930-1 990 824-849 1 850-1 910	 (See Table 5.3-4)	 (Dep. on region)
Duplex type Duplex spacing (MHz)	FDD 45		FDD DCS: 95 PCS: 80	FDD 45 or 80	FDD 83 or 48	FDD 45 or 80	FDD / TDD (See Table 5.3-4)	FDD / TDD
Modulation	0.3 GMSK			$\pi/4$ DQPSK	$\pi/4$ DQPSK	QPSK (forward link) OQPSK/HPSK (reverse link)	QPSK/16-QAM	QPSK-64-QAM
Number of carriers	124	124 174 (ext)	DCS: 374 PCS: 299	832 for lowest band 1 841 for the highest band	1600	20	(See Table 5.3-4)	(Dep. on region)
Carrier spacing (kHz)	200			30	25	1 250	5 000	Up to 20 000
Channels per carrier	8 (full rate) 16 (half rate)			3 (full rate) 6 (half rate)	3 (full rate) 6 (half rate)	64	64	Variable
Mobile maximum output power (W) depending on the power class declared by the manufacturer	(Most commonly used value underlined) 0.8; 2; 5; 8 In EDGE mode: 0.2; 0.5; 2		(Most commonly used value underlined) DCS: 0.25; 1; 4 PCS: 0.25; 1; 2 In EDGE mode for both DCS & PCS: 0,16; 0,4; 1	0.6, 1.6, 4	0.3, 0.8, 2, 3	1.0, 2.5, 6.3	0.125 ; 0.2 ; 0.25 ; 0.5 ; 2	
Base transmit power (W)	2.5 – < 640			Up to 100	Not specified	Not specified	Not specified	Not specified
Maximum Data rate (kbit/s)	14.4 GPRS: 171.2 EDGE: 384			48.6	9.6 in CSD 28.8 in packet mode	14.4 (IS-95A) 115.2 (IS-95B)	UMTS: 2 000 HSDPA: 14 000 in downlink HSUPA: 5 800 in uplink	> 10 000
Frame duration (ms)	4.615			40	40	20	10	10
Frame structure	0.577 ms slot 8 slots/frame			6.66 ms slot 6 slots/frame	6.66 ms slot 6 slots/frame	1.25 ms PCG 16 PCG/frame		

5.3.3 Personal communication systems description

Other than the previously described cellular radio systems, personal communication systems (PCS) are low mobility systems. The main standards are:

– the ETSI defined Digital European Cordless Telecommunications (DECT) standard;

– the Japan Research and Development Center for Radio Systems (RCR) developed standard RCR STD-28 – known as PHS (personal handyphone system).

These systems are usually used to establish a radio connection between portable user equipment (headsets, handsets etc.) and a base station that is connected to the PSTN via cable. Therefore, although having mobile capability, they usually provide radio access on a relatively local level. PCS can be point-to-point or point-to-multipoint in both terrestrial and satellite configurations.

As with the other cellular radio systems, the majority of PCS nowadays utilize digital modulation techniques. Table 5.3-2 provides information on some parameters affecting the air interface.

TABLE 5.3-2

Air interface characteristics of personal communication systems

Standard	DECT	PHS
Access method	TDMA/FDMA	TDMA/FDMA
Frequency band (MHz) – Base to mobile – Mobile to base	 1 880-1 990 1 880-1 990	 1 895-1 907 1 895-1 907
Duplex type Duplex spacing (MHz)	TDD 0	TDD 0
Modulation	GFSK	π/4 DQPSK
Number of carriers	10	77
Carrier spacing (kHz)	1728	300
Channels per carrier	12	4
Mobile transmit power (mW)	250	10
Base transmit power (mW)	250	10 private 500 public
Data rate (kbit/s)	1 152	384
Frame duration (ms)	10	5
Frame structure	417 υs slot 24 slots/frame	0.625 ms 8 slots/frame

The most common services related to the term PCS are the "micro-cellular" point-to-multipoint voice and data services, intended to provide the pedestrian user in the home, office, or on the street with a full array of voice and data services. The small cells are necessary to provide improved coverage and capacity. New technologies being developed are referred to as local multipoint distribution service (LMDS) and multimedia distribution service (MMDS). These systems operate in a cellular configuration and provide both interactive video and data services.

DECT added significant enhancements to the preceding CT2 technology and developed to accommodate the pedestrian on the street, as CT2 does, with an architecture that could also handle wireless in-building networks like PABX's and LAN's. DECT also provides for two-way calling and automatic roaming and hand-off capabilities.

PHS is a digital cordless telephone system with a concept that is similar to DECT. A personal station may be used either with a private cordless telephone base station or with a public cell station.

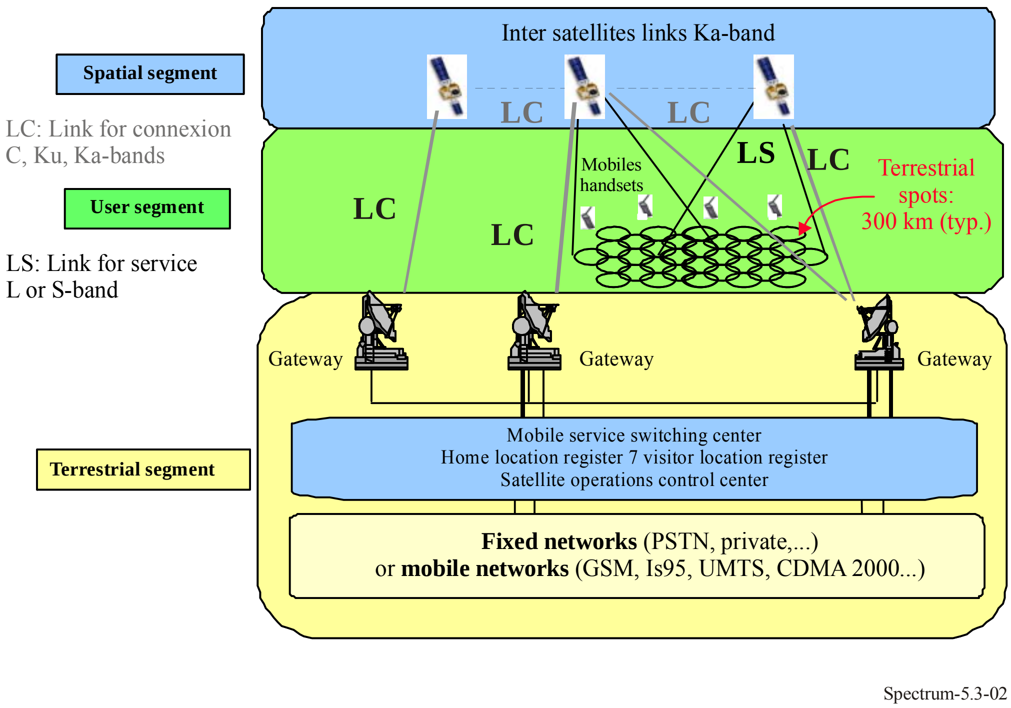
All DECT and PHS stations continuously monitor the channel for errors. If the number of time slots with errors in a defined period of time exceeds a threshold, interference avoidance is performed. This includes switching to another slot on same carrier, switching to another carrier, switching to another cell station, temporary halt to transmission, and release of the radio line.

5.3.4 Mobile-satellite service systems

Mobile-satellite service (MSS) systems use satellites on either geostationary orbits (GSO) or non-GSO with a number of different orbital characteristics. The mobile units communicate directly with the satellite currently passing over the region and the satellite relays the communication to another satellite or Earth station for further routing. Control stations track the satellites through their orbits and act as feeder links for traffic to the PSTN. Figure 5.3-2 illustrates the main components of MSS systems.

FIGURE 5.3-2

Main Components of MSS systems



5.3.5 Broadband Wireless Access

Broadband wireless access (BWA) systems are designed to provide high-speed access to data services such as the internet, using radio technology, at locations where broadband telecommunication lines are not available or not commercially feasible. Other than cellular phone systems described in § 5.3.2, BWA normally assumes quasi-stationary user equipment and therefore may not always apply handover procedures.

However, since BWA modulation, multiple access and cell structuring principles are similar to other cellular radio systems and, to a certain extent, require the same monitoring equipment and procedures, they are included in this section.

The most common BWA technologies used in cellular systems are:

– UMTS/CDMA2000 derivates.

– WiMAX (IEEE 802.16).

– LTE.

Because the main objective of BWA systems is to transmit a high data rate to and from the customer, modern systems are highly optimized to allow optimum performance even under changing propagation conditions. Furthermore, especially on the downlink, it is necessary to share the available bandwidth among many users in a very efficient way.

This includes continuous adaptation of modulation, bandwidth and transmit times to each user. Sophisticated access methods such as OFDMA used in WiMAX and LTE allow the base station to organize traffic in so-called resource blocks consisting of a small number of OFDM subcarriers and a short transmission time.

Each downlink burst can thus be built like a puzzle to best fit all resource blocks with variable bandwidth and transmission times for each user individually.

The result is a highly dynamic bursted RF signal that always changes in level, bandwidth and spectral shape which makes measurements for monitoring purposes quite challenging.

Table 5.2-3 provide information on some parameters affecting the air interface.

As the number of frequency bands used for these systems varies over the World, no complete frequency overview is included.

TABLE 5.3-3

Air interface characteristics of WIMAX and LTE systems

Technology	**WiMAX**	**LTE**
Access method	OFDMA	OFDMA/SC-FDMA
Frequency bands (MHz)	Various, e.g. 2 300-2 400 2 500-2 690 2 545-2 575 2 595-2 625 3 410-3 594 5 200-5 800	Various, e. g. 791-862 2 500-2 690
Duplex type	FDD (TDD)	FDD (TDD)
Modulation	OFDM	OFDM
Number of carriers	Variable	Variable
Channel spacing (MHz)	1.25 ... 20	5, 10, 20
Mobile transmit power (mW)	250	250
Frame duration (ms)	10	10

TABLE 5.3-4

Air interface characteristics of UMTS systems

Standard	**UMTS**									
	Band I	**Band II**	**Band III**	**Band IV**	**Band V**	**Band VI**	**Band VII**	**Band VIII**	**Band IX**	**Band X**
Access method	CDMA/FDMA									
Frequency band (MHz) – Base to mobile – Mobile to base	 2 110-2 170 1 920-1 980	 1 930-1 990 1 850-1 910	 1 805-1 880 1 710-1 785	 2 110-2 175 1 710-1 775	 869-894 824-849	 875-885 830-840	 2 620-2 690 2 500-2 570	 925 – 960 880 – 915	 1 844.9-1 879.9 1 749.9-1 784.9	 2 110-2 170 1 710-1 770
Duplex type Duplex spacing (MHz)	FDD 190	FDD 80	FDD 95	FDD 400	FDD 45	FDD 45	FDD 120	FDD 45	FDD 95	FDD 400
Modulation	QPSK (HSPA: QPSK/16-QAM)									
Number of channels	12	12	15	12	5	2	14	7	7	12
Channel bandwidth (MHz)	5									

5.3.6 Measurement considerations

Planning, setting up and successful operation of cellular radio systems is a complex task involving sophisticated computer aided planning tools and measurement systems for many different parameters. Most of the associated tasks, including measurements, are in the responsibility of the network operators. In general, monitoring services only need to assess coverage and investigate external interference. Advanced systems capable of measuring and analyzing all possible parameters that may be of importance for the use of the network will only be required by monitoring services in very rare cases and are therefore not detailed in this section. The same applies to monitoring methods that can only be applied with the cooperation of the network operator.

5.3.6.1 Measurement of RF parameters

In general, measurement of RF parameters of cellular system stations is similar to that of other services and is covered in Chapter 4.

However, some special considerations and difficulties arising when measuring cellular system stations are described in this sub-section.

RF level and field strength

Since most of the digital cellular systems transmit in bursts, the relevant RF level and field strength of interest is the average burst level (AV-burst) which is the RMS level during a burst. General purpose sweeping analyzers can only measure this level in the time domain (see § 4.3.7). The necessary measurement bandwidth, however, requires no interference from neighbouring frequencies. This is usually difficult to achieve in cellular bands as in many areas all channels will be occupied. Careful selection of the measurement location and the use of directive antennas are therefore necessary. In cellular systems using both FDMA and TDMA such as GSM, it may be possible to benefit from the fact that bursts on neighbouring frequencies are not (always) occurring in the same time slot as on the wanted channel. This makes it possible to perform a correct time domain power measurement even in case of overlapping channels and partly occupied neighbour frequencies.

In CDMA systems, the received useful energy is regained by the wanted receiver after dispreading. This enhances the S/N considerably by the so-called spreading gain. However, standard monitoring equipment cannot make use of this gain, so it sees only the widened RF spectrum with a very low level so that it is often hardly to detect. This applies especially in CDMA uplinks. Together with the necessary power control, the wanted signal from the mobiles even at the location of the base station are usually so close to the noise floor that level measurements are not possible. When the maximum possible level of a CDMA station is required, it has to be measured in the code domain, using a measurement receiver that is capable of dispreading the signal. The resulting signals are separated by their channel code and can be measured individually. At least one of the logical channels that is always transmitted with the highest constant power level is an organisational channel (e. g. CPICH) that is independent of the traffic load of the station. In UMTS systems, the maximum possible total level of the station is a fixed value over the level of the CPICH level. Although it is commonly admitted that this value is 10 dB, some network operators use different values for different base stations. These values can be more than 10 dB, therefore if 10 dB is applied, it might lead to an underestimation of the maximum possible power of the station.

In systems using OFDMA, even the AV burst level of the base station is hard to measure because it changes even during a burst. Usually, the monitoring service is interested to determine the maximum possible level of the emission, for example when comparing the results with the permitted maximum power. In these cases, the first part of each burst has to be measured where the preamble and sync information is transmitted with always the highest power level, regardless of the traffic load on the base station.

Modulation

Measurement of modulation parameters such as modulation error ratio (MER) in cellular systems is basically the same as for other digital systems and is described in § 4.6. Cellular systems using CDMA or LTE techniques, however, are often designed with overlapping service areas of the base stations. Since they are all transmitting on one frequency, it is often difficult to find a measurement location and setup that is able to separate the emission from the station under test from other stations. If it is impossible to find a suitable measurement location although directive receiving antennas are used, a conducted measurement on the (test) output of the transmitter may be the only practical way.

5.3.6.2 Quality of service measurements

Especially in cellular radio systems with their dense network of base stations, intra- or extra- network interference may result in the degradation of certain parameters attached to the so-called quality of service (QoS). These parameters can only be measured with specialized monitoring equipment that is tailored to the relevant cellular system.

The following list of parameters affecting the actual usability of a cellular network at a given location is not exhaustive:

– Signal-to-noise ratio (*S*/*N*) and signal-to-noise + Interference ratio (SINR).

– Bit error rate / packet error rate / symbol error rate.

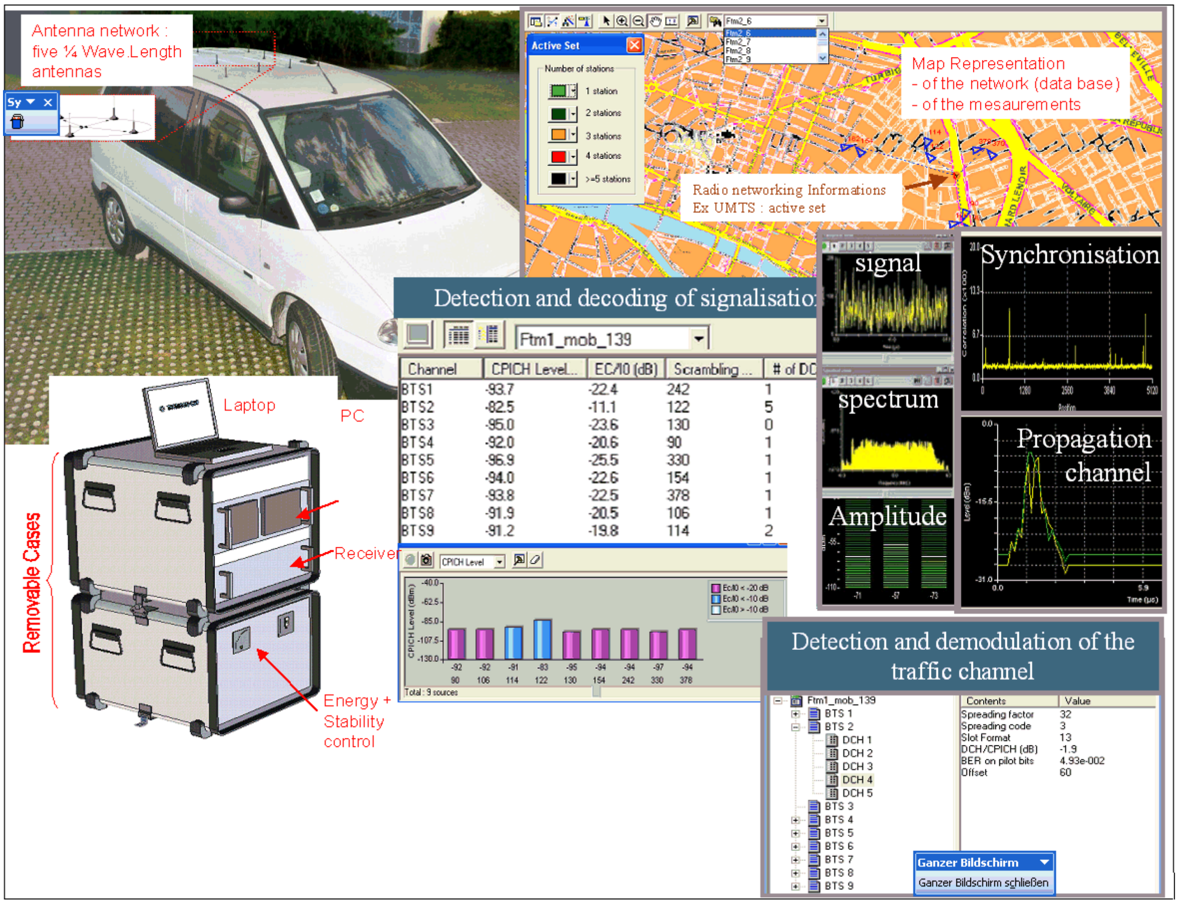
– Time delay of reflected signals due to multipath conditions / channel impulse response.

– Handover conditions.

Since the values of QoS parameters is dependant on the specific location, these monitoring systems are best fitted in measurement vehicles. Figure 5.3-3 shows an example of such a system together with some sample measurement evaluation displays that are possible.

FIGURE 5.3-3

Example of a measurement system for cellular radio networks



Spectrum-5.3-03

These specialized measurement systems can be used to detect problems in case of interference, especially due to poor propagation conditions interference from other transmitters inside the same network (intra-network interference) by comparing the measured QoS parameters with the minimum system requirements. Such equipment uses signal processing methods which may be performed by using multiple RF channel synchronous receivers and samplers, associated to the antenna arrays and cooperative adaptive spatial filters. Such techniques improve the radio measurement accuracy and reliability, the demodulation and the decoding performances by using cooperative techniques based on the recovery of known signals.

Additional information on adaptive filtering and cooperative processing approach are included in Recommendations ITU-R SM.1598 and ITU-R SM.1600.

5.3.6.3 Interference mechanisms

Interference analysis of several interference situations within digital cellular radio networks are described hereafter.

Co-channel interference: The interference generated by multiple transmitters operating on the same frequency in nearby cells is known as co-channel interference. This can be the case if a GSM repeater operates without the authorization of the network operator.

Adjacent channel interference: Adjacent channel interference is caused by RF energy spill-over from the next or nearby channels or from several channels.

Apart from standard measurement techniques for interference solving described in Chapter 4, the following sub-sections provide some examples of common interference situations and possible measurement techniques that are specific to cellular networks.

PCS: Too many stations in an area

Limitations in receiver selectivity and the missing time synchronization between stations of different networks operating on the same frequency make it impossible to use all theoretically available channels at a given location without interference. Example: In Europe, 10 frequency channels are assigned to the DECT service, designed to use 12 paired time slots per frequency.

So, in theory, 120 DECT stations should be able to co-exist at a given location. In practice, however, serious interference already occurs if more than about 10 stations are operated simultaneously. This is often surprising for the user and even technicians, although the situation occurs frequently in dense office areas where large companies use many DECT phones.

A good way to identify this situation using a standard spectrum analyzer is displaying a single RF frequency in zero span mode, triggered to the strongest signal. Bursts from other stations on the same frequency will slowly shift position in time until they coincide with the station triggered. Figure 5.3-4 shows an example display of the situation: The top part of the window displays an overview of the DECT band in the frequency domain.

All channels are occupied. The bottom part is a time domain representation at the frequency of the marker in above (1 895.6 MHz) showing one DECT frame (10 ms). On this channel, there is one active conversation (1), and several idle signals from other, unsynchronized base stations. The two marked with (2), for example, are less than one time slot apart and will soon interfere with each other.

If the practical band occupancy is already high, the colliding connection will not find an alternative frequency and/or time slot and will be dropped. The only possible solution is to reduce the number of PCS stations.

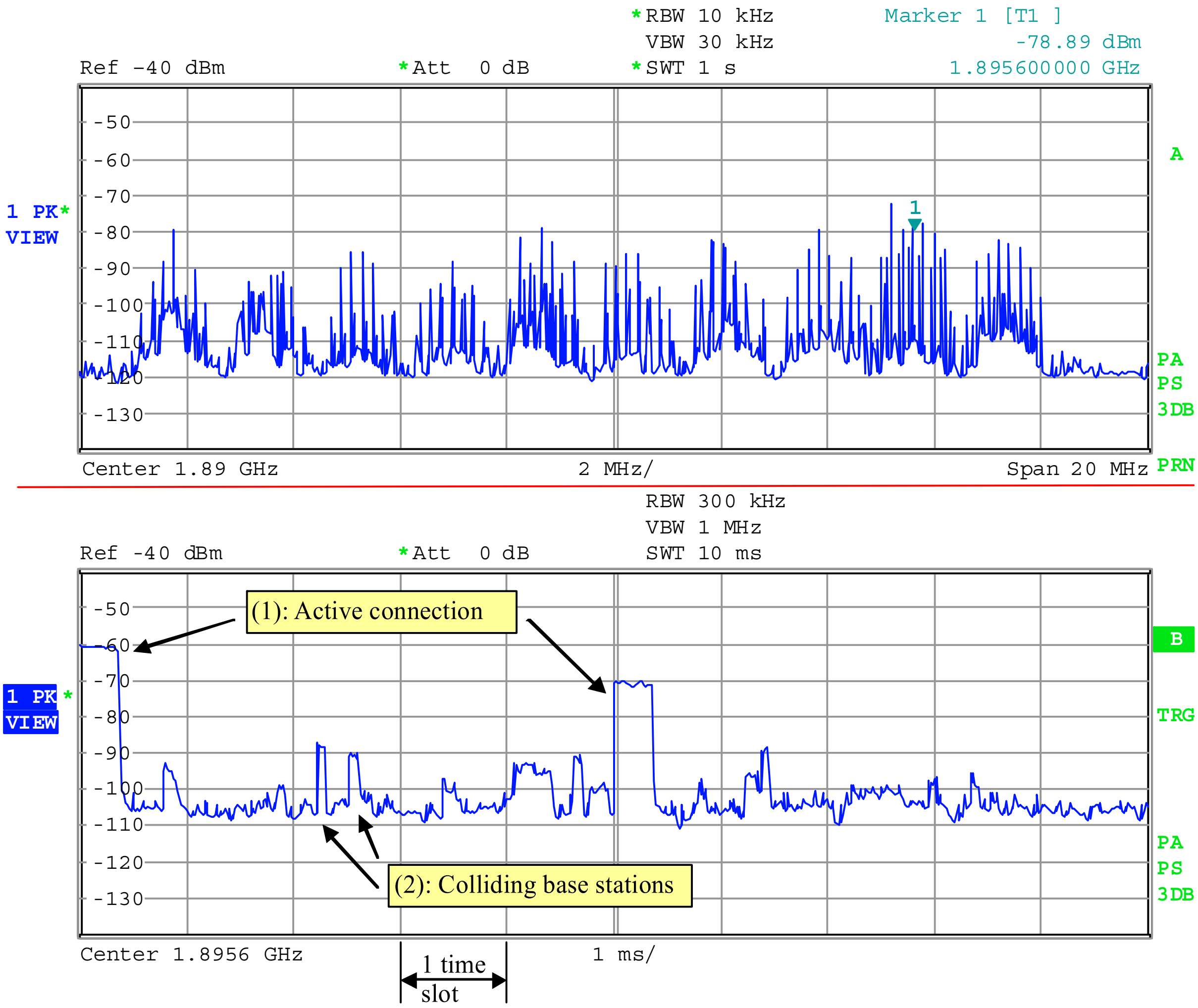
CDMA: Interference from external sources

The principle of CDMA requires all stations transmitting on the same frequency to be received with equal level at the base station. This is accomplished by a fast transmit power control of the mobile stations. If a base station receives an interfering signal from an external device, it will raise the power of the active mobiles until their level exceeds that of the interference in the code domain.

Usually the interfering signal is then well above the wanted signal in the frequency domain.

FIGURE 5.3-4

Multiple unsynchronized DECT connections on the same frequency



Spectrum-5.3-04

The first approach is to try and pick up the interfering signal off-air in a monitoring vehicle using standard measurement equipment such as a spectrum analyzer. If this is not possible, for example because the monitoring antenna could not be placed close enough to the source of a weak interfering signal, specialized measurement equipment can be used that allows to detect and identify interferers below the noise level and may make it possible to isolate the interfering signal. If this approach fails or such specialized equipment is not available, the spectrum analyzer or monitoring receiver can be connected to the interfered sector antenna. Usually this is possible using measurement outputs in parallel to the cellular network receiver. This way the measurement can be done without interrupting the regular service.

When connecting standard monitoring equipment such as spectrum analyzers to the antenna of the interfered CDMA station, the existence of external interference will show up as a wanted signal level from mobiles that is well above the noise floor. If it is a wideband interference, this may be the only indication for its presence. In this case, identification of the interference source is only possible by trying to find a location where the level of the interfering signal into a (directive) measurement antenna is higher than the signal of the active mobiles. In many cases, however, the interfering signal is of much narrower bandwidth than the CDMA signal. In this case, when it actually causes interference to the service, the signal is clearly seen above the signals from active mobiles due to the system gain (see descriptions under §§ 5.3.6.1 and 6.6.4.3). Localizing the source of interference using standard methods is therefore relatively easy.

No service well inside the coverage area

As in all radio networks, shading and especially reflections from surrounding obstacles such as buildings or mountains can cause service interruptions although the user is well inside the predicted coverage area. These cases are often reported as interference, but when the monitoring service examines the situation on site, the useful field strength may be sufficient and no external interferer can be detected. The most likely reason for the problem is extreme multipath reception (in OFDM networks a reflection outside the guard interval or missing synchronization between two transmitters inside an SFN). Such a situation may be verified by measuring the channel impulse response. However, this requires specialized measurement equipment.

Co-channel interference by an unknown station of the same service

Even if an operator uses a frequency exclusively, there may be cases where the service is interfered by the use of an unauthorized station of the same technology. The level of the interfering signal may be below the level of the useful signal in which case standard measurement equipment such as spectrum analyzers and receivers are not able to separate or identify the interferer. In these cases, specialized equipment is available that is able to identify the interfering signal by using correlation techniques and statistical analysis methods.

Use of specialized equipment for interference analysis

Although most of the interference cases can be solved by regular monitoring equipment, specialised measurement systems, such as shown in Fig. 5.3-3, can sometimes be used to detect problems and indentify the source more quickly or more easily.

Such equipment has the capability to measure signals under significantly degraded SNR and SINR conditions compared to the performance of regular receiving terminals. This improved performance allows rejection of interference, measurement of radio parameters and decoding of signalling common channels even under severe interference conditions.

5.3.6.4 Coverage measurements

Because the there is no unique definition of the term coverage, it depends on the interpretation of the service provider and/or regulatory body under which conditions a location is declared covered by a particular radio service or not. Computerized planning tools often calculate coverage areas for a certain minimum field strength where commercial equipment is expected to function properly. Consequently, when evaluating the coverage area, only the field strength (for example of an organizational channel) has to be measured. With the example of UMTS networks, this is described in detail in the ECC Report 103.

Sometimes, however, a location is only covered by definition when certain minimum requirements for the use of the service are fulfilled. In cellular networks, the following states of network usability are common, listed in ascending order of required signal strength and quality:

1. The mobile is logged out of the network.
2. An active connection to the mobile is lost although the mobile stays logged in the network.
3. The mobile is able to log on to the network.
4. The mobile is able to establish a new connection.
5. A certain data rate is reached.

Each of these states requires certain values for both field strength from the base station and certain QoS parameters.

To measure the coverage of a cellular system exactly and independent of a specific type of user equipment, special monitoring systems are necessary that are able to continuously measure the relevant system parameters along a route. Systems as described in § 5.3.6.2 are usually suitable for this task.

A much simpler approach of measuring coverage of a cellular network is based on a statistical method: By using a standard commercially available mobile unit for the particular service, a large number of randomly selected locations are visited. At each location a trial is made whether the unit can log on to the network, establish a connection and, if applicable, the available data rate is measured. Statistical calculations have proven that when 400 locations are measured, the resulting coverage area can be determined with 95%

confidence level. This approach has the benefit of not needing specialized monitoring equipment and can be performed by anyone who is able to operate a mobile unit. However, the method is dependant on the particular mobile unit that has been used for the tests and is as such not always objective. For example the size of the coverage area calculated according to this measurement method would depend on the sensitivity of the mobile units used. Therefore this method may only be regarded sufficient if the results do not justify legal action against the network operator for not providing satisfactory coverage.

5.3.7 Identification

Methods of positive identification of transmitted signals have been developed that do not rely on the need to decode the transmitted data stream. One such method uniquely identifies a particular transmission by measuring the individual electronic fingerprint of the transmitter. Each radio transmitter emits unique signal transmission characteristics (an electronic version of a human fingerprint), which cannot be duplicated. These characteristics are matched with the mobile identification number and the electronic serial number of the mobile phone to develop a unique pattern for each legitimate customer. This fingerprint capability provides a method to positively identify individual mobile units. This method, however, is not commonly available at spectrum monitoring services.

Recommendation ITU-R SM.1600 provides some information on measurements for the technical identification of digital signals.

5.3.7.1 Direction finding and emitter location

General methods of DF and locating radio transmitters are described in §§ 3.4, 3.6 and 4.7.

The concept of frequency re-use as applied to cellular radio systems and PCS poses a difficult challenge to any DF equipment. Such equipment must be capable of operating in the presence of co-channel interference and must provide unambiguous lines of bearing to multiple transmitters all operating on the same frequency.

Direction finding in TDMA systems such as DECT and GSM requires the DF unit to be time-synchronized with the base station that is to be located. In addition, the minimum time for a DF result must not exceed the burst time.

Direction finding in CDMA networks is often only possible with wideband DF systems, combined with specialized processing and display software designed for the analysis of spread spectrum emissions. Direction finding on DSSS transmissions requires the use of wide bandwidth (≥ 10 MHz) correlative interferometer DF equipment due to the fact that the power spectra of a DSSS signal will appear to be like white noise and will in most cases be close to, or even below, the system's noise floor. One exception is the location of base stations when only one of them is dominating at the location of the DF antenna. In this case, standard DF equipment and procedures can be used.

Recommendation ITU-R SM.1598 provides more detailed information about direction finding on TDMA and CDMA signals.

5.3.7.2 Decoding

In modern digital cellular systems, user information as well as the contents of the transmitted speech or data is encrypted by a unique key that is negotiated between base station and mobile at the beginning of the connection. It is therefore impossible to intercept and decode the user data or speech off air. The only possible way to intercept and decode the user data is to place an active intercept station between the user and the actual cellular network. From the user mobile's view, this intercept station may look like a repeater or even a real base station. The practical difficulty in the successful deployment of this method is the fact that the intercept station always has to be kept in very close vicinity of the user equipment to be monitored because its signal must provide the strongest RF level available to the mobile handset in order to prevent handovers. It should be noted that national law might not allow the monitoring service to use this type of equipment.

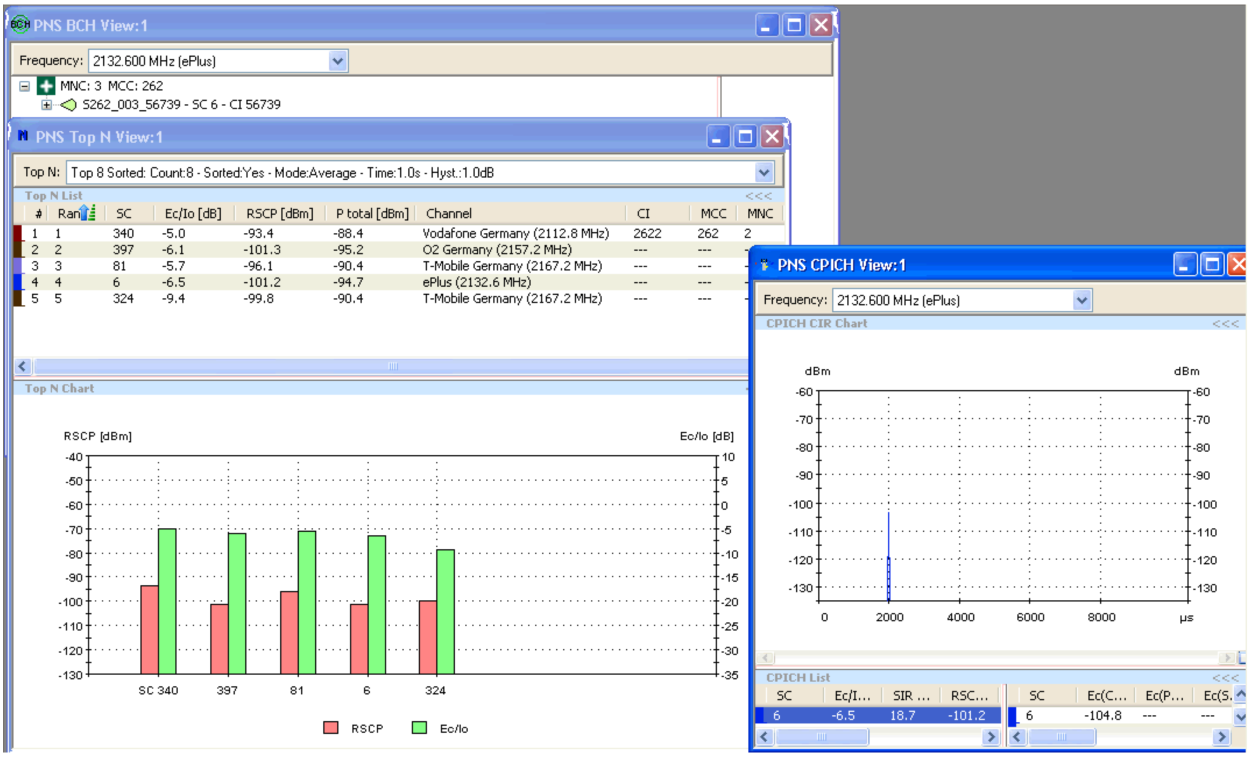
For most common monitoring tasks, however, it is sufficient to identify the network or base station(s) transmitting the signal that is currently measured. In cellular radio networks, each base station has a unique identification number that is more or less continuously transmitted via broadcast or organizational channels without encryption. To read this information, the monitoring system must be able to synchronize and decode the data stream, but it is not necessary to actively participate in the service or log on to the network.

In FDMA/TDMA networks such as GSM, suitable monitoring systems usually scan multiple frequencies available in order to display not only data from the serving base station but also from neighbouring cells.

In CDMA systems, the spreading code is either known or can be determined by so-called PN scanners. If more than one base station is receivable with sufficient carrier to interference ratio (C/I), the monitoring system can usually find and display all used scrambling codes. Figure 5.3-5 shows an example screen for the base station identification using PN scanner results in a UMTS network. Five different UMTS base stations were receivable in this example. The different scrambling codes are abbreviated with "SC". For each base station, the received signal code power (RSCP) of the control channel and the C/I equivalent (E_c/I_0) is displayed in the left hand window. For the tuned channel (2 132.6 MHz), the channel impulse response is displayed in the right hand window.

FIGURE 5.3-5

Identification of base stations in a UMTS network



Spectrum-5.3-05

The above mentioned capabilities are commonly available in monitoring systems dedicated to the specific cellular radio service such as described in § 5.3.6.2.

Modern digital cellular and PCS systems have enhanced security features, which minimize or eliminate the need to transmit sensitive subscriber identification information over the air. In these types of digital systems, subscriber information is only available from the cell centre in a co-operative environment. In the GSM system, personal mobility is provided through the use of subscriber identity modules (SIM), which carry the personal number, assigned to the mobile user.

Identification may be possible by monitoring and decoding the control channels in the downlink to obtain the SIM number of currently active mobile units.

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Project IST-2000-26222 ANTIUM (Advanced NeTwork radio Identification equipment for Universal Mobile communications): deliverable D3011b "UMTS multi-channel processing report", deliverable D6012 "Advantage of the Antium tool in comparison to standard measurement systems". http://www.ist-world.org/ProjectDetails.aspx?ProjectId=6c910dd880a24b468f976e98fa24c3df.

ITU-R Recommendations and Handbooks

NOTE – In every case the latest edition of the Recommendation should be used.

RECOMMENDATION ITU-R SM.1598 – Methods of radio direction finding and location on time division multiple access and code division multiple access signals.

RECOMMENDATION ITU-R SM.1600 – Technical identification of digital signals.

ITU-R Handbook [November, 1996] Land Mobile Wireless Access Local Loop, Vol. 1.

5.4 Microwave links and satellite up-links

5.4.1 General introduction

Except for a limited number of terrestrial radio-relay or microwave systems below 1 GHz, it is generally assumed that microwave links operate above this frequency. This section deals with these systems, whose detection and control is very different, compared to classical radio links.

The technology of microwave radio systems is founded on the possibilities offered by the very high frequencies from 1 to 100 GHz, to which correspond certain very short wavelengths called microwaves (30 cm > λ > 3 mm). These two aspects make it possible to obtain both wide base-bands and a very directive radiation, particularly suitable for transmitting large quantities of signals or data from point to point. Three types of propagation are used:

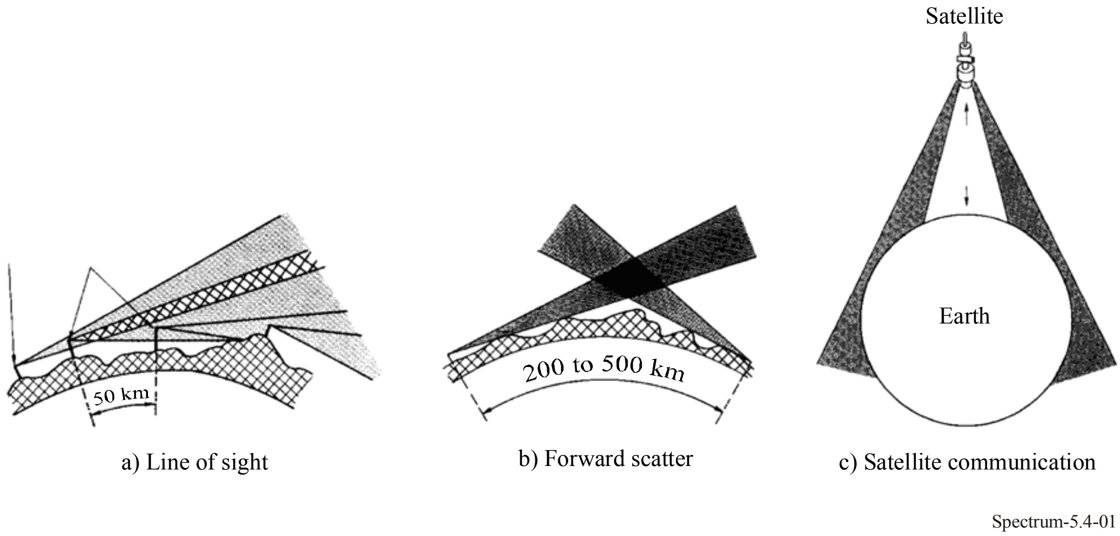
– LoS: to avoid the problem of the Earth's roundness, repeaters, receivers and transmitters are installed at approximately every 50 km. A series of radio hops is called a radio link (see Fig. 5.4-1a). The propagation is fairly stable.

– Troposcatter: in order to reach a radio hop extremity which would be beyond the optical horizon (see Fig. 5.4-1b). The reception is weak and fluctuating.

– LoS with an artificial satellite: placed in a GSO orbit at an altitude of 36 000 km (see Fig. 5.4-1c) and which contains an active repeater and antennas oriented toward the Earth.

FIGURE 5.4-1

Types of propagation



5.4.2 Use of microwave links

Microwave links are typically point-to-point (often with multiple links or chains of repeaters) with point-to-multipoint systems being adopted using latest technology. The distance between repeaters changes depending on used propagation mechanism and frequency from several km (LoS) to several ten thousands km (satellite). The use of digital techniques to regenerate the signal, usually having a low signal to-noise ratio at the far end of a link, allows increasing this distance.

The directivity of the transmitted signal also allows extension. Some systems now operate up to frequencies as high as the extremely high frequency band (EHF), e.g., 70 GHz where links on the order of 200 m are currently used for video cameras.

Concerning troposcatter communication, it employs the ability of the troposphere, acting as reflective medium, for providing communication between two long distance points, of several hundred km. Table 5.4-1 provides information on comparison between the two types of propagation LoS and troposcatter.

TABLE 5.4-1

Comparison of LoS microwave versus troposcatter

Item	LoS	Troposcatter
VF channel	Up to 1 800/2 700 per carrier	Up to 240 per carrier
Bit rate	90 Mbit/s or more per carrier	2 400 bit/s to 4 Mbit/s per carrier
Path length (km)	1.6-80	80-800
Transmit power (W)	0.1-10	100-50 000
Receiver noise figure (dB)	4-12	Less than 4
Diversity	None or dual	Dual or quadruple
Antenna aperture size (m)	0.3-4	1.5-40

The third type of propagation used in microwave communication is the transmission and reception of a telecommunication link via satellite.

The general configuration of an earth station is not substantially different from that of a radio-relay terminal, but the very large free-space attenuation (about 200 dB) undergone by the carrier radio waves on their path between the station and satellite (approximately 36 000 km) usually requires the main sub-systems of an earth station to have a much higher performance level than those of a radio-relay terminal.

A main advantage of the use of microwave links is that they can be used at large bandwidth for high data rates (typically over 2 Mbit/s to 200 Mbit/s and even higher). These are often used for transmitting digital information, audio and video signal, multiplexed audio or coded TV, or any other type transmission, which needs a high data rate or large bandwidth.

Microwave link RF modulation falls into two clearly defined types analogue and digital. Many new links are digital but analogue links will remain for the foreseeable future.

5.4.2.1 Analogue links

Analogue links are typically frequency modulated with a base-band signal of several or many multiplexed traffic channels. For multi-channel audio communications, the base-band structure follows established group, master-group, and super-group conventions as defined by the ITU-T. Each separate audio signal may be mixed to produce a single side-band suppressed carrier signal (J3E) on carriers at 4 kHz intervals.

A group of 24 voice channels can occupy the base-band spectrum from 12 kHz to 60 kHz (first 12 channels) and 60 kHz to 108 kHz (last 12 channels). Large groups of multiplexed audio channels can occupy base-bands up to a number of MHz wide. Other signals such as TV can be similarly multiplexed.

5.4.2.2 Digital links

Digital links display only a band of spectral occupancy visually similar to filtered white noise. It is not immediately evident from RF spectra whether any of the separate base-band channels are occupied or not. It is necessary to discuss the construction of these signals before any analysis is considered.

The source will typically be a single multiplexed digital signal as described by ITU-T Recommendation G.703. This describes the data and framing protocol of land line digital links. Since the transmitter has no control over the nature of the digital signal, it is exclusively ordered by a pseudo-random digital sequence generated within the system. The reason for this is to avoid situations of a no-data microwave signal (spectral dispersion) and, in some cases, to provide sufficient digital transitions for clock recovery. There is no global specification for this randomizing sequence that differs with equipment type and manufacturer.

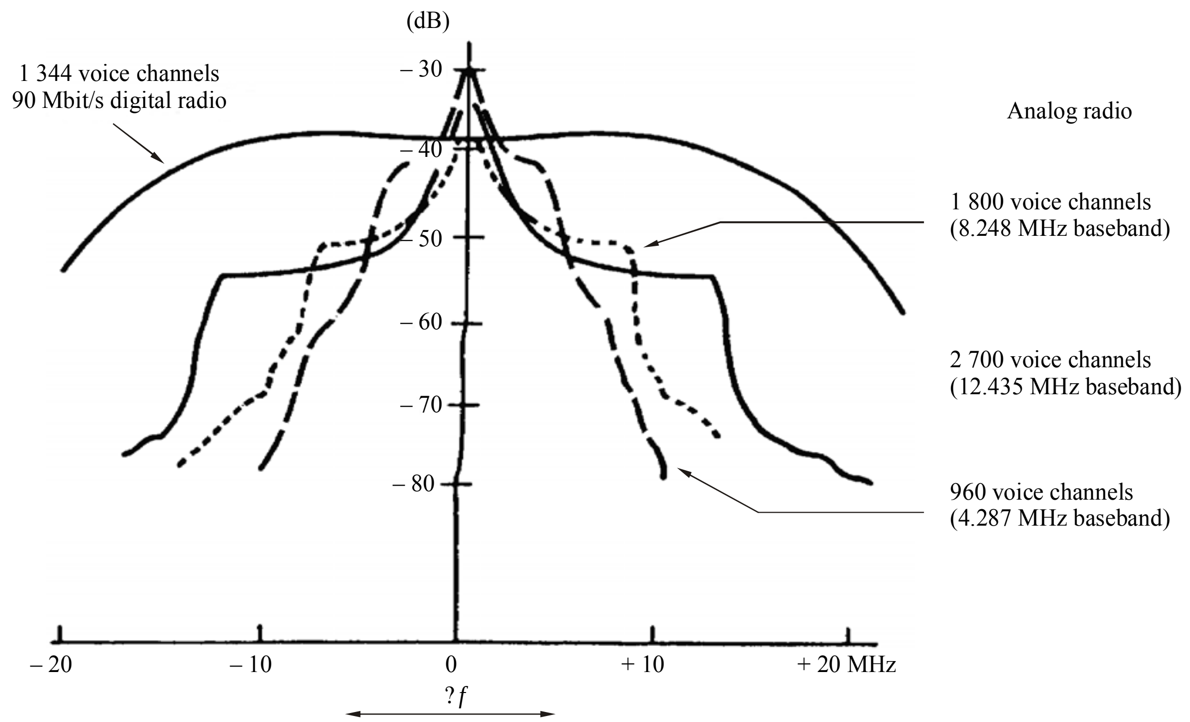
Similarly, digital modulation methods are equally varied, but may be consistent in any one band, depending on national spectrum management policy. QPSK or differential QPSK (DQPSK) is common but various quadrature amplitude modulation (QAM) schemes are used representing various ways of enhancing spectral efficiency and system design.

5.4.2.3 Output spectrum

The analogue microwave radio (AMR) spectrum differs from the digital microwave radio (DMR) spectrum as shown in Fig. 5.4-2.

FIGURE 5.4-2

Comparison of AMR and DMR RF spectra



Spectrum-5.4-02

Notice how the DMR spectrum almost completely fills the band, whereas the AMR spectrum has the peak at the carrier frequency and sidebands gradually decreasing in amplitude at frequencies away from the carrier. It is this characteristic which makes AMR vulnerable to interference by DMR. If the frequency band of a DMR operates too close to that of an AMR, the large amplitude at the edges of the band of the DMR can swamp the low-amplitude sidebands of the AMR, causing interference so severe that the AMR fails. This point stresses the need for adequate IF and RF filtering of microwave radio signals whose bands are operating very close to each other on the same route.

5.4.2.4 Multiplexing in microwave radio systems

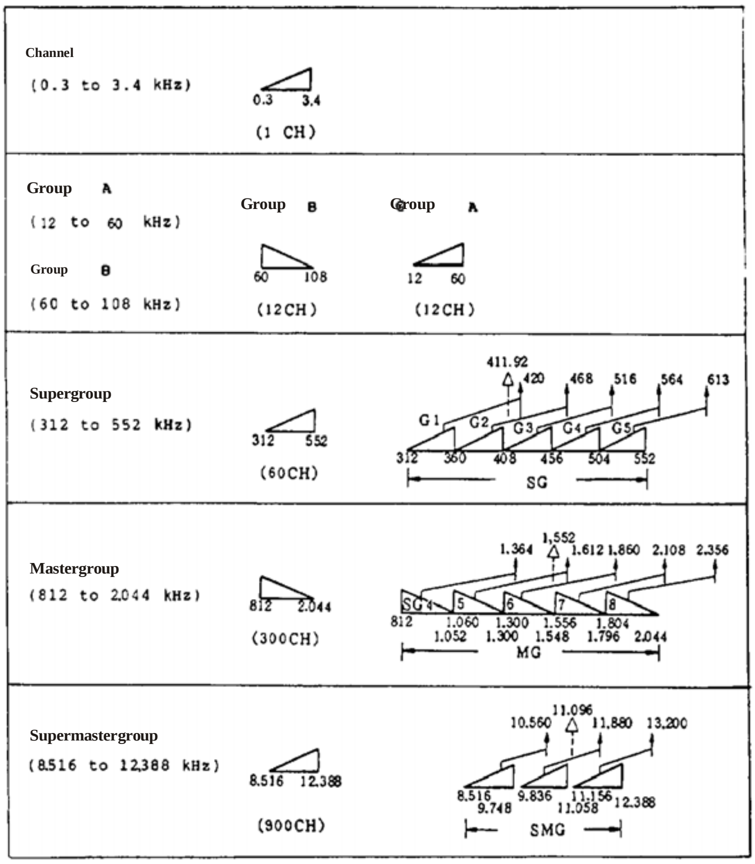
Multiplexing is the sending of a number of separate signals together, over the same carrier, simultaneously and without interference.

5.4.2.4.1 Frequency division multiplex

Frequency-division multiplex (FDM) (see Fig. 5.4-3) concerns itself with combining continuous (or analogue) signals. It may be thought of as an outgrowth of independent-sideband transmission, on a much-enlarged scale. As will be seen, 12 or 16 channels are combined into a group, 5 groups into a super group, and so on, using frequencies and arrangements that are standard on a world wide scale. Each group, super group or larger aggregate is then sent as a whole unit on one microwave link, cable or other broadband system.

FIGURE 5.4-3

FDM frequency grouping



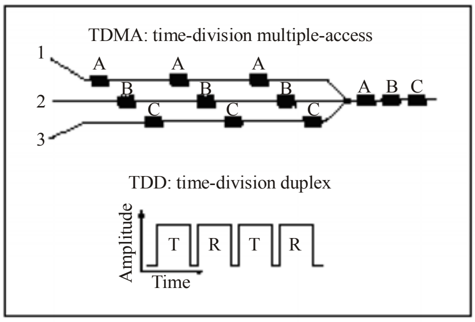
Spectrum-5.4-03

5.4.2.4.2 Time division multiplex

Time-division multiplex (TDM) (see Fig. 5.4-4) is a method of interleaving, in the time domain, pulses belonging to different transmissions. That is to say, use is made of the fact that pulses are generally narrow, and separation between successive pulses is rather wide. That being the case, it is possible, provided the two ends of a link are synchronized, to use the wide spaces for pulses belonging to other transmissions.

FIGURE 5.4-4

Multiplexing – Time



Spectrum-5.4-04

5.4.2.5 Monitoring operation

Following technological advances, the use of wide band microwave transmissions will increase over the next few years (fixed wireless access services for example). Interference between these systems has to be taken into account by administrations in order to manage and control the microwave part of the spectrum, this includes:

– investigation and elimination of harmful interference caused by others microwave systems;

– investigation and elimination of harmful interference caused by systems other than microwave systems;

– compliance with technical parameters;

– detection of illegal transmissions.

The main obstacle to be overcome in order to enforce regulations concerning these systems is the difficulty of detecting illegal transmissions because of their high directivity.

Monitoring of these transmissions has to be from mobile units, because of the reduced and narrowed geographical area covered by the transmitted signal at levels that can be received. Normally, to measure such a system, the monitoring antenna has to be in the beam from the microwave transmitting antenna, or otherwise closely coupled to the transmitter or feed line. A reliable method to achieve this is to locate the signal with a coarse adjustment of the antenna heading in both azimuth and elevation. Using the spectrum analyzer to locate the peak signal, the span of the analyzer can be reduced to zero and the sweep time extended to around 60 s. (This sweep time is not critical, but provides a visual trace to refer to.) Adjusting the antenna in one axis at a time the peak value will be found. It is important to look beyond the first peak in order to check alignment on the main lobe. Side lobes will be seen on either side of the main lobe. Once the peak value has been found the procedure is repeated for the other axis. If using a receiver it will be necessary to mentally track its signal strength meter to identify the peak values. Once the antenna direction has been optimized the required span, bandwidth, etc., can be re-established on the spectrum analyzer with the appropriate detector modes set.

5.4.3 General techniques for measurement

The need for administrations to monitor microwave links is dependent on the frequency management strategy adopted. In general, basic parameters to be measured are:

– carrier frequency;

– field strength or pfd;

– occupied bandwidth;

– deviation from assigned frequency;

– observed polarization;

– class of emission;

– identification of signal source.

The capability to perform additional measurements and observations beyond those indicated above is desirable for purpose of interference modelling. The addition of this capability increases the effectiveness of the monitoring facility as a spectrum management tool. The additional parameters that may be measured or observed depend on the type of emission as listed in Table 5.4-2.

TABLE 5.4-2

Parameters of emissions for additional measurements

Emission	Parameter
FDM-FM	Frequency and amplitude of baseband signals
	Number of voice or other channels
	Peak deviation of the carrier
	Frequency and amplitude of the energy dispersal signal
TV-FM	Frequency and amplitude of baseband signals
	Peak deviation of the carrier
	Frequency and amplitude of the energy dispersal signal
	Pre-emphasis characteristics utilised
SCPC-FM SCPC: single channel per carrier	Peak deviation of carriers
	Highest modulating frequency
	Carrier spacing
	Number of carriers per transponder
	Channel occupied bandwidth
	Relative power per carrier
Digital (PSK, FSK, SCPC, etc.)	Bit rate
	Number of phases
	Number of amplitude levels
	Number of carriers per transponder
	Carrier spacing
	Occupied bandwidth of channels
	Relative power per carrier

This may be accomplished using:

– direct interception system, or

– interception system using RF mixers.

5.4.3.1 Direct interception system

In this method the measured signal or survey band is applied directly to the spectrum analyzer or receiver via the antenna, filter and feeder, no signal conversion takes place. This system has the advantages of being simple to configure and calibrate, it gives a low set-up time and allows easy measurement observations (see Fig. 5.4-5).

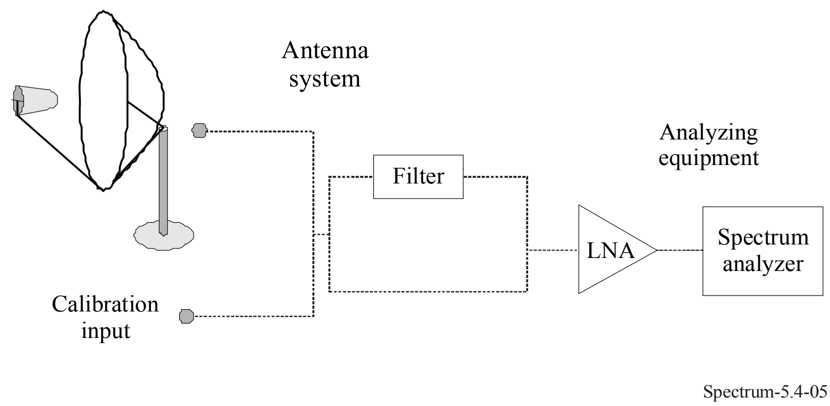
Filter could be inserted in order to reduce interfering inter-modulation products and LNA typically could be also inserted to improve the gain and noise characteristics of the measurement system. With these 2 added elements, it gives an excellent configuration to measure low level signals in the presence of adjacent emissions.

In this method, the limitation in the measurement frequency range is essentially due to the limitation of the analysing equipment (ranging up to about 40 GHz with currently available technology).

The disadvantages are that feeder losses at frequencies above 10 GHz can be considerable and detrimental to the sensitivity of the measurement system. It is essential that feeders used in this type of system are of the highest quality and that both the RF characteristics and physical condition of the cable are checked regularly. In most circumstances where measurements above 10 GHz are required the feeder length will need to be less than 1 m in length.

FIGURE 5.4-5

Direct interception system

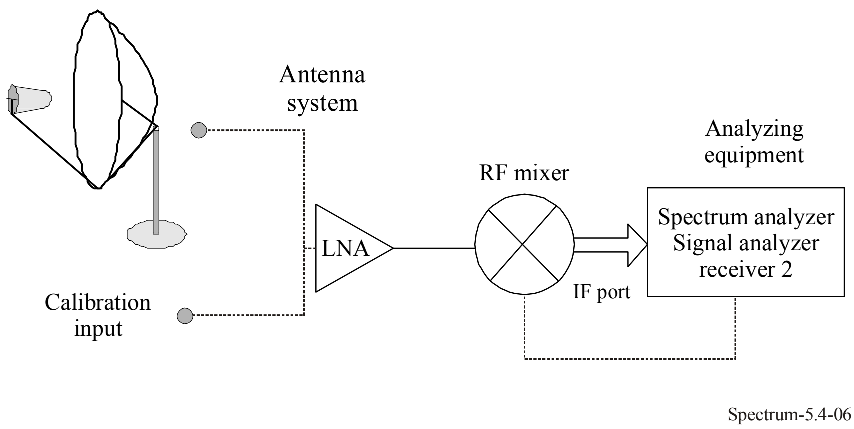


5.4.3.2 Interception system using RF mixers

In this method the measured signal or survey band is applied directly to a mixer or down converter via the antenna, filter and feeder. Signal conversion takes place and is then applied to the spectrum analyzer or receiver at a lower frequency (see Fig. 5.4-6).

FIGURE 5.4-6

Interception system using RF mixers



LNA typically inserted to improve the gain and noise characteristics of the measurement system.

RF mixer extends the frequency range of analysing equipment. Two concepts are available, via single diode and double diode mixers. Due to their design, double diode mixers feature flat frequency response and require no additional biasing which makes them especially suitable for automated measurements.

In this method, the frequency range that can be covered is higher (e.g., from 18 GHz to 325 GHz) than with the direct interception monitoring method, depending on characteristics of the RF mixer, LNA, and monitoring antenna system.

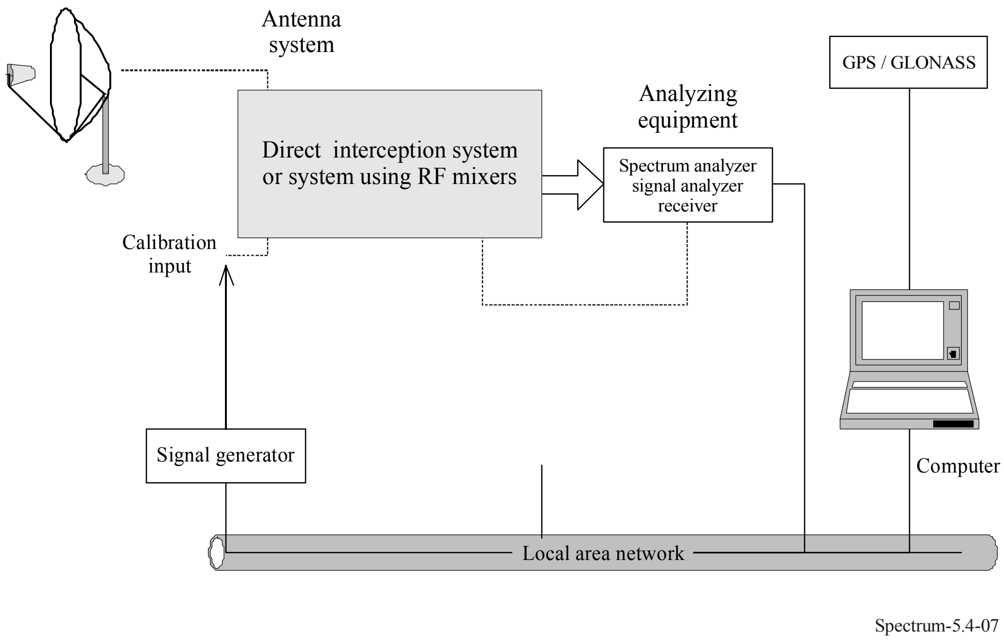
The disadvantages of this system are lower measurement system sensitivity due to conversion losses and high mixer noise figures, calibration uncertainties due to mixer drift and band flatness characteristics, inter-modulation problems, possible interference from high power systems operating on or near the down conversion frequency.

5.4.4 Equipment for monitoring vehicles

A block diagram of a microwave monitoring unit is shown Figure 5.4-7.

FIGURE 5.4-7

Microwave monitoring unit



5.4.4.1 Antenna system

The antenna type chosen will depend on the measurement to be carried out. Certain antenna types will have characteristics more suitable for a particular measurement task. For instance a Horn antenna would be best suited to a polar survey to determine signals present in the survey band 360° around the measurement location whereas a dish antenna would be better suited for direction finding a single source signal.

Horn antennas tend to be more robust and lighter weight than Dish antennas and are normally easier to deploy in a transportable measurement scenario. They are also more stable in the windy conditions normally associated with elevated measurement locations. The trade off between the Horn antenna and Dish antenna is that Horn antennas have normally lower gain figures compared with Dish type antennas. Antenna stability will be an important factor at higher frequencies where antenna beam-widths are small.

Following these general considerations, recommendation below, according to the frequency range can be introduced.

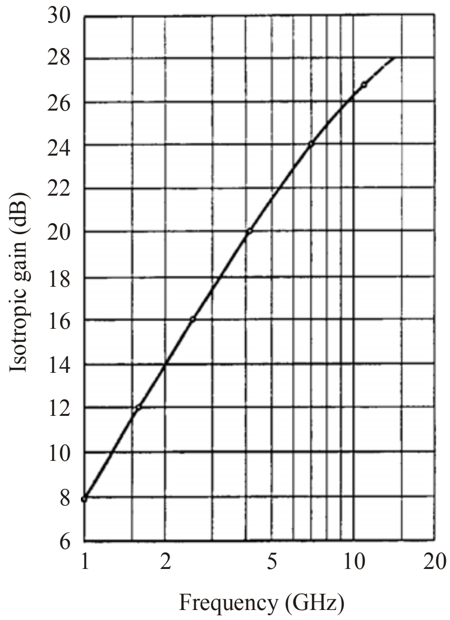
5.4.4.1.1 Frequency range from 1 to 18/26 GHz

A broadband parabolic antenna with a reflector diameter of about 90 cm or so, or a log-periodic antenna, along with an integrated preamplifier and a polarization-switching network for the feedpoint, is needed. Polarization should be selectable from X linear, Y linear, left-hand or right-hand circular.

In the vehicle, the following elements could be included YIG filter with a 3 dB bandwidth of 35 MHz or wider and frequency tuning from 1 to 18 GHz, and LNA with a gain of typically 40 dB. The typical gain of a 1 to 20 GHz antenna, of the type mentioned above, is shown in Fig. 5.4-8.

FIGURE 5.4-8

Typical gain of a calibrated directional log-periodic antenna with a 60 cm diameter reflector, as a function of the frequency



Spectrum-5.4-08

5.4.4.1.2 Frequency ranges 18-26 GHz and 26-40 GHz

A standard gain horn (with a reflector antenna diameter of about 1/3 m) can be used. The antenna units for the 18-26 GHz and 26-40 GHz frequency ranges could form one unit together with a horn. In the vehicle, the following elements could be included: LNA with a gain of typically 30 dB, and down converter.

5.4.4.2 Analysing equipment

Two main cases have to be considered, depending on the type of interception:

– Direct interception system:

  Traditional receivers tuning up to 3 GHz may be used with various filters and detectors, e.g., SSB, ISB, etc., covering a range down to 12 kHz to demodulate individual audio channels. Spectrum analyzers are currently available up to at least 40 GHz.

– An interception system using RF mixers:

  All available monitoring equipment (traditional spectrum/signal analyzer or receiver) covering the IF band can be used. The IF output ports of the system should be amplitude matched and phase locked with the RF subsystem, thereby enabling an accurate analysis of the RF signal at the intermediate, down-converted frequency.

The following devices may be connected to the IF output port:

– Pulse analyzer: for the accurate measurement of radar pulses (up to 1 ns resolution).

– Digital oscilloscope: 500 MHz oscilloscope for the analysis of repetitive signals.

– Time and frequency interval analyzer: real time analyzer capable of 250 MSamples/s and having a bandwidth on the order of 110 MHz.

For the analysis of modulated signals, a vector signal analyzer or FFT spectrum analyzer can be used to provide precise demodulation (AM, FM, PM, digital), narrow-band spectrum measurements (300 Hz-3 MHz) and measurements with a high frequency resolution (< 0.001 Hz) and accuracy (< ±0.1 ppm).

5.4.4.3 Calibration equipment

There are several ways that a measurement system can be calibrated or confidence checked before undertaking measurements.

a) Beacon method

The procedure for this calibration method is to site a temporary source operating on a frequency as close to the RF signal or in the band being investigated (taking into account other users and the interference potential to the licensed users).

The source and measurement antennas will need to be precisely aimed by use of positioners to achieve accurate calibration. An accurate distance measurement between the beacon and measuring antennas will need to be made so that the free space path loss (FSPL) between antennas at the calibration frequency can be calculated. A calibrated signal divider, signal generator and power meter will be required to drive the beacon antenna.

In this method the received power can be compared with calculations derived from system data in the form of antenna, amplifier, filter and cable charts.

The beacon method is ideally suited to lengthy surveys and allows the measuring system to be constantly checked during the survey period. The disadvantage of the method is that a considerable amount of test equipment is required to perform the calibration. This could cause difficulties on sites such as rooftops where the equipment will need to be transported to and where space may be limited.

This method assesses all the components in the measurement system including the antenna.

b) Signal substitution method

In this method a signal injection point is required in place of the measurement antenna to inject a known signal level from a calibrated signal generator. This method will calibrate the measurement system including filters, amplifiers and feeders. The measurement antenna will require at least an annual calibration certificate from a test facility. For measurement systems fitted with horns and waveguide amplifiers a cross-guide coupler fitted between the horn output and amplifier input can be used to inject a calibration signal. The horn antenna will also require a calibration certificate from a test house.

It is desirable that the response characteristic of the antenna with connecting cable, and the gain of any pre-amplifier be known so that RF signal levels can be measured to an accuracy of from 3 dB to 6 dB (as a worst case).

The purpose of the signal generator is to produce reference signals; its recommended characteristics are the following:

– spectrally-pure frequency synthesiser;
– frequency range 0.01-40 GHz;
– external pulse, AM and FM modulation;
– frequency resolution of 1 Hz;
– dynamic output level range –90 to about +10 dBm;
– harmonics < –20 dBc.

c) Measurement of a known source

When carrying out measurements with transportable equipment on locations such as high rise building rooftops it is not always possible to have calibration equipment available. For basic confidence checking in these remote environments it is sometimes possible to measure a known stable signal source operating in or close to the measurement frequency band. In these circumstances satellite signals can be a reliable basic calibration source.

5.4.4.4 Navigation and positioning systems

The monitoring vehicle should be equipped with a navigation and positioning system to enable accurate determination of position (geographical coordinates) and bearing of the vehicle (azimuthal orientation). A description of this system may be found in § 6.1.

The positioning system receiver installed in the vehicle can fulfil other tasks:

– frequency standard (frequency accuracy of 1×10^{-11});

– current date and time information (YY-MM-DD and hh:mm:ss.sss).

5.4.4.5 Rotation steering and telescopic supports

The measuring antennas may be installed directly on a bi-axial turntable (with typical characteristics of azimuth: 370°; elevation: –20° to +90°; positioning accuracy: 0.1°), which is attached to a mast. The base of the mast should rotate. The equipment should be configured for rapid set-up and dismantling for transport.

The vehicle may be fitted with telescopic or adjustable supports to ensure that the rotational plane is horizontal. The supports could be adjusted from within the vehicle. Coordination of the turntable with true North is achieved with the aid of a gyrocompass.

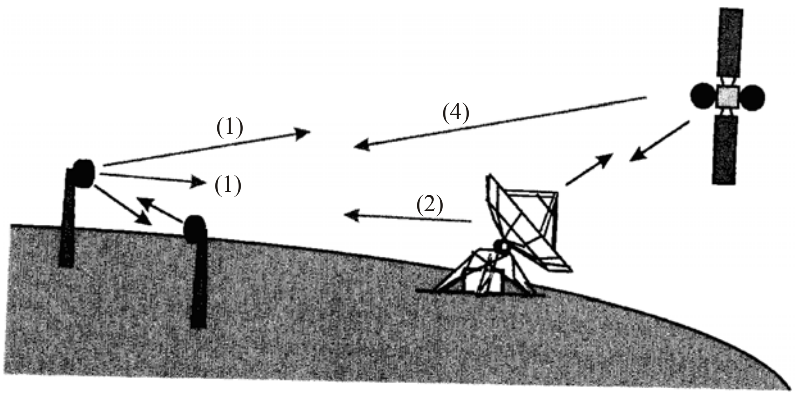
5.4.5 Fixed-satellite service sharing with the fixed service

5.4.5.1 FSS and FS interference

There are a number of standard interference paths, called interference mechanisms, which are encountered in satellite and terrestrial microwave communications (see Fig. 5.4-9). These are controlled through various regulatory mechanisms, including frequency coordination. Normal operation of the respective links is indicated by the short solid arrows, which provide full duplex transmission.

FIGURE 5.4-9

Interference potential between satellite links and terrestrial microwave links that use the same frequency band



The interference paths, indicated by path numbers 1 to 4, can be described as follows:

Path 1: terrestrial radio interference into the uplink receiver of the satellite. The satellite is protected by a maximum radiated power limit of the terrestrial microwave antenna and by a stipulation that these antennas should not be directed at the GSO orbit. As a result of the low radiated power from terrestrial stations, interference of this type is not normally experienced in practice. The one possible exception is high-power tropospheric scatter links that employ billboard-sized antennas.

Path 2: Earth station interference into the terrestrial radio receiver. This is the most important interference case for determining if a transmitting earth station can be operated in a particular location. The radiation along Path 2 is in the side lobes of the earth station antenna and propagates along a variety of paths to the terrestrial receiver. The ITU has regulations and procedures to coordinate earth stations in one country that could interfere with terrestrial microwave links in adjacent countries.

Path 3: terrestrial radio interference into the downlink receiver of the earth station. The earth station antenna could be shielded from the terrestrial transmitter, a technique that has been applied to Path 2 as well.

Path 4: satellite interference into the terrestrial radio receiver. The radiation level from a satellite is typically too weak to be of much concern to terrestrial receivers. The RR typically place a maximum allowed PFD from the satellite on the surface of the earth.

Path 2 is of concern for transmitting earth stations while Path 3 must be addressed for any satellite receiving system on the ground.

5.4.5.2 Analysis methods

Interference to satellite communication ground stations as well as to terrestrial stations that share the same frequency bands can be evaluated using the technique of carrier-to-interference C/I calculation. For the receive earth station geometry illustrated in Fig. 5.4-9, the C/I equation can be expressed in dB as follows:

$$C/I = \left(G(0) - G(\theta)\right) + \left(P_t - P_t'\right) + (G_s - G') - 20 \log\left(\frac{R}{R'}\right)$$

where:

- $G(0)$: gain of the earth station antenna in the direction of the satellite
- $G(\theta)$: gain of the earth station antenna in the direction of the terrestrial station
- P_t: transmit power of the satellite into its antenna
- P_t': transmit power of the terrestrial station into its antenna
- G_s: gain of the satellite antenna in the direction of the earth station
- G': gain of the terrestrial antenna in the direction of the earth station
- R and R': distances between the earth station, and the satellite and terrestrial station.

This equation shows the terms that are different, in dB, between the desired and interfering contributors. A simpler way to examine the problem is in terms of an interference budget, which is nothing more than two link budgets: one for the desired path and the other for the undesired (interfering) path. C/I is the difference in dB between the desired and interfering received carrier powers.

An example of an interference budget is presented in Table 5.4-3 for the interference geometry indicated in Fig. 5.4-10.

There are several significant issues that arise when evaluating C/I in this manner. Some relate to the actual physical characteristics being modelled (e.g., the sidelobe gain of the earth station and terrestrial microwave antennas and the amount of expected terrain shielding or blockage to be realised), while others are statistical in nature (e.g., atmospheric absorption and tropospheric scatter propagation of the terrestrial microwave signal).

The analysis in Table 5.4-3 makes certain assumptions about the strength of the interference. The terrestrial station is 8.5 km from the earth station and the path is partially obstructed (e.g., with 20 dB of shielding from hills). At a C/I of 28.6 dB, the interference would be detectable and may need further consideration.

Propagation losses, other than free space loss, may represent a significant challenge for anyone estimating a realistic interference budget before field measurements can be made.

Other factors relating to earth station and terrestrial antenna performance, particularly in the back lobe and side lobe regions, are also difficult to assess.

FIGURE 5.4-10

Interference geometry for terrestrial interference to reception at an earth station with a large diameter antenna

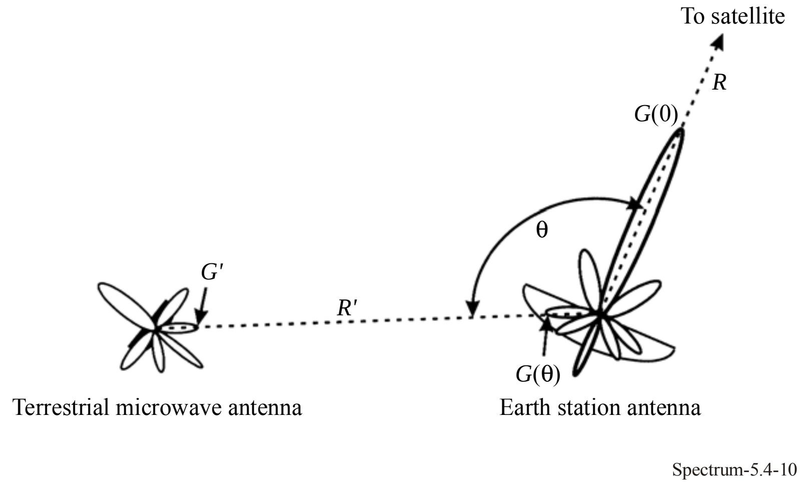


TABLE 5.4-3

Transmitter interference budget for a digital video link interfered by a terrestrial microwave (transmitters operate on the same frequency)

Factor	Value
Desired Signal (transmitted by satellite)	
Satellite transmit power per carrier at antenna port (W)	20
Satellite antenna gain in direction of earth station (dBi)	30
Satellite e.i.r.p. in direction of earth station (dBW)	43
Free space loss (dB)	196.2
Atmospheric loss (no rain) (dB)	0.1
Earth station antenna gain (3 m dish) (dBi)	39.8
Received desire carrier power (dBW)	–113.5
Undesired signal (transmitted by terrestrial microwave station)	
Transmit power per carrier at antenna port (W)	10
Transmit antenna gain in direction of earth station (dBi)	0
Terrestrial microwave e.i.r.p. in direction of earth station (dBW)	10
Free space loss (8.5 km path) (dB)	132.1
Terrain shielding (dB)	20
Earth station antenna gain in direction of terrestrial microwave station (dBi)	0
Received interference power (dBW)	–142.1
Carrier-to-interference ratio (C/I) (dB)	28.6

5.4.5.3 Ground search phase of a GSO satellite interference investigation

5.4.5.3.1 General

Interference can pose great threat to the GSO satellite communications and broadcasts businesses. By geolocation measurement, which is elaborated in § 5.1 of this Handbook, the interference can be located within an elliptical area covering tens to hundreds of square kilometres. This should be regarded as a great improvement comparing with the uplink coverage of the satellite within which the interference could arise. In many cases, the geolocation result will help the satellite operator identify the interferer by technical or procedure means, especially for those interfering user with faulty equipment. However, in some cases where the interferer is intentional or the satellite operator is unable to find it, an investigation known as a "ground search" becomes necessary. This poses another problem to the monitoring staff because of the difficulties to receive weak signals from the side-lobe of the transmitter. These weak signals transmitted by side-lobes are normally monitored by portable equipment or equipment installed on mobile vehicles. The ground search phase of an interference investigation can be conducted by conventional approaches, or by adopting advance DSP algorithms to improve the sensitivity of the measurement system. These approaches are discussed in the text below.

5.4.5.3.2 Conventional approaches using directional antennas or omnidirectional antennas

The detection of the interference can be achieved by a receiving directional antenna such as a horn antenna, a LNA, and receiving equipment such as a spectrum analyzer. The portable equipment should normally be carried to higher locations in order to avoid reflection to the largest extent. The operator is able to find the location of the transmitter by combining different DF results. This proved to be a difficult task because it is usually required to conduct the measurement on top of high buildings, especially in urban areas. Another drawback is that AC power is not always available on roof-tops; therefore long-lasting batteries are required for the spectrum analyzer. Omnidirectional antenna can also be applied in the ground search. On most occasions, a monitoring vehicle equipped receiving omnidirectional antenna, LNA and the spectrum analyzer can be used to detect the signal from the transmitter. Two drawbacks of the omni-antenna solution should be considered by the operator, one is the lower gain of the antenna and the other is that it is only possible to conduct monitoring along the road because the equipment is typically installed on the vehicle.

FIGURE 5.4-11

An example of a monitoring vehicle capable of receiving signals from both space and terrestrial directions

Spectrum-5.4-11

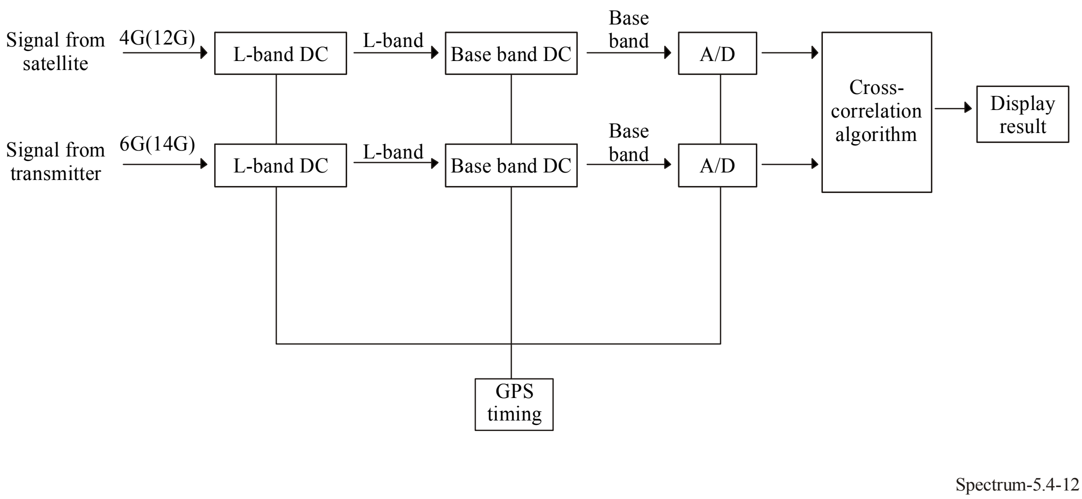
5.4.5.3.3 Using cross-correlation algorithms for improving system sensitivity

A monitoring vehicle capable of receiving signals from both space and terrestrial directions can also be used in the ground search (see Fig. 5.4-11 for an example of such a vehicle). Instead of a spectrum analyzer, DSP module is used to capture the signals below the noise floor, so that the sensitivity of the monitoring system can be improved. A block diagram of this system can be found in Fig. 5.4-12. In this approach, cross-correlation algorithm is utilized in DSP module to process signals separately from satellite by parabolic antenna and transmitter by horn antenna or omnidirectional antenna directly.

A block diagram of this solution can be described below:

FIGURE 5.4-12

A block diagram of the cross-correlation solution



In practice, the directional antenna rotates a certain angle followed by a correlation process. After rotating 360°, the operator is able find the direction of the transmitter when the correlation SNR of the both channels (space and terrestrial) maximizes, even when the level of the terrestrial signal is too weak to be observed on a spectrum analyzer (see Fig. 5.4-13).

5.4.6 Safety

There are many safety issues associated with these types of measurements. These issues arise from both RF exposure issues and the type of environments that the measuring equipment will be deployed in. A majority of the measurements will involve equipment being deployed on high rise building rooftops of even communication mast platforms.

There will be many hazards involved in this type of measurement. There may also be RF exposure hazards due to other microwave systems operating close to the measurement location. It is advisable that a full risk assessment is carried out before undertaking the measurement.

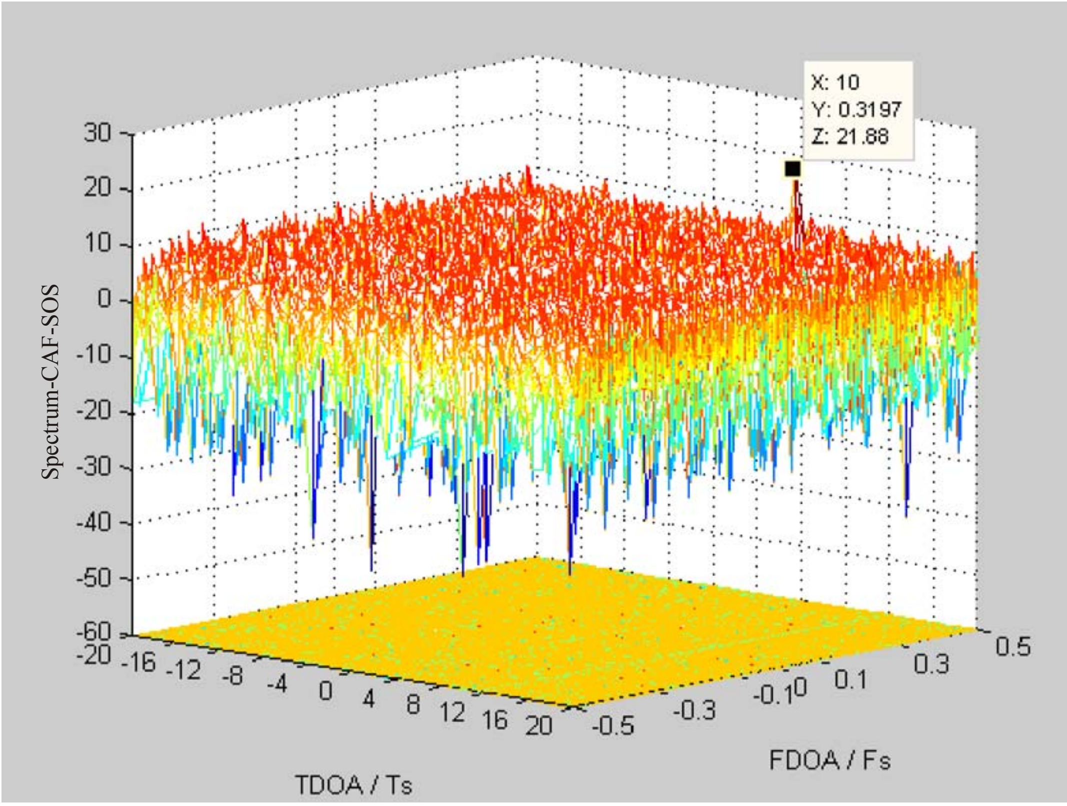
Each person has a duty to satisfy him/herself of safe working practices. This is particularly important when working in unfamiliar surroundings and when you may be under considerable pressure to resolve interference or calm political situations. Measurement staff must ensure that they understand the risks associated with the environment and the measurements being made. They must also ensure that other people present are aware of any risks and they have taken appropriate action to protect themselves and others from such risks.

Safety is of paramount importance, not only for measurement staff, but also for all other people working or present on or near the measurement location. All cables, antennas and test equipment must be clearly marked to avoid accidents. In the case of high power emitters, a basic RF exposure test should be conducted by measuring the field strength at the positions where staffs are operating.

Either a probe or calibrated dose meter can be used to assess the risk. If the levels are of concern, calibrated exposure measurements should be made using a minimum of personnel until the situation is quantified.

FIGURE 5.4-13

A cross-correlation surface



Spectrum-5.4-13

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5.5 Monitoring of radar emissions

5.5.1 Introduction

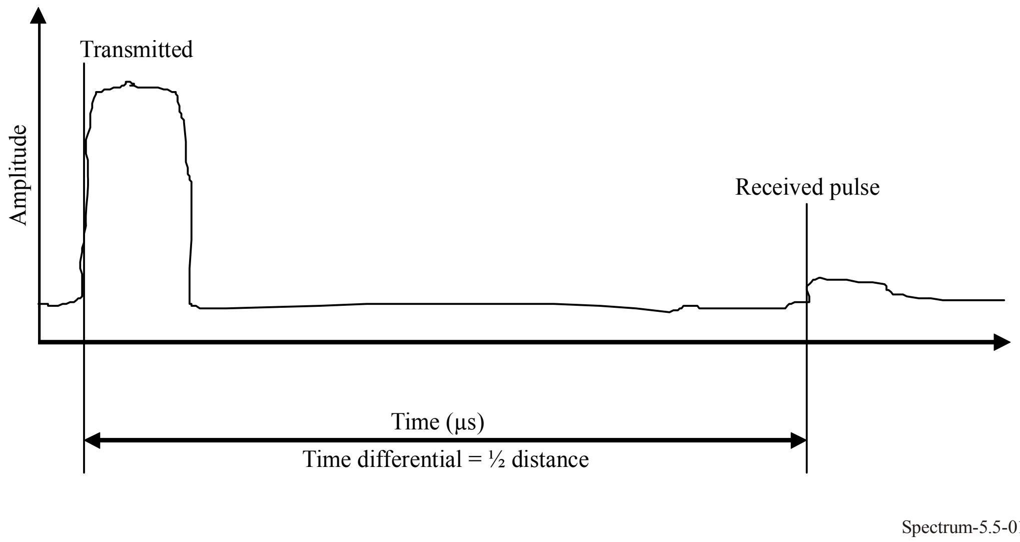
Radar, an acronym for radio detection and ranging, was first applied to military use in the 1930s to detect the presence of aircraft. Today radar applications are ubiquitous. Typical properties as high frequencies, short pulses and rotating antennas require specific radio monitoring techniques.

5.5.2 Radar basic principle

The radar is based on the principle of transmitting an electromagnetic pulse and then checking by means of a receiving device whether a reflected signal can be received. If the electromagnetic wave (the transmitted pulse) encounters an object, e.g. an aircraft, car, birds, clouds, mountains, water, this pulse will be reflected, either strongly or less so, depending on the effective radar cross-section of the target. The reflected part of the pulse radiates in all directions, i.e. also in the direction of the transmitter. The receiver of the radar receives the reflected pulse and amplifies and evaluates it.

FIGURE 5.5-1

Typical radar pulse



The time needed by the pulse to be radiated by the antenna right up to when the reflected pulse is received can be converted into distance since the speed of the electromagnetic wave is known. Furthermore, the receiver is also aware of the direction of the antenna at each instant and hence the direction to the reflecting obstacle may also be determined. In the case of moving objects, e.g. flying objects, the relative speed of the object results in a shift in the frequency of the reflected pulse in relation to the transmitted pulse called the Doppler effect. The relative speed of the object can be calculated from the frequency shift. If the received pulses are presented as a dot on a map, several measurements carried out in series also allow the direction of the object to be determined. Modern radars fitted with appropriate evaluation circuitry are even capable of depicting the position, size and contours of an object and perhaps even to recognize type or class of the object.

The transmitted pulses are made up of several pulses having a form resembling a square (pulse sequence). A medium-range-radar as used by air traffic control at airports is taken as an example. This type of radar generally transmits in the 2.7-2.9 MHz frequency range and has a pulse power of, for example, 1 MW (90 dBm). The pulse duration of such a system is typically 1µs, the pulse repetition frequency is 1 ms. The mean transmitter power is hence 1 kW. This means that an area of 50-60 NM (93-111 km) can be covered. The minimum receivable power level may be 10^{-13} W (–100 dBm). As such, the transmitter power exceeds the received power by 190 dB.

5.5.3 The radar range equation

The radar range equation in its general form yields the maximum distance over which a target can still be detected. This assumes that there is no radiated disturbance power, that free-space propagation conditions prevail and that one antenna is used for transmission and reception.

$$R_{max} = \sqrt[4]{\frac{P_T \cdot G^2 \cdot \lambda^2 \cdot \sigma}{P_{R\,min} \cdot (4 \cdot \pi)^3}}$$

where:

P_T: Transmitted power

G: Antenna gain (transmit antenna = receive antenna)

λ: Wavelength

σ: radar cross-section

$P_{R\,min}$: Minimum received power

This equation illustrates that in order to double the range it is necessary to increase the antenna gain fourfold or the transmitter power sixteen fold. The range of a radar also depends on the effective cross-section of the target. Depending on the radar application, range may be increased or decreased artificially.

5.5.4 Main components of radar systems

The transmitter consists of a waveform generator and a power amplifier. This final stage consists either of a klystron, magnetron or a semiconductor output stage.

The multiplexer ensures rapid antenna switchover from the transmitter to the receiver and vice versa.

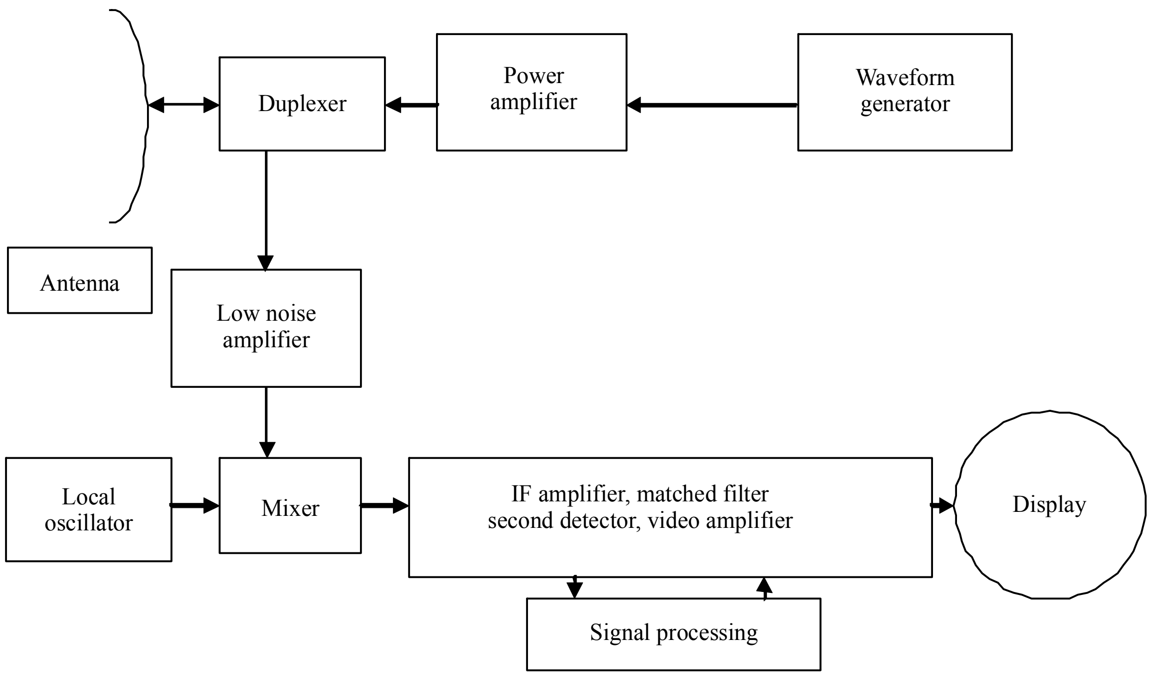
The antenna transmits and receives the pulses. In surveillance radars the antenna is mounted on a rotating actuator which is equipped with a gadget continuously providing the receiver with information about the current direction. In other radars, the antenna faces one direction only.

The receiver must amplify the weak incoming signals and suppress the noise components as far as possible (low noise amplifier).

Signal processing must now be used to separate the undesired echoes (e.g. from mountains) from desired echoes (e.g. from aircraft). To this end the Doppler Effect which reveals the relative speed of a moving object is also evaluated. This allows moving objects to be distinguished from stationary objects. The antenna direction is also evaluated. All signals exceeding a preset threshold are then displayed.

FIGURE 5.5-2

Schematic diagram of a radar with a power amplifier



Spectrum-5.5-02

The measured data are graphically displayed on the radar screen by means of the visual display unit. In the case of moving objects not just their position but also their direction can be displayed.

5.5.5 Application of radar

Today, radar engineering is deployed in many areas. But its main uses are still in aviation, navigation and the armed forces. Radar engineering is now also the mainstay of meteorology (precipitation or cloud radar, wind profiler). The police use radars to monitor vehicle speed. In industry and in motor vehicle technology there are distance measuring radars, level probe radars, etc. Last but not least, radar engineering is also used in research and in space technology.

Radars on board ship, in harbours, locks, lighthouses

In these instances radars serve to determine the distance to and position of other ships, icebergs, land, etc. The frequency ranges and power levels vary depending on the application and size of the ship.

Radar in aircraft, on airports, etc. (air traffic control)

The radars on board of aircraft are used to determine the distance (anti-collision radars) to other aircraft, to the earth's surface or other obstacles (radio altimeters). Many aircraft are also equipped with a weather radar (airborne weather radars). On airports there are landing and short-range radars, at locations at higher altitudes long range air search radars are used.

Radars for weather observation

Wind profilers are used to determine the velocity and direction of wind at different altitudes. Precipitation or cloud radars measure the movement of storms, accumulation of clouds and precipitation. These radars are also found on airports, terminal doppler weather radar (TDWR) and in larger aircraft to issue warnings about serious turbulence.

Vehicle speed measurements

Here, the Doppler effect is used to measure the speed of an object.

Use of radars in industry, space technology, etc.

In industry, for example, radar engineering is used for the non-destructive examination of construction materials, in the form of filling level radars or radar motion detectors. It is also employed for investigating geological formations (ground probing radars). In motor vehicle technology distance measuring radars determine distances. In space technology and astronomy radars are used, for remote sensing (surveying and mapping of planets) and for monitoring space debris.

5.5.6 Basic radar technologies

There are two basic radar technologies:

– Tube-type radars. This type of radar uses magnetrons, klystrons, travelling wave tubes (TWTs) etc. They have been around for half a century and are still very popular.

– Solid-state radar transmitters. They have become very popular in the last twenty years. Solid state radars can offer advantages in cost and maintainability. But they can be heavier than tube radars, and they cannot develop as much peak power as tube radars.

Table 5.5-1 shows the advantages and disadvantages of the different technologies.

5.5.7 Types or classification of radars

Radars can be classified according to very different criteria, e.g.:

– Location (on the ground, in the air, in space, on board ship, etc.).

– Frequency band.

– Function of the radar (distance measuring radar, weather radar, speed measurement, etc.).

– Signal shape (pulse, CW, FMCW).

TABLE 5.5-1

Advantages and disadvantages of different radar technologies

Radar Technologies	Advantages	Disadvantages
Magnetron	High transmitter power Inexpensive Large adjustable frequency range	High noise level Not suitable for radars with pulse compression or for using the Doppler effect (speed measurement)
Klystron and TWT	High transmitter power Satisfactory stability Low noise Well suited for use with the Doppler effect	More expensive than a Magnetron X-radiation due to the high voltage
Solid-state transmitters	Excellent stability Well suited to pulse modulation and for using the Doppler Effect (speed measurement) No X-radiation Long durability and easy maintenance (short outages)	Lower powers than those of a Klystron possible Less energy-efficient Often heavier and more expensive than a Klystron

Primary radar

A primary radar transmits an electromagnetic signal, receives the signal's reflection, evaluates the result and displays it. This type of radar is the most common one.

Secondary radar

The secondary radar actively responds to a request. If the secondary radar receives a radar pulse, it responds and sends its code and other data. This also substantially increases the range of the radar. This is how the secondary radar operates globally for aircraft.

The request is transmitted on 1 030 MHz, the response on 1 090 MHz. Distance measuring equipment (DME) also functions like a secondary radar. The aircraft transmits a pulse, the ground station responds and the time delay is used to calculate the exact distance. In navigation, the radar beacons are often installed on navigation marks.

They respond to a radar signal with a unique code to render also smaller navigation marks, which would not be detected by the radar, visible on the radar screen.

Continuous wave radar

A continuous wave radar continuously transmits a radar signal whilst at the same time receiving continuously.

The frequency shift caused by a moving object (Doppler frequency shift) is evaluated. This is used in the case of radar-speed measurement.

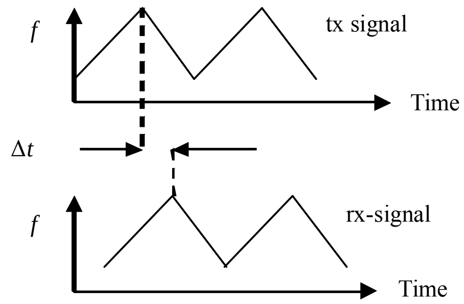
FM-CW radar

The FM-CW radar (frequency-modulated continuous wave radar) also transmits a continuous signal but a frequency-modulated one. The delay of the signal causes a frequency offset which can easily be converted into distance.

This principle is used by FM-CW radio altimeters.

FIGURE 5.5-3

Principle of an FM-CW radar



Spectrum-5.5-03

Short pulsed radar

This radar application is the one most commonly used. If a radar application bears no further identification, then this form is referred to. A short pulse is transmitted.

The antenna is subsequently switched to the receive mode and awaits a reflected signal. The direction, field strength and usually also the frequency shift (Doppler effect due to moving objects) of the received signal are then evaluated.

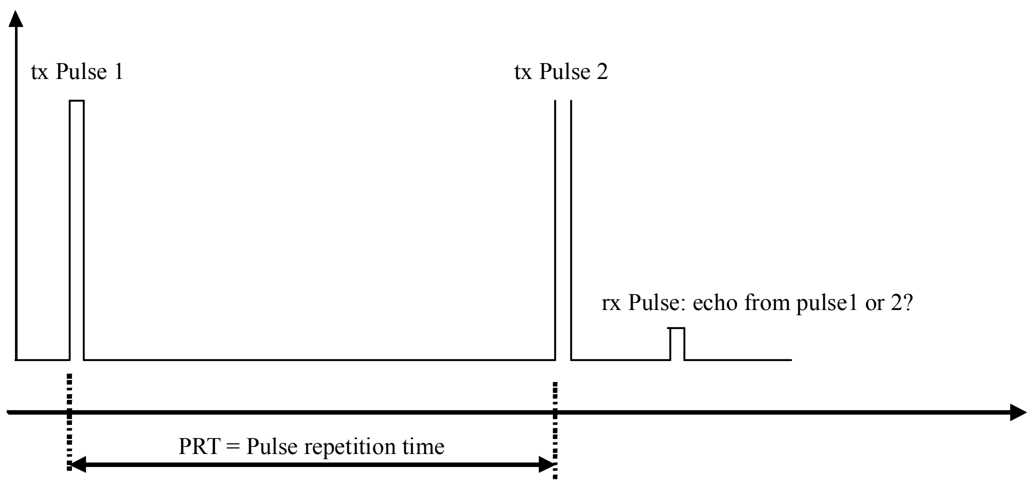
Radars used for identifying moving objects (MTI = moving target indication) often rely on different pulse repetition times to be able to recognise clutter notch and incorrect measurements due to lengthy delays.

Clutter notch occurs when the Doppler effect is used to suppress fixed targets. If the relative speed of the moving object causes a shift in phase by 360° or a multiple thereof compared with the transmitting wave then the object is recognised as a fixed target and not displayed.

When an echo is received, it is not clear whether this is an overshoot due to the reception of Pulse 1 or normal reception of Pulse 2. If the pulse repetition times were changed, in the case of an overshoot the echo pulse would reappear elsewhere. In the case of normal reception, however, the distance transmitted pulse – echo pulse is retained.

FIGURE 5.5-4

Ambiguity of detected pulses



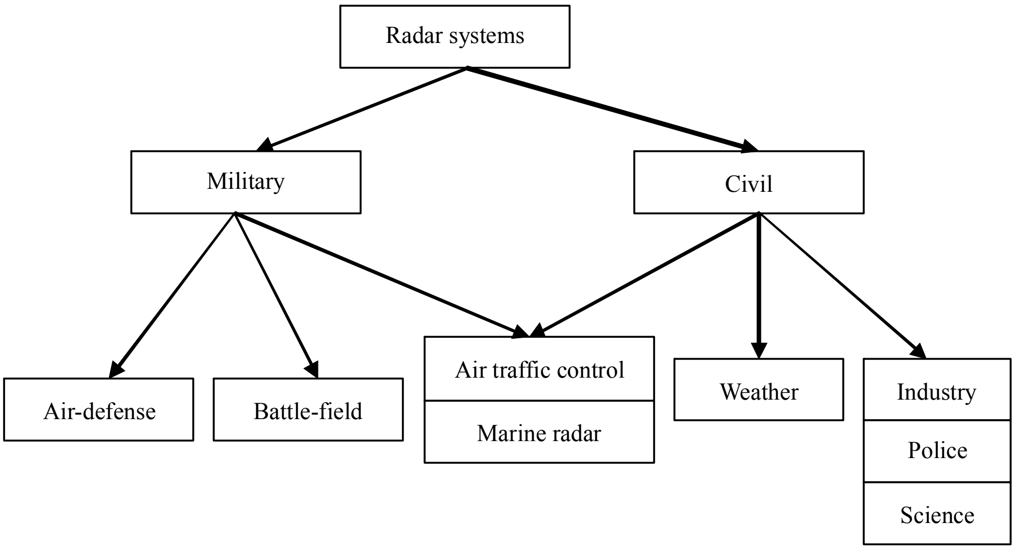
Spectrum-5.5-04

Pulse compression radar

In this type of radar engineering the frequency or phase of a long pulse is modulated to achieve the range of a long pulse together with the distance resolution of a short pulse.

FIGURE 5.5-5

Classification according to radar use



Spectrum-5.5-05

The following figures illustrate some typical radars.

FIGURE 5.5-6

Long range air search radar and secondary-radar-antenna on the top

Spectrum-5.5-06

FIGURE 5.5-7

Maritime search and navigation radar

Spectrum-5.5-07

5.5.8 Main frequency bands for radar systems

Table 5.5-2 lists the main frequency bands for radar systems along with their application.

TABLE 5.5-2

Main frequency bands for radar systems

Frequency	Band	Application
5-25 MHz	HF	Over the horizon radar
420-450 MHz	UHF	Radio location, e.g., windprofiler
960-1 215 MHz	L	Air search (DME application)
1 030/1 090 MHz	L	Primary/secondary radar
1 250-1 350 MHz	L	Long range air search radar
2 700-2 900 MHz	S	Air traffic control on airports
2 900-3 100 MHz	S	Ship navigation
3 100-3 600 MHz	S	Air search
4 200-4 400 MHz	C	Low range radio altimeter
5 000-5 850 MHz	C	Air navigation and air search
8 500-10 500 MHz	X	Radio location, air and marine search
13.25-14 GHz	Ku	Radar-motion sensor, radio location
15.4-17.7 GHz	Ku	Air navigation and air search
24.0-24.25 GHz	K	Radar-motion sensor, industry, radio location
31.8-36 GHz	Ka	Radar-motion sensor, industry, radio location
59.3-64 GHz	V	Radar-motion sensor, industry, radio location

5.5.9 Instrument to measure radar signals

The following equipment should be available if radar measurements have to be carried out:

Spectrum analyzer

Many radar features as pulse width, pulse repetition frequency, speed of rotation, pulse power, centre frequency, occupied bandwidth and unwanted emissions can be measured with a spectrum analyzer. The analyzer can also be used to measure rising and declining slopes, providing the bandwidth of the RF filter is large enough.

Digital oscilloscope

A digital oscilloscope in conjunction with a broadband demodulator is very suitable for measuring the pulse duration, rising and declining slopes, and pulse length. To this end many devices are fitted with special measurement functions.

With the aid of the substitution method it is also possible to measure the pulse power. The phase modulation can also be at least determined.

A prerequisite for using the oscilloscope for these measurements is, however, that adequate signal level is available and that there are no other emissions at the input of the oscilloscope. This is always the case if the measurement is carried out at the radar.

Vector signal or FFT analyzer

With a vector signal analyzer or FFT analyzer the measurement functions of the spectrum analyzer can be complemented by displaying the phase or frequency over time, allowing the phase and frequency modulation of a pulse to be measured. However, unlike in the case of a spectrum analyzer, the spectrum can be captured and displayed in full after a single rotation of the radar. A spectrum analyzer would need very long to achieve this. Due to the special requirements described in § 5.5.10.7, an FFT analyzer may not be suitable for measurements of the unwanted emissions in all cases.

Power meter (thermal power meter)

With a modern thermal power meter both the mean power and the pulse power can be measured direct at the measurement output of a radar. The pulse power can be calculated from the mean power, using the duty cycle.

Pulse analyzer

Pulse analyzers scan the pulses at high speed, digitize them and automatically evaluate the result. Frequency, amplitude, pulse width and pulse repetition frequency of each incoming pulse are measured.

This measurement method allows the major parameters of a radar to be surveyed accurately within a short period of time. Especially staggered radars, i.e. radars where pulse length or pulse repetition times are not constant, can easily be surveyed.

5.5.10 Measurement of radar signals

5.5.10.1 Main radar parameters

– Centre frequency;
– pulse duration (pulse width);
– pulse rise and decay time;
– pulse repetition frequency (pulse rate);
– speed of rotation of the radar;
– pulse power (peak power);
– occupied bandwidth;
– unwanted emissions (spurious emissions and out-of-band emissions);
– modulation of the pulse.

5.5.10.2 Measurement set-up

General

Principally there are two ways to survey a radar: at the actual radar at the measurement output or via the radio interface (free space measurement).

To determine the speed of rotation of the transmitting antenna, the measurement has to be carried out at the radio interface. This also applies when the radiation pattern has to be surveyed.

If the unwanted emissions are to be measured at the measurement output of the radar, the exact radiation pattern in relation to the behaviour of the antenna at different frequencies needs to be known (see Recommendation ITU-R M.1177-3) since the antenna may amplify the unwanted emissions on adjacent frequencies differently from the main emission.

Not all of the smaller radars have a measurement output so that in these cases the measurement has to be carried out at the radio interface.

Measuring at a radar's measurement output

The transmitter power of a radar can frequently only be measured via its measurement output because especially in the case of the stationary radars used in aviation the elevation cannot be decreased sufficiently for a direct measurement to be carried out in the main lobe.

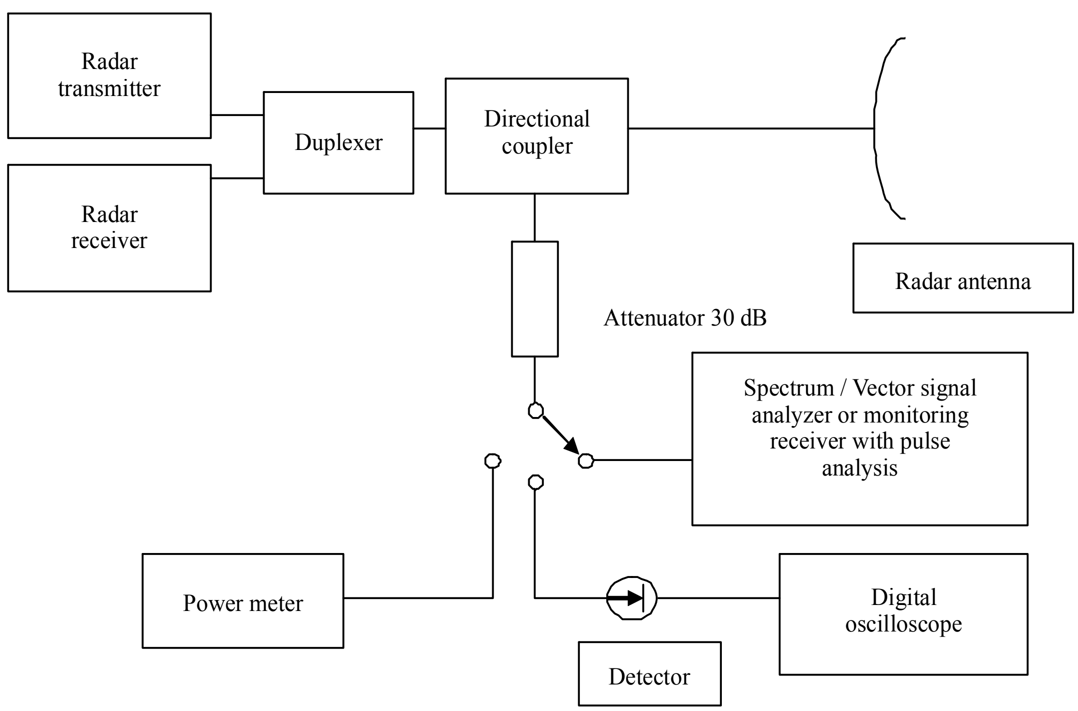
Measuring at the measurement output of a radar ensures that only frequency components from the actual radar are measured. This renders the measurements less problematic than those via the radio interface.

However, the antenna characteristics must be known in detail so as to be able to calculate the transmitter power or the power of the unwanted emissions.

To this end most radars have a measurement output. A directional coupler with 30 dB coupling attenuation is inserted between the radar transmitter and radar antenna.

FIGURE 5.5-8

Schematic diagram for the measurement of typical radar features at the radar itself



Spectrum-5.5-08

Measuring a radar by means of the radio interface (free space measurement)

In this constellation it is necessary to make sure that the measuring antenna is stable and is accurately oriented towards the radar's transmitting antenna (azimuth and elevation). There should not be any obstacles between transmitting and receiving antenna, and the far field condition must be adhered to.

The far-field condition of large antennas is derived from the following formula:

$$\frac{2D^2}{\lambda} \qquad (4.2\text{-}1)$$

where:

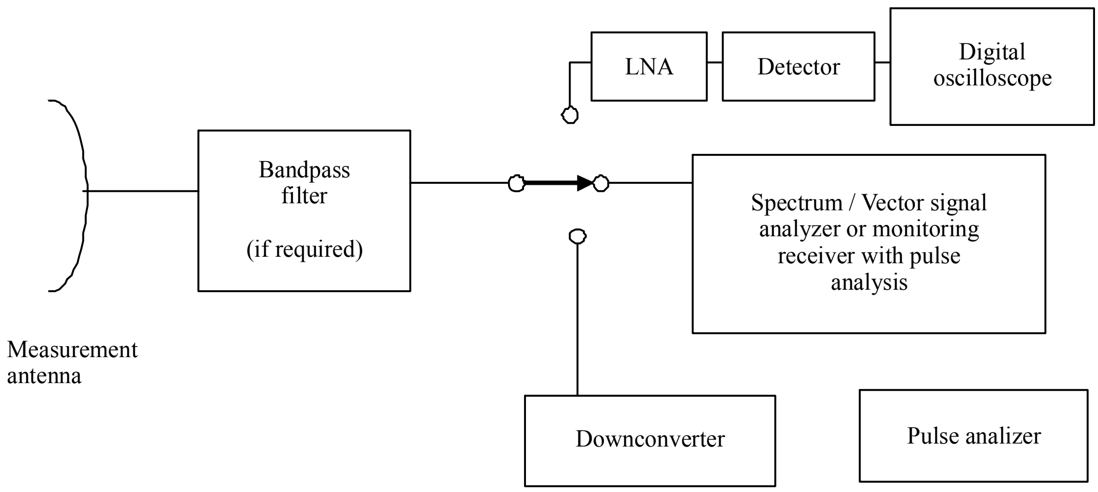
D: antenna diameter

λ: wavelength

Example: a long-range air search radar has an antenna diameter of 6 m and a frequency of 1 300 MHz. The far field condition is met at 312 m and beyond.

FIGURE 5.5-9

Schematic diagram for measuring the radar by means of its radio interface (free space measurement)



Spectrum-5.5-09

5.5.10.3 Measurement of the centre frequency

The centre frequency is obtained by operating a spectrum analyzer for some time in the detection mode “positive peak” and the display mode “maximum-hold”. The smaller the measurement filter (RF bandwidth), the more accurately the centre frequency will be read.

The spectrum is displayed best when each horizontal sweep point on the analyzer is hit once by the maximum power of the radar. However, with a conventional spectrum analyzer this measurement takes quite long.

Example: A long range air search radar needs 11.6 s for a rotation, the analyzer has 500 sweep points, so the measurement takes at least 1.5 h.

The measurement is much shorter if carried out with an FFT analyzer. The entire spectrum is displayed after a single rotation since the FFT analyzer can process and display the required frequency bandwidth during a single scan.

5.5.10.4 Measurement of the pulse parameters

Here, pulse duration, pulse rise and decay time, pulse repetition frequency and speed of rotation must be measured. The measurement method has largely already been described in Chapter 4.9. For measuring the speed of rotation, it is merely necessary to raise the analyzer's sweep time until at least one rotation can be measured in the zero span mode.

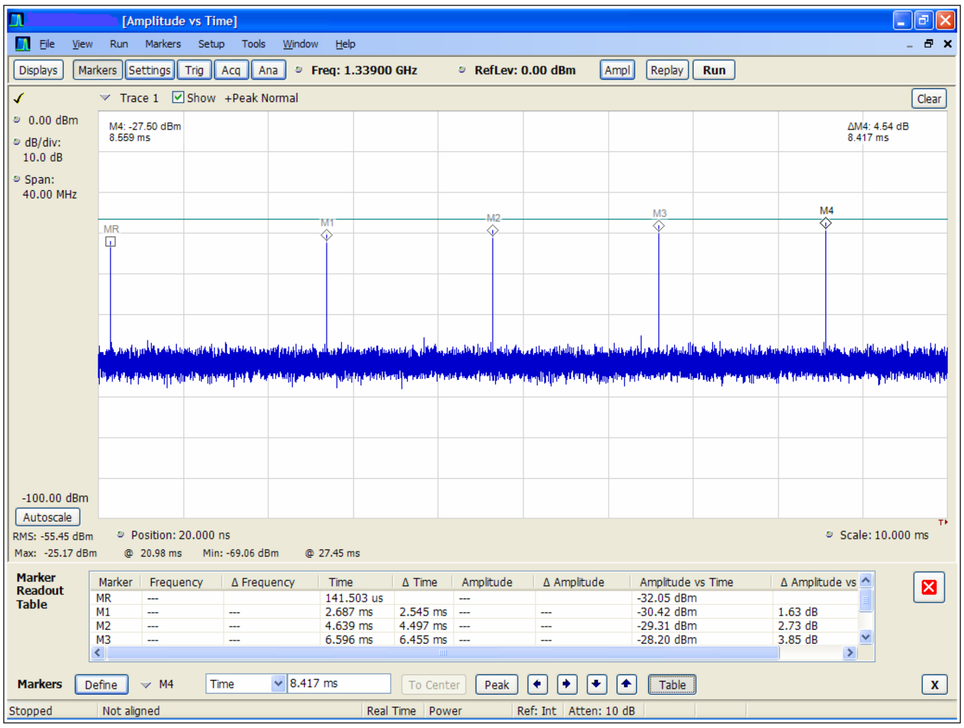
To be able to measure a staggered radar with the spectrum analyzer, several pulses must be captured sequentially. The number must be high enough for the pulse repetition times to repeat themselves.

Figure 5.5-10 illustrates the example of a long range air search radar using 14 different pulse lengths. Visible on the screen is a sequence of 5 of 14 pulses at intervals of 2.545 ms, 1.952 ms, 1.957 ms and 1.963 ms.

Of course it is easier to use a pulse analyzer for such a measurement since a higher number (e.g., 1 024) of pulses are captured and in each case pulse length, pulse repetition frequency and further parameters are output.

FIGURE 5.5-10

Pulse measurements of a long range air search radar



Spectrum-5.5-10

5.5.10.5 Measuring the pulse power

The peak transmitter output power (pulse power) can be measured at the radar direct, using a test coupler. This can be done either with a spectrum analyzer or a thermal power meter.

To this end, either the power meter must be capable of measuring the power solely during the pulse or else the mean power and duty cycle are used to calculate the pulse power with the formula "mean power/duty cycle = pulse power".

Example: when the mean power of a radar transmitter is 1 KW and the duty cycle is 1/1 000, then the pulse power is 1 MW.

The e.i.r.p. is determined by adding the antenna gain G_i and taking the line loss into account.

Should it be possible to orient the transmitting antenna to the main lobe direction receiving antenna, the pulse power can also be measured at the radio interface. To be able to do so, far-field and free space conditions are needed. The spectrum analyzer is used for the power measurement. The pulse power and the pulse length can be measured simultaneously. See § 4.9 for pulse measurements. The radiated power can then be calculated with the help of the formulae in § 6.3.2.1.

5.5.10.6 Measurement of the occupied bandwidth

Measuring the occupied bandwidth is of relevance in connection with the measurement of the unwanted emissions. According to Recommendation ITU-R M.1177, radars must not exceed a maximum bandwidth of B_{-40}, i.e. 40 dB below the PEP (peak envelope power). This power is calculated from the pulse length and the rise or decay time, depending on which of the two is shorter. The occupied bandwidth must be within the calculated bandwidth. The formulae for the B_{-40} bandwidth measurement are described in detail in Annex 8 of Recommendation ITU-R SM.1541.

When measuring the occupied bandwidth it should be borne in mind that the maximum bandwidth of the measurement filter depends on the type of modulation, pulse length, phase-chirp length and range of frequency sweep. Further details may be found in Recommendation ITU-R M.1177.

According to Annex 1 of Recommendation ITU-R M.1177 a larger filter than usually employed in other radio applications is used as measurement filter for measuring the unwanted emissions and with them the occupied bandwidth. The calculated bandwidth B_{-40} already takes into account the ensuing measurement error. The measuring bandwidth B_m in the case of, for example, non-pulse-coded radars, yields $B_m \leq 1/T$ where T = pulse length. In the case of a pulse length of 1 µs, this results in a B_m of 1 MHz. This measuring bandwidth is important for the correct measurement of the overall level of unwanted emissions and hence also for the occupied bandwidth.

The occupied bandwidth can be measured both at the radio interface and at the measurement output of a radar. The measurements at the radio interface should be carried out at a non-rotating radar antenna.

5.5.10.7 Measurement of unwanted emissions

a) General considerations

A distinction is made between “out-of-band emissions”, emissions outside the necessary bandwidth which are the result of modulation and as such inevitable, and “spurious emissions” which are not directly related to the actual emissions. Spurious emissions include harmonic emissions, parasitic emissions, intermodulation products and frequency conversion products.

A mask which has to be adhered to and consisting of B_{-40}, out-of-band limits and spurious limits, must be calculated for each radar. This procedure is described in detail in Recommendation ITU-R M.1177.

The measurements of the occupied bandwidth and unwanted emissions are carried out with a spectrum or FFT analyzer. Care should be taken to ensure that, if an amplifier is used, it is not overloaded and that sufficient dynamic range is available for measuring the unwanted emissions. The receiver noise must be visible at the borders of the spectrum.

Figure 5.5-11 shows the example of a calculated spectrum mask and of measured spectrum from Recommendation ITU-R M.1177-3. For demonstration purposes the filter curve was recorded with a measuring bandwidth of 100 kHz although a measuring bandwidth close to 1 MHz would have been more appropriate. Because the measurement was carried out with a narrower measuring bandwidth, correction values have been applied in the spurious domain and for the determination of the PEP.

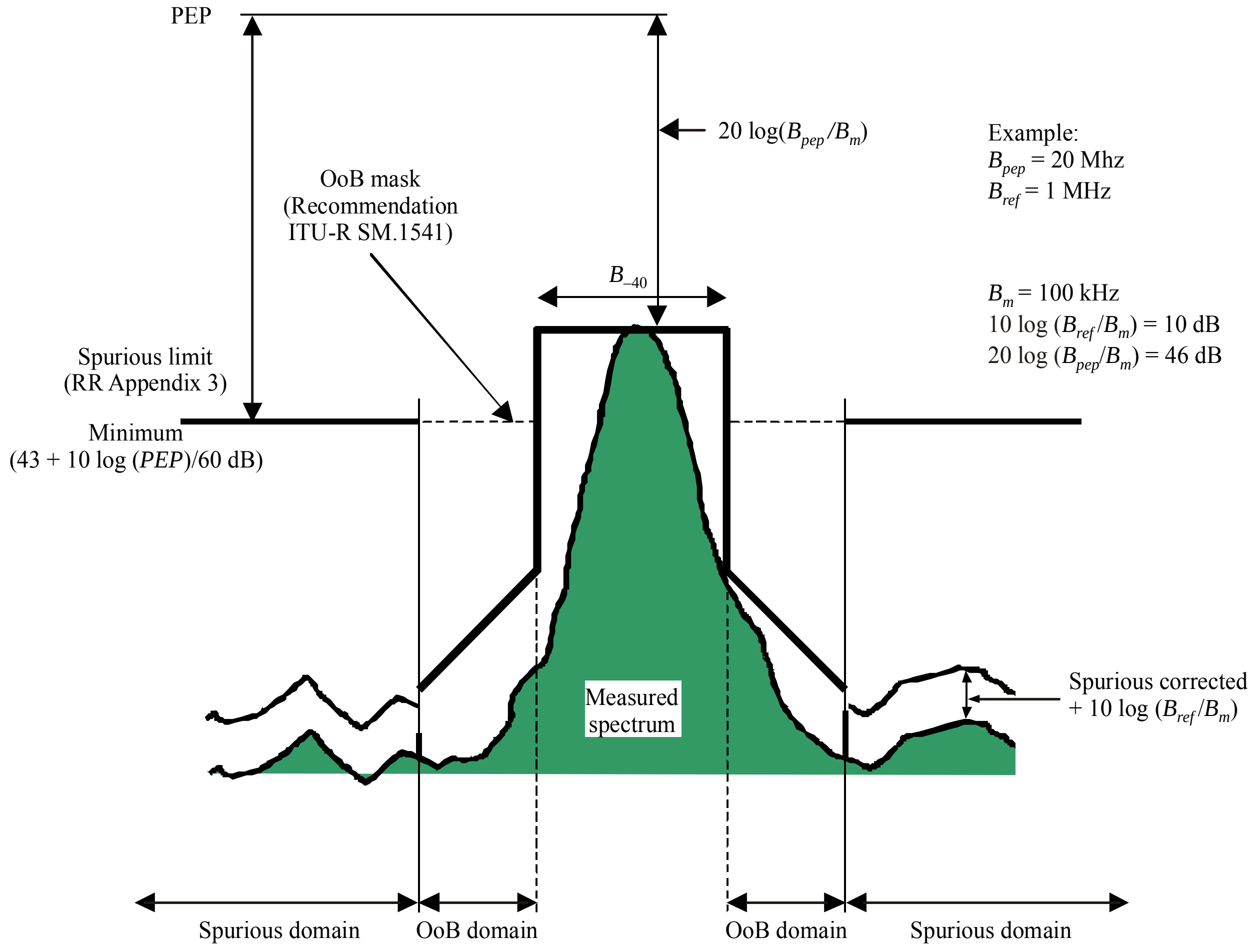
The spectrum masks for radar emissions usually span a level range of at least 60 dB, sometimes up to 100 dB. Assuming that the lowest level of an unwanted emission should be at least 10 dB above the equipment sensitivity, a minimum dynamic range of the measurement setup in excess of 70 dB (up to 110 dB) is required which is beyond the specification of commercially available measurement receivers or spectrum analyzers.

Therefore, the measurement has to be made through a filter suppressing the main emission and passing the whole frequency range of interest with almost no attenuation.

For radar unwanted emissions, the frequency range to measure may cover many GHz. Band reject filters (notch filters), tuned on the main radar frequency, are often not suitable because they do not provide “near zero” attenuation over the whole frequency range. Since radar emissions and hence the frequency range to measure are usually above 1 GHz, YIG filters are best suited as they are electrically tuneable and act as narrow bandpass filters. However, the use of these band pass filters requires a stepped measurement where the tuned frequency of the bandpass filter is synchronized with the current measurement frequency of the analyzer. This requirement is best fulfilled with sweeping analyzers whereas FFT analyzers covering a wide instantaneous bandwidth may not be suitable.

FIGURE 5.5-11

Example of a calculated spectrum mask



Spectrum-5.5-11

b) Example of unwanted emission measurement of a radar

Taking into account information described in the § 4.12 on unwanted emission measurements, the following paragraph intends to provide an overview about the overall approach which should be taken when an unwanted emission measurement is carried out on a radar system. This example is based on radiated measurement of a radar in the 5 GHz band on site and the rotating of the radar antenna is stopped.

Preliminary considerations

First of all, a theoretical approach is required to define and evaluate the appropriate measurement chain.

– Recommendation ITU-R SM.329 Table 1 defines the frequency range to consider (for a radar at 5,6 GHz the upper frequency of the measurement should be 26 GHz and the lower frequency is 30 MHz).

The lower frequency forces the use of a large antenna. Considering the large frequency range to cover, two measurement antennas are required.

– Recommendation ITU-R M.1177 defines the measurement setup (RBW 1 MHz), a span of the applicable mask of 60 dB, and boundary limit between OoB and spurious domain.

The mask requires a measurement chain with a dynamic range of at least 70 dB.

– Recommendation ITU-R SM.1541 Annex 8 provides some guidelines in order to define the necessary bandwidth (equal to the bandwidth at –40 dB). According to parameters of the radar in this example, B_{-40} is 15.5 MHz.

After these considerations, it is required to establish a link budget in order to find a suitable site for the measurement, considering the available e.i.r.p. and the dynamic range of 70 dB. This budget also permits to define the necessary gain of measurement antennas. During the choice of the measurement site, the environment should also be taken into account (no obstacles within the first Fresnel zone, line of sight to the radar antenna).

When the site is selected, a final link budget should be established in order to calculate the maximum possible received signal level at the measuring site. This information is helpful in the process of adjusting the optimum angle of the radar antenna to optimize the dynamic range of the measurement.

TABLE 5.5-3

Link budget

Nominal power of the radar (dBm)	81
Radar antenna gain (dBi)	43.8
e.i.r.p. (dBm)	124.8
Path loss (3.3 km, free space) (dB)	117.8
Level at the input of the measurement chain (dBm)	7
Measurement antenna gain at the radar centre frequency (dBi)	8.5
Cable loss (dB)	6
Maximum possible level at the input of the analyzer (dBm)	9.5

Knowing that for a typical spectrum analyzer the maximum input power is +20 dBm (with maximum attenuation) and the displayed average noise level in a RBW of 1 MHz is around –90 dBm (without attenuation), the site is validated.

For the purpose of this measurement, a software program has been developed in order to control the spectrum analyzer and to collect data. The principle of the monitoring program is as follows:

– configuration of the spectrum analyzer (RBW 1 MHz, detector peak, trace maxhold, attenuation 0 dB);
– the frequency spectrum is divided in slices of 100 MHz;
– each slice is measured by the spectrum analyzer with an integration time of 15 s;
– after each measurement, the trace data is recorded by the PC.

Measurement

Before starting the measurement, the radar should be rotated in the direction of measurement site. To optimize the orientation of the radar, measurements on the fundamental are carried out. The direction of the radar should be adjusted to be as close as possible to the radar power level found in the link budget.

The principle of the measurement is based on:

Step 1: Capture the spectrum of the radar signal around its central frequency.

Step 2: Carry out the measurements from 30 MHz to 26 GHz with the radar signal switched on.

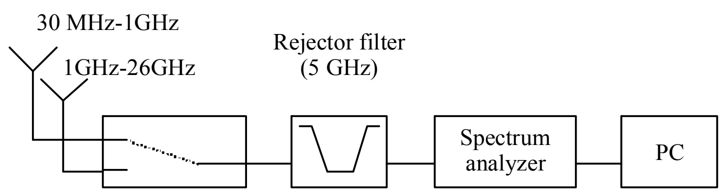
Step 3: Carry out the measurement from 30 MHz to 26 GHz with the radar switched OFF).

The first Step is carried out with a spectrum analyzer (Att. max, RBW 1 MHz, Span 50 MHz, centre frequency according to the fundamental of the radar, detector peak, trace maxhold). A first recording is done.

The two other Steps are carried out assisted by the developed software. For these two steps, the measurement setup is illustrated in the Fig. 5.5-12.

FIGURE 5.5-12

Measurement setup



Spectrum-5.5-12

Post-processing

Post-processing is realised in three steps:

Step 1: Level correction of the different measurements.

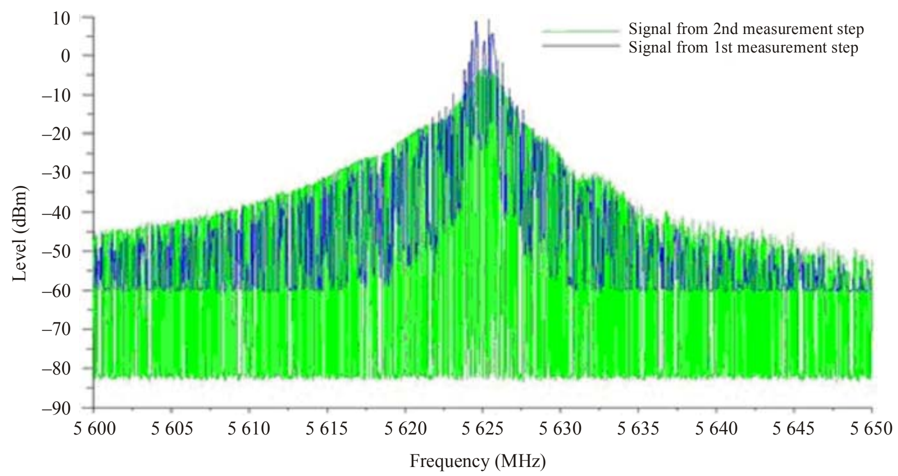
Step 2: Correlation process.

Step 3: Applying the spectrum mask to the measured radar signal.

The first step equalizes the level of all three measurements, taking into account the attenuation of the filter and different attenuation of the spectrum analyzer. The result of this first step is illustrated in Fig. 5.5-13.

FIGURE 5.5-13

Correction of level at the radar central frequency



Spectrum-5.5-13

The correlation process is applied to data acquired with and without the radar signal. This step improves the dynamic range and should remove emissions which are not originating from the radar. This operation is illustrated in Figs 5.5-14 and 5.5-15.

FIGURE 5.5-14

Correlation process

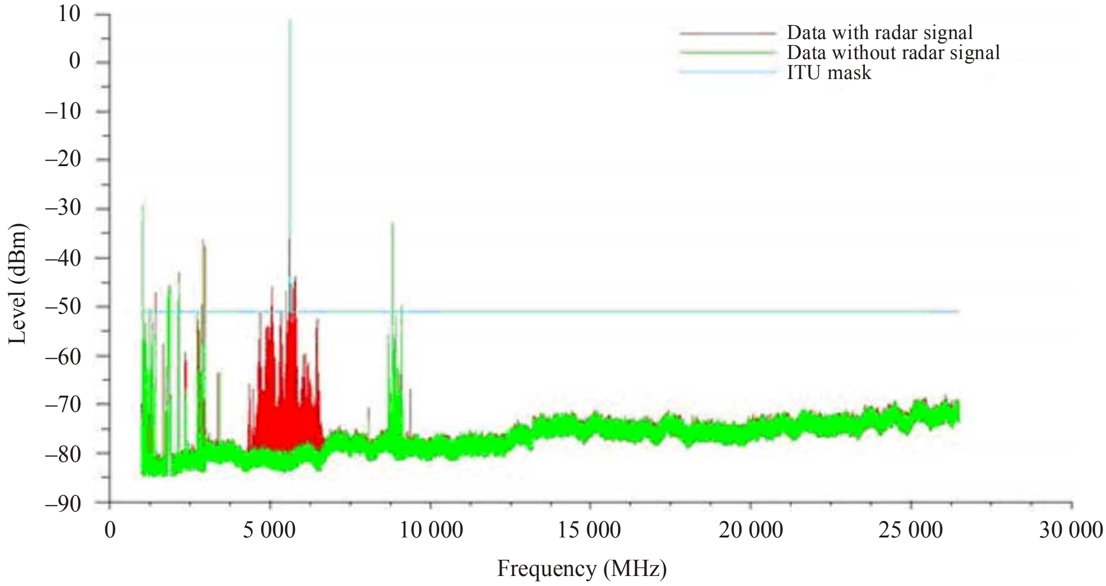
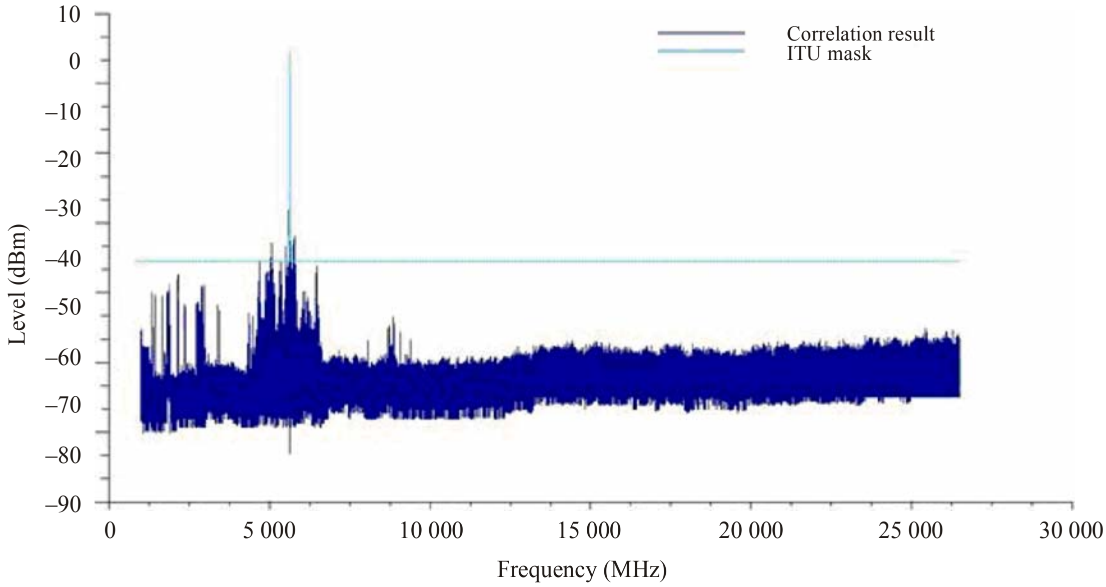


Illustration of the two series of collected data



Result of correlation process

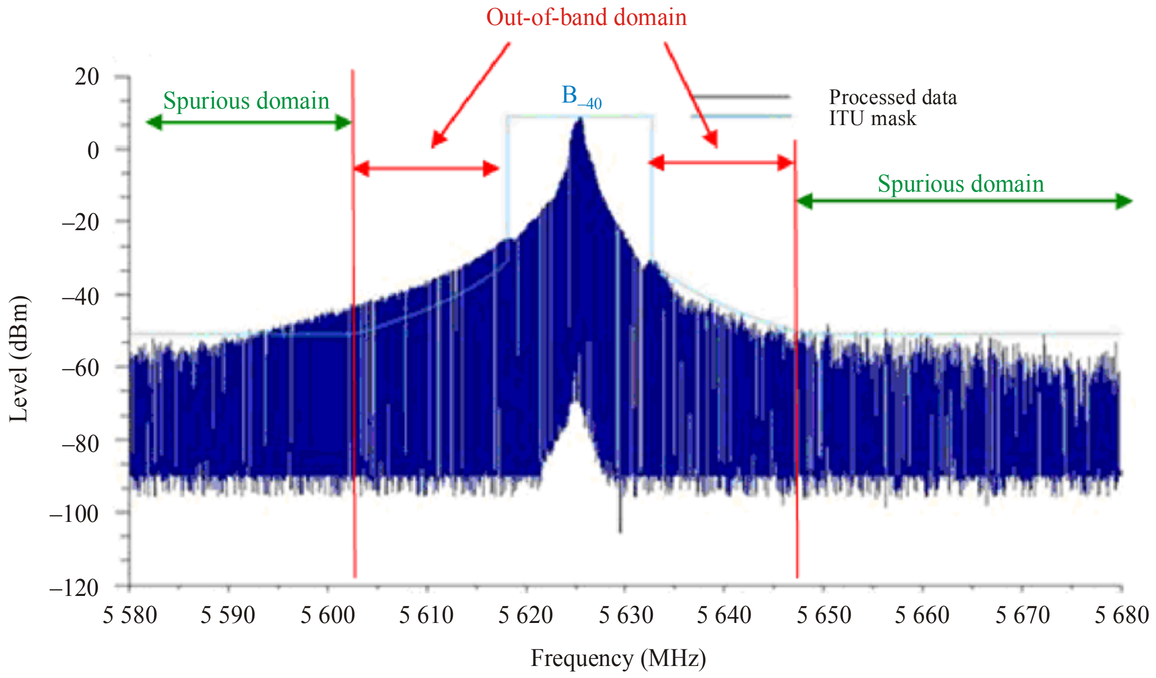
Spectrum-5.5-14

In this case, not all external signals could be eliminated. Possible reasons are the integration time being too short and the relatively long time between measurement 2 and 3.

The last step consists of applying the spectrum mask to the processed data. This is shown in Fig. 5.5-15.

FIGURE 5.5-15

ITU mask and radar signal



Spectrum-5.5-15

5.5.10.8 Measuring the phase modulation of a pulse

In modern radar engineering pulse compression is increasingly being used to achieve good quality object resolution in spite of a wider range of the radar (long pulse).

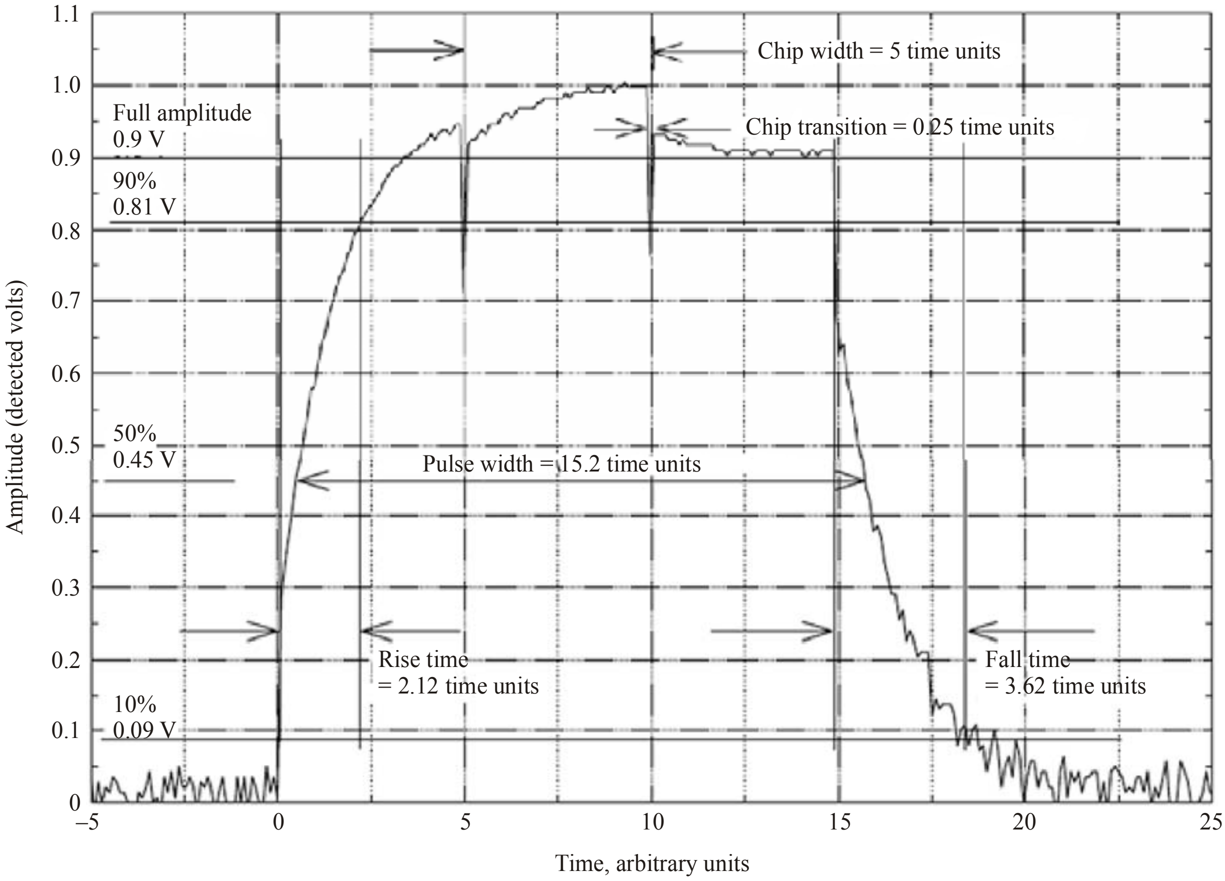
This pulse compression can be achieved by phase or FM modulation of the pulse.

The modulation of a pulse can be measured with a vector signal analyzer. In contrast to a spectrum analyzer in this case not just the amplitude over the frequency but also the phase or frequency over time is displayed.

If there are not too many phase shifts, these features may also be measured with an oscilloscope.

FIGURE 5.5-16

Example of a phase-modulated pulse



Spectrum-5.5-16

Example of phase modulation with three phase shifts.

(Source: Detection and Measurement of Radar Signals by Frank H. Sanders.)

References

Detection and Measurement of Radar Signals, NTIA Institute for Telecommunication Siences, Frank Sanders.

Radar Handbuch Third Edition by Merrill Skolnik.

Radar Measurements Application Note from Agilent.

Spektrum-Analysator-Meßtechnik-Seminar für Hochfrequenz- and Mikrowellentechnik, Hewlett Packard, September 1981.

ITU-R Recommendations

NOTE – In every case the latest edition of the Recommendation is encouraged to be used.

Recommendation ITU-R M.1177 – Techniques for measurement of unwanted emissions of radar systems.

Recommendation ITU-R SM.1541 – Unwanted emissions in the out-of-band domain.

5.6 Non-ionizing radiation measurements

5.6.1 Introduction

The enormous prevalence of mobile phones and the availability of wireless Internet go along with an increasing number of base stations. This phenomenon, associated with researches developed on the last few decades, increased the public awareness about the possible undesirable effects of non-ionizing radiation (NIR) (see Note 1) emitted by base stations, broadcasting transmitting stations and other radio devices that may be perceived as a possible danger to the public health. This phenomenon has been of increasingly concern from the general population on the past few years in more and more countries.

NOTE 1 – The more general abbreviation EMF (Electromagnetic Field) is used on several of the references about this topic instead of the one used here, NIR. This approach was preferred to make clearer the distinction between the specialized topic discussed on this section and those of other sections of the Handbook, more general in terms of electromagnetic field measurements.

Studies on this subject have been conducted since 1974, within the International Radiation Protection Association – IRPA, followed by the formation of the International Non-Ionizing Radiation Committee – INIRC in 1977 and finally the International Commission for Non-Ionizing Radiation Protection – ICNIRP in 1992. These studies were used to establish the guidelines on NIR from the World Health Organization (WHO) and provide in many countries the basis for the regulatory framework on this subject.

Many Administrations assigned the enforcement of regulations relating to maximum NIR levels from telecommunication devices to the authority responsible for the spectrum management, taking advantage of the existing expertise in this field. Therefore the national monitoring and inspection services were assigned with this task of measuring NIR levels.

NIR measurements may be conducted:

– in association with the issue of a radio license;

– regularly, according to a NIR control and monitoring plan; or

– with good cause, i.e., due to public or official demands.

NIR measurements are in principle simply field strength measurements. However, there are some constraints to be considered and the evaluation of the results is different. Considering these specificities, § 5.6 is intended to provide additional support for spectrum monitoring personal and organizations on how to perform this task. It describes the basic principles and references for in-situ measurements in order to assess electromagnetic fields for the purpose of comparison against limits for human exposure. They are not applicable for cases where the critical exposure is strongly localised, e.g. with cellular phone handsets in relation to the human head.

Additional significant information on characteristics of electromagnetic fields, measurements (procedures and Instruments), comparison between predictions and measurements, examples of calculated field strengths, limits and levels can be found on ITU-T Recommendations K.52, K.61, K.70 and Recommendation ITU-R BS.1698.

5.6.2 NIR limits and exposure quotient

There are two types of limits, the basic restrictions and the reference levels. The basic restrictions are directly related to the biological effects but they are sometimes expressed in quantities, which are difficult to measure (e.g. current density in the human body). The reference levels are derived from the basic restrictions and are formulated in easily measurable quantities. The exact definitions are as follows.

Restrictions on exposure to time-varying electric, magnetic, and electromagnetic fields that are based directly on established health effects are termed "basic restrictions." Depending upon the frequency of the field, the physical quantities used to specify these restrictions are:

– current density (J);

– specific energy absorption rate (SAR);

– power density (S).

Only power density in air, outside the body, can be readily measured in exposed individuals.

The reference levels are provided for practical exposure assessment purposes to determine whether the basic restrictions are likely to be exceeded. Some reference levels are derived from relevant basic restrictions using measurement and/or computational techniques, and some address perception and adverse indirect effects of exposure to EMF.

The derived quantities are electric field strength (E), magnetic field strength (H), magnetic flux density (B) and power density (S). In any particular exposure situation, measured or calculated values of any of these quantities can be compared with the appropriate reference level.

Compliance with the reference level will ensure compliance with the relevant basic restriction. If the measured or calculated value exceeds the reference level, it does not necessarily follow that the basic restriction will be exceeded.

However, whenever a reference level is exceeded it is necessary to test compliance with the relevant basic restriction and to determine whether additional protective measures are necessary.

The reference levels applicable to occupational and general public exposure are derived from the basic limits of exposure of human beings to electromagnetic fields adopted by competent bodies for comparison against measured electromagnetic fields. Measurements below the reference level guarantee that the requirement that basic limits of exposure are not exceeded is satisfied.

More relaxed limits may be applicable for time limited occupational exposure. The reference levels are frequency-dependent and may be taken from the relevant international, regional or national documents. As an example, see the ICNIRP guidelines presented in Table 5.6-1, but national regulations should take precedence.

Although the reference levels are given in effective (RMS) values, there are limitations on the peak values as well (see Notes 3 and 4 in Table 5.6-1). They become important when the peak to RMS ratio of the signal is high. (e.g. pulsed radar signals).

The exposure quotient is the ratio of the measured maximum electromagnetic power density or field strength (E, H field-strengths or S) to the appropriate reference level at a given frequency. A value greater than "1" signifies that levels to which people may be exposed exceed the reference level.

Several reference levels and thus several exposure quotients may be applicable for one frequency (e.g. E and H-field), and different quotients may apply across the frequency band of interest.

The total exposure quotient is a summation of all the individual frequency exposure quotients in the measured frequency band at a single location. The calculation of this value from the individual frequency quotients is defined in the exposure limits. Several total exposure quotients may be applicable (e. g. for E and H).

Some examples for the calculation of the total exposure quotients referenced to ICNIRP guidelines, can be found below.

In the frequency ranges, where the electrical stimulation effects are dominant, the calculation of the total exposure quotient is based on the field strengths directly (see 2nd example). In the frequency ranges, where the thermal effects are dominant, the calculation of the total exposure quotient is based on the square of field strength values (see 3rd example) or on the power flux densities (1st example). It can be seen from the last two examples that the respective frequency ranges overlap. In case there are spectral components situated in the common part of the two ranges (100 kHz-10 MHz), both types of total exposure quotients should be calculated and the value of both of them should be below one.

– Total exposure quotient (or cumulative exposure ratio) based on pfd:

$$\sum_{i=1}^{N} \frac{S_i^{meas}}{S_i^{guid}} = \frac{S_1^{meas}}{S_1^{guid}} + \frac{S_2^{meas}}{S_2^{guid}} + \frac{S_3^{meas}}{S_3^{guid}} + \ldots.. + \frac{S_N^{meas}}{S_N^{guid}} < 1$$

where:

S_i^{meas}: measured pfd of index i

S_i^{guid}: pfd limit according to the guideline in use, at the same frequency as the S_i^{meas}

N: total number of measurements considered.

TABLE 5.6-1

ICNIRP 1998: Reference levels for occupational and general public exposure to time-varying electric and magnetic fields

Type of exposure	**Frequency range**	**Electric field strength (V/m)**	**Magnetic field strength (A/m)**	**Equivalent plane wave power density S_{eq} (W/m^2)**
Occupational exposure	Up to 1 Hz	–	2×10^5	–
	1-8 Hz	20 000	$1.63 \times 10^5/f^2$	–
	8-25 Hz	20 000	$2 \times 10^4/f$	–
	0.025-0.82 kHz	$500/f$	$20/f$	–
	0.82-65 kHz	610	24.4	–
	0.065-1 MHz	610	$1.6/f$	–
	1-10 MHz	$610/f$	$1.6/f$	–
	10-400 MHz	61	0.16	10
	400-2 000 MHz	$3f^{1/2}$	$0.008f^{1/2}$	$f/40$
	2-300 GHz	137	0.36	50
General public	Up to 1 Hz	–	2×10^4	–
	1-8 Hz	10 000	$3.2 \times 10^4/f^2$	–
	8-25 Hz	10 000	$4000/f$	–
	0.025-0.8 kHz	$250/f$	$4/f$	–
	0.8-3 kHz	$250/f$	5	–
	3-150 kHz	87	5	–
	0.15-1 MHz	87	$0.73/f$	–
	1-10 MHz	$87/f^{½}$	$0.73/f$	–
	10-400 MHz	28	0.073	2
	400-2 000 MHz	$1.375f^{1/2}$	$0.0037f^{1/2}$	$f/200$
	2-300 GHz	61	0.16	10

NOTE 1 – f is as indicated in the frequency range column.

NOTE 2 – For frequencies between 100 kHz and 10 GHz, the averaging time is 6 min.

NOTE 3 – For frequencies up to 100 kHz, the peak values can be obtained by multiplying the r.m.s. value by $\sqrt{2}$(≈1.414). For pulses of duration t_p, the equivalent frequency to apply should be calculated as $f = 1/(2t_p)$.

NOTE 4 – Between 100 kHz and 10 MHz, peak values for the field strengths are obtained by interpolation from the 1.5-fold peak at 100 MHz to the 32-fold peak at 10 MHz. For frequencies exceeding 10 MHz it is suggested that the peak equivalent plane-wave power density, as averaged over the pulse width, does not exceed 1 000 times the S_{eq} limit, or that the field strength does not exceed the field strength exposure levels given in the table.

NOTE 5 – For frequencies exceeding 10 GHz, the averaging time is $68/f^{1.05}$ min (f in GHz).

– Total exposure quotient referred to electrical stimulation effects:

$$\sum_{i=1\text{ Hz}}^{1\text{ MHz}} \frac{E_i}{E_{l,i}} + \sum_{i>1\text{ MHz}}^{10\text{ MHz}} \frac{E_i}{a} \leq 1$$

where:

E_i: the measured E field at frequency i

$E_{l,i}$: frequency dependent limit

a = 87V/m for general public exposure or 610V/m for occupational exposure.

$$\sum_{j=1\text{ Hz}}^{65\text{ kHz}} \frac{H_j}{H_{l,j}} + \sum_{j>65\text{ kHz}}^{10\text{ MHz}} \frac{H_j}{b} \leq 1$$

where:

H_j: measured H field at frequency i

$H_{l,j}$: frequency dependent limit

b = 5A/m for general public exposure or 24.4A/m for occupational exposure.

– Total exposure quotient referred to thermal effects:

$$\sum_{i=100\text{ kHz}}^{1\text{ MHz}} \left(\frac{E_i}{c}\right)^2 + \sum_{i>1\text{ MHz}}^{300\text{ GHz}} \left(\frac{E_i}{E_{l,i}}\right)^2 \leq 1$$

where:

E_i: measured E field at frequency i

$E_{l,i}$: is a frequency dependent limit

c = $87/f^{1/2}$ V/m for general public exposure or $610/f$ V/m for occupational exposure.

$$\sum_{j=100\text{ kHz}}^{1\text{ MHz}} \left(\frac{H_j}{d}\right)^2 + \sum_{j>1\text{ MHz}}^{300\text{ GHz}} \left(\frac{H_j}{H_{l,j}}\right)^2 \leq 1$$

where:

H_j: is the measured E field at frequency j

$H_{l,j}$: is the reference limit at frequency j

d = $0.73/f$ A/m for general public exposure or 1.6A/m for occupational exposure.

5.6.3 Electric and magnetic fields

Electromagnetic fields can be sub-divided into two components: the electric field E (measured in V/m) and the magnetic field H (measured in A/m). The E-field and the H-field are mathematically interdependent in the far-field, that means only one component has to be measured. For example, in free space if the H-field is measured in this region, it can be used to calculate the magnitude of the E-field and power density S (W/m^2):

$$E = H \times Z_0,\ S = H^2 \times Z_0 \qquad \text{knowing } Z_0 = 377\ \Omega$$

In contrast, the H-field and E-field must be measured separately in the reactive near-field region and considered against the respective limits.

In general, the inner boundary of the far-field is considered to be at a radius of about 3 λ from the emitter site (or $2D^2/\lambda$ if the size of the antenna is large compared with the wavelength λ). A good explanation of near- and far-fields can be found on ITU-T Recommendation K.61.

If no isotropic sensor can be used, e.g., 3 measurements with a dipole or a loop antenna should be performed in 3 orthogonal directions to obtain the different components of the field. The total field strength is obtained by using the following expression:

$$|E| = \sqrt{|Ex|^2 + |Ey|^2 + |Ez|^2}\ ,\ |H| = \sqrt{|Hx|^2 + |Hy|^2 + |Hz|^2}$$

5.6.4 Instruments for NIR measurements

5.6.4.1 Broadband isotropic probes and meters

Broadband isotropic probes are devices specifically designed to quantify hazardous electric or magnetic fields. They usually consist of integrated (E or H field) antenna and detector elements. The broadband probes usually provide d.c. voltage proportional to the measured field strength.

The Electric field antennas generally use arrays of resistive dipoles while magnetic probes use arrays of loops. These antennas are arranged in such way to be mutually orthogonal and, as such, provide readings on all polarizations and directions, creating the near isotropic characteristics of these sensors that are able to provide a single figure representing the total radiation level received at a specific location.

The isotropic probes have separate detectors for each of the three spatial dimensions. Usually Schottky diodes or thermocouples are applied for this purpose. With Schottky diodes a wider dynamic range can be achieved and they provide a d.c. level proportional to the r.m.s. value of the RF signal while they are used on the square-law section of their characteristic.

Although their sensitivity and dynamic range are lower than that of the Schottky diodes, the thermocouples always provide true r.m.s. values regardless of the RF signal waveform. So they are better suited to measurement of RF signals with high peak to RMS ratio.

The detected d.c. levels originating from the different spatial components are usually combined in the instrument the probe is connected to, but in some cases it happens in the probe itself.

As the broadband probes cannot distinguish the different spectral components one can have only one single measurement results. Detectors with flat frequency response provide the total field strength value in the band, but they are not suitable for the measurement of the total exposure quotient. There are probes available equipped with built-in frequency dependent weighting circuits that realize the weighting characteristic required by a particular standard. These weighted probes can provide only the value of the total exposure quotient, and not suitable for the measurement of the total field strength. The following figure provides some diagrams and a picture of an isotropic electric field sensor constructed over thick film, such as described by Botelho, *et al.* [2008].

Regarding the use of broadband isotropic probes and meters, one can point to the following main benefits:

– Provide fast reading, usually in the order of 1/3 of a second or less, reducing the exposure of the personal handling the equipment and allowing the use of techniques for quick overviews or mobile monitoring.
– Usually are harnessed against strong EMF, allowing its operation near radio frequency sources, places of interest for NIR measurements. Also the upper limit of the measurement scale is usually high, more than 70V/m and in some cases up to hundreds (V/m), allowing the evaluation of extremely hazardous RF environment, activity that might be necessary to solve a dispute about occupational hazard.
– Simple to operate.

On the other hand, one should be aware of the following limitations:

– Increased uncertainty under modulated signals and places with multiple sources at various frequencies, whenever the probe uses Schottky diode detectors. As pointed out on theoretical studies [Randa and Kanda, 1985] the error can be as high –15 dB to +3 dB for energy density measurements, being typically in the order of a few dB (usually less than 4 dB). Experimentation with probes, as displayed on commercial datasheets, confirms that this error has the tendency to overestimate the real value, i.e. the displayed value is higher than the “real” EMF level.

– Presents a single value, not frequency dependent, which means that unless the equipment is used to evaluate a specific single source, the lower limit should be used and no error correction is applicable.

– Low sensitivity, due to its broadband characteristics, noise level for isotropic probes and meters is usually between 0.1 V/m and 0.8 V/m, which is not a problem when the lower regulatory limit applicable to general public environment is in the order of 28 V/m, such as proposed by ICNIRP and WHO, but might be a significant limitation if the applicable regulations are more strict. In general, is desirable that the sensitivity level should be at least 3 times lower than the intended evaluation limit.

FIGURE 5.6-1

(a) diagram of arrange of resistive dipoles to compose an E-field sensor;
(b) picture example of isotropic E-field sensor;
(c) picture example of a isotropic H-field sensor

a) b) c)

Spectrum-5.6-01

Is recommended that isotropic probes and meters should conform with the following characteristics:

– Anisotropy better than 1dB (deviation from ideal isotropic characteristics).

– Assess the root mean square (r.m.s.) value of field strength.

– Maximum operational level higher than the highest regulatory limit applicable within the instrument band.

– Noise level lower than the minimum regulatory limit applicable within the instrument band. 10 dB lower would be the minimum reasonable requirement. If possible, this difference should be larger.

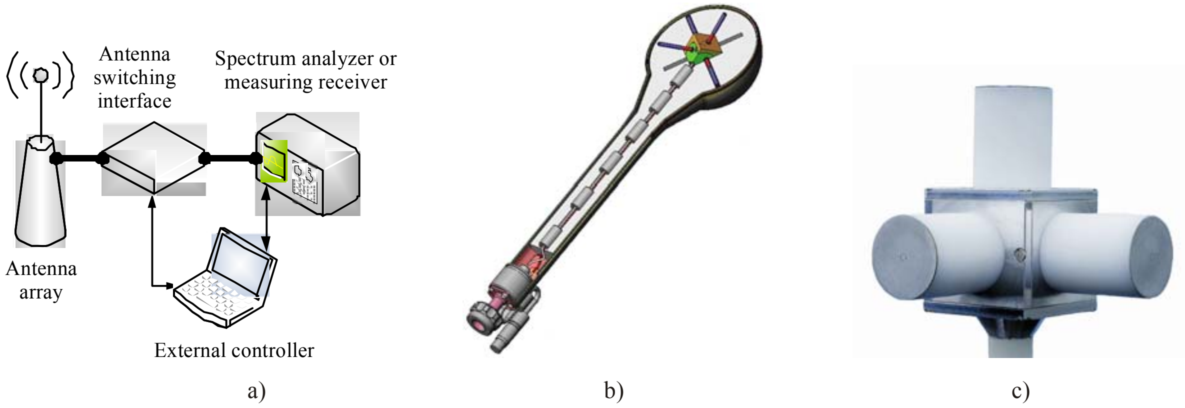
5.6.4.2 Tri-axis antennas and field strength meters

Tri-axis antennas refer to specific antennas designed to perform on-site non-ionizing radiation measurements. These usually are designed as an array of 3 short orthogonal antennas (dipoles, monopoles or loops). Instead of combining the RF signals from the 3 elementary antennas, they are sequentially connected to the output port of the antenna by a switching unit. The field strength meter (spectrum analyzer or measuring receiver), performs the electric field measurements from the antenna output, for each spatial components. A separate external controller, such as an industrial computer or laptop, might be needed to control the antenna switching and collect the measurement data for post processing, providing a result and reports in accordance to previously defined parameters and regulations. There are solutions available that integrate the antenna switching on the antenna, and the controller on the measurement instrument used, such as it become more portable and adequate for field use.

Figure 5.6-2 presents an example of such measurement system such as described by [Gallee *et al.*, 2007].

FIGURE 5.6-2

(a) System diagram including external controller, which might be eliminated if the spectrum analyzer or receiver incorporate the antenna control functions;
(b) diagram displaying a set of short dipoles constructed to provide a near isotropic measurement characteristics;
(c) picture example of tri-axis short monopole antenna



Spectrum-5.6-02

The processing of the raw field strength measurements into cumulative exposure quotient, such as described in § 5.6.2, is essential to allow the proper evaluation of the measurements in accordance with the established exposure limits. This increases the importance of the tasks performed by the component above described as "external controller" and the proper validation of the algorithms used to perform this computation.

Regarding the use of tri-axis antennas and field-strength meter, one can point to the following main benefits:

– Provide frequency selective measurements, allowing operation on multiuser (multiple signals) environment and the assessment of each spectrum user contribution. The measurement uncertainty also is usually better than observed for broadband isotropic probes, being, in general, comparable to the uncertainty observed on other on-site field strength measurement methods.
– Provide greater sensitivity than isotropic probes, in the order of mV/m, allowing the evaluation of sites subjected to much more strict regulations than those stated by ICNIRP and WHO.

On the other hand, one should be aware of the following limitations:

– Slow acquisition time. Quick overviews can be performed on a few seconds, allowing the use, with caution, of methods such as stirring, but reliable measurements might take several minutes to be performed. Complete detailed scans over the full spectrum range might take closer to an hour.
– As a consequence of switching the spatial components there are short periods of time when a tri-axis antenna does not provide any output (blind periods). So it is not suitable for the measurement of RF signals consisting short peaks (e.g. pulsed radar signals).
– Although the antenna and switching units are usually harnessed against strong EMF fields, the same does not hold truth to spectrum analyzers and measuring receivers that usually can withstand, within manufacturers guaranties, no more than 10 or 20V/m, most of time below the lowest level defined as limit by ICNIRP and WHO. If commercial laptops or computers are used, these might also be affected by even lower levels of EMF fields.
– Due to greater complexity, the system might be more suitable to failure especially from software components.

5.6.4.3 Transportable station

EMF measuring instruments are available in manually operated (handheld or portable) forms and in versions, which are suitable for autonomous operation in long term. These are referred as transportable stations.

On some countries (Brazil, Germany, Hungary; Israel, Italy, Spain (Cataluña)), specially due to public claims, the monitoring of NIR has been complemented with the addition of transportable station, allowing the long term and/or "real time" monitoring of specific sites or, in the Brazilian case, the quick overview over large areas with the transportable station being installed on a vehicle.

A transportable station is composed of a NIR measuring instrument, such as broadband isotropic probes or tri-axis antennas and field strength meters, associated with support sub-systems, such as special power supply, data storage and control unit, communication interface and shelter. These items are described in more detail on the following items:

– **Power supply**: isotropic probes and meters, due to their construction characteristics and broadband, are very susceptible to conducted noise from the power line. To reduce this noise, isotropic probes usually do not connect directly to a power line, deriving power from a DC source, such as batteries. For long term operation, such as expected for a transportable station, the power might come from solar panels or specially adapted power supplies, which provide energy to the probe by automatically switching batteries from time to time or other means, such as lasers. Stations using tri-axis antennas usually are not subjected to such problem due to the use of filters before the RF detector that reduces the interference from such sources.

– **Data storage and control unit**: Most of the stations count with some sort of data storage and control unit. For systems with tri-axis antennas, usually this is an industrial PC, since the tasks of controlling and processing are more sophisticated and the volume of data is much larger. For systems using isotropic probes, this section might be much simpler; in fact, most of modern portable meters already encompass memory and processing characteristics enough to handle the task of a transportable station. In both cases, is expected that such system should be able to store enough data to operate up to a week without communication or assistance.

– **Communication interface**: Transportable stations are intended to operate collecting long term measurements, but in several cases are also used to provide "real time" measurements for the general population. To perform this task, some sort of communication interface is necessary. Most of the time, due to the small volume of information to be transmitted, this can be easily performed using a public wireless network. To avoid interference to the measurements, the control unit usually perform measurement and data transmissions in sequence and at regular periods, for example, 6 min measuring + 1 min for data transmission.

– **Shelter**: Since transportable stations are intended to be installed on outside environments, they should be properly protected against humidity, heat, cold and vandalism.

On the Brazilian case, the stations were equipped also with a GPS receiver, allowing then to be installed and operated in a vehicle. Such station can be used to provide a quick overview over a large area, driving slowly through it, and can quickly provide information about specific spots, just packing the vehicle.

On any case, transportable stations, due to its larger size, usually does not eliminate the need for portable devices in other to properly characterize a site. Sometimes, portable equipments are also needed for an initial inspection and to determine the place where to install such stations.

5.6.4.4 Use of standard field strength measurement equipments

It is possible to use standard field strength measurement equipment to perform NIR measurements, including spectrum monitoring stations such as described on the other chapters of this handbook. Such use should be made with caution, since the expected strong EMF can damage more sensitive systems such as these and in any case one should consider the following points.

– Due to the larger antenna size, is not possible to make near field measurements with these equipments.

– Whenever strong fields are expected, one should use attenuators to keep the signal level from the antenna within the measurement instrument operational range.

– Measurement should be performed and computed considering all polarizations and directions in accordance with the different sources considered.

The time taken to perform NIR measurements in a complex environment with standard equipments can be from 4 to 8 times larger than the time to perform the same task with a tri-axis antenna, considering only the time needed to repeat the measurements on different directions and polarizations. This may be simplified by measuring only on the directions and polarizations effectively in use, but thus demanding greater care when preparing for the measurement and on the setup.

5.6.5 Measurement procedures

The following sections provide basic guidelines that can be used to perform measurements of the non-ionizing radiation levels.

5.6.5.1 Measurement site selection

Measurement location should be chosen to represent the highest levels of exposure to which a person might be subjected, considering the positions of neighbouring antennas. These locations can either be found by a "quick check" using measuring equipment, or, by calculation based on the theoretical propagation from neighbouring antennas.

Details on calculation procedures can be found on ITU-T Recommendations K.52 and K.70, which includes the software EMF-estimator, one of the applications that can be used to estimate the cumulative exposure in the vicinity of transmitting stations.

The theoretical approach usually can save a lot of time, allowing the selection of relevant areas prior to any field trip. It is also important to notice that this delimitation is critical for the quality of the results, since the combination of different transmitters with varying emission antenna patterns might turn difficult an evaluation based only on the technical expertise of the person conducting the tests.

Also is important to highlight that the need for measurement can be discarded in most public sites when considering that the results obtained by theoretical calculations are far below the threshold limit established, which increases the importance of availability and use of simulation tools to reduce the number of measurement tasks to be performed.

The empirical alternative, previously described as "quick check", also known as "stirring evaluation method", consists in using a probe performing fast scans to locate the probable point of maximum exposure, preferably within a delimited region.

By this method, the probe should be slowly moved through this area, avoiding close proximity to any metallic surface and also to the body of the operator, sweeping from a height of about 1.1 m up to 1.7 m from the floor. The speed of this sweep should be in accordance with the acquisition time of the sensor used. The places where the instantaneous value observed is higher should be selected for a detailed evaluation according to the procedures described on the following sections.

This method is important because the calculation methods will only limit the area of investigation to a few square meters, such as a rooftop or an apartment, but the person responsible for the tests should narrow this area to a specific point, where the instruments will be set up for measurement as described on the following sections.

5.6.5.2 Instruments positioning and averaging

Once chosen a specific location for the measurement, the RF radiation sensors or antennas should be mounted on a non conductive tripod in order to reduce the perturbation of the electromagnetic field. For the same reason staff should be retreat from the antenna during the measurements.

If the location chosen is within the expected near field region, both electric and magnetic fields should be measured, as discussed in § 5.6.3. This is done by using distinct probes or antennas. The electric component (E) of the electromagnetic field can be easily measured using suitable antennas, e.g. dipole, bi-conical, log-periodic etc. and the magnetic component (H) of the electromagnetic field is usually measured with loop antennas:

– To reduce the effects of non-uniform field distributions due to multi-path propagation, also is recommended to perform the spatial averaging of the measurements, e.g., 3 points at heights of 1.1 m 1.5 m and 1.7 m, as proposed as basic reference on ITU-T Recommendation K.61.

– The measurement time also has to be chosen according to the relevant exposure guidelines, e.g., 6 min in ICNIRP guidelines. One should be aware that although current guidelines establish a single time averaging period, this in fact should be adjusted in accordance with the signal characteristics and measurement equipment in use, for example, accommodating modulation and duty cycle of the carrier under consideration to the sweep time and detector in use.

5.6.5.3 Precautions on strong electric or magnetic fields

When strong electromagnetic fields have to be measured, safety measures against radiation exposure of the staff have to be taken. Field strength predictions, the use of radiation protection gauges and explicit work instructions may be appropriate tools to ensure safe working conditions.

Immunity of equipment, especially for receivers or spectrum analyzers, has to be checked, and if necessary, probes with a better immunity against strong signals have to be used.

One should also guarantee the immunity of essential support equipment, such as computers that are responsible for measurement automation, since the strong EMF may produce intermittent malfunction on these equipments that might interfere on the measurements.

5.6.5.4 Use of broadband probes and meters

This method should be applied when:

– only the total non-ionising radiation level is required, i.e., one does not need to know the independent contributions of each source operating on different frequencies, or there is only a single major source active on the vicinity to be considered;

– the total field strength expected and given by this method does not exceed the lowest guideline reference level for the investigated frequency range;

– the instrument noise floor is at least 10dB below the lowest guideline reference level for the investigated frequency range.

The probes must cover the full frequency range of interest, if necessary two or more probes may be required. If so, the final result will be calculated using the values provided by each probe according to the following formula:

$$E = \sqrt{\sum_{i=1}^{n} E_i^2} \quad \text{or} \quad H = \sqrt{\sum_{i=1}^{n} H_i^2}$$

where n is the number of probes and E_i or H_i are the values obtained by the individual probes. Whenever using multiple broadband probes, the result may be overestimated if the frequency ranges of the probes overlap.

If there is only a single relevant source, i.e. a short wave transmitter on a remote location, frequency specific corrections based on calibration factors for the probe can be applied in order to improve the quality of the results.

If the results obtained are close to the lowest applicable guideline level (within the range of measurement uncertainty) the frequency selective evaluation should be performed. This is especially critical for signals with complex modulation schemes, where broadband probes equipped with Schottky diode detectors might provide incorrect figures, such as previously discussed.

5.6.5.5 General considerations for frequency selective evaluation

The frequency selective evaluation should be applied when non-ionising radiation levels are required by frequency within the scanned band.

A frequency selective evaluation is best carried out using a lightweight battery powered receiver or spectrum analyzer.

As the receivers or analyzers sometimes have to be operated in strong electromagnetic fields, good dynamic range and inter-modulation performance are essential for reliable and repeatable results.

Lightweight, robust antennas and high quality feeder cables should be used. Preferred types of antennas are:

– Selective 3-axis probe.
– Magnetic loop for HF.
– Broadband dipole antenna or (encapsulated) log periodic antenna.
– Bi-conical antenna.
– Directional antennas (usable when there is one main contribution and the levels of other emissions negligible).

For lower frequencies, taking into account the significant wavelength, electrically small antennas should be chosen.

The minimum distance between the antenna and any obstacle in the direction of the transmitter (e. g. wall or ground elevation for example) must be at least 1 λ. Measurements of frequencies lower than 600 MHz with a 50 cm height above ground-level should use broad band, electrically small magnetic or electric antennas rather than a dipole. Personnel should retreat from the antenna during measurements, which should be mounted on non conductive tripods in order not to perturb the electromagnetic field.

Software control of the receiver/analyzer is an essential feature due to the vast amount of data to be collected during the survey. The software should also allow for the correction of antenna factors and cable loss over the frequency range. The use of software automation also allows the use of different settings in accordance with the various services being monitored, and this alternative should always be preferred.

5.6.5.6 General evaluation between 9 kHz and 6 GHz

Throughout the spectrum there is a mixture of wide/narrow, analogue/digital and continuous/discontinuous sources with widely different signal characteristics. Hence the measurement bandwidth will be a compromise. At this section we present a generic configuration that can be used between 9 kHz and 6 GHz whenever specific service configurations are not applicable, relevant or unknown and only a general evaluation is required.

The settings described below are suitable for a general evaluation or for a quick overview of the spectrum depending on the detector used. A peak detector with max hold is useful to find all of the transmission sources but in this case, the calculated final total exposure quotient usually is over estimated. For general evaluation of the total human exposure quotient, an RMS detector should be used for accurate measurements.

In fact, whenever possible, is preferable that the configuration parameters should be adjusted in accordance with the expected emissions, i.e., using bandwidth and sweep times matching services operating in each frequency sub-bands.

Some examples of configurations for most common services are described on the subsequent sections.

We consider important to highlight that the proper use of service specific configurations might not only provide a more accurate result, but also a more time efficient operation, since the number of channels are usually reduced, for example, considering only the control channels for mobile services or using a channel power measurement for broadband systems.

Having this in mind, the most advisable approach for an initial evaluation of an unknown site would be to combine sweeps with service specific configuration and more general evaluation sweeps as defined below.

With this approach, more reliable results could be obtained in bands where there is greater concern about NIR levels, such as those assigned for broadcast and personal communication services.

On other bands, where the complexity of such detailed configurations is unjustified due to the reasons already described, representative results could be obtained.

One should try by to achieve an acceptable compromise between the measurement quality and a full spectrum sweep.

The full spectrum sweep might be of interest in order to detect emissions, such as from unauthorized stations and/or from industrial, scientific, and medical (ISM) devices.

Settings of receivers and spectrum analyzers

– For receivers the following bandwidth/step sizes have been proven adequate:

9 kHz-30 MHz	BW = 9 or 10 kHz	with a step size of 10 kHz
30 MHz-3 GHz	BW = 100 kHz	with a step size of 100 kHz
3 GHz-6 GHz	BW = 1 MHz	with a step size of 1 MHz

Receiver dwell time: ≥ 0,1 s

– For spectrum analyzers the following bandwidth/sweep settings can be used:

9 kHz-30 MHz	BW = 10 kHz	with a sweep time of 50-100 ms
30 MHz-300 MHz	BW = 100 kHz	with a sweep time of 100 ms
300 MHz-3 GHz	BW = 100 kHz	with a sweep time of 700 ms-1 s
3 GHz-6 GHz	BW = 1 MHz	with a sweep time of 700 ms-1 s

Max-hold and peak detector for quick overview or RMS detector for general evaluation as discussed above.

– The threshold level is chosen 40 dB below the reference level. If no emission exceeds the threshold level within a frequency band the 2 highest emissions may be reported as reference.

– Antenna Polarization: Measurements shall be made with the measurement antenna in such a way that field strength components of all spatial directions are detected.

5.6.5.7 Signals above 6 GHz

Normally directive antennas are used, e.g., horns, dishes and log-periodic antennas. The measurements are done according to the following steps:

– Set the centre frequency on each channel of the emission with a resolution equal (if possible, otherwise larger) to the bandwidth of the channel.

– Select RMS detector.

– The antenna should point to the transmitter (maximum signal) with the appropriate polarization. For practical reasons possible reflections are neglected.

5.6.5.8 Radar and pulsed emissions

For this type of signals, the energy is carried in short bursts. The pulse is usually short compared to the interval between pulses.

There is a great diversity of radar, in particular for aeronautical applications. These applications have very varied characteristics, typically in frequency between 100 MHz and 95 GHz and in peak power between 1 W and 50 MW.

There may be additional limits regarding the peak power which will be relevant to radar systems. For example the peak power should not exceed the reference level by a factor of 30 dB according to EU 1999/519/EC and is not directly related to the pulse characteristics of the radar.

Thus, the values to be assessed for the electric and magnetic field strength are the peak values and r.m.s values of the pulsed field.

For the assessment of the peak value, the procedure should be in accordance with the following steps:

– Choose a sufficiently broadband filter to take measurements over one duration lower than the impulse. In the case of an unmodulated impulse, a filter bandwidth of $4/\tau$, with τ being the duration of the impulse, is sufficient to capture 99% of the power of the signal.

– Select positive peak detection mode.

– Select max hold mode for 1 or several rotations of the radar until the signal is stable.

– Select zero span centred on the frequency of the emission.

For the assessment of the r.m.s field-strength it is necessary either to know the temporal characteristics of the signal and to derive the average value from the peak value or to measure the average of the signal in RMS mode.

Because of the movement of the beam in azimuth and elevation special measures have to be taken in order to measure the signal properly.

5.6.5.9 Discontinuous signals

If the technical parameters of the signal are unknown, the measurements are done according to the following steps:

– Set the centre frequency on each channel of the emission with a resolution equal (if possible, otherwise larger) to the bandwidth of the channel.

– Check both the r.m.s and the peak values and take into consideration the most critical one in accordance with Note 4 on Table 5.6-1.

5.6.5.10 GSM

Although the goal of the EMF measurements is usually to find the actual exposure values, sometimes the possible maximums should be extrapolated in the vicinity of the base stations.

Transmissions of these systems consist of 1 permanent control, e.g. the BCCH channel in GSM 900/1 800 systems, and (n-1) traffic channels where n is the total numbers of channels of the base station. Hence the total power depends on the traffic load.

The following procedure can be used to assess the maximum possible traffic and thus the maximum power:

– Identify the permanent control channel.

– Set the centre frequency on the permanent control channel with a resolution equal (if possible, otherwise larger) to the bandwidth of the channel.

– Select peak detector.

– Select max hold mode.

– Measure $E_{control\ channel}$.

– Determine the number of channels of the base station. This may be difficult in case of frequency hopping.

– The extrapolation to the maximum traffic is then calculated by:

$$E_{max} = E_{control\ channel} \times \sqrt{n_{transmitters}}$$

– If the transmitting channels of a base station are operated at different power levels, the following expression should be used:

$$E_{max} = E_{control\ channel} \times \sqrt{\frac{P_{total}}{P_{control-channel}}}$$

where:

P_{total}: maximum possible power of the base station.

5.6.5.11 Wide-band emissions (analogue/digital TV; digital networks...)

The measurement equipment is the same as used for general measurement procedures. Some types of emissions, notably pulsed signals and UWB emissions, require the use of a time domain analyzer to pre-analyze the signals and to adapt the measurement settings accordingly.

For these types of emissions, it could be difficult to get a resolution equal to the bandwidth of the emissions, so the procedure should be according to the following steps: select a lower resolution filter and carry out a cumulative calculation taking into account the shape of the resolution filter.

This type of process is known as the “Channel Power” mode, and many spectrum analyzers will provide this feature as a standard or optional measurement tool.

5.6.5.12 CDMA systems (UMTS...)

The extrapolation can also be done for UMTS networks or other systems using CDMA technology to determine the situation at maximum traffic. However, the methodology is different compared to that used for GSM since is necessary to measure the power in the code domain.

Taking UMTS as an example, the first step is to identify a particular common channel, the "P-CPICH" (common pilot channel) and then to measure the power of this channel PP-CPICH. The UMTS maximum power associated with this channel will be deduced from PP-CPICH using a coefficient shown below. The principle of measurement and calculation is as follows:

– The centre frequencies $freq_0$ of all UMTS emissions are determined with a spectrum analyzer and recorded. The power P-CIPCHi of the various detected channels "CPICHi" is measured by an UMTS scanner. Then the power for all the CPICHi channels is summed up.

$$P_{P-CPICH}(freq_0) = \sum_{i=1}^{n} P_{P-CPICH_i}(freq_0)$$

The equivalent $E_{P\text{-}CPICH\ (freq0)}$ will be calculated starting from the value of P-CPICH ($freq_0$) by integrating the antenna factor and the cable losses. The following formula makes it possible to calculate the E field for the maximum traffic at the frequency $freq_0$ by using the $R_{P\text{-}CPICH}$ coefficient.

$$E_{max}(freq_0) = E_{P-CPICH}(freq_0) \times \sqrt{R_{P-CPICH}}$$

with:

$$R_{P-CPICH} = \frac{P_{max}}{P_{P-CPICH}}$$

Concerning the UMTS scanner, it should be noted that there is no calibration method internationally recognized because of the lack of reference on software-defined code (like CPICH).

To carry out reliable measurement, a qualification of the equipment may be required to ensure that there is no problem on results provided by UMTS scanner.

A way to perform such qualification could be to use at least two UMTS signal generators and to check the following characteristics of the scanner:

– *Frequency response:*

  By using a reference signal at 2 different frequencies in the UMTS band with the same P-CPICH power and the same total emitted power in the 5 MHz block.

  The difference between the two P-CPICH measured power and the two channel measured power should be minimized.

– *Linearity:*

  By using a reference signal at a fixed frequency, with a fixed ratio between P-CPICH power over total channel power and with different total emitted power in the 5 MHz block.

  The difference between the measured power and emitted power should be less than 2 dB.

– *Traffic:*

  By using a reference signal at a fixed frequency, with a fixed total emitted power in the 5 MHz block and different ratio between P-CPICH power over total channel power.

  The difference of the measured ratio and the ratio of the emitted signal should be minimized.

  The checking of these three parameters should be performed with the two signal generators and the difference of the result (with the two signal generators) should be minimized.

Obviously all uncertainties and calibration factors of the measurement chain must be known and taken into account in the calculation.

5.6.6 Uncertainty

Uncertainty for NIR measurement can be divided in two parts: uncertainty due to the environment and uncertainty due to the instruments.

Uncertainty due to the environment: there are uncertainties inherent to on site measurement, due to various parameters (fading, multipath….).

This value can be reduced with the spatial averaging method as described in § 5.6.5.2.

One can consider that the uncertainty due to the environment is reduced to 3 dB with 3 measurement points and 2 dB with 6 points.

More detailed information about the application of time and space averaging can be found on ITU-T Recommendation K.61.

Uncertainty due to the equipment will be intrinsic each instrument and as such, should be provided by the manufacturer.

Care should be taken whenever buying such equipment that all necessary information for the computation of the uncertainty is provided, including calibration certificates and uncertainty propagation functions that allows the proper use of the information provided on such certificate to determine the final measurement result uncertainty.

It is preferable to maintain the overall uncertainty below an acceptable level.

As an example, the European standard EN 50 492 recommends a value of 4 dB as the maximum uncertainty.

5.6.7 Reporting

The measurement results for each location should be documented on a report, preferably using tables. The corresponding values for H (or E) and S can be calculated according to § 5.6.3 if not measured on the field.

Measured and calculated quantities have to be compared to the lowest reference level of the applicable legal provisions.

If the quantities of measured or calculated values are higher, this should be highlighted on the report and applicable provisions should be taken in accordance with the regulations in force.

Is expected that a comprehensive measurement report should also contain the following information:

– purpose and objectives of the measurements;
– date, start and stop time;
– geographic co-ordinates, altitudes above ground level, and particular characteristics of the measurement sites;
– list of identified transmitters;
– temperature;
– the used equipment and its serial numbers;
– uncertainty of the measurements.

Additionally, in order to improve the intelligibility of the report is desirable to use graphical representation of the results in the form of maps, diagrams and photos.

These may present the measurement results in its locations and also the relative position of main emitters and areas of concern, such as schools, hospitals and houses.

Finally the report compares the measured values with the applicable total exposure quotients and draws a conclusion on the conformity of the RF exposure with respect to the limits in the relevant regulations.

References

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GALLEE, F.; CHAINON, S.; LATTARD, H.; GORON, E.; TOUTAIN Y. [October, 2007] Development of an isotropic sensor 2 GHz-6 GHz. Proceedings of the 37th European Microwave Conference Munich, Germany.

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RANDA, J.; KANDA, M. [January, 1985] Multiple-Source, Multiple-Frequency Error of an Electric Field Meter; IEEE Transactions On Antennas And Propagation, Vol. Ap-33, No. 1.

ITU-R Recommendations

NOTE – In every case the latest edition of the Recommendation is encouraged to be used.

Recommendation ITU-R BS.1698 – Evaluating fields from terrestrial broadcasting transmitting systems operating in any frequency band for assessing exposure to non-ionizing radiation.

ITU-T Recommendations

ITU-T Recommendation K.52 – Guidance on complying with limits for human exposure to electromagnetic fields.

ITU-T Recommendation K.61 – Guidance on measurement and numerical prediction of electromagnetic fields for compliance with human exposure limits for telecommunication installations.

ITU-T Recommendation K.70 – Mitigation techniques to limit human exposure to EMFs in the vicinity of radiocommunication stations.

5.7 Radio noise measurements

5.7.1 Introduction and background

The *C*/*I* is a key parameter when planning radio networks and assessing their performance. In the absence of additional interferers such as co-channel emissions, the interference is basically the noise floor. In this case, *C*/*I* becomes equal to the *S*/*N*. In many radio applications and frequency ranges, the external noise due to unwanted emissions from electrical and electronic devices is higher than the noise floor of the receiving equipment.

Knowledge of the level of this external noise therefore determines the coverage area of a transmitter or network with a given radiated power, or the necessary radiated power when a given area should be covered.

Network planning is usually based on radio noise figures published in Recommendation ITU-R P.372, but these values are derived from measurements made in the 1970s and may not be applicable today.

Radio noise measurements may therefore be necessary for the following reasons:

– To provide up-to date values for the noise level in order to allow realistic network planning.

– To assess the system performance of existing networks in different surroundings or at specific locations.

– To update the old values used for network planning in Recommendation ITU-R P.372.

Measuring radio noise, however, can be a very difficult task, and the level may not be the only parameter necessary to fully characterize it. This subchapter provides necessary background information on the complex issue of radio noise measurements, whereas the actual measurement setup, required equipment, the measurement procedure, evaluation and presentation of the results is described in all detail in Recommendation ITU-R SM.1753.

5.7.2 Sources of radio noise

According to Recommendation ITU-R P.372 the three main sources of radio noise are atmospheric, galactic and man-made noise (MMN). While the first two are well known and do not change significantly over a long time, the MMN is often dominant and may change with the increasing density of electrical and electronic devices, so this is the part that is mainly of interest when performing radio noise measurements.

TABLE 5.7-1

Importance of radio noise sources per frequency range

Noise source	Frequency range of importance
Atmospheric noise	below 100 kHz
Galactic noise	3 MHz to 100 MHz
Man-made noise	9 kHz to 1 GHz

Measuring galactic noise usually requires an antenna directed towards the sky. Most communication receivers, however, receive their main energy from the vicinity of the Earth's surface. When assessing the impact of radio noise to communication services, antennas using the preferred direction of those services should be used because then the main source of measured radio noise will be man-made noise.

5.7.3 Components of radio noise

Using the definition given in Recommendation ITU-R P.372, radio noise is the sum of emissions from multiple sources that do not originate from radio communication transmitters. If at a given measurement location there is no dominance of single noise sources, the characteristic of the radio noise has a normal amplitude distribution and can be regarded as white Gaussian noise (WGN).

However, with the high density of noise emitting devices especially found in cities and residential areas, it is virtually impossible to find a location that is not at least temporarily dominated by noise or emissions from single sources.

These sources often emit impulses or single carriers. Since radiocommunication equipment has to operate in such an environment, it is unrealistic to exclude these components from radio noise measurements.

SCN is only detected as such when it comes from a single source nearby the measurement location. Multiple sources emitting single carriers quickly add up to a noise-like spectrum as their numbers increase. Recommendation ITU-R P.372 defines radio noise as the *aggregated* unintended radiation from various sources and specifically excludes emissions from single, identifiable sources.

It is therefore necessary to select measurement locations and frequencies/ranges that are not dominated by emissions from these single sources which make further consideration of SCN unnecessary in the context of MMN measurements.

TABLE 5.7-2

Components of radio noise

Noise component	Properties	Sources (examples)
White Gaussian Noise (WGN)	Uncorrelated electromagnetic vectors. Bandwidth equal to or greater than receiver bandwidth. Spectral power level increases linear with bandwidth.	Computers, power line, ultra wideband devices, wired computer networks, galactic noise.
Impulse noise (IN)	Correlated electromagnetic vectors. Bandwidth greater than receiver bandwidth. Spectral power level rises with square of bandwidth.	Ignition sparks, lightning (atmospheric noise), gas lamp starters, computers.
Single Carrier Noise (SCN)	One or more distinct spectral lines. Bandwidth smaller than receiver bandwidth. Spectral power level independent of bandwidth.	Wired computer networks, computers, switched mode power supplies.

5.7.4 Key parameters

While the WGN component is sufficiently characterized by the RMS level value, this is much more difficult for the IN. Modern digital communication services almost always apply error correction, making it more immune especially against impulse noise. However, when certain pulse lengths and repetition ratios are reached, IN can significantly interfere with the operation of such a service. It is therefore desirable measure radio noise in a way that gives not only the level of IN but also information about the statistical distribution of pulse parameters like pulse duration and repetition frequency.

5.7.5 Measurement types

Determining the true MMN level and characteristics including IN for all frequency ranges can be a very time consuming and complex measurement task. However, when only the WGN component is of interest, or only certain frequency ranges have to be investigated, the measurements can be simplified significantly without loosing important information or reducing accuracy. For this reason, the following three different types are possible when performing radio noise measurements:

Type A: WGN only. This methodology delivers only WGN levels, disregarding IN. It only requires measurements of the remaining RMS level on a "free" frequency. Evaluation of data is simplified. Standard monitoring equipment can be used in most cases.

Type B: WGN and IN. This methodology delivers WGN levels and characteristics of the important IN parameters of radio noise. It requires measurement equipment capable of sampling the momentary signal level at a very fast speed. Data evaluation is more complex and requires extensive post- processing, most of which can only be performed by computers.

Type C: WGN, IN and separation of MMN. In addition to WGN level and IN characteristics, this methodology separates atmospheric impulse noise from MMN to a large extent which may be important in the HF frequency range. The measurement process is equal to B), but it has to be performed at two different locations and the equipment of both locations has to be exactly time synchronized.

5.7.6 Measurement locations and frequencies

Even on one frequency the radio noise level, especially when dominated by MMN, varies depending on things like time, location and propagation conditions. A statistically relevant figure for the noise level can only be derived by averaging results from multiple measurements at different but similar locations. Recommendation ITU-R P.372 defines four different location categories: City, residential, rural and quiet rural. Only measurement results taken from locations of the same category should be combined.

The practical way to select a proper frequency (band) is to first find a possible candidate band by scanning the desired frequency range and identify the frequency (band) with the lowest level. The usability of this frequency (band) can be verified by applying the singular value decomposition (SVD) process or with the help of an Amplitude Probability Distribution Plot (APD).

Both methods are described in detail in Recommendation ITU-R SM.1753. If they reveal that the scan contains mostly WGN, the measurement can be used. If not, an alternative frequency (band) has to be selected.

Because of the different propagation conditions, different typical bandwidths of communication receivers and different measurement antennas to be used, radio noise measurements may be made separately in the three main frequency ranges of interest, namely:

– LF to HF (9 kHz to 30 MHz).

– VHF (30 MHz to 300 MHz).

– UHF and above (more than 300 MHz).

Recommendation ITU-R SM.1753 provides more detailed information on the selection of measurement locations and frequency (bands).

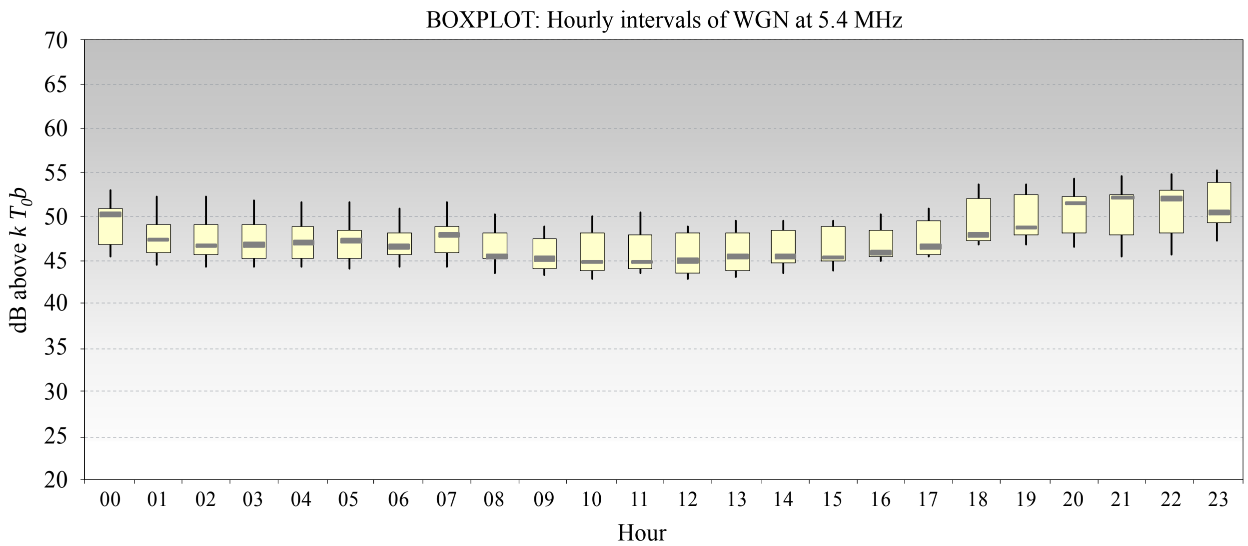
5.7.7 Examples of result presentation

As mentioned before, MMN level is determined as a statistical value that can also change with time.

A typical presentation of the WGN would be a so-called “box-plot” that indicates the highest, lowest and median values, together with upper 75 and lower 25% of the values like in Fig. 5.7-1.

FIGURE 5.7-1

Box plot example

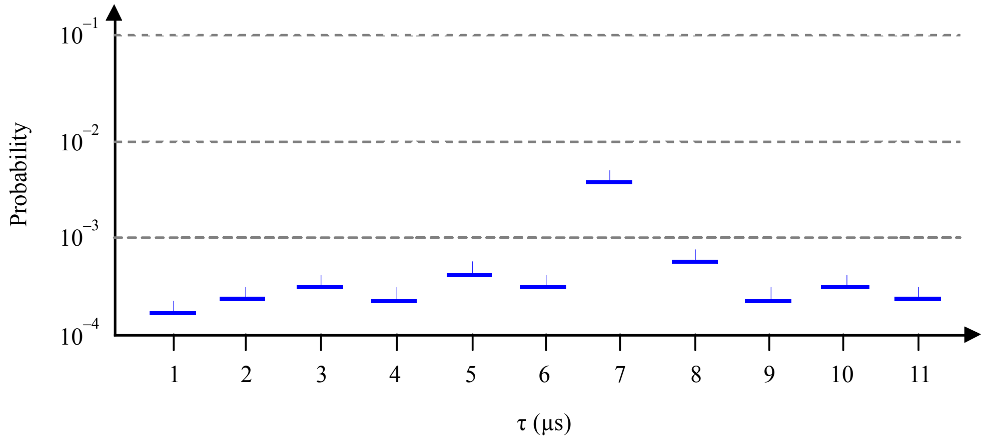


Spectrum-5.7-01

Impulse noise parameters will be presented as a probability distribution like in Fig. 5.7-2 that illustrates the pulse duration.

FIGURE 5.7-2

Example of impulse/burst length distribution



Spectrum-5.7-02

5.7.8 ITU radio noise databank

Radio noise levels and statistics are most valuable when a large number of registrations can be compiled. For this purpose, the ITU has established a databank where all administrations can access the available measurement data. Radio noise data is contained in Table C9-1 of the databank. Search and filter functions on various fields are provided in order to retrieve only data of interest.

The databank is available at: http://www.itu.int/ITU-R/go/sg3-dtbank-dbsg3/en.

Information on how to use and get access to the databank is provided in a user manual that is downloadable from the site above.

In its first stage the databank contains only WGN levels. Administrations performing radio noise measurements are encouraged to provide their data in order to make it accessible for all interested parties.

References

ITU-R Recommendations and Reports

NOTE – In every case the latest edition of the Recommendation should be used.

Recommendation ITU-R P.372 – Radio noise.

Recommendation ITU-R SM.1753 – Method for measurements of radio noise.

Report ITU-R P.2089 – The analysis of radio noise data.

CHAPTER 6

FUNDAMENTALS AND SUPPORTING TOOLS

Page

6.1 Global positioning by satellite

6.1.1 General

6.1.1.1 Purpose

The radionavigation-satellite service (RNSS) systems are essential for monitoring purposes such as:

Positioning:

– **Licensing**: verification of the position of the stations as stated in the licence, determination of the position of illicit stations.

– **Mobile DF systems**: predict of the exact position of mobile DF systems.

– **Mobile field strength measurements**: coverage of FM broadcasting stations; verifications of maximum field strength for safety reasons.

– **Measurement of radiation patterns**: helicopter based radiation pattern measurement.

Timing and frequency standard:

– **Time:** synchronizing of DF networks in case of very short duration signals.

– **Frequency:** synchronizing of receivers.

The RNSS systems have also capability to predict velocity and direction but not all of them are so accurate for the monitoring requirements.

These services provide positioning globally, continuously and under all weather conditions to users at or near the surface of the Earth. Receivers operate passively, thus allowing an unlimited number of simultaneous users. The RNSS systems have features, which can deny accurate service to unauthorized users.

The ranging codes broadcast by the satellites enable the receiver to measure the transit time of the signals and thereby determine the range between a satellite and the user. Four satellites are normally required to be simultaneously "in view" of the receiver for three-dimensional (3-D) positioning purposes.

Recommendation ITU-R TF.767 recommends the use of GPS and GLONASS in those applications requiring global coverage and accuracy levels of about 10-100 ns. GPS and GLONASS common-view are considered to determine 1 m coordinates for the receiver antennas. Since the receiver is provided with a highly accurate integrated rubidium frequency standard, it may serve also as the frequency standard for all of the monitoring equipment.

In mobile monitoring applications, the use of the RNSS systems have become the default standard where accuracies within 20 m are sufficient. Once initiated, the system can provide updated positioning information approximately every 2 s (this period of time can be adjusted upon user's preference). In a mobile vehicle, this typically provides enough accuracy to determine which side of the street you are on and is usually sufficient for performing coverage measurements of large cells or broadcast systems. Other commercial satellite navigation systems are being developed as part of new mobile-satellite services but the GPS system is the most widely used today.

6.1.1.2 Systems available

The following RNSS systems are available at present:

NAVSTAR GPS American system originally designed for military use also available for civilian applications, allows user better accuracies with differential GPS applications.

GLONASS Russian system, which can be, used solely or with NAVSTAR+GPS for better accuracy.

6.1.1.3 Equipment available

Standard, commercial RNSS systems receivers can be expected to provide position solutions accurate to within a few tens of metres as a worst case; time accuracy is typically within ±250 ns. Measuring an additional satellite and second ground position will improve accuracy through different readings to within cm. Receivers can easily be integrated into a mobile system. They are available as stand-alone modules, as battery-operated hand-held receivers, or as plug-in cards for popular computer busses. Portable antennas are extremely compact and rugged, and can be mounted on vehicle roofs with a little effort.

Many commercial receivers provide additional outputs derived from the satellite data, including elevation, velocity, and acceleration. Options for waypoint navigation are also available from several manufacturers. For use in mobile systems, which include a computer workstation, stand-alone receivers are equipped with a suitable data interface to the computer. GPS information can be integrated with computerized map packages (see § 6.2) to provide real-time display of a vehicle's position while the vehicle is in motion.

Accuracy and signal capture can be problems when using GPS in mobile applications. Much higher accuracy positioning is required when measuring micro-cells in building areas and areas for pedestrian traffic. Signal capture from the satellites is problematic in urban areas, inside buildings, and other areas where substantial obstructions may obscure reception. In these cases it becomes necessary to use an alternative positioning technique.

6.1.1.4 Improvement in accuracy

Accuracy of RNSS systems can be improved by combining systems such as altimeters, inertial navigation systems as well as techniques provided by the system itself (differential GPS (DGPS) for NAVSTAR, GPS+GLONASS for GLONASS System, etc.).

6.1.2 NAVSTAR GPS

6.1.2.1 System description

The 24 GPS satellites orbiting at very high altitude provide both position and time information to users worldwide through synchronized signals. Measuring those signals from at least three different satellites enables the position of the receiving Earth site. The constellation provides the user with eight satellites visible from any point on the Earth.

Navigation in three dimensions is the primary function of GPS. Precise positioning is possible using GPS receivers at reference locations providing corrections (DGPS) and relative positioning data for remote receivers. Time and frequency dissemination, based on the precise clocks on board of satellites and controlled by the monitor stations, is another use for GPS. Telecommunications facilities and laboratory standards can be set to precise time signals or controlled to accurate frequencies by special purpose GPS receivers.

6.1.2.2 System performance

Two levels of navigation are provided by the GPS: the precise positioning service (PPS) and the standard positioning service (SPS). Civil users worldwide use the GPS without charge or restrictions (see Table 6.1-1).

Most receivers are capable of receiving and using the SPS signal. The SPS accuracy was intentionally degraded formerly by the DoD (US Department of Defence) by the use of Selective Availability (SA). But SA ended after the end of 1 May 2000 and the United States of America has no intention to ever use SA again.

TABLE 6.1-1

GPS accuracies

Predictable accuracies (without SA)	Standard positioning service (SPS)
Horizontal Accuracy (95%)	22 m
Vertical Accuracy (95%)	33 m
Time Accuracy (95% relative to UTC)	200 ns

Receiver manufacturers may use other accuracy measures (RMS, Circular Error Probable, Spherical Error Probable, with/or without SA) than mentioned here. As a result of this, some receiver specification sheets make those receivers appear more accurate than those specified by more responsible vendors using more conservative error measures.

6.1.3 GLONASS

6.1.3.1 System overview

A completely deployed GLONASS constellation is composed of 24 satellites in three orbital planes. GLONASS satellites provide two types of navigation signals: high accuracy signal and standard accuracy signal. The high accuracy signal is primarily intended for authorized users only. The high accuracy signals are transmitted in both L1 and L2 sub-bands to ensure ionosphere correction. The access to standard accuracy signals on frequency sub-band L1 is available to all users on a free-of-charge basis. The standard accuracy navigation signal as given in Table 6.1-2, but can be significantly improved using differential navigation mode and/or the additional special measurement techniques.

TABLE 6.1-2

Predictable accuracies of GLONASS

Predictable accuracies	GLONASS
Horizontal Accuracy (95%)	28 m
Vertical Accuracy (95%)	60 m
Time Accuracy (95%)	700 ns
Velocity Vector	15 cm/s

6.1.3.2 GLONASS and GPS combined use features

The user segment of GPS and GLONASS systems consists of antennas and receivers with processing features performing a signal reception and navigation solution for providing the users with the information about location, velocity, and accurate time. The satellites transmit a pseudo-random synchronizing signal and a navigational message, which contains parameters of orbits for each satellite (ephemeris). The receiver uses ephemeris data to determine the position of a satellite. Acquiring accurate positions of four satellites the receiver can determine its own 3D-position and time.

Modern digital signal processing methods make it possible to process the signals of GPS and GLONASS using the same receiver architecture despite the differences pointed out in Table 6.1-3. GPS and GLONASS frequency ranges are close, thus allowing the use of a combined antenna and common input preamplifier in the user equipment. Optimal receiver design and appropriate signal-processing software should allow the development of a combined receiver at a price only slightly higher than that of a GPS or GLONASS receiver. The differences in the ephemeris information and almanac representation of GPS and GLONASS do not pose an obstacle for user equipment operation. Navigation processor software provides appropriate corrections and permits the processing of both data flows.

User equipment, the most flexible part of the entire system, continuously improves. At present, most existing receivers are multi-channel, and are capable of simultaneously tracking pseudo-ranges and pseudo-velocities for a number of visible satellites. Thus they provide maximum accuracy and integrity of navigation observations.

Technological progress in the field of digital signal processing provides the means for a very high degree of integration that already permits a discrete conversion and digital processing of the satellite’s signals at a stage near the front-end input.

Combined application of GLONASS and GPS provides significant advantages versus stand-alone use any of these systems:

Enhanced Availability: For operations in obstructed environments, like mountainous terrain or urban “canyons”, the doubling of the number of available satellites often means a valid solution versus no solution for GPS-or GLONASS-only receivers.

Improved Accuracy: The increased number of satellites will usually lead to better user-to-satellite geometry.

Faster Cold Start: When no position or time information is assumed by the receiver, the probability of acquiring a satellite is increased when the number of satellites in view is increased, thereby reducing acquisition time.

Robust System Integrity: The ability to detect and isolate a malfunctioning satellite is greatly enhanced by the increased number of satellite in view. Also, reliance on two independent systems provides an added level of integrity against a system-wide malfunction.

On the market, there is equipment available using the signals of navigation satellites of the GLONASS and GPS systems simultaneously in topological and geodetic survey on the land, at the sea and in the air.

This equipment when operating in a differential mode guarantees the precision of geodetic fixing for earth stations 1-3 cm + 10^{-6} L (L = 1 000 km), where L is the distance between geodetic stations, cars, aircrafts, vessels.

6.1.3.3 Characteristics of GPS and GLONASS

The characteristics of GPS and GLONASS are given in Table 6.1-3.

TABLE 6.1-3

Comparison of GPS, GLONASS and GPS + GLONASS

Parameter	GLONASS	GPS
Ephemeris information presentation method	Earth Centred Fixed coordinates and its derivatives of first and second order	The modified Kepler elements of orbit
Geodesic coordinate system	PZ-90	WGS-84
Time corrections relative to the (UTC)	UTC (SU)	UTC (USNO)
Number of satellites (fully operational)	24	21 + 3 spares
Number of orbital planes	3	6
Orbital inclination	64.8°	55°
Orbit altitude	19 100 km	20 180 km
Orbital period	11 h 15 min	12 h
Satellite signal division method	FDMA	CDMA
Frequency band L1 (MHz)	1 601.489-1 609.8235 (1 597.5 515-1 605.886)[(1)]	1 575.42 ± 1.023
Frequency band L2 (MHz)	1 245.489-1 252.1985 (1 242.4265-1 249.136)[(1)]	1 227.6 ± 1.023
Duration of almanac transmission	2.5 min	12.5 min
Super frame capacity	7 500 bits (5 frames)	37 500 bits (25 frames)
Frame length	30 s	30 s
Synchro-code repetition period	2 s	6 s
Cross-talk between neighboring channels	–48 dB	–21 dB
C/A-code chip rate	0.511 MHz	1.023 MHz
C/A-code length (symbols)	511	1 023
C/A-code type	PRN-sequence of max. range	Gold codes

TABLE 6.1-3 (*end*)

Parameter	GLONASS	GPS
Modulation	BPSK	BPSK
Navigational data rate	50 bit/s	50 bit/s

(1) Up to and beyond (in brackets) 2005.

Accuracy Parameters (standards, 95%)	GLONASS	GPS(1)	GPS + GLONASS
Horizontal	28 m	22 m	20 m
Vertical	40 m	33 m	30 m
Velocity	15 cm/c	0.5 m/c	5 cm/c
Timing	0.7 µs	0.20 µs	0.25 µs

(1) GPS figures based on SPS without SA.

Bibliography

GLONASS ICD [1998] Global Navigation Satellite System GLONASS. Interface Control Document (4th edition), Moscow.

ICD-GPS-200C [12 April, 2000] Global Positioning System. Interface Control Document.

Signal specification [2 June, 1995] Global Positioning System, Standard Positioning Service, 2nd Edition.

ITU-R Recommendations

NOTE – In every case, the latest edition of the Recommendation is encouraged to be used.

Recommendation ITU-R TF.767 – Use of global navigation satellite system for high-accuracy time transfer.

6.2 Maps

6.2.1 Use of maps for monitoring stations

These days, digital Geographic Information Systems (GIS) are one of the key components of computer-based automated spectrum management and spectrum monitoring systems. Their utilization is helpful in monitoring systems, which operate either in stand-alone mode or as part of complete spectrum management systems.

The digital GIS is very useful for several reasons: most obviously, the GIS provides a quick and detailed overview of the geographical location of important objects for monitoring, such as sites of licensed (and sometimes unlicensed transmitters) of the spectrum management database, sites of fixed monitoring stations, locations of mobile measurements, estimated locations of unknown transmitting stations from direction finder measurements, and more besides. Depending on the requirements, these objects can be displayed on different maps. A useful map can be a political map to check if the object is located in a certain district or country, or a road map to verify if the measurements were taken along a certain road or in the desired city.

While displaying these objects on digital maps, the monitoring system can further provide fast and convenient access to their properties, including the most important technical and administrative data when connected to the central database of the spectrum management system.

Another crucial component of computer-based automated spectrum management and spectrum monitoring systems is the calculation of the predicted field strength of transmitting stations based on common wave propagation models. More accurate propagation models require access to different types of geographical data including topographic data, land-use data, and sometimes also to other types of data to ensure proper calculation. This geographical data is usually organized as different map layers within the digital GIS.

Therefore, digital mapping is the essential basis of most wave propagation calculations (see § 6.4). But creation of terrain data and precise land use is frequently a costly task.

Although these calculations only provide an approximation to the set of real emission scenarios over a long time, they can be used for coverage simulations, the identification and the analysis of measurements. Accurate field strength measurements and emitter location are most important to check if emissions of transmitting stations are in compliance with their licence.

Wave propagation calculations strongly depend on the quality of their input data. In all calculations, one significant parameter is the proper resolution of the map layer used. The main relationship is that between the utilized layer resolution and the considered transmitting frequency and power. In general, the resolution used is higher when the frequency is increased and the power decreased. The necessary resolution is relative to the range of emission, as it is lower the resolution should be better; it also depends on other parameters such as the radio service, the elevation of the transmitting and receiving antennas and the geographical area under investigation. For instance, in a mountainous area, the calculations may be based on high-resolution data whereas lower-resolution is normally sufficient in flat terrain. Resolution to be used is also affected by cost and availability of digital data and the computer programs to use these data.

6.2.2 Sources of digital data

Digital topographic data is available in many formats from different sources – most frequently from government agencies of the different administrations. A single unified digital topographic database for most of the world is available in [GLOBE, 2001]. Program GLOBE is a file of digital topographic data covering most of the world.

The most common sources for the generation of digital geographic data are conventional paper maps, satellite images, and aerial photography. "Laser Scanning" allow more automatic generation of digital terrain model (DTM). DTM's of 100 m or 200 m and clutter data derived from conventional paper maps are available almost all over the world. Due to micro cells in cellular RF planning and new digital radio technologies such as UMTS and CDMA2000 much more accurate data exists. DTM's of 10 m, 5 m, and even 1 m derived from satellite images, aerial photography or laser scanning gradually replace the DTM's created from conventional paper maps.

Useful data sources must meet the following conditions:

Availability: It has to be checked if the data source is not protected by copyright or classified by governmental or military authorities.

Quality and density of information: The requested types of information contained in the data source do not always match the user's needs. Furthermore, in some countries map accuracy and reliability do not meet conventional needs.

Up-to-date information: In many countries and for a lot of data source types, the interval between updates may be very long, which particularly impacts the reliability of land use layers. By contrast, elevation values, such as those required to compile a DTM, remain reliable over a long period (with no earthquake).

6.2.2.1 Paper (printed) maps

The information portrayed on a conventional paper map can be digitized to yield a geographic database. DTM's can be interpolated from digitized contours. Land-use maps and linear features (vectors) can be extracted by scanning the maps first and converting the raster into vector information.

Table 6.2-1 provides information on the achievable accuracy of digitized terrain data from typical paper maps for different map scales.

Presently, map scanning is both the cheapest and fastest way to produce medium-accuracy geographic databases of large areas. Maps at 1:200 000 or larger are available for nearly all parts of the world. Normally, these can be obtained and scanned without too much trouble. The information available at such scales is generally reliable enough for operational needs.

The accuracy is dependent on the map scale and can be estimated as follows: a 1 mm in the map is a the serious eye resolution; the resolution of the map is restricted to this length; therefore, for a paper map of scale 1:50 000 a DTM resolution of 50 m can be achieved, for a paper map of 1:250 000 scale a resolution of 250 m is achievable.

Here, the accuracy in XY-direction is determined mainly by the line thickness of the height contours on the map. The accuracy in Z-direction is related to the number of available contours per area and its area type.

TABLE 6.2-1

Typical achievable accuracy from different map scales

Map scale	XY (m)	Z – Flat area (m)	Z – Mountain area (m)
1:25 000	10	2.5	10
1:50 000	20	7	10
1:100 000	40	10	20
1:200 000	80	20	40
1:250 000	100	25	50
1:500 000	250	60	150

6.2.2.2 Satellite imagery, aerial photography and laser scanning

Optical Earth observation satellites carry passive instruments designed to measure the brightness, or radiometry, of the Earth's surface at different "optical" wavelengths. The satellite is characterized by its orbit and imaging instruments, which defines the resolution of the system. Most Earth observation satellites are placed in a sun-synchronous orbit at an altitude of 800 km approximately This enables them to acquire imagery of virtually any point of the Earth's surface (cloud cover permitting), covering several thousands of km^2, and passing over any given location at regular time intervals.

The chief shortcoming of optical satellite data is the limited resolution. The imaging instruments and sensors carried by current civilian satellites cannot acquire very high-resolution imagery from sun-synchronous orbits. In addition, since they are optical instruments they cannot "see" through clouds, haze, or mist.

Several optical satellites that are available on a commercial basis are specified in Table 6.2-2.

TABLE 6.2-2

List of several optical satellites in orbit

Satellite	Owner	Sensor	Resolution (m)	Image size (km)
Landsat	Space Imaging Corporation	TM	30 (MS)	185
Landsat-7	Space Imaging Corporation	ETM	30 (MS) 15 (PAN)	185
		HRMSI	10 (MS) 5 (PAN)	60
SPOT	CNES (Centre National d'Etudes Spatiales)	HRV	20 (MS) 10 (PAN)	60
JERS-1	NASDA (National Space Developing Agency)	ADEOS	16 (MS) 8 (PAN)	75
IRS-1C		LISS-III	23	70
		PAN	5.8	70

Sample of satellites in orbit (MS – Multi spectral sensor; PAN – Pan chromatic sensor).

Aerial photography becomes an important data source for the generation of high-resolution digital elevation model (DEM); it is widely used in conventional mapping.

Aerial photography is particularly useful at resolutions and accuracies beyond the capabilities of satellite-borne sensors currently available to users in the civil sector. The starting point is aerial photos at scales typically ranging from 1:10 000 to 1:30 000. Generous overlap between adjacent frames results in stereo pairs of images. These photos are digitized using precision scanners to yield digital images with resolutions between few decimetres and 1 or 2 m. Such imagery can then be processed on a digital production line to yield products ranging from ortho photos, DTMs, DEMs; building data to land-use maps and vector information. The main drawback of these photos is their lack of availability. For many regions of interest up-to-date air photos simply do not exist, and if so, they are often regarded as confidential. Furthermore, the area covered by each frame being relatively small, the user generally has to purchase and process a large number of photos, thus adding considerably to project costs.

The laser scanning process allows creating a DEM with a high degree of automation. The laser scanning system is airplane-based and incorporates a differential GPS system as well as an inertial system to measure the acceleration and change of orientation of the sensor platform. This equipment permits to determine the trajectory of the airplane with an accuracy of about 2 cm. The actual laser scanning system guarantees very precise measurements of the distance (accuracy 1 cm) between the platform and the object, or the Earth’s surface, respectively; thus using laser impulse reflectometry. Therefore, the integration of the three sensors allows a highly accurate measurement of the terrain surface.

In summary, Table 6.2-3 provides an overview of the various data sources and the horizontal resolution, which can be generated using the respective source.

TABLE 6.2-3

Overview of various data sources

Data Source	Data Type	Achievable Resolution (m)
Paper mapsScale: 1:20 000 – 1:500 000	Road map	2-100
	Digital terrain model, clutter	10-200
Satellite imagery	Image	1-50
	Digital elevation model, clutter	5-50
Aerial photography	Photo	0.5-5
	Digital elevation model, buildings, clutter	1-5
Laser scanning	Photo	0.5-5
	Digital elevation model, buildings, clutter	1-5

6.2.3 Types of digital map data

There are various wave propagation models for particular frequency ranges and services that differ substantially in their complexity; more information on propagation is in § 6.4. The Earth’s surface and the atmosphere have a major impact on the propagation of electromagnetic waves. Depending on the model chosen, the calculations use different types of data to model the properties of the Earth’s surface:

– geographical maps, road maps, and geo-referenced photos;

– digital terrain model (DTM);

– building data and digital elevation model (DEM);

– clutter data;

– ITU Digitized World Map (IDWM).

This data has to be geo-referenced as usual digital maps by a suitable cartographic coordinate system. It is included in the GIS as specific layers for visualization of the corresponding characteristics of the Earth's surface, and to provide access to the data for wave propagation calculations.

A cartographic data workshop enables the administration itself to produce the digitized maps used by the management and monitoring system, and to integrate these maps into the system. The workshop can also be used to produce or update the cartographic data.

Generally most of this digital terrain data is available in two data formats:

– *Vector data (Line data)*: The geographical information is stored in polygons that follow linear features (roads, railways, contour lines, etc.) or surround areas of the same feature (political boundaries, lakes, city contours, forest contours). Additional information (number of inhabitants, income, inhabitants by age, names of streets or cities) can be attached to the geographical information. Information stored in vector data generally requires less memory on hard disk than raster data. On the other hand, it is more time-consuming to obtain the information on a certain point, e.g. the exact terrain height of a point that is located between several contour lines. This terrain height first has to be interpolated from the adjacent contour lines. Adding layers of information is possible to get the required data.

– *Raster data (Gridded data)*: The area is divided into equally spaced rectangles of a certain size. The size of these rectangles is called horizontal resolution. For each of these rectangles, one element of information is stored. This can be the terrain height, the clutter class, the number of inhabitants living in this rectangular area or simply graphical information of a photo or a scanned paper map. If more than one piece of information of the total area is to be stored, it is necessary to generate a raster layer for each class of information. Raster data generally needs more memory on hard disk than the same information in vector format. The advantage of raster data is in the very fast access to each raster point. The image looks like a map, but by zooming the information (such as names, rivers) is also enlarged.

Common data exchange formats for vector and raster data files are listed in Table 6.2-4.

TABLE 6.2-4

Common data exchange formats for vector and raster data files

Data type	Common file formats
Vector data	AutoCAD DXF / DWG, Esri ArcInfo E00, Esri ArcView Shape, MapInfo TAB, MapInfo MIF / MID (ASCII Export Format), Microstation DGN, SDTS, TIGER, VPF
Raster data – Image formats	BMP, GIF, JPG, TIFF, GeoTIFF
Raster data – Terrain data formats	ASCII Grid, ASCII XY Value, BIL, BIP, BSQ, DTED, ESRI Generic Binary, Planet

6.2.3.1 Political maps, road maps and geo-referenced photos

Political maps and road maps can be used to display site positions, coverage areas, and the direction beams toward transmitters or monitoring stations. Political maps generally show the transmitter and monitoring stations for a larger area. Road maps in different resolutions can help to identify the locations of known and unknown transmitter stations. Aerial photos or satellite images provide an up-to-date view of the area of interest and help to identify reflection areas or obstacles.

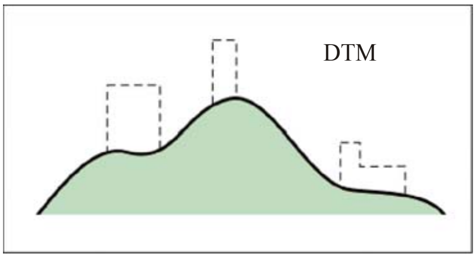
6.2.3.2 Digital terrain model

The digital terrain model (DTM) represents the Earth's surface in raster or vector format, supplying the altitude of each point above mean sea level (AMSL) of the represented area. The elevation of buildings, trees, or other land use above the Earth's surface is not part of the DTM. The resolution of the DTM is given by the resolution in XY-direction and the resolution of the point altitude. As specified before, the required resolution is derived from the range of operation, the area of interest, the services under examination, and the propagation models used.

Some map resolutions are in a range between 1 km in horizontal direction, combined with 100 m height resolution, and 1 m in XY-direction as well as 0.1 m vertical resolution. More precise propagation models and micro-cells RF planning require a higher precision. A good resolution for common technical analysis is a map with pixels of 100 m^2 and a vertical resolution of 10 m. Figure 6.2-1 depicts a schematic digital terrain mapping without buildings, trees, etc.

FIGURE 6.2-1

DTM: Earth surface without buildings, trees, etc.



Spectrum-6.2-01

6.2.3.3 Building data and digital elevation model

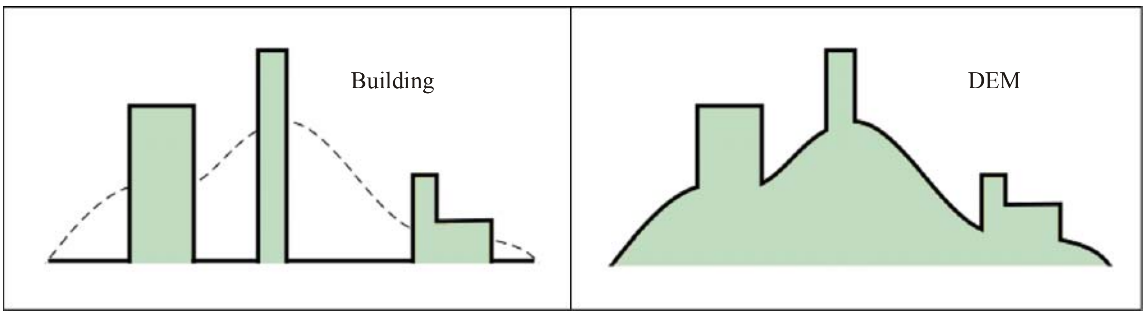
The building data typically adds the building height to the Earth's surface. Building data is often used for line-of-sight checks for microwave-link and point-to-multipoint (P-MP) planning. Typical resolutions are in a range of 1 m to 10 m, but not above the size of the objects.

Building data are stored in raster format or vector format. The vector format is preferred for 3D simulations of urban areas. Compared to raster data, vector data can include more details such as roof-tops. This information needs more updates, relative to DTM only, as buildings and their heights are changing more than the ground level above sea.

The digital elevation model may combine the building data. It shows the surface of the Earth plus the building height. Apart from the buildings, the height of the Earth's surface is displayed as well. DEMs are used for microcell, microwave-link and PMP planning purposes, whereas GIS tools make line-of-sight checks and field strength calculations. Typical resolutions for DEMs are between 1 m and 25 m. Figure 6.2-2 depicts building data: surface of the Earth plus building height.

FIGURE 6.2-2

DEM: Earth surface plus building height



Spectrum-6.2-02

6.2.3.4 Clutter data

Clutter data, also called land use, morpho, land coverage, or ground occupancy data, contain classification information of the clutter items (ITU-R classification), such as for instance bare mineral surface, field or cultivated land, forest, water, dense urban area, diffuse urban area, or mixed urban area. This information could be supplied as vectors (by supplying polygon surfaces of points of the same class: e.g. lake, forest, and city contour) but the raster format is more convenient to be used by propagation models. In the latter case, the clutter data map represents either qualitative data as to which item (e.g. urban, suburban, forest and water) exists at each pixel, or rather quantitative values such as the vegetation density or building density or height. Propagation models can use these clutter data maps. Some field strength prediction models such as Okumura-Hata and Walfish Ikegami require clutter data in addition to DTM's, to improve the precision of the predictions. Typical resolutions for clutter data maps are between 10 m and 100 m.

6.2.3.5 ITU Digitized World Map

The ITU Digitized World Map (IDWM) has been developed to integrate necessary geographical, political, meteorological, and technical data, which depends on geographical coordinates of points and areas. The information contained is very useful in a wide range of calculation tasks. The IDWM consists of two parts: the IDWM database and the IDWM subroutine library. The IDWM database contains the following data: geographical data (such as coastlines, seas, islands, and lakes), political data (such as country and region borders), meteorological data for rain climatic zones and technical data such as ground conductivity areas and noise zones. In addition, IDWM provides a subroutine library offering a great series of functions to make full use of the above-mentioned database, such as determination of the region, country, rain climatic zone, etc. for a given point, calculation of the distance from a given point to the coast, country border, etc. for a given azimuth, calculation of the distance and the azimuth for a given point to the nearest coastline, country border point, etc. and several other functions. The IDWM is included in most of the software packages offered by the ITU; as example, the ITU be-weekly BR IFIC depicts the registered stations on a map.

6.2.3.6 Web mapping services

An interesting alternative is the use of Web mapping services. They provide World-maps that are created by superimposition of images obtained from satellite imagery, aerial photography and GIS information. Most land areas are covered in satellite imagery with a resolution of about 15 m per pixel or even better.

The digital maps provide functions such as:

– Fast map zooming.

– Measurement of distances and directions.

– Using different types of coordinates.

It should be noted that the use of Web mapping services may require a licensing contract for government and/or commercial users although their use may be free of charge for private users.

6.2.4 Map resolutions for wave propagation calculations

The required resolution of all types of map data layers for wave propagation calculations depends on the following parameters:

– terrain;

– emission frequency and power that define the operation range;

– type of service.

The resolution of the map data should be sufficient to take into account significant variations of the terrain. Otherwise there is the risk to lose important data, which may result in completely incorrect calculation results. The level of detail of variations of map data required for particular calculations strongly depends on the wavelength of the emission. As a rule of thumb, details smaller than the wavelength do not affect the propagation loss very much. Table 6.2-5 provides a rough overview of map resolutions required for calculations in the various frequency bands. The terrain profile is more important for frequencies above HF (30 MHz); wavelengths smaller than 10 m.

For frequencies above 5 to 10 GHz, with no line-of-sight (LoS) between emitter to receiver there is no accurate communications; so to calculate the received signal, the DTM accuracy is more important than the utilized propagation models.

TABLE 6.2-5

Map resolutions for the various frequency ranges

Band	Frequency range	Wavelength	Approximate range of emission	Suggested resolution of map data
VLF	3-30 kHz	100 000-10 000 m	several 1 000 km	1 km
LF	30-300 kHz	10 000-1 000 m	several 1 000 km	1 km
MF	0.3-3 MHz	1 000-100 m	few 1 000 km	1 km
HF	3-30 MHz	100-10 m	few 1 000 km	1 km
VHF	30-300 MHz	10-1 m	up to 1 000 km	~1 km
UHF	0.3-3 GHz	1-0.1 m	up to 100 km	~ 100 m
SHF	3-30 GHz	0.1-0.01 m	up to 30 km	~ 10 m
EHF	30-300 GHz	0.01-0.001 m	up to 20 km	~ 1 m

6.2.5 Coordinate systems

Two coordinate systems are used to define maps of interest to spectrum management and monitoring. Spherical coordinates are used to define maps, which attempt to portray the spherical Earth's surface on flat map sheets. Lines of latitude and longitude are used in the most common coordinate systems and these are "projected" from the spherical surface to a flat surface using various projections to achieve different results. For spherical coordinate systems: the main questions to be solved by GIS applications concern objects and phenomena on the Earth's surface, the atmosphere above and the landmasses below. It is necessary to know the exact position on the map as well as the reference towards the Earth's surface, to examine the relationship between these objects. Therefore, it is necessary to find a procedure to represent a part of the three-dimensional Earth's surface on a two-dimensional map.

The basic approach is the following:

– First, a sphere or an ellipsoid approximates the true shape of the Earth. Its form and orientation in space is described by the so-called geodetic datum: the set of reference values upon which a coordinate system must be based (see Note 1).

– Second, a part of this three-dimensional object has to be put onto a two-dimensional plane typically called map.

NOTE 1 – The WGS 84 datum, which is based on the GRS 80 geoid, is recommended for international coordination.

This transformation is carried out by the map projection. Both, the map projection combined with the datum, form a coordinate system, which fully describes the complete procedure. Using diverse ellipsoidal Earth models uses various cartographic coordinate systems for definition of geographical locations on the maps. Normally, these projections are particularly suited only for a limited area of the Earth's surface.

In many cases, the monitoring operator can choose from different types of maps with several different coordinates Latitude-longitude (dd.mm.ss), (UTM (Universal Transverse Mercator), Lambert, Mercator, etc.) within his monitoring system.

The GIS system must interchange all the different coordinate types. Using only one internal reference coordinate system normally does this and all other coordinate systems are transformed to it. This automatic mechanism allows the operator to use all the different maps without taking into account their different coordinate systems.

A rectangular coordinate system is frequently used for relatively small areas because of the ease of plotting and calculation (distance separation, for example). In this case, errors from the assumption that the Earth is flat are acceptably small. Table 1 of Recommendation ITU-R P.1058 summarizes the differences among coordinate systems.

TABLE 6.2-6

Coordinate systems

Parameter	Latitude-longitude	UTM	Other
Applicability	Complete Earth	Most of Earth	Usually local
Grid cell shape	Curvilinear trapezoid	Good approximation to square	Usually good approximation to square
Scale-factor variation	Varies with latitude	Good approximation to constant	Usually good approximation to constant
Boundaries	None	According to longitude	Varies

Care must be taken in transferring locations between maps using different coordinate systems. There are a number of references that present a clear description of these and other important map projections. The following references provide good graphic descriptions and the mathematics necessary for interpretation and conversion.

References

GLOBE [2001] 30 arc-second (1 km) gridded quality controlled global DTM is available from NOAA National Data Centres via the Web page: http://www.ngdc.noaa.gov/mgg/topo/globe.html.

Bibliography

SNYDER, J. P. [1987] Map Projections, A Working Manual. U.S. Geological Survey Professional Paper 1395, United States Government Printing Office, Washington, United States of America.

Institut Géographique National, 135 bis rue de Grenelle, Paris, France, http://www.ign.fr.

ITU-R Recommendations and Resolutions

NOTE – In every case, the latest edition of the Recommendation and Resolution is encouraged to be used.

Recommendation ITU-R P.1058 – Digital topographic databases for propagation studies.

Resolution ITU-R 40 – Worldwide databases of terrain height and surface features.

6.3 Equivalent isotropically radiated power (e.i.r.p.) calculations

6.3.1 Introduction and e.i.r.p. definition

The e.i.r.p. is an important parameter of the emitter and it is needed in determining the operational range, RF interference zone for other receivers, RF hazards to personnel, medical equipment, ordnance and fuel. So, it is essential that the monitoring site be able to estimate the e.i.r.p. of an emitter. It is also needed to calculate the power level of the transmitter, to compare the actual transmitted power to the licence data: maximum allowable power and antenna gain. The calculation of e.i.r.p. is essential for the monitoring of spacecraft emissions (see § 5.1.2.4).

According to RR No. 1.161:

"equivalent isotropically radiated power (e.i.r.p.): The product of the power supplied to the antenna and the antenna gain in a given direction relative to an isotropic antenna *(absolute or isotropic gain)"*.

The e.i.r.p. can be computed by the following formulae:

$$e.i.r.p. = P_t + G_t - L \qquad \text{dBm} \tag{6.3-1}$$

where:

- P_t: output power of the transmitter (dBm)
- G_t: gain of the transmitting antenna, in the direction of the receiver, (dB) relative to an isotropic antenna (dBi)
- L: transmission line and matching losses (dB).

In the case of an omnidirectional transmitting antenna, the e.i.r.p. is uniform in all directions. For a directional antenna, this value generally depends upon both azimuth and elevation. When e.i.r.p. is stated independent of the direction, the maximum value is implied.

NOTE 1 – A similar term, called e.r.p. (effective radiated power) is often used in the same area of application. According to RR No. 1.162 definition is as follows:

"effective radiated power (e.r.p.) (in a given direction): The product of the power supplied to the antenna and its *gain relative to a half-wave dipole* in a given direction".

It is frequently used in EMC measurements, where an equipment under test (EUT), whose emission has been measured using a measuring antenna and receiver, is replaced by a half-wave dipole and a signal generator whose output power is adjusted to give the same reading on the measuring receiver display as with the EUT in place. The input power to a lossless half-wave dipole is the e.r.p. to be measured.

Generally e.r.p. and e.i.r.p. are related by:

$$e.i.r.p. = e.r.p. + 2.1 \qquad \text{dBm} \tag{6.3-2}$$

6.3.2 Estimation of the e.i.r.p. using monitoring measurements

At a monitoring station, the received power level (P_r (dBm)) can be measured at the input to the receiver. Frequently, the receiver's input impedance is 50 Ω, and the received power is recorded as a voltage V_r (dB(μV)) across 50 Ω.

For input resistance of 50 Ω, P_r and V_r are related by:

$$P_r\ (\text{dBm}) = V_r\ (\text{dB}(\mu\text{V})) - 107 \tag{6.3-3}$$

For input resistance of 75 Ω, P_r and V_r are related by:

$$P_r\ (\text{dBm}) = V_r\ (\text{dB}(\mu\text{V})) - 108.8 \tag{6.3-4}$$

The e.i.r.p. of the emitter can be computed from either P_r or V_r as determined at the monitoring site, when the propagation loss is known.

6.3.2.1 Calculation of the e.i.r.p. from received power and field strength

The e.i.r.p. of the emitter can be calculated from calibrated received power when the antenna gain, receiving transmission line loss, polarization mismatch loss and propagation loss are known, if the measurement takes place in the maximum gain direction of the emitter antenna:

$$e.i.r.p. = P_r - G_r + R_{loss} + X_{pol} + L_{prop} \qquad \text{dBm} \tag{6.3-5}$$

where:

P_r: measured power of the signal at the receiver input (dBm)

G_r: gain of the receiving antenna toward the direction of the monitored Tx (dBi)

R_{loss}: receiving transmission line losses: cable, feed and mismatch losses (dB)

X_{pol}: polarization mismatch (discrimination of transmit and receive antennas) (dB)

L_{prop}: propagation loss (dB).

It is assumed that the receiver bandwidth is greater than the emission bandwidth.

The e.i.r.p. is easily calculated for the case of free-space propagation. The free-space propagation loss, L_{prop}, can be determined by using the following equation:

$$L_{prop} = 20 \log f + 20 \log d + 32.45 \qquad \text{dB}$$

where:

d: distance between the transmitter and the receiver (km)

f: frequency (MHz)

and

$$e.i.r.p. = P_r - G_r + R_{loss} + X_{pol} + 20 \log f + 20 \log d + 32.45 \quad \text{dBm} \tag{6.3-6}$$

These formulas assume free-space propagation and do not include effects such as those due to the ground, obstacles, ducting effects, etc. For other cases the propagation loss is computed using propagation models; more details in § 6.4.

Before using the free-space formula, it is necessary to check the path profile to ensure that a free-space path exists. A path may be considered free-space when no terrain extends inside the first Fresnel zone (or, more conservatively, the third Fresnel zone). The formula for the third Fresnel zone radius r (m):

$$r = 30 * \sqrt{\frac{d_1\, d_2}{fd}} \tag{6.3-7}$$

where:

d_1: distance from the obstacle to the transmitter (km)

d_2: distance from the obstacle to the receiver (km)

d: total path length (km)

f: frequency (GHz).

To explain the application: for $d_1 = d_2 = d/2$, $d = 10$ km, $f = 2.5$ GHz, the third Fresnel zone radius equals 30 m; i.e. to get a free space loss signal, no building or other obstacle may approach more than 30 m the LoS in the middle of the profile. If one the first Fresnel zone radius is required, only 17.32 m protection is needed.

The first Fresnel zone radius is given by the third Fresnel zone radius divided by 1.732 (= √3).

In order to compute the maximum LoS distance, it is necessary to consider the effects of atmospheric refraction. This normally is accomplished by plotting the path profile using an Earth radius that is larger than the actual radius (6 370 km) by a factor (k). In temperate climates, the median value of k is approximately 4/3. For this case, a relatively simple formula can be used to compute the distance to the horizon (d_{los}) over the sea, or smooth Earth:

$$d_{los} = 4.1 \left(\sqrt{H_t} + \sqrt{H_r}\right) \ \text{km}$$

where:

H_t and H_r are the transmitter and receiver antenna heights (m) above ground level, respectively.

It is possible to relate the field strength to the receiver voltage using an antenna factor. When these quantities are converted to dB:

$$E = V_r + k_e \qquad \text{dB}(\mu\text{V/m}) \tag{6.3-8}$$

where:

V_r: the measured voltage at the receiver input (dB(μV))

k_e: antenna factor (dB/1/m m) = –29.77 – G_r + 20 log f (MHz).

Therefore

$$P_r = E\ (\text{dB}(\mu\text{V/m})) - k_e - 107 \qquad \text{dBm}$$

and the formulae provided in above can be used:

$$e.i.r.p. = E - 20 \log f\ (\text{MHz}) - 77.23 + R_{loss} + X_{pol} + L_{prop} \qquad \text{dBm} \tag{6.3-9}$$

For free-space propagation:

$$e.i.r.p. = E + R_{loss} + X_{pol} + 20 \log d\ (\text{km}) - 44.78 \qquad \text{dBm} \tag{6.3-10}$$

This equation may be derived directly from the well known expression (see Recommendation ITU-R P.525):

$$E = 30 * \sqrt{\frac{e.i.r.p}{d}} \tag{6.3-11}$$

where:

E (V/m), e.i.r.p. (W), distance (m)

6.3.3 Propagation influence

The changing in propagation losses influences the results. By averaging the measured data over a longer period of time the accuracy is increased. The influence of propagation effects increases with the distance between transmitter and receiving station, and if there is no LoS between them. Also the behaviour of the transmitters in the neighbouring channels is important.

6.4 Propagation models

When radiowaves propagate in a homogeneous ideal dielectric medium of infinite extent, they are subject to free space propagation. In such a situation, propagation is influenced neither by the atmosphere nor by any terrain obstacles. The transmitted power decreases with the square of the distance and the free-space basic transmission loss given by (see Recommendation ITU-R P.525):

$$L\ (\text{dB}) = 20 \log f\ (\text{MHz}) + 20 \log d\ (\text{km}) + 32.45 \tag{6.4-1}$$

In more practical situations radiowave propagation between transmitter and receiver is usually influenced by many different effects, which can, in turn reduce the received signal. Such effects arise from:

– the neutral atmosphere or ionosphere;

– the terrain, including the Earth's surface, terrain irregularities, buildings and vegetation.

A good propagation prediction method is a valuable tool for assessing the probability of receiving a particular transmission at a certain power or signal strength, at a given location. Comparison between the predicted and measured values will provide useful information for monitoring purposes, e.g. identification of excessively high values of received signal level. Such comparisons can be done automatically in real time by storing the predicted and measured values in databases.

6.4.1 Effects of the atmosphere

The Earth's atmosphere influences radiowave propagation. It is necessary to distinguish between the effects due to the neutral atmosphere, e.g. the troposphere, and those due to the ionized part of the atmosphere – the ionosphere. The height of the troposphere extends from about 9 km at the Earth's poles to about 17 km at the equator. The height of the ionosphere extends from about 50 km to approximately 2 000 km. The properties of the troposphere are particularly important for propagation at frequencies above about 30 MHz and those of the ionosphere for frequencies on terrestrial parts below about 30 MHz. It should be noted however that significant transionospheric effects (on Earth-to-space paths) can occur at frequencies extending up to several GHz.

6.4.1.1 Effects below about 30 MHz

In general at frequencies between about 9 kHz and 30 MHz two types of propagation are to be considered: ground-wave propagation along the Earth's surface and sky-wave, or ionospheric propagation. Ground-wave propagation refers to propagation within LoS as well as diffraction beyond the horizon. The propagation of a ground-wave signal depends mainly on the electrical characteristics of the ground and the radio frequency. The attenuation is lower over surfaces with a high conductivity. Sky-wave propagation is caused by refraction or reflection from the ionosphere. At ELF and VLF electromagnetic waves may propagate in a wave guide mode in the lower ionosphere. Theoretical curves for ground-wave propagation are given in Recommendation ITU-R P.368. The recommended prediction method for HF sky-wave propagation is in Recommendation ITU-R P.533.

6.4.1.2 Effects above about 30 MHz

Variations in the refractive index of the neutral atmosphere greatly influence radio wave propagation at frequencies above about 30 MHz. At frequencies greater than about 6 GHz, effects due to precipitation become significant and as the frequency increases, other effects such as those due to atmospheric gases, water vapour and clouds must also be considered. The refractive index of the troposphere decreases slightly with height. Variations in refractive index and its vertical gradient caused by changes in temperature, pressure and humidity can influence the propagation range of a signal. Of particular significant is the case where the vertical gradient becomes more negative than that of the standard atmosphere. Under such conditions, (referred to as super-refraction or ducting), propagation ranges can extend well beyond those normally expected, thereby providing the potential for interference when frequencies are shared. The behaviour of atmospheric refractivity is treated in Recommendations ITU-R P.453 and ITU-R P.834. Other ITU-R Recommendations dealing with radiometeorological effects are ITU-R P.676 – Atmospheric gaseous absorption; ITU-R P.837 – Rainfall model and ITU-R P.835 – Water vapour.

6.4.2 Effects of irregular terrain

Features along the terrain also affect the propagation of radio waves, particularly when the frequency increases above about 30 MHz. Propagation mechanisms include diffraction, scattering and reflection from obstacles. It is important, therefore, to examine the propagation path to determine the degree of obstruction due to terrain obstacles.

6.4.2.1 Line-of-sight path

Although line-of-sight (LoS) may exist between the two antennas, the terrain influences the propagation if there is insufficient clearance between the ray-path and the terrain obstacle. A commonly used criterion is that the propagation path should clear all obstacles by at least 0.6 times the first Fresnel zone distance, otherwise some diffraction loss may be suffered. When making such an assessment of clearance, it is necessary to take into account the refractive bending of the ray by the atmosphere and for this the concept of an effective Earth's radius is often used (see Recommendation ITU-R P.530).

6.4.2.2 Diffraction over obstacles and irregular terrain

Many propagation paths encounter one or several separate obstacles between the antennas, and the resulting diffraction loss can be calculated using well-established methods such as those described in Recommendation ITU-R P.526. The influence of terrain irregularities, and thus diffraction loss increases with frequency.

6.4.3 Effects of reflections by the surface of the Earth

Electromagnetic waves are reflected from the surface of the Earth and, on a LoS path, a combination of the direct ray and the reflected ray may arrive at the receiving antenna. In the case of a perfectly conducting surface the maximum received field strength of the combination of the two rays can reach (in theory) twice the value of the field strength of the direct ray when both signals are in phase but the waves will cancel for a phase difference of 180°. The height of the antenna influences the phase of the arriving signals and thus the magnitude of the resulting signal. Techniques are available for reducing the reflected signal on a LoS path thereby avoiding interference effects between the two rays (see Recommendation ITU-R P.530).

6.4.4 Propagation on Earth-satellite paths

Methods for predicting the propagation effects on slant paths, for the frequency range 1-55 GHz, are treated in Recommendation ITU-R P.618. Where appropriate, the Recommendation refers to other Recommendations in the ITU-R P Series, in particular those containing radio meteorological information and data.

6.4.5 Available propagation models

There are many propagation prediction methods available for point-to-area and point-to-point communications, both for terrestrial and slant paths, depending on frequency range, services concerned, etc. Therefore it is impossible to make a complete overview but the reader's attention is drawn to Recommendation ITU-R P.1144, which is a guide to the application of the propagation methods contained in the ITU-R P Series of Recommendations. A few of these Recommendations are mentioned below.

Recommendation ITU-R P.368 contains ground-wave propagation curves for frequencies from 10 kHz up to 3 MHz. These are for antennas located on the Earth's surface and apply to an exponential atmosphere. No account is taken of irregular terrain. Ground-wave propagation is mainly governed by the electrical characteristics of the ground. The electrical characteristics may be expressed by three parameters: the permeability, the permittivity and the conductivity (see Recommendation ITU-R P.527). This conductivity is the most important electrical characteristic for frequencies below 3 MHz. Recommendation ITU-R P.832 contains the World Atlas of Ground Conductivities (but should be updated). The computer program GRWAVE available from the Radiocommunication Study Group 3 website, can be used to compute these curves.

Recommendation ITU-R P.1546 contains the method for point-to area predictions for terrestrial services in the frequency range 30 to 3 000 MHz. As can be seen from the title, this Recommendation covers an extended frequency range. But also the distance range on which prediction calculations can be made is extended from 1 to 1 000 km.

Recommendation ITU-R P.526 is a general method for one or more obstacles.

The NTIA's (National Telecommunications and Information Administration), ITS (Institute for Telecommunication Sciences) method, Irregular Terrain Model, also known as the Longley and Rice method, contains a set of algorithms developed for computer applications. The C++ code http://flattop.its.bldrdoc.gov/itm.html provides a debugged code.

Various empirical models for propagation in urban areas have been developed (e.g. Hata- Okumura and Walfish-Ikegami) and converted to computerized versions. Such models are employed mainly in planning cellular radio systems. Recommendation ITU-R P.1411 provides prediction methods for short range outdoor propagation in the frequency range 300 MHz to 100 GHz and includes situations where antennas at both ends of the path are obstructed.

6.4.6 Propagation models and usage of various frequency bands

Table 6.4-1 describes the usage of various frequency bands from 3 kHz to 300 GHz, based principally on propagation characteristics. Recommendation ITU-R P.1144 provides a general guide to the application of the propagation methods of the Radiocommunication Study Group 3.

TABLE 6.4-1

Propagation models and usage of various frequency bands

Band	Frequency	Mode	Range	Examples of usage	Rec. ITU-R
VLF	3-30 kHz	Waveguide	several 1 000 km	Worldwide, long range radionavigation and radiocommunications	P.684
LF	30-300 kHz	ground-wave, sky-wave	several 1 000 km	Long range radionavigation and radiocommunications	P.368; P.1147
MF	0.3-3 MHz	ground-wave, sky-wave	a few 1 000 km	Medium range point-to-point, broadcasting and maritime mobile	P.368, P.1147
HF	3-30 MHz	sky-wave	up to several 1 000 km	Long and short range point-to-point, broadcasting, mobile	P.533
VHF	30-300 MHz	space-wave, tropospheric scatter, diffraction	up to a few 100 km	Short and medium point-to-point, mobile, LAN, broadcasting (sound and TV), personal communications	P.1546, P.617
UHF	0.3-3 GHz	space-wave, tropospheric scatter, diffraction, line-of-sight	less than 100 km	Short and medium point-to-point, mobile, LAN, broadcasting (sound and TV), personal communications, satellite communications	P.1546, P.530, P.617, P.618, P.452, P.1238, P.1411
SHF	3-30 GHz	Line-of-sight	less than 30 km	Short range point-to-point, broadcasting-satellite (sound and TV), LAN, mobile/ personal communications, satellite communications, radionavigation	P.530, P.618, P.452, P.1410, P.1411
EHF	30-300 GHz	Line-of-sight	less than 20 km	Short range point-to-point, microcellular, LAN and personal communications, satellite communications	P.618, P.1238, P.1410, P.1411

References

ITU-R Recommendations and Reports

NOTE – In every case, the latest edition of the Recommendation and Report is encouraged to be used.

Recommendation ITU-R P.310 – Definitions of terms relating to propagation in non-ionized media.

Recommendation ITU-R P.368 – Ground-wave propagation curves for frequencies between 10 kHz and 30 MHz.

Recommendation ITU-R P.453 – The radio refractive index: its formula and refractivity data.

Recommendation ITU-R P.525 – Calculation of free-space attenuation.

Recommendation ITU-R P.526 – Propagation by diffraction.

Recommendation ITU-R P.527 – Electrical characteristics of the surface of the Earth.

Recommendation ITU-R P.530 – Propagation data and prediction methods required to design terrestrial line-of-sight systems.

Recommendation ITU-R P.533 – Method for the prediction of the performance of HF circuit.

Recommendation ITU-R P.618 – Propagation data and prediction methods required to design Earth-space telecommunication systems.

Recommendation ITU-R P.676 – Attenuation by atmospheric gases.

Recommendation ITU-R P.832 – World Atlas of Ground Conductivities.

Recommendation ITU-R P.834 – Effects of tropospheric refraction on radiowave propagation.

Recommendation ITU-R P.835 – Reference Standard Atmospheres.

Recommendation ITU-R P.837 – Characteristics of precipitation for propagation modelling.

Recommendation ITU-R P.1144 – Guide to the application of the propagation methods of Radiocommunication Study Group 3.

Recommendation ITU-R P.1411 – Propagation data and prediction methods for the planning of short-range outdoor radiocommunication systems and radio local area networks in the frequency range 300 MHz to 100 GHz.

Recommendation ITU-R P.1546 – Method for point-to-area predictions for terrestrial services in the frequency range 30 MHz to 3 000 MHz.

Recommendation ITU-R P.1791 – Propagation prediction methods for assessment of the impact of ultra-wideband devices.

Recommendation ITU-R P.1812 – A path-specific propagation prediction method for point-to-area terrestrial services in the VHF and UHF bands.

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6.5 Intermodulation

6.5.1 Background

Unwanted emissions which consist of spurious and out-of-band emissions may interfere with licensed radio-communication systems. The most commonly encountered types of spurious emissions are harmonic emissions or intermodulation products, which are produced in a non-linear device such as an output amplifier of a transmitter. Such transmitted emissions are undesired spurious outputs, which can cause interference.

Intermodulation products (IMP) are produced in a non-linear device when two (or more) signals interact and generate an undesired signal. An undesired IMP can cause interference when it is:

– at or near the tuned frequency of a receiver; or

– at any other frequency to which a receiver is susceptible, such as the intermediate frequency (IF) of a superhetrodyne receiver.

IMP can be produced in transmitters or multi-channel output amplifiers (and radiated). They can also be produced in distribution amplifiers or in receiver input and IF stages. It is important for the monitoring operator, when resolving interference cases, to be able to determine if a legitimate signal or intermodulation product is being measured.

6.5.2 Intermodulation analysis equations

In many cases, intermodulation products are those which are most difficult to detect and identify at a monitoring station and this is a reason why the following sections are mainly devoted particularly to intermodulation analysis, detection and identification.

The following section, excluding the example, is copied from the documentation of NTIA Microcomputer Spectrum Analysis Model (MSAM) Version 5.24 February 1997. MSAM programs were reviewed by the Radiocommunication Study Group 1 and are available at: http://ntiacsd.ntia.doc.gov/msam/.

The analysis only considers in-band intermodulation products (i.e. products whose frequencies are close to the input signal frequencies). Intermodulation interference is defined to be any of the following equations:

Two Signal Case:

3rd order: $2T_{f1} - T_{f2} = R_f \pm \mathrm{BW}$

5th order: $3T_{f1} - 2T_{f2} = R_f \pm \mathrm{BW}$

7th order: $4T_{f1} - 3T_{f2} = R_f \pm \mathrm{BW}$

Three Signal Case:

3rd order: $T_{f1} - T_{f2} + T_{f3} = R_f \pm \mathrm{BW}$

5th order: $2T_{f1} - 2T_{f2} + T_{f3} = R_f \pm \mathrm{BW}$

$3T_{f2} - T_{f2} - T_{f3} = R_f \pm \mathrm{BW}$

7th order: $2T_{f1} - 3T_{f2} + 2\,T_{f3} = R_f \pm \mathrm{BW}$

$3T_{f1} - 3T_{f2} + T_{f3} = R_f \pm \mathrm{BW}$

$4T_{f1} - 2T_{f2} + T_{f3} = R_f \pm \mathrm{BW}$

where:

T_f: transmitter frequency

R_f: receiver frequency

BW: receiver bandwidth.

A practical example of an IMP:

The transmitted frequencies are $f_1 = 232$ MHz (mobile channel), $f_2 = 229.75$ MHz (Sound Carrier of TV channel 12, for European Standard B) and the interfered frequency is 234.25 MHz (another mobile channel): thus IMP $= 2T_{f1} - T_{f2} = 2 \times 232 - 229.75 = 234.25$.

Usually intercept points and noise figures are given by manufacturers to characterize amplifiers and receivers. The following can be calculated from this data:

a) receiver noise level u_N for given values of measurement bandwidth B_{3dB} (Hz), noise figure NF (dB) and detector weighting factor W (dB):

$$u_N = -67 \text{ dB}(\mu\text{V}) + NF + 10 \log (B_{3dB}) + W \qquad \text{dB}(\mu\text{V})$$

The detector type weighting factor W is 0 dB for average, 1.1 dB for r.m.s., typically 7 dB for quasi-peak, and typically 11 dB for peak.

For example for NF = 10 dB, B_{3dB} = 9 kHz, average detector:

$$u_N = -67 + 10 + 39.5 = -17.5 \qquad \text{dB}(\mu\text{V})$$

b) level of the intermodulation product u_{IMP} for given values of 3rd order intercept point IP_3 and individual level of two IMP generating signals u_{IMS}:

$$u_{IMP} = IP_3 - 3(IP_3 - u_{IMS}) \qquad \text{dB}(\mu\text{V})$$

For example for IP_3 = 20 dBm = 127 dB(μV), u_{IMS} = 80 dB(μV), input resistance = 50 Ω (for details see § 6.3):

$$u_{IMP} = 127 - 3\ (127 - 80) = -14 \qquad \text{dB}(\mu\text{V})$$

c) level of the intermodulation product u_{IMP} for given values of 2nd order intercept point IP_2 and individual level of two IMP generating signals u_{IMS}:

$$u_{IMP} = IP_2 - 2\ (IP_2 - u_{IMS})$$

For example for IP_2 = 50 dBm = 157 dB(μV), u_{IMS} = 80 dB(μV):

$$u_{IMP} = 157 - 2\ (157 - 80) = 3 \qquad \text{dB}(\mu\text{V})$$

Intermodulation-free dynamic range:

1. calculate the noise level u_N
2. calculate the individual level of the two IMP generating signals using: $u_{IMS} = 1/3\ (u_N + 2\ IP_3)$, where all units are in dB(μV)
3. calculate: $D_{IMF} = u_{IMS} - u_N$ for the intermodulation free dynamic range.

For example for NF = 10 dB: B_{3dB} = 9 kHz, IP_3 = 20 dBm, average detector:
$u_{IMS} = 1/3\ (-17.5 + 2(127)) = 78.8$ dB(μV)
$D_{IMF} = 78.8 - (-17.5) = 96.3$ dB.

Detailed analysis of IMP created in transmitters appears at Recommendation ITU-R SM.1446 and Report ITU-R SM.2021. Recommendation ITU-R SM.1134 presents calculation method for determination of IMP produced in receivers, that permits to determine levels of IMPs up to 5th order. An example of calculations is also given.

6.5.3 Detection and identification of intermodulation products

The practical situation confronted by the operator of a monitoring receiver is determining whether an observed signal is a legitimate signal delivered to the receiver by the antenna or an IMP generated in the receiver by two or more strong signals. A first indication that IMPs are present in the receiver's output often is the observation of what appears to be the same signal modulation on more than one frequency.

A simple test for IMP is to insert a known amount of attenuation in front of the input of the receiver. If the observed signal amplitude decreases by the amount of the known added attenuator, then the observed signal is legitimate. If the amplitude decreases by an integer multiple of the attenuator value, then the observed signal is an IMP of the order of the integer multiple, that is produced in the receiver. If the IMP is generated both internally and externally, the observed signal will drop by more than the added attenuation, but would not be an integer multiple of the attenuator value.

For example, if 10 dB is inserted and the amplitude of the observed signal drops by 30 dB, then the observed signal was a 3rd order IMP. If the observed signal is fading, then the size of the attenuator should be sufficiently large so that decreases due to fading are not misinterpreted as changes due to IMPs. Care should be taken to avoid using an attenuator that is so large that, after attenuation, the signal falls below the level where it is at least 5 dB above the receiver's noise floor.

Alternatively, the built-in input attenuation of a spectrum analyzer or measuring receiver can be used. Most such instruments keep their reference level constant as the input attenuation is changed; which gives a different criterion than when using uncoupled attenuation. If the observed signal amplitude stays constant, then the observed signal is legitimate. If the amplitude changes, the IMP is generated internally or is the sum of externally and internally generated products.

If a spectrum analyzer is available, then various resolution bandwidths can be used to facilitate the detection and identification of IMPs. This approach is especially effective when there are many IMPs present simultaneously such that the apparent receiver noise floor is elevated across a wide frequency band.

Finally, IMPs can result from in-band signals (e.g., HF signals causing IMPs in the HF band) or from out-of-band signals (e.g., VHF signals causing IMPs in the HF band). Low-pass, high-pass and band-pass filters are useful with spectrum analyzers for identifying IMPs and whether they are in-band products or out-of-band products. Spectrum analyzers with digital storage, that have multiple traces and the ability to store and view a trace; make it easy to compare spectrums with and without filters to look for the presence of absence of the intermodulation products.

Spectrum analyzers with 3-axis displays (amplitude versus frequency and time using multiple sweeps) are especially well adapted to the detection and identification of IMPs when observing the spectrum with and without the filters.

When trying to solve interference problems, it is useful to determine if the interference results from IMPs produced in the transmitter or in the receiver. A large signal survey is useful to reveal potential causes of IMPs products. The intermodulation analysis equations can be used to look for a match between computed IMPs and the interfering signal.

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NOTE – In every case, the latest edition of the Recommendation and Report is encouraged to be used.

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Recommendation ITU-R SM.1134 – Intermodulation interference calculations in the land-mobile service.

Recommendation ITU-R SM.1446 – Definition and measurement of intermodulation products in transmitter using frequency, phase, or complex modulation techniques.

Report ITU-R SM.2021 – Production and mitigation of intermodulation products in the transmitter.

6.6 Modulation and spectrum access methods

6.6.1 Introduction

RF modulation is the variation of a sinusoidal electromagnetic carrier (voltage, current or field) by a signal. The purpose of modulation is to transpose the baseband signals, which in general have neither a suitable shape nor a directly transmittable frequency, to a higher frequency, which can be emitted via an antenna.

The modulating signal may change the amplitude or the frequency/phase of the carrier or both. It may be an analogue or a digital signal, e.g. a bit stream.

The designations of the types of modulations are listed in RR Appendix 1.

Spectrum access methods define how and when a modulated signal has access to the spectrum resources. If signals from multiple sources (e. g. different users or transmitters) want to have access to the spectrum inside the same area, access methods have to be applied to allow sharing of the resource without interference.

6.6.2 Analogue modulation

6.6.2.1 Amplitude modulation

If a carrier wave with the amplitude E_C (Fig. 6.6-1a) is amplitude-modulated by a sinusoidal oscillation (a tone) a wave is obtained as shown in Fig. 6.6-1b). In these figures, the abscissa represent time and the ordinates the voltage (or current) of the wave ("time domain presentation").

The amplitude will thus change with the modulating sine wave signal, to which the envelope of the carrier wave will correspond.

If the amplitude of the modulating signal is increased, the variation in amplitude of the modulated wave will likewise increase up to the point where an instantaneous suppression of the envelope takes place, as shown in Fig. 6.6-1c).

If the maximum amplitude of the modulated wave is E_{max}, and the minimum amplitude of the envelope E_{min} (see Fig. 6.6-1b), the *modulation depth m* is given by:

$$m = \frac{E_{max} - E_{min}}{E_{max} + E_{min}} \quad \text{or expressed as percentage:} \quad m\ (\%) = \frac{E_{max} - E_{min}}{E_{max} + E_{min}} \tag{6.6-1}$$

If the amplitude of the modulating signal is increased further, the maximum amplitude of the wave will also increase, but there will be a break in the wave for a short period of time, as shown in Fig. 6.6-1d). This is called overmodulation.

In order to detect overmodulation using the equations (6.6-1), the system must be able to determine a value of $E_{min} < 0$.

Alternatively, other definitions can be used for m which are related to the average voltage E_c.

These definitions give the same values as equation (6.6-1) for sinusoidal modulation waveforms, but with the advantage that symmetry and overmodulation are defined.
Using E_{max} and E_c we get:

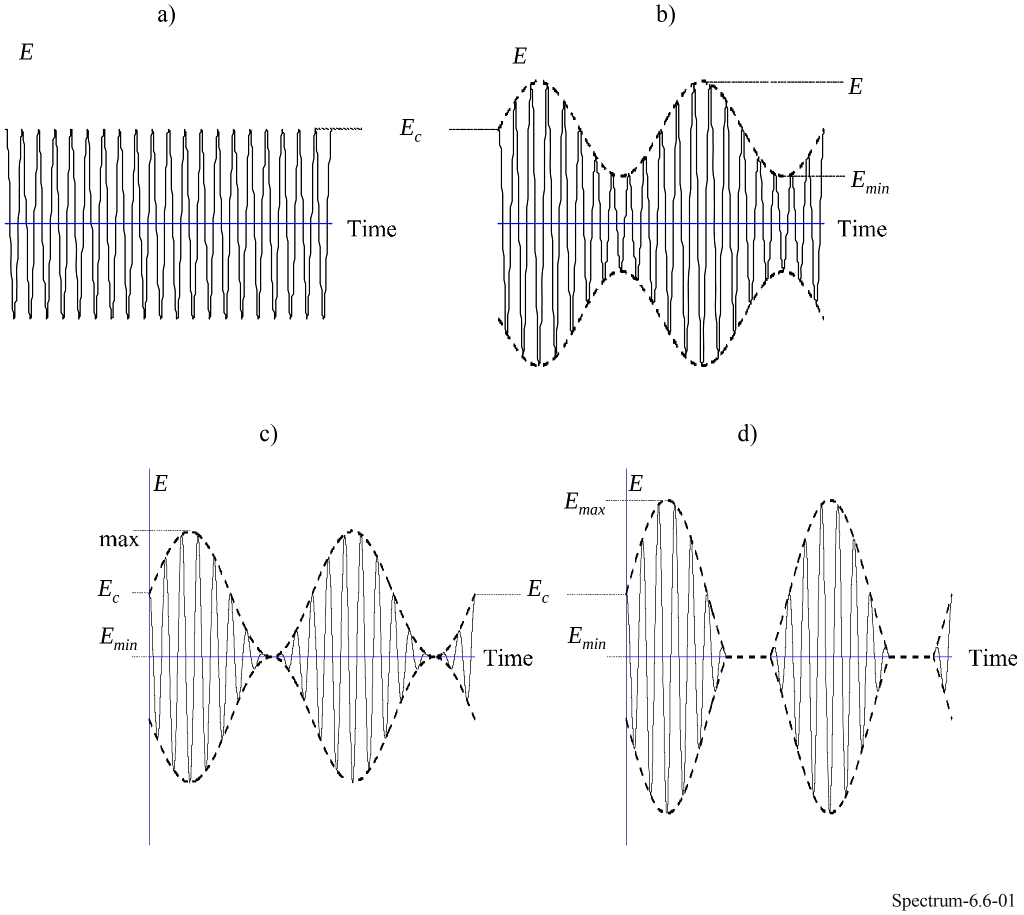
$$m_+(\%) = \frac{E_{max} - E_c}{E_c} \times 100 \tag{6.6-2}$$

Using E_{min} and E_c we get:

$$m_-(\%) = \frac{E_c - E_{min}}{E_c} \times 100 \tag{6.6-3}$$

FIGURE 6.6-1

Time domain presentation of the amplitude-modulated signal



Taking into consideration E_{max}, E_{min} and E_c we find:

$$m_{+/-}(\%) = \frac{E_{max} - E_{min}}{2E_c} \times 100 \tag{6.6-4}$$

With $m_+ = m_- = m_{+/-}$, the modulation can be considered symmetrical, i.e. the value of the carrier amplitude ($= E_c$) is not changed by modulation and the modulation percentage is < 100% in any case which means no overmodulation takes place.

The modulation is called non-symmetrical if:

$$m_+ \neq m_- \neq m_{+/-}$$

When an overmodulated signal is received, a sine wave signal with clipped peaks is given at the audio-frequency output of the receiver instead of the sine wave signal used to overmodulate the transmitter.

This leads to appreciable distortion. Overmodulation and the resulting transmission impairment should therefore be avoided; moreover, overmodulation increases the bandwidth occupied by an emission.

Figure 6.6-2 shows the amplitude-modulated signals in the frequency domain ("spectrum presentation"). The abscissa represent the frequency and the ordinates the voltage or current of the wave.

As can be seen, the carrier modulated by one sinewave signal is accompanied by two sidebands whose frequencies are $f_c + f_m$ and $f_c - f_m$, each of them having the amplitude:

$$E_m = \frac{m}{2} \cdot E_c \tag{6.6-5}$$

The *occupied bandwidth* is:

$$(f_c + f_m) - (f_c - f_m) = 2f_m \tag{6.6-6}$$

i.e. twice the frequency of the modulating signal.

Figure 6.6-2d) shows the spectrum of an overmodulated wave. Assuming that the over modulation causes distortion products up to the third harmonic of the modulating signal, the occupied bandwidth is three times the occupied bandwidth of the distortion-free modulated signal. Over modulation must therefore be avoided.

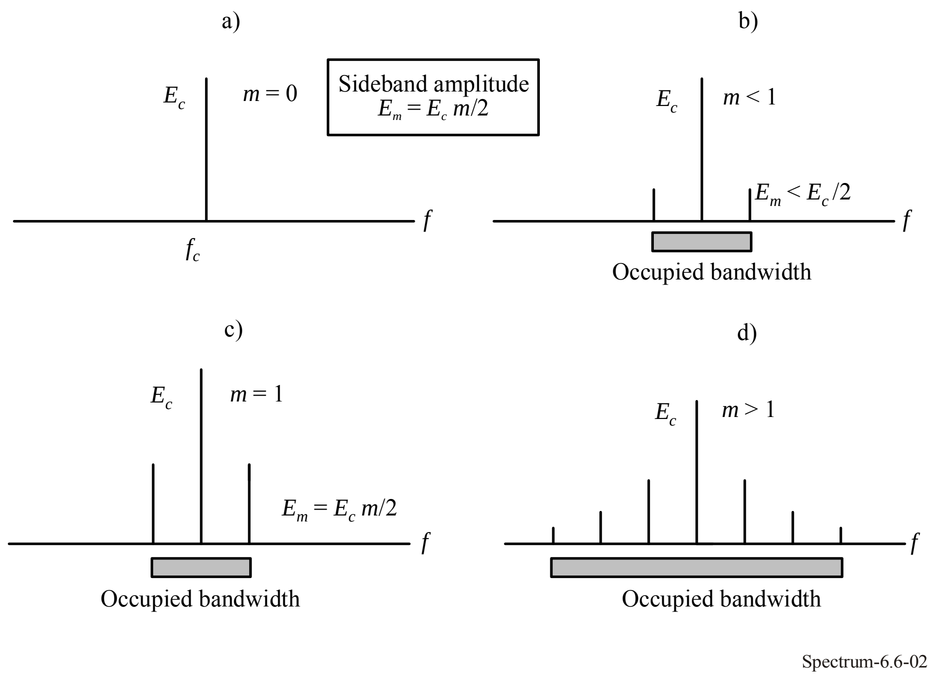
As can be seen from Fig. 6.6-1a) and 6.6-1c), the amplitude of the carrier and the occupied bandwidth remain unchanged if no over modulation occurs. Additional power is contained in the side-bands. The total power of a modulated wave is equal to the sum of carrier power and power of the sidebands. It is given by:

$$P_m = P_C\left(1 + \frac{m^2}{2}\right) \tag{6.6-7}$$

Overmodulation reduces the carrier amplitude.

FIGURE 6.6-2

Frequency domain presentation of the amplitude-modulated signal



6.6.2.2 Frequency modulation

A frequency-modulated signal is a signal whose instantaneous frequency is deviated in accordance with the modulating signal.

The wave form, for a sinusoidal modulating signal, is described by the following general equation:

$$s(t) = a * \cos[2\pi.f_c.t + m.\sin(2\pi.f_m.t)] \tag{6.6-8}$$

a is the amplitude of the frequency modulated signal, f_c is the frequency of the carrier, f_m is the frequency of the modulating signal and m is the index of modulation.

The index of modulation is proportional to the frequency deviation and is defined as:

$$m = \frac{\Delta f}{f_m} \tag{6.6-9}$$

Δf is the frequency deviation.

The frequency domain is more interesting than the time domain since it allows calculating the total energy of a frequency modulation (FM) signal.

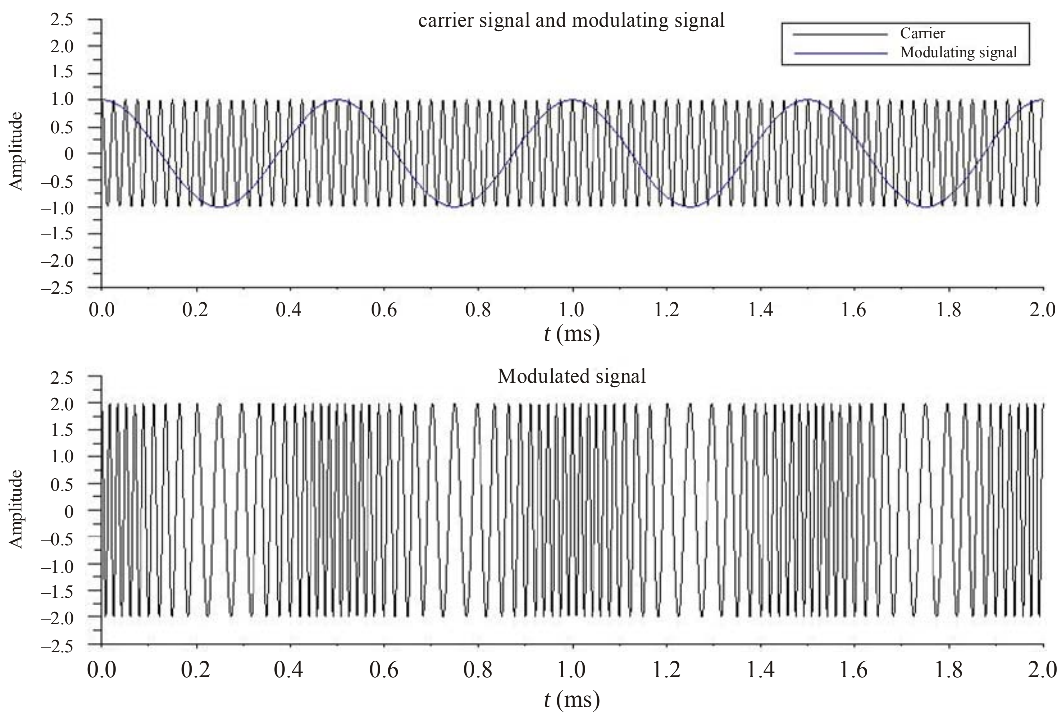
By applying fast Fourier transform (FFT) reckoning on the time domain equation, the spectrum is described by the following general relation:

$$S(\omega) = a.\sum_{k=-\infty}^{+\infty} m\left(\omega_p - k.\omega_m\right).J_k(m) \tag{6.6-10}$$

$J_k(m)$ terms are Bessel functions of the first kind which are represented below.

FIGURE 6.6-3

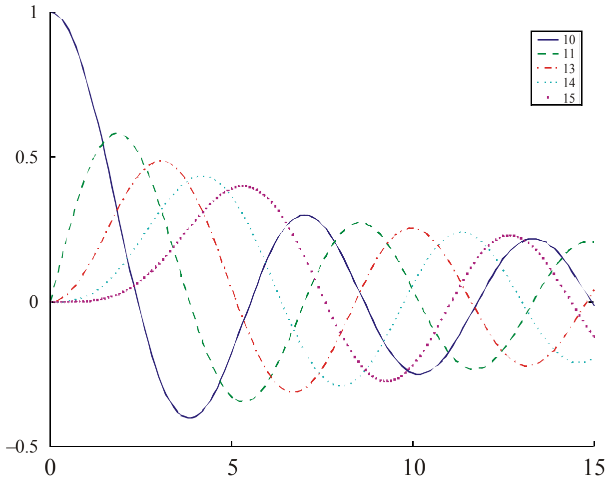
Time domain presentation of the frequency-modulated signal



Spectrum-6.6-03

FIGURE 6.6-4

Bessels function of the first kind



Spectrum-6.6-04

In theory, the FM signal is built by an infinite number of sideband pairs; practically speaking, 99% of the energy is included in a finite bandwidth which can approximately be defined as follows:

– for narrow band modulation ($m \leq 1$), the bandwidth is equal to 2 x f_m;

– if the modulating signal is a continuous or broad spectrum of frequencies, the Carson's bandwidth rule is expressed as $2(\Delta f + f_m)$ or $2 \cdot f_m \cdot (m + 1)$.

Example:

f_c = 100 MHz, f_m = 2 kHz, Δf =10 kHz, m = 5

Reckoning of the bandwidth: B = 2*2k*(5 + 1) = 24 kHz.

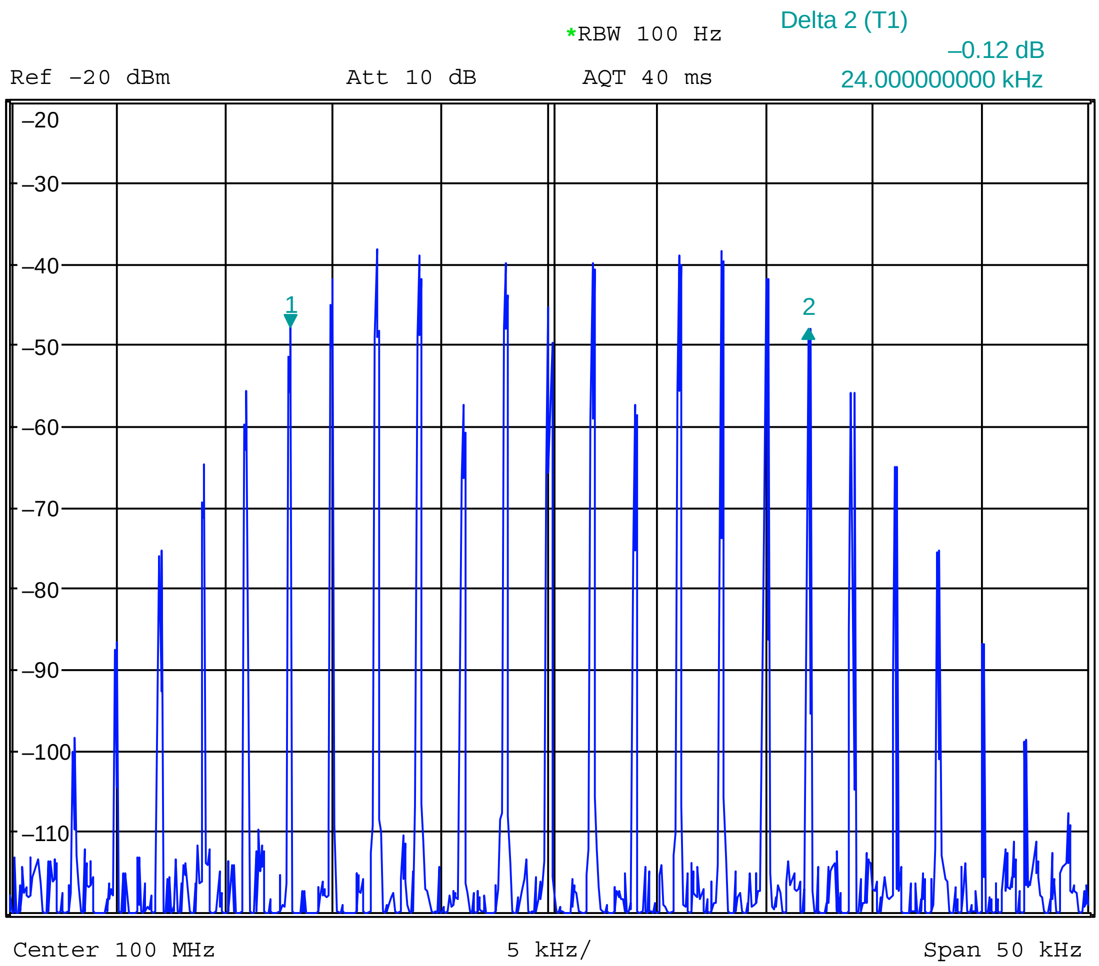
Computing of amplitude of each sideband pairs (Bessel's function for m = 5):

Frequency	**Amplitude**	
f_c	$J_0(5)$	–0.18
$f_c \pm f_m$	$J_1(5)$	–0.33
$f_c \pm 2\ f_m$	$J_2(5)$	0.05
$f_c \pm 3\ f_m$	$J_3(5)$	0.36
$f_c \pm 4\ f_m$	$J_4(5)$	0.39
$f_c \pm 5\ f_m$	$J_5(5)$	0.26
$f_c \pm 6\ f_m$	$J_6(5)$	0.13
$f_c \pm 7\ f_m$	$J_7(5)$	0.05
$f_c \pm 8\ f_m$	$J_8(5)$	0.02
$f_c \pm 9\ f_m$	$J_9(5)$	0.005

Figure 6.6-5 shows the resulting FM spectrum for the example:

FIGURE 6.6-5

Example FM spectrum



Spectrum-6.6-05

6.6.2.3 Phase modulation

Phase modulation (PM) and Frequency modulation are principally the same: Changing the frequency also changes the momentary phase of the resulting RF signal relative to the start phase of the unmodulated signal, and vice versa.

Therefore, the same formulas as for FM also apply to PM, and the resulting spectra are equal. The only difference is the way the receiver demodulates the signal to retrieve the modulating information.

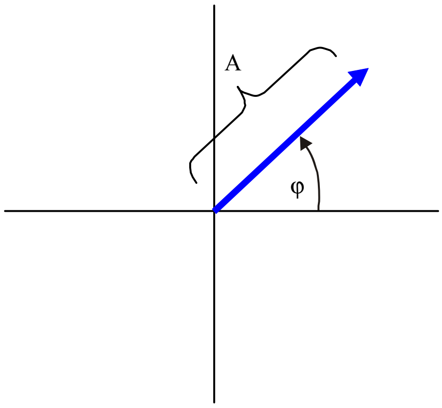
The frequency domain, however, is not suitable to symbolize phase modulation because only frequency and amplitude can be seen. A more common way to symbolize phase modulation is by using a polar diagram in which the RF signal is represented by a vector that starts at the centre. The length of the vector is the RF amplitude; the angle relative to the horizontal line is the momentary phase. Figure 6.6-6 shows an example.

An unmodulated carrier would be represented by a constant, steady vector. If the signal is frequency modulated, the vector would rotate left or right depending of the momentary frequency being lower or higher as the unmodulated carrier.

At the same time, the angle φ would also change constantly. So modulating the frequency is in fact equal to modulating the phase.

FIGURE 6.6-6

Momentary polar diagram of a phase modulated signal



Spectrum-6.6-06

6.6.2.4 Special analogue modulations

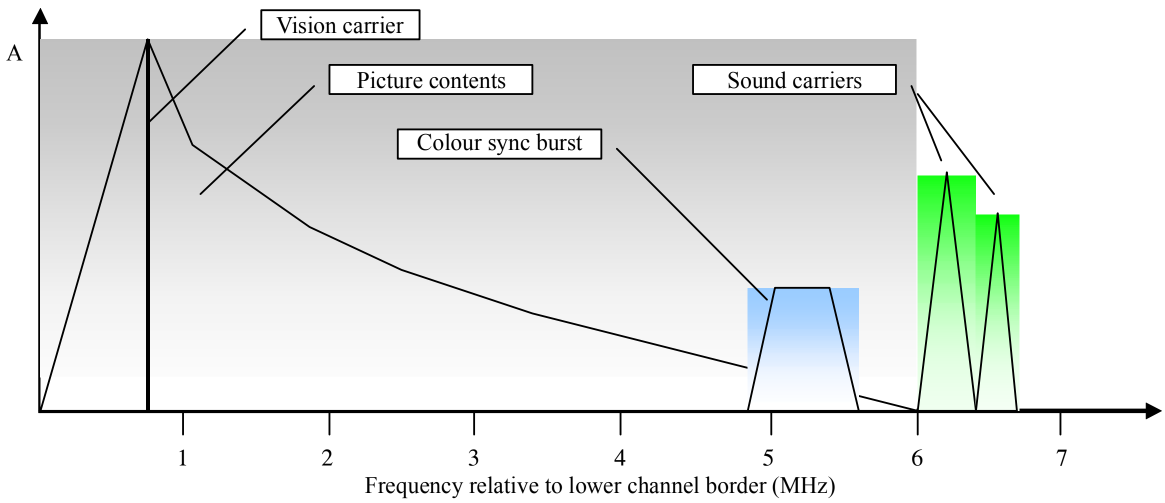
6.6.2.4.1 TV broadcast modulation

Analogue TV broadcast transmissions in the VHF/UHF bands use vestigial sideband modulation (VSB) (negative or positive) for the video signal and one or more separate sound carriers which are frequency or amplitude-modulated.

The resulting spectrum is complex and the single components as well as their amplitude and frequency spacing relative to the carrier depends on the particular standard. Figure 6.6-7 shows a simplified example of an analogue colour vision signal together with stereo sound.

FIGURE 6.6-7

Simplified PAL TV spectrum with stereo sound



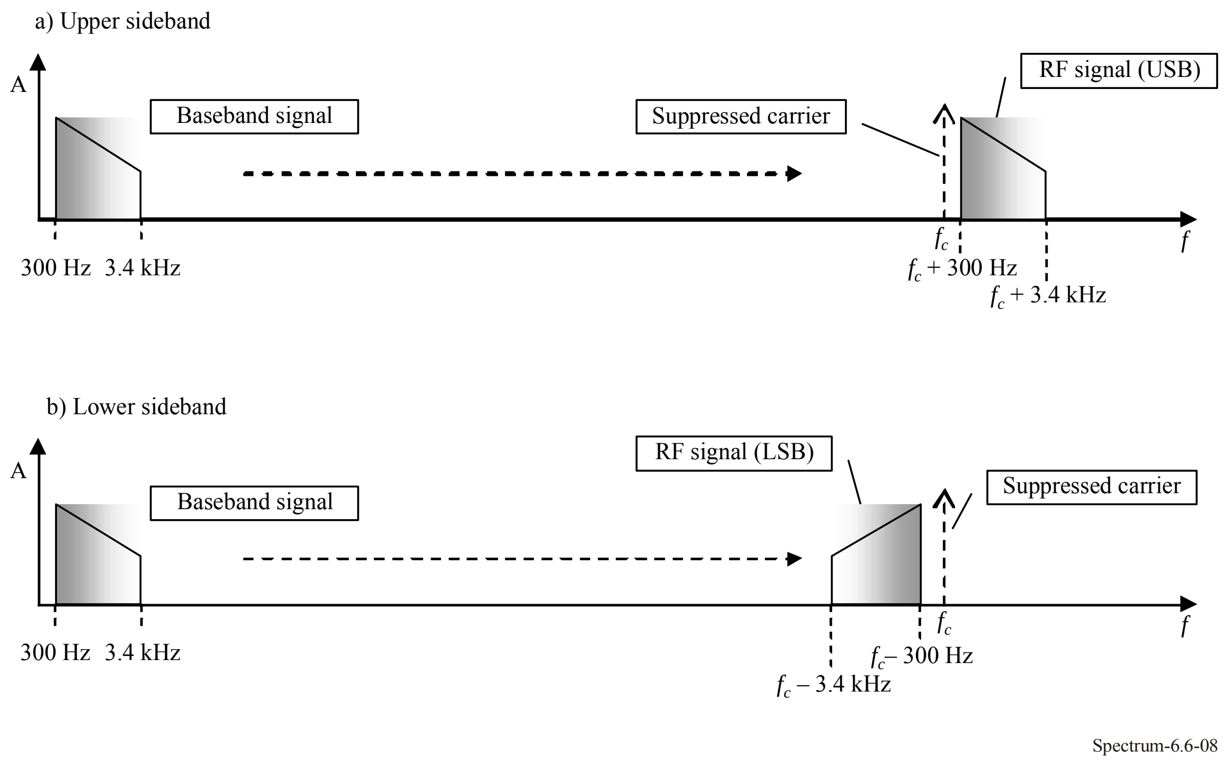
Spectrum-6.6-07

6.6.2.4.2 Single sideband modulation with suppressed carrier

Single sideband modulation with suppressed carrier (SSB or J3E) is widely used for narrow band voice transmissions. For this type of modulation the telephony baseband is only shifted (or shifted and inverted) to the assigned frequency, amplified and emitted via an antenna. In consequence, if there is no voice signal, then only the carrier remains but since it is suppressed, nothing is transmitted. Figure 6.6-8 illustrates the SSB principle.

FIGURE 6.6-8

SSB modulation principle



Generally the upper sideband is used (USB, Fig. 6.6-8a), only amateur stations use the lower sideband (LSB, Fig. 6.6-8b).

The advantage of SSB compared to standard amplitude modulation (AM) is that it uses only half of the spectral bandwidth and does not waste transmitter power by emitting the carrier.

6.6.2.4.3 Independent sideband modulation

Independent sideband modulation (ISB) with suppressed carrier (B8E) work to the same principles as SSB, only that two independent audio basebands are transmitted: baseband 1 is shifted into the upper sideband; baseband 2 is inverted and shifted to the lower sideband range of the RF.

6.6.2.4.4 Dynamic amplitude modulation

The conventional two-sideband AM transmitter is – from the point of view of power consumption – a very uneconomical device. Even at a modulation depth m = 100% only 17% of the radiated power is used for the information (one sideband), and 66% is carrier power without any information content (see equation (6.6-7)).

For lower values of m the relations are even worse. As a solution to this problem several attempts were made to reduce the carrier power dynamically at times when the modulation depth m is low (which is the fact in practice for most of the time).

One solution is called dynamic amplitude modulation (DAM), which reduces the carrier power when m is significantly lower than 100%. Evidently, this procedure saves energy.

6.6.3 Digital modulation

6.6.3.1 Principles of digital modulation

The information in digital communications is transmitted in quantized form, i.e. the amplitude and/or the phase of the signal can only have discrete values. The information to be transmitted is a data stream consisting of “ones” and “zeros”. The transmitter looks at the input bits with the speed of a so-called “clock rate”. The receiver looks at the state of the RF signal with the same clock rate and decodes the source bit(s) accordingly.

Like analogue signals, digital baseband signals have neither a suitable shape nor an appropriate frequency to be emitted via an antenna. To enable transmission in a radio channel they must first be transposed to a higher frequency by modulating a sine wave RF carrier.

The data signal containing the information influences the amplitude, frequency and/or phase of the RF carrier at the clock rate of the data signal. The clock rate is also called the symbol rate. Amplitude and angular modulation are used simultaneously in some cases.

In digital techniques the word “modulation” is frequently replaced by the word “keying”. The abbreviations ASK, FSK and PSK are used for amplitude shift keying, frequency shift keying and phase shift keying.

The advantage of digital signals is that they can be restored without any degradation by noise under certain circumstances.

6.6.3.2 Amplitude shift keying

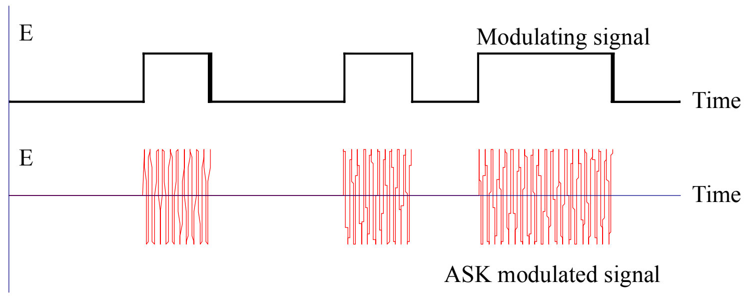
The simplest way of modulating the carrier wave with digital baseband signals is by amplitude shift keying (ASK). This is achieved, for example, by a signal, which switches the carrier on and off. If a 1 is to be transmitted, the carrier is switched on, for a “0” the carrier is off.

The classical example of this is the Morse code. If a carrier is merely switched on and off at the pulse rate of the data signal this is referred to as on-off keying (OOK).The modulating and modulated signals of this type of modulation are presented in Fig. 6.6-9.

In some cases, e.g. for standard-time signals, keying is less than 100%. This has the advantage that even when the data stream consists of multiple zeros, still some energy is transmitted so that the receiver does not lose the signal and keeps synchronized.

FIGURE 6.6-9

Amplitude shift keying



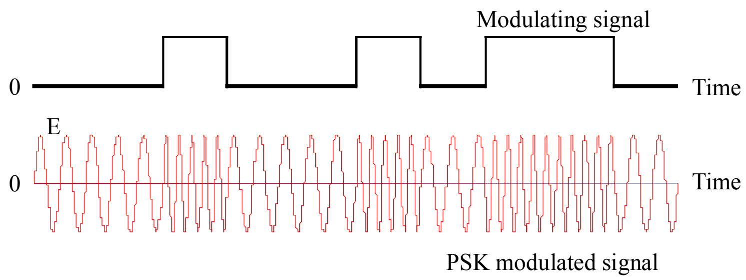
Spectrum-6.6-09

6.6.3.3 Frequency-shift keying

With FSK, the frequency of the carrier is altered according to the modulating signal: if a “1” is to be transmitted, the carrier frequency f_c is raised to f_1, during the transmission of a 0 it is lowered to f_2. The modulating and modulated signal of this type of modulation is presented in Fig. 6.6-10.

FIGURE 6.6-10

Frequency shift keying



Spectrum-6.6-10

The amplitude of the carrier wave remains constant whereas the frequency can assume two values:

$$f_1 = f_C + \Delta f \quad \text{and} \quad f_2 = f_C - \Delta f \qquad (6.7\text{-}11)$$

For successful decoding, the spacing Δf depends on the clock rate: the higher the clock rate, the higher the spacing has to be.

6.6.3.4 Phase-shift keying

A third method for modulating a carrier wave with digital signals is phase shift keying (PSK). The modulating data signal and the modulated RF signal of this type of modulation are presented in Fig. 6.6-11.

As can be seen, the level of the modulated signal remains constant, but the phase is switched (in this example) by 180° if the modulating signal changes from “0” to “1” (2-PSK).

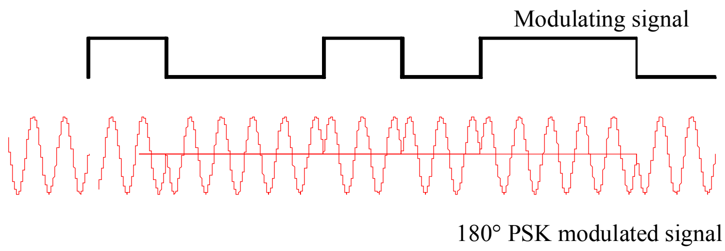
As with analogue phase modulation, the best way to symbolize PSK is a polar diagram like in Fig. 6.6-6.

However, it is most common to draw the RF vector only at those points in time where the receiver attempts to decode the signal. All possible states at that time are drawn in the same diagram.

To improve the reading, only the end points of the vectors are drawn as dots.

FIGURE 6.6-11

Phase shift keying

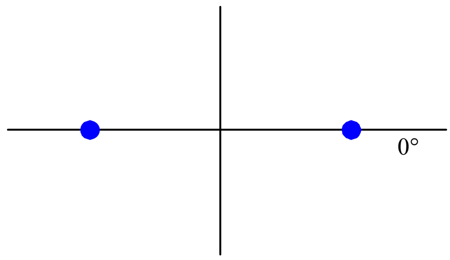


Spectrum-6.6-11

The resulting figure is called “constellation diagram”. Figure 6.6-12 shows the constellation diagram of a 2-PSK.

FIGURE 6.6-12

Constellation diagram of a 2-PSK



Spectrum-6.6-12

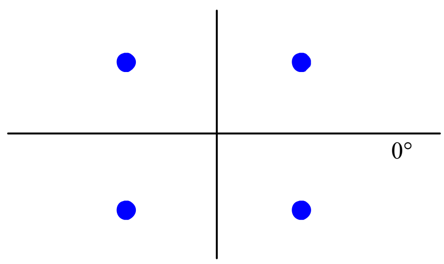
In all the examples of ASK, FSK and PSK used so far the RF carrier can only have two allowed states at the time of decoding (ASK: carrier "on" or "off", FSK: frequency f_1 or f_2, PSK: phase "0°" or "180°"). These systems can therefore transmit one bit of source data per step. In these cases the clock rate and the bit rate are equal.

If we define more than two distinct states of the RF carrier, it is possible to transmit the information contained in two or even more bits in one step. An example is the so-called 4-PSK or Quadrature Phase Shift Keying (QPSK). The phase of the RF carrier at the decoding time can be 45°, 135°, 225° or 315°. The constellation diagram is shown in Fig. 6.6-13.

Each of the four constellation points represents two source bits. The bits that are transmitted in one step are called symbol. The connection between symbol and RF state (constellation point) is established through a coding scheme:

FIGURE 6.6-13

Constellation diagram of a QPSK



Spectrum-6.6-13

TABLE 6.6-1

Example of a coding scheme for QPSK

Symbol (source bits)	RF carrier phase
00	45°
01	135°
10	225°
11	315°

The number of symbols that are transmitted in 1 s is called the symbol rate. The RF carrier keeps changing its state with the speed of the symbol rate, but in the example of QPSK the bit rate is twice the symbol rate. This principle allows increasing the bit rates without increasing the bandwidth because that only depends on the symbol rate. However, because the constellation points in QPSK are closer together as they are in 2-PSK, a higher signal-to-noise ratio is required for QPSK, making this modulation not as robust as 2-PSK.

Modern digital systems use up to 8-PSK modulation to combine 3 bits to a symbol.

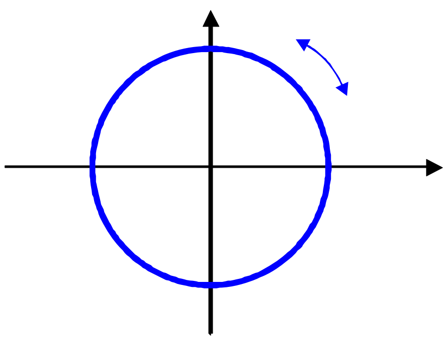
6.6.3.5 Minimum shift keying

Although all constellation points of a PSK signal have the same amplitude, this parameter is not constant for the whole time when the signal bandwidth is limited by filtering: On its way from one constellation point to the next, the length of the momentary RF vector changes and hence the RF amplitude. For example in a 2-PSK like in Fig. 6.6-2, the direct way between the constellation point 0° to the opposite one at 180° is by going through the centre of the diagram. At that moment, the RF amplitude would even be zero.

An alternative way of modulating the RF phase (or frequency) is by going on a circle and keeping the amplitude constant. The information to be transmitted is then coded into the direction with which the RF vector rotates. The receiver only has to detect the rotation direction in order to decode the signal (e. g. left = 0, right = 1). As mentioned in § 6.6.2.3, rotating the RF vector is equal to rising or lowering the RF frequency. In order to detect the vector rotation correctly, the minimum possible change in the vector's angle between two steps (bits) is 90°. This modulation is called minimum shift keying (MSK). Figure 6.6-14 shows the "constellation" diagram of an MSK which is a circle, because the actual angles of the vector at each time of decoding are not defined.

FIGURE 6.6-14

MSK constellation diagram



Spectrum-6.6-14

Major advantages of MSK against PSK are that cheaper equipment can be used (e. g. linear amplifiers at the transmitter and simpler receivers), and that the RF signal is always present allowing continuous receiver synchronization and very low *S*/*N* ratios.

6.6.3.6 Quadrature amplitude modulation

When more than 3 bits have to be combined to a symbol, PSK is not ideal because the constellation points would come too close together, requiring more and more *S*/*N*.

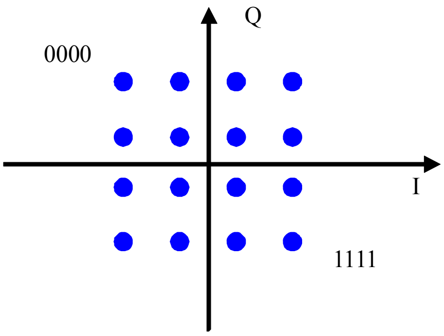
Instead, both amplitude and phase of the constellation points is altered in a way that the constellation diagram is a square, evenly filled with constellation points. An example of 16-QAM is shown in Fig. 6.6-15.

In a 16-QAM, 4 bits are combined to a symbol. If enough *S*/*N* can be assumed (for example in cable transmissions), 256-QAM with 8 bits per symbol are common and up to 1 024-QAM with 10 bits/symbol are sometimes used.

Modern transmitters employing digital signal processors (DSP)s do not actually alter the amplitude and phase of the RF carrier directly. Instead, the transmitted RF signal is composed of two component audio frequency (AF) signals amplitude modulating two RF carriers of the same frequency that have a constant phase offset of 90°. The components are called inphase (I) and quadrature phase (Q). In Fig. 6.6-15 the axes are labelled I and Q accordingly. Each constellation point can be reached by changing (modulating) the amplitude of each component to a certain value.

FIGURE 6.6-15

Constellation diagram of a 16-QAM



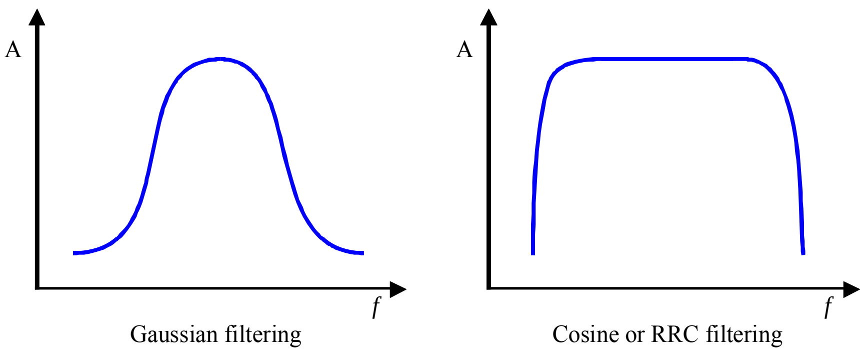
Spectrum-6.6-15

6.6.3.7 Baseband filtering for single carrier modulations

The digital modulating signal consisting only of "ones" and "zeros" has a rectangular time domain representation. If the RF signal would follow the digital data signal exactly, the resulting vector would have to change states (amplitude, frequency or phase) immediately each time the data signal has a slope. This would result in very broadband, radar-like RF spectra. Because the receiver only expects the RF vector to be on one of the constellation points at the time of decoding, it is possible to change states slowly in the time between two steps. This can be done by applying a low pass filter before the modulation process (i. e. in the baseband). The effect is that sharp edges in the time signal are avoided and the resulting RF bandwidth is reduced considerably. Due to certain constraints (no interference between one symbol and the next), only Gaussian and raised cosine filters can be used. Some systems split the cosine filter in a way that half of the filter is applied in the transmitter while the other half is applied in the receiver. These "half cosine" filters are called "Root Raised Cosine" or RRC filters. Figure 6.6-16 shows the spectrum shape of digital single carrier signals after the baseband filtering.

FIGURE 6.6-16

Spectra of filtered digital single carrier signals



Spectrum-6.6-16

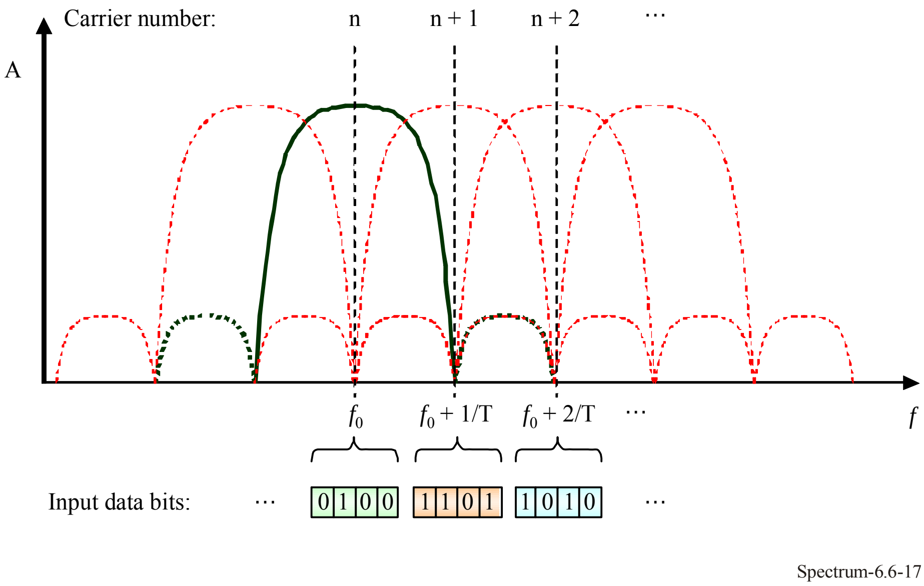
6.6.3.8 Orthogonal frequency-division multiplex

Orthogonal frequency-division multiplex (OFDM) is a method of combining a large number of digitally modulated carriers to form an ensemble [Carlson, 1986], [Lymer, 1994]. Depending on its modulation, each carrier is modulated with the information contained in a number of bits (usually 4 or 6). The input data stream is therefore split in as many groups as there are OFDM carriers (up to a few thousand). Because all carriers are transmitted at the same time (in one step), the symbol size of an OFDM system is extremely high (several kbits), allowing very slow symbol rates while still maintaining a high useful data rate.

When the reference phase of neighbouring carriers has an offset of 90°, the carrier spacing can be as low as the symbol rate. Then spectra of the modulated carriers overlap without influencing the decoding of the neighbouring carriers. Figure 6.6-17 illustrates the forming of OFDM ensembles. The example uses 16-QAM modulation of the carriers, so that each carrier is modulated with a group of four bits.

FIGURE 6.6-17

OFDM carriers with 16-QAM modulation



The complete OFDM signals are generated using an inverse FFT and demodulated using a FFT.

Due to the overlapping spectra of the modulated carriers, the resulting complete OFDM spectrum has a rectangular shape like in Fig. 6.6-18 with a noise-like top line. The single carriers are not distinguishable.

As an example, one of the digital video broadcasting – terrestrial (DVB-T) systems used in Europe has 6 817 carriers, modulated with 64-QAM, each carrying 6 bits of information per step. The total symbol size is then:

$$6 * 6\,817 = 40\,902 \text{ bits}$$

The carrier spacing is 1,11 kHz, fixing the symbol rate to 0.9 ms. The gross data rate of this system is therefore:

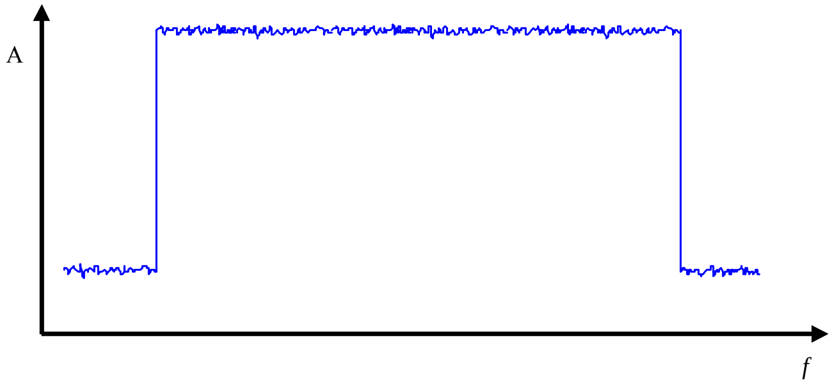
$$40\,902 \text{ bits} / 0.9 \text{ ms} = 45.447 \text{ Mbit/s}$$

Because the input data is spread over so many carriers, the system is very robust against frequency-selective fading and interference. Even if several carriers are unusable, data from the remaining carriers are still decidable.

If intelligent forward error correction (FEC) is applied, the receiver may still be able to reconstruct the whole symbol.

FIGURE 6.6-18

OFDM spectrum (principle)



Spectrum-6.6-18

The low symbol rate allows introducing a relatively long “guard interval”. This is additional time in front of each symbol where information is repeated. The receiver can wait for the guard interval to pass before it starts the decoding process. If echoes from multipath reception arrive at the receiver before the guard interval has passed, they can improve the reception by adding up to the direct signal.

If the input data has a regular pattern, situations may arise where all (or at least many) of the carriers have equal phase and amplitude. Due to the high number of carriers in the ensemble, this would result in extremely high peaks of the total level to be transmitted. The output stages of an OFDM transmitter would have to be dimensioned for this peak level, whereas the average level affecting the coverage would be much lower.

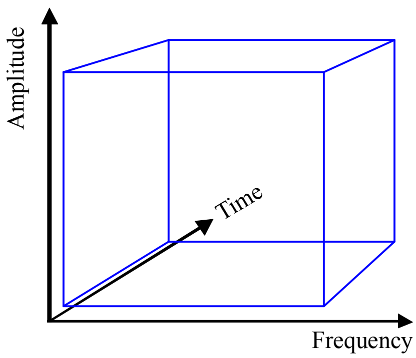
To prevent this from happening, the data stream is coded before transmission in a way that the resulting signal is always noise-like. The abbreviation for such systems is then COFDM for coded orthogonal frequency-division multiplex.

6.6.4 Spectrum access methods

The total capacity of a transmission channel can be symbolized as a cube in a three-dimensional Cartesian diagram like in Fig. 6.6-19.

FIGURE 6.6-19

Capacity of a transmission channel



Spectrum-6.6-19

The amount of information that can be transmitted is limited by three parameters:

– *Time:*

It is quite obvious that the more time we have, the more information can be transmitted.

– *Frequency or bandwidth:*

The digital modulations presented all have a dependency between symbol rate and resulting RF bandwidth. So if we have more bandwidth available, we can modulate with a higher symbol rate and transmit more useful data (bits/s).

– *Level or signal-to-noise and signal-to-interference ratio:*

If we increase transmitter power, improving the signal- to-noise or signal-to-interference ratio at the receiver, we can use a higher modulation scheme that combines more bits per symbol (e. g., 64-QAM instead of 16-QAM). This also allows more useful bits to be transmitted in the same time.

In many practical systems, more than one user (or station) needs access to the transmission channel and its resources. Example: a cellular phone system where many persons want to telephone at the same time within the range of a base station.

The optimum usage of the channel capacity would be if the cube in Fig. 6.6-19 is completely filled without gaps. However, the system has to be organized in a way that multiple users can have access to the resources. The spectrum access methods to organize this are called multiple access modes.

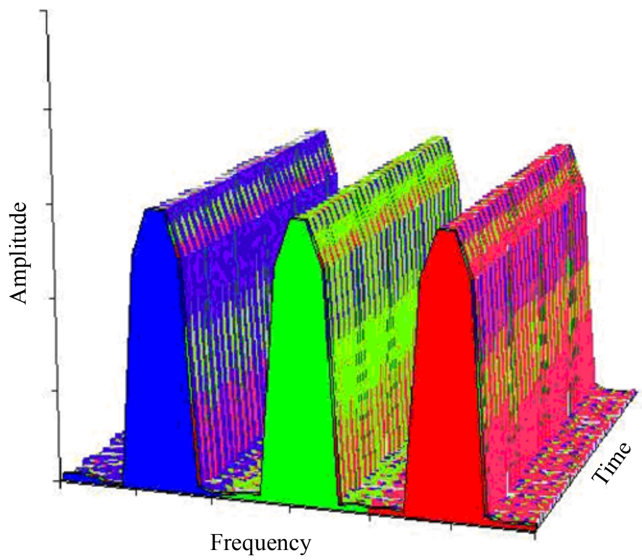
6.6.4.1 Frequency-division multiple access

Frequency-division multiple access (FDMA) is the simplest multiple access method and works also in analogue systems. Each user gets a different frequency on which he can use a certain part of the available spectrum continuously. The principle is illustrated in Fig. 6.6-20.

Because the selection filters of real receivers are not rectangular, a certain frequency spacing has to be maintained between the emissions of each user. Due to this requirement, there are "gaps" in the frequency domain that cannot be used for data transmission. The capacity cube of the transmission channel is not fully used.

FIGURE 6.6-20

Frequency-division multiple access



Spectrum-6.6-20

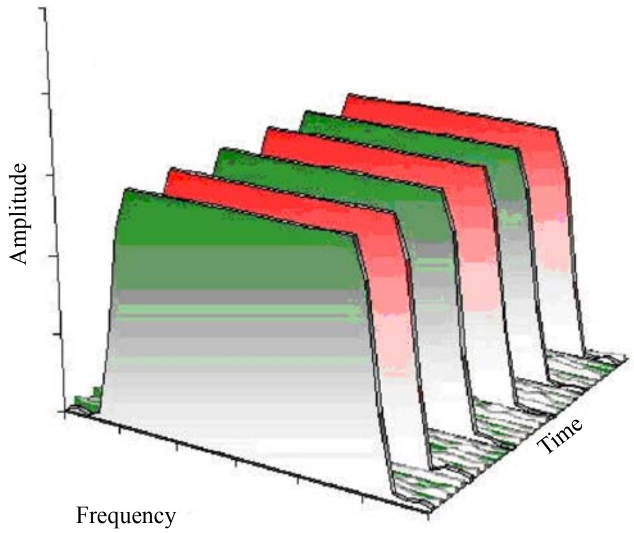
6.6.4.2 Time-division multiple access

Digital transmission has the advantage that the data can often be transmitted faster than the data source supplies it. In our example of the cellular phone system, continuous speech is digitized and split in time block of a certain length. If the transmission speed permits, data in these blocks can be transmitted in bursts, leaving unused time in which other users can transmit their data. So this system divides the available time among the users, hence the name "time-division multiple access" (TDMA). Each user transmits his data in so-called "time slots", using the full bandwidth of the transmission channel. Figure 6.6-21 illustrates this principle.

If one of the users is far away from the common receiver (e. g. base station), his signal will arrive relatively late due to the limited speed of light and his emission may reach into the next time slot belonging to a user may that is close to the common receiver. To avoid interference, guard times must be inserted during which no user is allowed to transmit. Therefore there will be "gaps" in the time domain where no data can be transmitted. So also with TDMA, the capacity cube of the transmission channel is not fully used.

FIGURE 6.6-21

Time-division multiple access



Spectrum-6.6-21

6.6.4.3 Spread spectrum

FDMA and TDMA signals are generally susceptible to interference and therefore require time or frequency coordination between users. Spread spectrum signals are much less susceptible to interference and are often described as power-sharing signals. Multiple spread spectrum signals may simultaneously occupy the same spectrum.

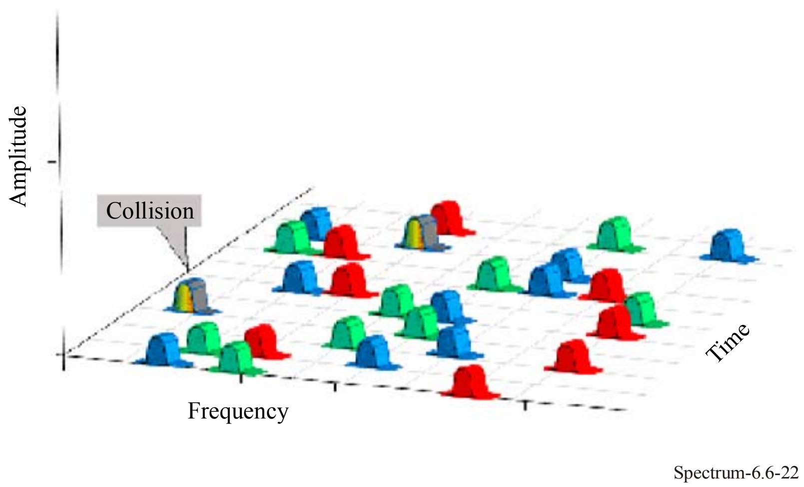
Spread spectrum signals are created when a narrowband signal is modulated to occupy a larger bandwidth (spreading). As the spreading process does not increase power, power spectral density is decreased, making non-coherent signal detection more difficult. For example, the signal will be harder to observe in a power-spectrum measurement. The effects of interference from other signals are minimized in the spread-spectrum receiver when the signal is despread. The two most common techniques for creating a spread spectrum signal are frequency hopping (FHSS) and direct-sequence (DSSS).

6.6.4.3.1 Frequency hopping spread spectrum

As the name implies, frequency hopping spread spectrum (FHSS) signals are created by periodically changing the transmission frequency. Receivers must know, or recover, the timing and frequency hopping pattern to demodulate the signal. To minimize interference, different radios will have different frequency-hop sequences, or will be at different phases in a long sequence. The hop sequences may not be coordinated or time synchronized between transmitters resulting in occasional collisions as indicated by the higher power rainbow spectrums in the three-transmitter example illustrated in Fig. 6.6-22. Error correction codes are typically used to recover data lost during these brief periods of interference. Because the signals are harder to detect, and are more robust against interference, FHSS signals are often used in military applications. FHSS signals are also found in unlicensed spectrum where coordination between users is difficult. Coordinated frequency hopping is also part of the Global System for Mobile communications (GSM) cellular standard.

FIGURE 6.6-22

Frequency hopping spread spectrum



6.6.4.3.2 Direct sequence spread spectrum

Direct sequence spread spectrum (DSSS) signals are broadband signals created from narrowband signals by modulating a low-data rate sequence or modulation, with a higher data-rate sequence or modulation. For example, a low-rate data sequence may be combined with a high-rate sequence using an exclusive OR (XOR) function. Alternatively, a low-rate binary phase shift keying (BPSK) modulation might be modulated with a high-rate QPSK modulation using a complex multiplication, or mixing operation. The binary sequence used for the higher-rate sequence, or modulation, is often referred to as a spreading code, scrambling code, or key. The spreading code may be long or short, and may be a specialized sequence, such as a Barker code, or a more general sequence which might be obtained from a psuedo-random number (PRN) generator.

The despreading process in the receiver recovers the original narrowband signal. Other unwanted signals will be spread by the despreading process, but are not completely removed and will appear as broadband noise in the receiver. Much, but not all of the interfering signal's energy is removed using narrowband filters (usually in the form of integrators). Figure 6.6-23 illustrates the power-sharing concepts of DSSS. In the figure, TX1 is higher power. This results in higher levels of interference from TX1 in RX2. CDMA systems constantly adjust the transmitted power to balance performance amongst all system users.

6.6.4.4 Code-division multiple access

In order to avoid unused "gaps" in the transmission capacity cube (see Fig. 6.6-19), the user data can be digitally "modulated" on to a so-called "key" which is a fixed bit sequence. This modulation is a logical "XOR" operation on each bit of the user data. As a result, instead of a "1", the key is transmitted, instead of a "0", the inversed key is transmitted. Figure 6.6-24 illustrates this principle with an example of a key that is 4-bit long.

The receiver operates in the same way: always groups of 4 bits (example) are compared with the key. The result is always "1111" or "0000". These 4-result bits are then "averaged" to form the actual output bit. This process is illustrated in Fig. 6.6-25.

FIGURE 6.6-23

Direct sequence spread spectrum

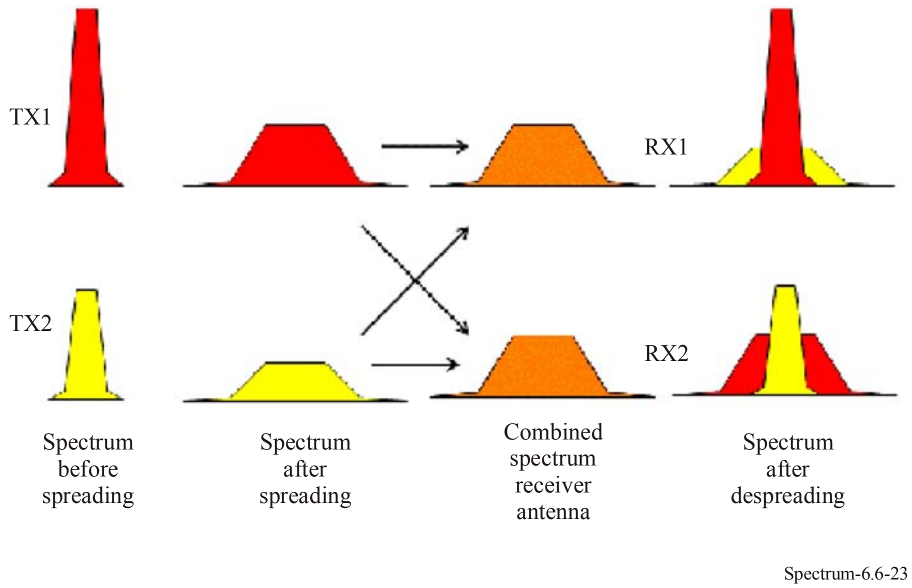


FIGURE 6.6-24

Digital modulation with a CDMA key

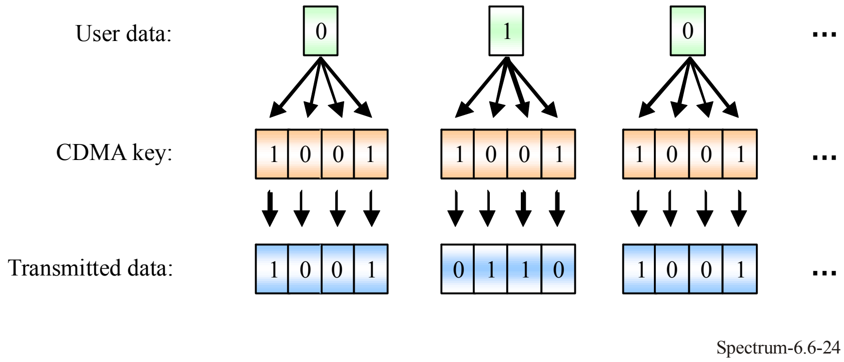
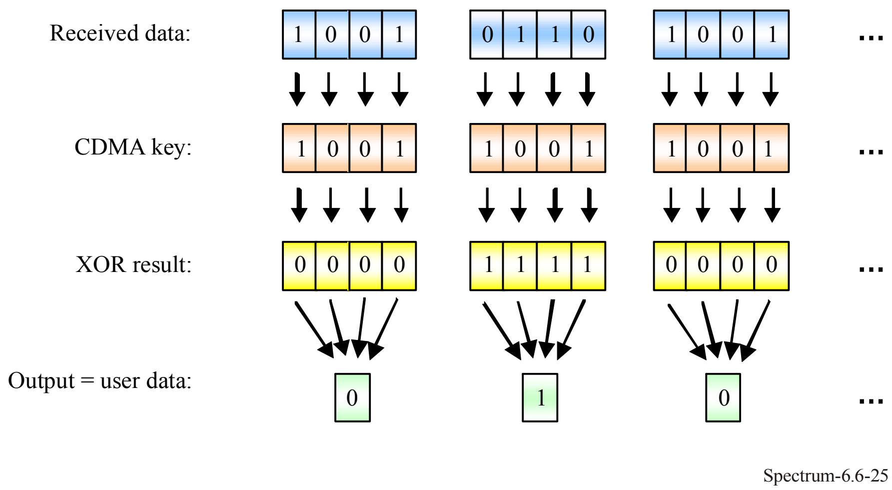


FIGURE 6.6-25

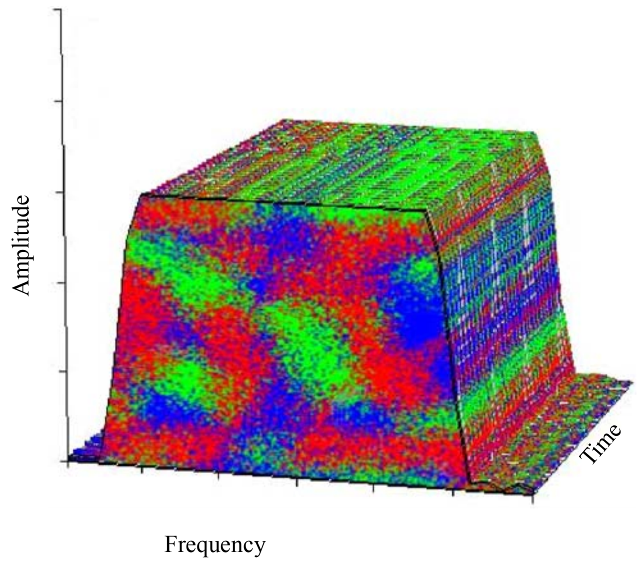
CDMA reception with correct key



Because the amount of data to be transmitted is much higher (by the factor of the key length) than the user data, the transmission speed must also be higher, resulting in much more required bandwidth. Our Example with a 4-digit key creates a data stream that is four times as fast as the user data stream. To transmit this amount of data with the same modulation parameters, the symbol rate has to be 4 times higher resulting in a 4 times wider bandwidth. If certain mathematical requirements are fulfilled by the keys, then the "redundancy" of user data at the receiver can be used to allow very high error rates before the signal is detected incorrectly. In such a system, up to four stations, each using a different 4-digit key, can transmit at the same time on the same frequency, and still the receiver is able to filter out "his" signal from all the others. The "trick" is to design the different keys used in such a way that the XOR comparison with a block coded with any "wrong" key has equal number of "1" and "0", so that the integration over the whole block is in the middle between "0" and "1". A 4-bit sequence supports up to four data channels. Four 4-bit keys which meet the described requirements are: 1111, 1100, 1010, and 1001. Four data streams spread with these keys are summed together for transmission. The received signal is separated back into four independent data streams in the receiver using the same keys to despread the composite signal. The gross spectrum efficiency of CDMA is better than FDMA and TDMA, because the transmission capacity cube has no gaps. This is illustrated in Fig. 6.6-26.

FIGURE 6.6-26

Code-division multiple access



Spectrum-6.6-26

In the case where signals from multiple users can be controlled so as to arrive at a receiver with proper time-alignment, it is possible to eliminate the mutual interference between users through the use of orthogonal spreading codes, or keys. Proper time alignment is required as the spreading codes are only orthogonal (non-interfering) when time aligned. With orthogonal spreading codes, users are not sharing power, but are instead sharing a code space, hence the term "code-division multiple access" (CDMA). Cellular CDMA systems use both orthogonal spreading codes to separate data streams (traffic and control channels) in a sector, and non-orthogonal (cover) codes to separate base stations and mobiles.

As cellular systems use non-orthogonal spreading codes to separate transmitters (base stations and mobiles), optimal performance requires that signals from all users arrive at the receiver with nearly the same field strength. In a real environment like in our cellular phone network example, this is not possible unless all transmitters are constantly adjusting their transmit power according to the information given to them by the common receiver (base station). This requires a fast organisation channel that can occupy a considerable part of the available data rate, reducing the net rate for user data. Once the signal from a single transmitter has been isolated by first despreading with the non-orthogonal cover code, the independent data channels can be subsequently separated and recovered using the orthogonal codes (keys).

6.6.4.5 Spatial multiplex (SDMA) and spatial channels

Location is a fourth dimension which can extend the channel capacity model in Fig. 6.6-19. Two obvious and simple examples come from traditional cellular systems where spectral resources are re-used at multiple locations according to a frequency, or code re-use pattern, or where directional antennas are used to allow re-use at different angles (sectors).

In reflective environments with significant multipath, it is possible take advantage of the multipath to create multiple spatial channels which can then be used to increase data capacity, increase robustness, or to support more users.

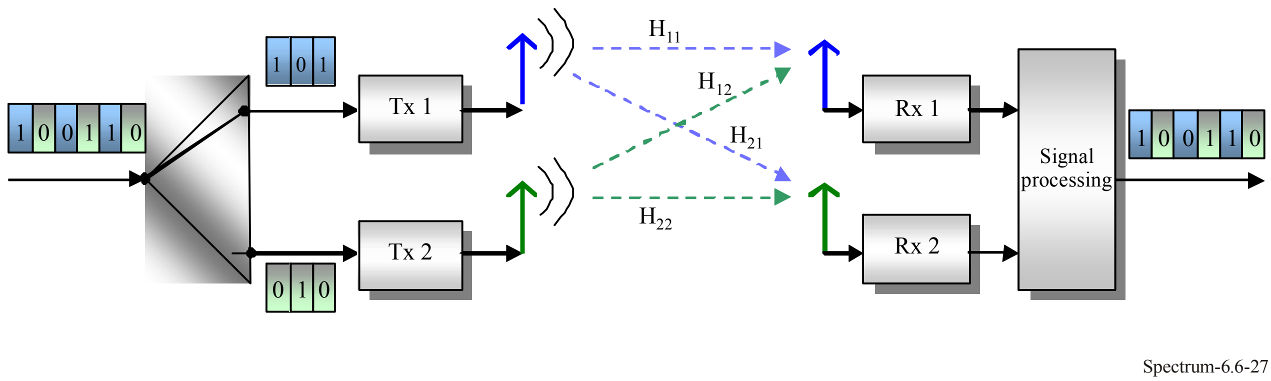
Close-spaced antenna arrays combined with gain and phase modulation on each antenna allow maximum energy to be delivered to one location, while minimizing it at another. This is often referred to as spatial-division multiple access (SDMA). A simple example would be beam steering and null steering, which is effective in non-reflective environments. One user's beam would be pointed in the direction of that user, while nulls would be steered to prevent the first user's signal from interfering with other users. SDMA also works in reflective environments, though the radiation pattern is much more complicated, and knowledge of the channel is required to create the steering vector. The steering vector is the collection of magnitude and phase adjustments applied to the signal fed to each antenna.

Closely related to SDMA is multiple input, multiple output (MIMO) which refers to a system employing multiple transmit antennas and multiple receive antennas. MIMO radio systems use wide-spaced antenna arrays to minimize correlation between antennas. The wide spacing generally precludes beam-forming. Wide antenna spacing and other factors such as polarization can increase the number, or quality of the spatial channels.

The theoretical increase in the capacity of a MIMO system is determined by the number of transmit and receive antennas. A 2x2 MIMO system, as illustrated in Fig. 6.6-27 could theoretically have as much as twice the capacity of a radio system employing only one transmit and one receive antenna; a 3x3 MIMO system could have triple the capacity.

FIGURE 6.6-27

Multiple Input, Multiple Output



MIMO techniques are included in the LTE, WiMax and WiFi (802.11n) standards.

The concept is similar to running a second pair of wires to double the capacity of a cable. Of course wires generally have good isolation between cable pairs, whereas in MIMO radio systems, the received signal at each receive antenna is a linear 1combination of the transmitted signals. This would be similar to a cable with significant amounts of crosstalk between wire pairs. In a MIMO system the cross-talk terms, H_{12} and

H_{21} illustrated in Fig. 6.7-27 may be non-zero without causing a loss of capacity. What is important is the condition of the channel matrix [H]. Provided the multipath causes the received signals Rx1 and Rx2 to contain significantly different linear combinations of the Tx1 and Tx2 signals, then the original data streams can be recovered. For example, if the two received signal streams are Rx1 = (Tx1+Tx2) and Rx2= 2*(Tx1-Tx2), then we can recover Tx1 by summing the two received signals using 0.5*Rx1 + 0.25*Rx2. Tx2 can be similarly recovered. Alternatively, if the MIMO system is in a non-reflective environment, both receivers could see the same linear combination of signals (e.g. Rx1=Tx1+Tx2 and Rx2=0.9*(Tx1+Tx2)). In this situation, while the two received signal levels may be different there is only one spatial channel. Tx1 and Tx2 cannot be independently recovered through any linear combination of the received signals.

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ITU-R Recommendations and Reports

NOTE – In every case, the latest edition of the Recommendation and Report is encouraged to be used.

Recommendation ITU-R SM.328 – Spectra and bandwidth of emissions.

Recommendation ITU-R SM.1541 – Unwanted emissions in the out-of-band domain.

Report ITU-R SM.2048 – Use of the *x*-dB bandwidth criterion for determination of spectral properties of a transmitter in the out-of-band domain.

6.7 Fast Fourier transform

6.7.1 Basics

Whenever a signal is to be transformed from time domain into frequency domain, a mathematical method called Fourier transformation can be used.

This method is based on the fact that any real signal, irrespective of its waveform, can be constructed by adding up a number of sine wave signals of different amplitudes, frequencies and phases. Consequently, any received time signal can be broken up into a number of different sine waves in the frequency domain.

Whereas the Fourier transform method at first sight seems to be the best way to solve all signal analyzing problems, there are certain restrictions as well as measurement uncertainties which originate from both the necessary analogue-to-digital conversion process and the Fourier Transform itself. To understand these restrictions, a short look into the principles is necessary.

Jean Baptiste Joseph, Baron de Fourier, proved in 1822 that each time variable phenomenon can be seen as an addition of a number of sinusoidal frequency components, each with their own amplitude and phase.

He presented this in Fourier series for periodic and band limited signals, presented in a common form in equation (6.7-1).

$$x(t) = \sum_{k=-N}^{N} C_k e^{j(\omega_k t)} \qquad (6.7\text{-}1)$$

The Fourier series are only valid for periodical signals that have a mutual harmonic relation with each other, but in practice a non periodical signal is much more common. The number of components that composes the waveform becomes infinite. This changes the equation to an integral form as:

$$x(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} X(\omega) \cdot e^{j(\omega t)} \mathrm{d}\omega \tag{6.7-2}$$

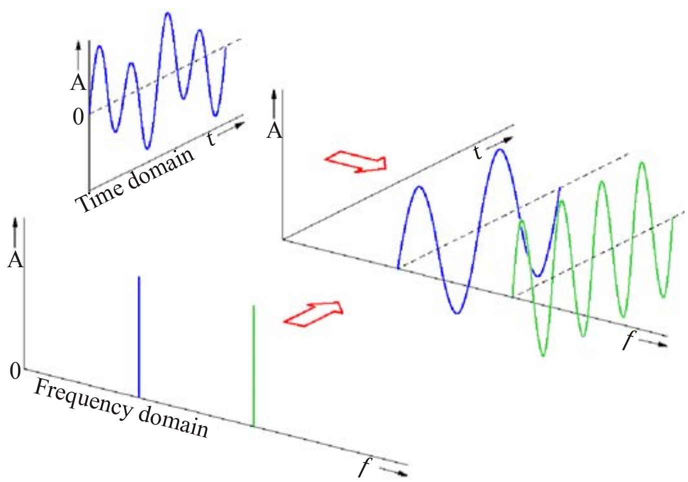
The inverse function of this equation can be written as:

$$x(\omega) = \int_{-\infty}^{\infty} X(t) \cdot e^{j(\omega t)} \mathrm{d}t \tag{6.7-3}$$

This last equation makes it theoretically possible to calculate the complex spectrum of a continuous signal in the frequency domain with the use of its time domain waveform.

FIGURE 6.7-1

Time and frequency domain



Spectrum-6.7-01

Unfortunately the method is not suitable for the calculation of the spectrum of arbitrary signals. While the signals are continuous and the integration should be carried out from minus infinity to plus infinity, it would require an infinite computing capacity. The problem can be resolved by making the signal discrete in time by sampling and introducing the discrete Fourier transform (DFT). If a signal has a limited bandwidth it can be characterized by its samples taken in the $n \cdot T_s$ time instances,

where:

- n: an integer number running from 0 to $N - 1$,
- T_s: the period of sampling
- N: the total number of the samples (see § 6.7.2).

Applying the DFT algorithm for this N element array of time domain samples, it provides an N element array of frequency domain components.

The formula of the DFT is:

$$X[k] = \frac{1}{N} \sum_{n=0}^{N-1} x[n] \cdot e^{-j\frac{2\pi kn}{N}} \tag{6.7-4}$$

The inverse of it is:

$$x[n] = \sum_{k=0}^{N-1} X[k] \cdot e^{j\frac{2\pi kn}{N}} \tag{6.7-5}$$

$X[k]$ denotes the value of the spectral component at the frequency of $k \cdot f_0 = k\frac{1}{N \cdot T_s}$, while x[n] denotes the value of the time domain signal in the $n \cdot T_s$ time instance.

The combination of both equations is called the DFT pair.

A DFT can process blocks of samples of arbitrary length. However, if the block has a length that is a power of 2, the calculation can be performed in a much faster way. This is called Fast Fourier transform or FFT.

Before the mathematical Fourier transform can be applied, a certain amount of data representing the waveform has to be stored in memory as a so-called “time record” or “frame”. The minimum duration of this time record is the period of the lowest frequency to be processed. The time this takes is called collection time or acquisition time. Then the whole waveform is analyzed in one go and mathematically converted into a series of sine waves of different amplitudes, frequencies and phases. The result is an analysis of the whole spectrum part at a certain point in time.

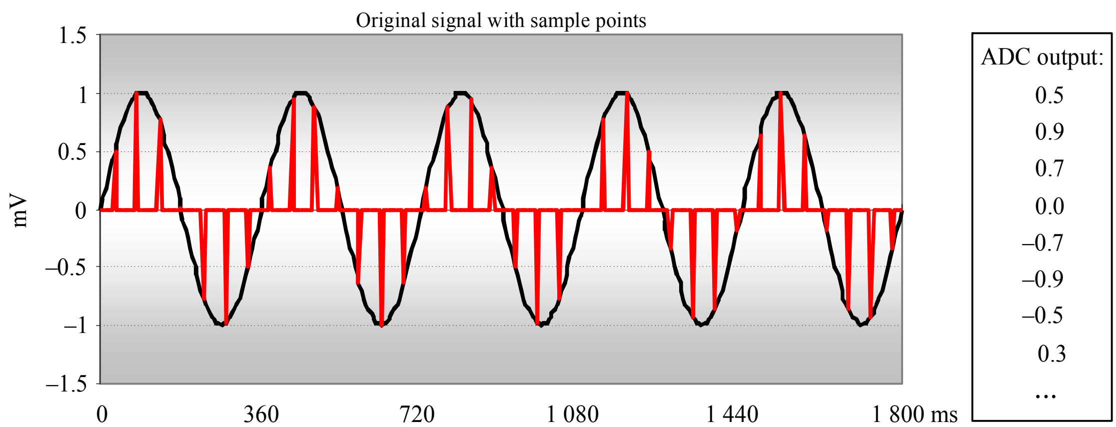
The output of the Fourier transform is complex valued regardless whether the input time waveform is real, or complex (e.g., real and imaginary, or *I* & *Q*). If the input waveform is real-only, the spectrum result will be conjugate symmetric. To compute the power spectrum from the Fourier transform result requires computing the magnitude-squared value of each frequency point. The power spectrum is the quantity that will usually be averaged when averaging is utilized.

6.7.2 Analogue to digital conversion, sampling

Being a mathematical process, the Fourier Transform is best performed by a digital signal processor (DSP), which basically is a special computer. For this purpose, the time signal has to be present in digital form. This is done by analogue-to-digital conversion (ADC).

FIGURE 6.7-2

Analogue to digital conversion



Spectrum-6.7-02

An analogue signal is converted into a digital signal by taking samples of its current amplitude during a certain period of time. Nyquist’s theorem states that the sampling frequency has to be more than twice the bandwidth of the waveform to be sampled:

$$fs > 2b$$

Nyquist noted that the sampling frequency must be more than 2 times the highest frequency present in the waveform to be sampled:

$$fs > 2f_{max}$$

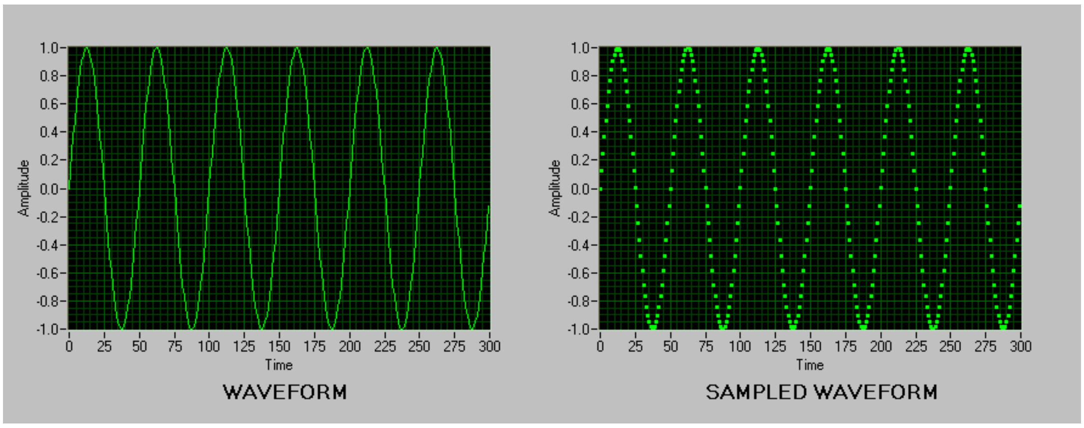
This is called the Nyquist frequency as applied to real signals. For complex signals, such as can be obtained with two ADC's sampling the output of an IQ demodulator, the sample rate must be greater than the bandwidth of the signal ($f_s > b$). Information is not lost because with complex signals, there are two values per sample, so the sample density is the same as in the case of real signals with one value per sample, but at twice the rate.

The output of the ADC is a bit stream in which a number represents the amplitude of the original signal at the time of each sample.

If the sampling frequency is high enough, output of the ADC can be reconstructed into the original waveform in a unique way. An example of sampling is given in Fig. 6.7-3.

FIGURE 6.7-3

Sampling



Spectrum-6.7-03

The accuracy of this digital representation depends on the number of bits reserved for each amplitude value. Typical ADC resolutions are 14 to 18 bits, resulting in up to 262.144 different amplitude steps. Although the discrete amplitude values cannot accurately represent the original signal, the error due to this effect can be minimized by proper selection of the spacing between two steps (narrow spacing at low, wide spacing at high amplitude values). This way, the dynamic range of the digitized signal can be better than 100 dB.

Frequencies higher than twice the sample rate would be "undersampled", resulting in additional frequency components in the digitized signals that are not part of the original signal. To avoid this error, it is essential that the analogue signal is fed through a low pass filter placed before the ADC.

In principle, the accuracy of the digitizing process is therefore only limited by the speed of the ADC unit. Today, ADC chips allowing for signal frequencies of up to around 100 MHz and a digitization depth of 18 bits are available. To analyze higher frequencies, the RF signal first has to be down-converted to a range that can be digitized.

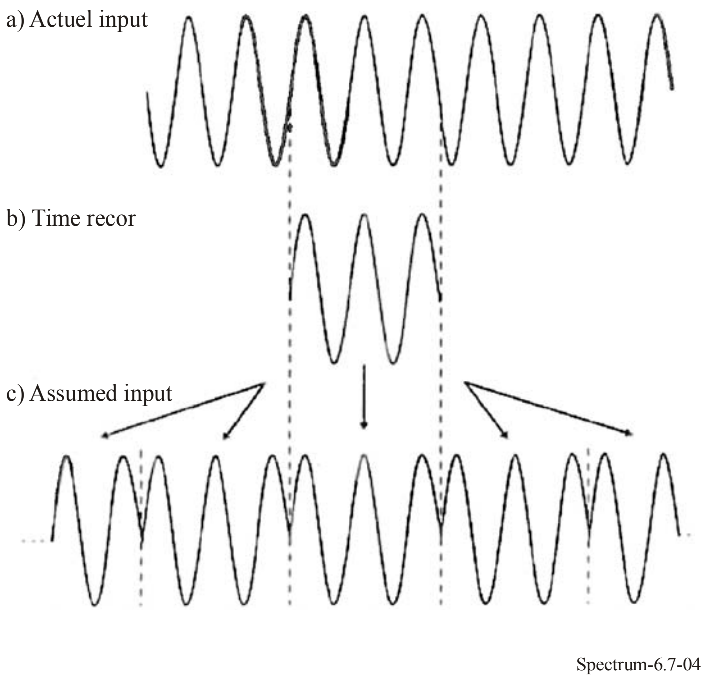
6.7.3 Windowing

The FFT is computed over a finite time interval. If the collected signal is periodic within that interval, then the result is considered to be an accurate representation of the signal's spectrum. If the signal is not periodic within the interval, then the fundamental assumptions made in defining the FFT are no longer true, and the resulting spectrum estimate will be less accurate. Window functions are used to improve the accuracy of the spectrum estimate by shaping the signal, minimizing the cutting effects (sudden changes) at the window edges.

The FFT procedure implies that the collected signal is continuously present for an infinite time and that it is periodic within the time record. If the signal is not periodic, then there will be a discontinuity as shown in Fig. 6.7-4. While this signal is continuous, the time record used to compute the FFT contains 2.5 cycles of the sine wave, instead of the assumed integral number of cycles.

FIGURE 6.7-4

FFT of a continuous sine wave signal



The FFT result can only accurately represent a finite set of integral frequencies such as 2 cycles, 3 cycles, etc. As there is not a 2.5 cycle coefficient, the result in this example will erroneously indicate energy at a number of integral frequencies.

Signals that fall completely within one time record appear to be periodic to the FFT. These signals are called self windowing. To analyze them accurately with FFT, no extra windowing has to be applied (sometimes this is called applying a rectangular window): examples of this kind of signal are spikes occurring only once and digital burst signals, as long as the burst lies completely within the time record.

For continuous signals, however, it is quite obvious that we alter the original waveform due to the need for windowing, and always introduce a certain error. This error lies in the principle of the FFT windowing and cannot be completely avoided. However, depending on the parameter to be measured (amplitudes, frequencies, phases), this error can be minimised by choosing an appropriate window function.

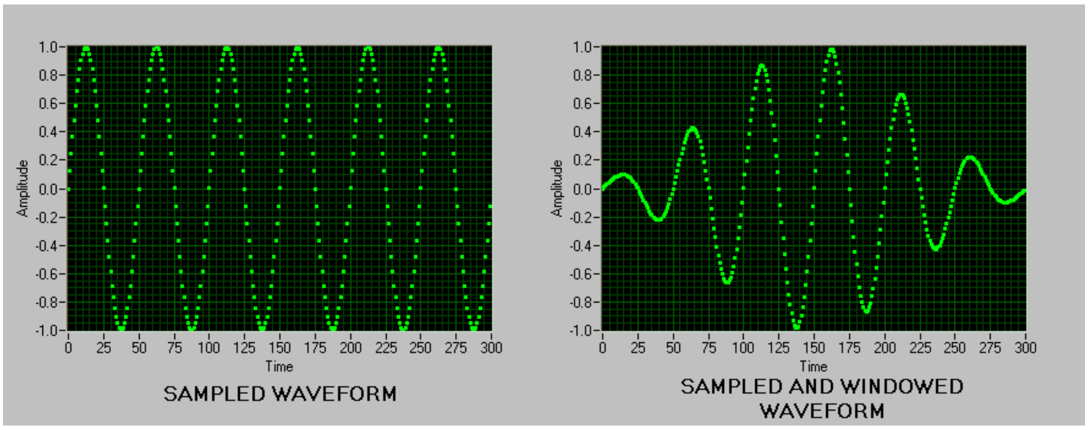
Figure 6.7-5 gives an example of the effect that the windowing process has on the signal.

The windowing has influence on the frequency spectrum in both frequency resolution and amplitude accuracy. The DFT/FFT can be depicted as a bank of parallel filters, each filtering out a frequency component. The window function is comparable to the impulse response of a resolution bandwidth filter in a spectrum analyzer as it defines the corresponding frequency domain characteristics of bandwidth, shape factor and sidelobe (stopband) performance.

Many different windows have been developed, each with their own specific properties.

FIGURE 6.7-5

Windowing



Spectrum-6.7-05

With this information it is obvious that there cannot be one single window type that is a good choice in all cases. One always has to consider the kind of signal to be analyzed (transient or continuous) and the aim of the measurement (emphasis on frequency resolution or amplitude accuracy) in order to find a window that offers the best compromise.

FFT equipment used for spectrum monitoring often allow the user to select between different FFT windows. It is necessary to know the characteristics of the window functions implemented in order to select the appropriate one for the respective measurement task. Table 6.7-1 shows examples of windows commonly implemented in RF measurement equipment.

TABLE 6.7-1

Examples of common FFT window functions

Window function	Application
Rectangular	Used for transient signals that lie completely within the time record
Hann	High frequency accuracy
Blackman-Harris or Flattop	High amplitude accuracy, high dynamic range and noise suppression
Gaussian	Compromise between frequency and amplitude accuracy (depending on shape factor)

6.7.4 FFT implementations

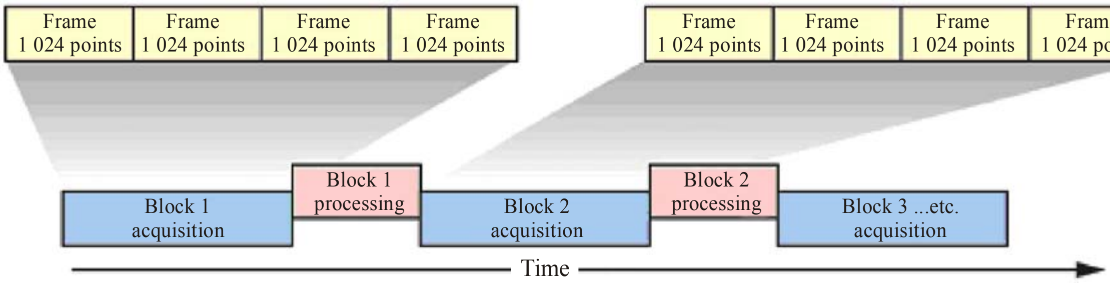
The FFT can be viewed as a parallel bank of resolution bandwidth (RBW) filters. As the spectrum is estimated at all frequencies simultaneously, the FFT produces a self-consistent spectrum estimate when applied to highly dynamic waveforms.

The parallel nature of the implementation also provides faster spectrum measurements for narrow RBW's when compared to a swept spectrum analyzer that can only measure one frequency at a time.

If the FFT is implemented in such a way that the FFT analyzer cannot collect data while computing the FFT, then the receiver is "blind" during the FFT calculation, so there is no continuous reception and short time signals may be lost. To overcome this limitation, different techniques have been developed in modern FFT analyzers. One method is to collect multiple time records first and compute all the FFTs afterwards in one block (see Fig. 6.7-6).

FIGURE 6.7-6

Block acquisition



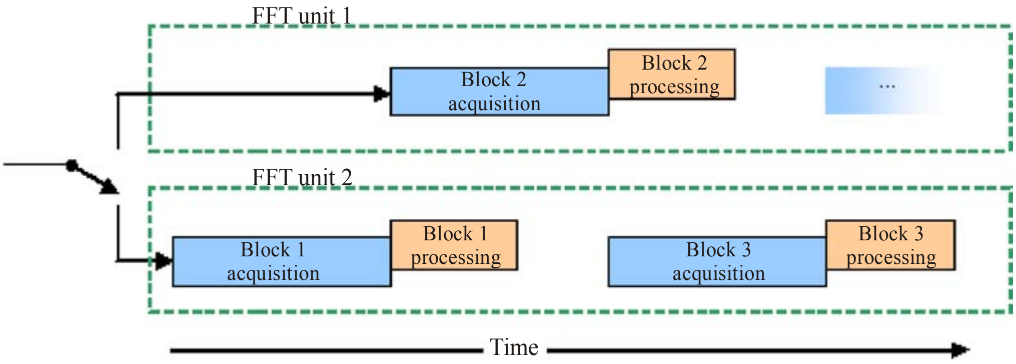
Spectrum-6.7-06

During the longer computation time, reception is discontinued, but if the acquisition can be triggered to the signal of interest, and if the available memory allows long acquisition times, continuous reception at least over the time period of interest is possible.

One method to provide continuous reception is to implement two acquisition and FFT computation units that take turns in the processing of the signal (see Fig. 6.7-7).

FIGURE 6.7-7

Continuous reception with two FFT units



Spectrum-6.7-07

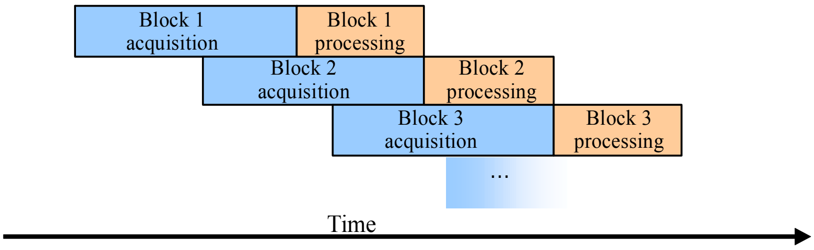
While not obvious, there are still gaps in the processing in Fig. 6.7-7. This occurs as the window function weights the waveform to zero at the beginning and end of each acquisition block. This problem can be resolved using overlap processing as described below.

The FFT is not immune from time-frequency resolution tradeoffs. The number of frequency lines in the FFT spectrum is equal to the number of samples in the time record. The minimum duration of the time record is 1/frequency resolution. To increase frequency resolution, we also have to increase the length of the time record (thereby losing time resolution), and vice versa.

Some FFT analyzers can minimize this limitation by overlapping time records (see Fig. 6.7-8) thus improving visual representation of short pulses. This method is also known as short time FFT, sliding window FFT or overlap processing. A similar time-frequency resolution tradeoff exists in swept spectrum analyzers where sweep time must be increased as the resolution bandwidth is decreased.

FIGURE 6.7-8

Overlapping time records



Spectrum-6.7-08

6.7.5 Range of applications

FFT techniques are commonly used in spectrum analysis and spectrum monitoring. The following enumeration is a non-exhaustive list of parameters which can be measured by using FFT techniques.

- Level.
- Frequency.
- Occupied bandwidth (*x*-dB method and β/2-method).
- Spectrum occupancy (spectrograms and frequency channel occupancy).
- Detection of short time emissions.
- Detection of signals below the noise floor.

For more details please refer to the relevant sections in Chapters 4 and 5.

Since the complex FFT gives both amplitude and phase information, wideband direction finders can use FFT algorithms to make bearings on multiple signals at the same time. Another example is the Goertzel algorithm, an FFT for one frequency point. If the FFT is considered as a bank of filters the Goertzel algorithm is just one of them. Applications are the dual tone multiple frequency (DTMF) and the continuous tone-coded squelch system (CTCSS) decoders or other tone-decoders, filters in receivers, filters for FSK demodulators etc. All the properties (resolution, dynamic range) of the FFT apply to these applications. The reason for using FFT algorithms is not always better performance. FFT enables a seamless processing of a given spectrum over time which is not possible with an analog sweeping process. The availability of cheap DSPs makes FFT-based products cheaper to manufacture than their conventional analogue counterparts. Although excellent products are available a careful review of equipment is always recommended.

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6.8 Planning and optimization of spectrum monitoring networks

6.8.1 Introduction

The planning of spectrum monitoring networks, whether global, comprising many monitoring stations, or local, comprising only a handful of stations, has to do with the optimal siting of fixed stations taking into account their interaction with one another and with mobile stations. The term "monitoring station" hereinafter refers both to a fully equipped station performing all of the monitoring functions referred to in Chapter 4, and to remote automatic stations performing only direction finding.

The process of planning a spectrum monitoring network generally involves covering the greatest possible land area using the smallest possible number of stations. The planning of new and optimization of existing spectrum monitoring networks is of great economic significance inasmuch as the cost of the monitoring system generally accounts for the bulk of the cost of any national spectrum management system. Optimization of a spectrum monitoring network can result in considerable financial savings in respect of each fixed or mobile station.

Once a station has been optimally sited within the network by means of calculations for which the methodology is shown below, that station has to be specifically customized to the locality and surrounding features, in accordance with the provisions of § 2.6. Should that customization require that the station be sited other than in the calculated location, it may prove necessary to recalculate the network parameters in view of the new configuration of stations.

6.8.2 Principles for the planning and optimization of spectrum monitoring networks

The planning of a new or optimization of an existing spectrum monitoring network may be performed by calculating the corresponding coverage zones with reference to the two tasks for which spectrum monitoring is typically used [Kogan and Pavliouk, 2004].

The first of those tasks has to do with the functions described in §§ 4.2 to 4.6 and 4.10. They are related to the remote measurement of emission parameters such as frequency, field strength, spectrum occupancy, bandwidth, type of modulation and so on. This task can also include listening (aural monitoring) of emissions and direction finding of their sources, emission identification and signal analysis, as described in §§ 4.7 and 4.8. All of these functions are carried out independently by each individual and suitably equipped monitoring station.

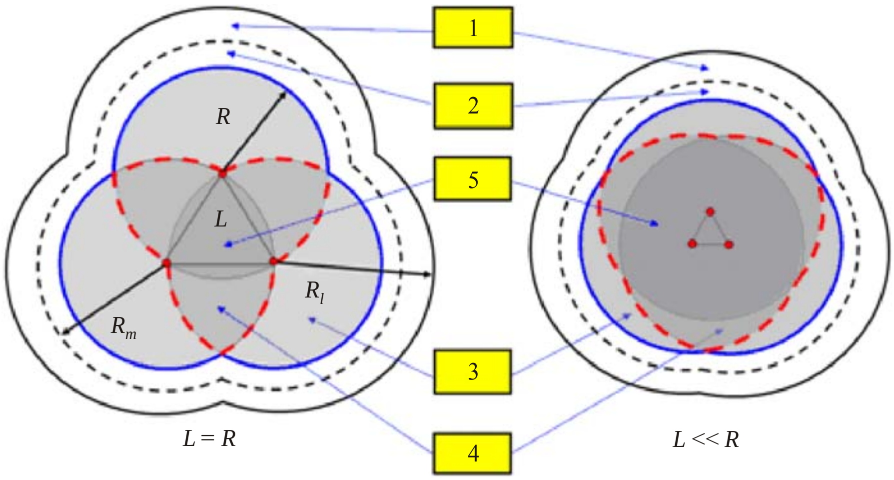
The second task involves only one function, albeit a complex, labour-intensive and at the same time very important one, namely the location of emission sources through use of the SSL mode in the HF band (see § 4.7.3.4) or the triangulation mode in all frequency ranges through processing of the bearing data obtained from two or more direction finders that are either independent or part of the monitoring stations. The specific features of triangulation-based location are described in § 4.7.3.1.

Given that the measuring receiver sensitivity will, as a rule, be different for different monitoring functions, several coverage zones may be identified, as is conventionally shown in Fig. 6.8-1, which portrays three monitoring stations with different distances $\boldsymbol{L}$ between them. Bearing in mind that the receiver sensitivity is usually at maximum for listening, somewhat lower for measuring signal characteristics, and at minimum for direction finding, it is possible – as can be seen from Fig. 6.8-1 – to identify three coverage zones (1 – 3) with radiuses $\boldsymbol{R}_l$, $\boldsymbol{R}_m$ and $\boldsymbol{R}$ (in the interests of simplicity, the zones are at this stage considered to be circular).

Where direction finding is concerned, zone 3 constitutes the land area within which sufficiently reliable bearings are obtained.

FIGURE 6.8-1

Monitoring coverage zones



Spectrum-6.8-01

These three coverage zones are each individual to each station and do not depend on one another. Therefore, the overall listening, emission parameter measurement and direction-finding blanket zones increase as the distances between the stations increase, up to $\boldsymbol{L} = \sqrt{3}\ \boldsymbol{R}$. Where $\boldsymbol{L} > \sqrt{3}\ \boldsymbol{R}$, non-covered areas will appear between the direction-finding coverage zones of the different stations.

The behaviour is different in the case of location coverage zones, which correspond to the overlapping direction-finding coverage zones from two or three stations (zones 4 and 5, respectively, in Fig. 6.8-1). These zones, and especially zone 5, become smaller as the distance ***L*** between the stations increases, this being particularly rapid in the range $\boldsymbol{R} < \boldsymbol{L} < \sqrt{3}\ \boldsymbol{R}$, when zones 4 and 5 become considerably smaller than the overall direction-finding zone. Where $\boldsymbol{L} \geq \sqrt{3}\ \boldsymbol{R}$, direction-finding coverage zone 5 (three stations) disappears, and with $\boldsymbol{L} > 2\ \boldsymbol{R}$ direction-finding coverage zones 4 (two stations) disappear, there being then no point at which location is effected.

At the same time, where there is a decrease in ***L*** and an increase in the overall location coverage zone, the location uncertainties at the periphery of this coverage zone increase considerably on account of the fact that the bearings from all three stations in these areas intersect one another at increasingly acute angles as the boundary of the zone is approached. This increases the difficulty of finding transmitters by means of homing by mobile stations at the periphery of the overall location coverage zone where $\boldsymbol{L} \ll \boldsymbol{R}$.

Nevertheless, Fig. 6.8-1 graphically shows location to be the most critical monitoring function, and one which has to be set up on the basis of network planning if the aim is to achieve blanket coverage of a given land area, albeit within the bounds of local networks. The term “monitoring coverage” will hereinafter be used to refer to the coverage provided by all spectrum monitoring functions, i.e. listening, signal characteristic measurement, direction finding and, unless otherwise specified, location.

In any case, achieving blanket location coverage of a sufficiently large territory using fixed monitoring stations in the VHF/UHF frequency bands calls for a large number of such stations sited at relatively short distances from one another, with the sharp increase in network costs that this entails. In order to cut down on the number fixed stations it may in some cases be acceptable to leave greater distances between fixed stations, resulting in some areas being left out of the location coverage zone. These areas can then be covered using mobile stations working interactively with the fixed stations. In such cases it is advisable to ensure that the network provides blanket direction-finding coverage by means of the fixed monitoring stations so that they can then interact with the mobile stations to provide location by means of triangulation throughout the territory. This will significantly boost the operating efficiency of the mobile stations, including their homing operations for finding particular transmitters.

From the foregoing it can be concluded that with increased distances between fixed monitoring stations operating in the VHF/UHF frequency bands, i.e. with a reduced number of such stations, an increasing burden is placed on the mobile monitoring stations, which, in addition to homing operations, are also required to interact with the fixed stations in performing location tasks when it appears possible. An integral part of fixed monitoring station network planning therefore has to do with establishing the optimum ratio between the number of fixed and mobile stations depending on a configuration of fixed monitoring stations in a network.

The planning methodology for spectrum monitoring networks differs considerably between the VHF/UHF and the HF bands. The size and shape of monitoring coverage zones in the VHF/UHF bands are influenced to a great extent by the relief, as is shown in § 6.8.3, making it necessary to use the corresponding radio wave propagation models in the calculations. The small dimensions of monitoring coverage zones require, if blanket coverage is to be achieved, that stations be sited no further than 30 – 60 km apart. In the HF bands, relief does not exert an appreciable influence on the shape of monitoring coverage zones. Thus, where the use of omnidirectional antennas is concerned, the skywave (reflected from the ionosphere) coverage zones will be circular with radiuses in the order of 2 000 – 2 500 km. One of the features of ionospheric radio wave propagation is the presence of "blind spots" ("silent zones"), which need to be taken into account in the planning and optimization of spectrum monitoring networks, as it is described in [Krutova *et al*., 2008].

6.8.3 Planning and optimization of monitoring networks in the VHF/UHF bands

In many countries, the solution most commonly found in the VHF/UHF bands is that of local monitoring networks comprising a number of fixed stations serving individual large cities and industrial centers. The planning of such local networks can be effected through the trial calculation of monitoring coverage zones, taking account of relief, for different station siting configurations, with subsequent selection and implementation of the best option based on all of the desired criteria. The principles for putting together the corresponding software are to be found in [Krutova *et al*., 2005] and [ITU-R Handbook, 2005]. Based on the results of calculations which take account of the availability of the infrastructure necessary for organizing attended monitoring stations, it is possible to identify those stations which are to perform the full range of monitoring functions and be attended and those which can serve as remote automatic direction finders.

Optimization of an existing spectrum monitoring network, particularly in the course of its modernization, may be effected through the trial virtual siting of new fixed monitoring stations at points within zones where the level of coverage provided by the existing stations is inadequate, with subsequent selection and implementation of the best option. Similarly, by calculating the coverage zones of the existing stations, it is possible to identify those existing stations which, for one reason or another, are not making an essential contribution to the required coverage and may therefore be considered candidates for transfer to other locations where they will perform to greater effect. If the requirement is for blanket monitoring coverage within the bounds of a given region, the planning and optimization must be effected on the basis of the location function, which is the most critical in terms of the siting of monitoring stations, or, as a last resort, on the basis of the direction-finding function, geared towards the more intensive use of mobile monitoring stations for location purposes, and not only for finding transmitters by means of homing.

When performing the calculations it is necessary to select the most appropriate radio wave propagation model, which takes account of the actual relief of the region in question, and to select the minimum field strength values at the boundaries of the monitoring coverage zones, as well as the powers and antenna heights of the test transmitters for which the calculations are to be performed.

By way of a radio wave propagation model, it is expedient to select the methodology set forth in Recommendation ITU-R P.1546, whose new provisions (see Annex 5, § 1.1 of the Recommendation) allow to take into account specific features of monitoring by fixed stations. These specific features are due to the fact that fixed monitoring stations, as a rule, have high receiving antennas, whereas the monitored transmitters may have low antennas – for example, private mobile radio (PMR) transmitters carried in light vehicles. It is just such an approach that is used in the software described in [Krutova *et al*., 2005] and [ITU-R Handbook, 2005]. To be noted in this regard is the recent adoption of Recommendation ITU-R P.1812, which more fully allows for the relief factor to be taken into account. Use of this model may serve to enhance the accuracy of the calculations.

As regards the spectrum monitoring network planning parameters which determine the boundaries of coverage zones, according to [Kogan and Pavliouk, 2004] and [Bondarenko *et al.*, 2008], at least for the purposes of comparison the following coverage zone field strength boundary values may be proposed:

– Minimum field strength from the test transmitter at the site of the monitoring station antenna in the case of listening: $\boldsymbol{E_{min(l)} = S}$, where $\boldsymbol{S}$ is the sensitivity of the monitoring receiver used for listening, taking account of antenna gain and feeder loss. A typical sensitivity value for a $S/N \geq 10$ dB is 1 (μV/m), since in most cases (or for purposes of comparison) it can be considered that $\boldsymbol{E_{min(l)}}$ = 0 dB(μV/m).

– The minimum field strength for measuring the transmitter signal characteristics as indicated in Chapter 4 is: $\boldsymbol{E_{min(m)}} = \boldsymbol{E_{min(l)}} + 12$ dB, i.e. in most cases (or for purposes of comparison) it can be considered that $\boldsymbol{E_{min(m)}}$ = 12 dB(μV/m).

– The minimum field strength in the case of direction finding, as described in § 4.7, with a view to achieving reliable bearings, is: $\boldsymbol{E_{min(df)}} = \boldsymbol{E_{min(l)}} + 20$ dB, i.e. in most cases (or for purposes of comparison) it can be considered that $\boldsymbol{E_{min(df)}}$ = 20 dB(μV/m).

The monitored VHF/UHF transmitters are characterized by an extremely wide spread of power levels and antenna heights – ranging from 10 W and 1.5 m (PMR transmitters carried in light vehicles) to 40 kW and above and 500 m (television transmitters). The dimensions of the corresponding monitoring coverage zones likewise vary within very broad limits.

For network planning and comparative calculation purposes it is expedient to determine three categories of low-power transmitter [Krutova *et al.*, 2009] with relatively low antennas, it being reckoned that the more powerful transmitters with higher antennas are bound to be well covered by these networks:

– *Category I:*

  Power 10 W, antenna height 1.5 m (PMR transmitters carried in light vehicles).

– *Category II:*

  Power 10 W, antenna height 20 m (land mobile radiocommunication base stations, low-power broadcasting transmitters, television transponders).

– *Category III:*

  Power 20 W, antenna height 40 m (the same types of transmitter as in category II, but with somewhat greater power levels and antenna heights).

These and other parameters which may be used as criteria in the planning and optimization of monitoring networks in the VHF/UHF frequency bands (and which are used in the calculations presented below) are shown in Table 6.8-1.

An example of a local spectrum monitoring network planning procedure for the parameters indicated in Table 6.8-1 is presented below and demonstrated in Figs 6.8-2 to 6.8-5.

Let us take the case of a city, located in a hilly area as shown in Fig. 6.8-2, and assume that it is necessary to implement spectrum monitoring for this city and its fairly densely-populated suburbs in regard to category I test transmitters.

Given the more or less circular configuration of this city, the required service may be provided using a minimum of three fixed monitoring stations.

An initial pilot plan is drawn up, with the stations (***S1*** – ***S3***) being sited on hilltops, as shown in Fig. 6.8-2, since in this way the station antennas may be kept relatively short at a height of 10 m.

The monitoring coverage zones of station ***S1*** are shown in Fig. 6.8-3.

The zones are identified by means of the coloured palette on the right-hand side of the figure. The boundary values of the different coloured areas relating to the different coverage zones are shown as being equal to 0, 12 and 20 dB for listening, signal characteristic measurement and direction finding, respectively, as indicated in Table 6.8-1.

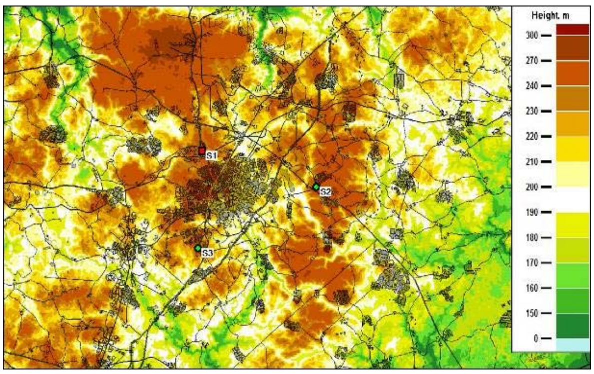
TABLE 6.8-1

Criteria for the planning and optimization of monitoring networks in the VHF/UHF frequency bands

Parameter	Value
Test transmitter antenna height	Category I: 1.5 m Category II: 20 m Category III: 40 m
Test transmitter power	Categories I and II: 10 W Category III: 20 W
Probability of finding the test transmitter within the location uncertainty ellipse (see § 4.7.3.4)	0.5
Fixed monitoring station antenna height	10-50 m (according to installation site)
Mobile monitoring station antenna height	2.5 m (antenna mounted on vehicle roof) 10 m (semi-fixed extendable antenna)
System direction-finding uncertainty (see § 4.7.3.1.3)	1º r.m.s. (fixed station) 2º r.m.s. (mobile station)
Minimum field strength at the boundary of the listening coverage zone	0 dB(μV/m)
Minimum field strength at the boundary of the signal characteristic measurement coverage zone	12 dB(μV/m)
Minimum field strength at the boundary of the direction-finding coverage zone	20 dB(μV/m)

FIGURE 6.8-2

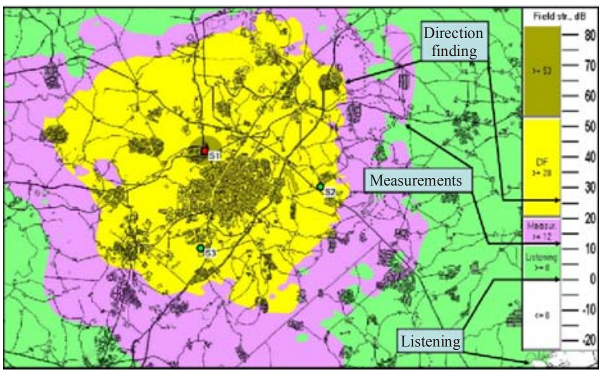
Topography of the area in question and siting of the three fixed stations, S1 – S3, on high ground (first option)



Spectrum-6.8-02

FIGURE 6.8-3

Monitoring coverage areas of station S1, showing the external boundaries of the listening, measurement and direction-finding coverage zones



Spectrum-6.8-03

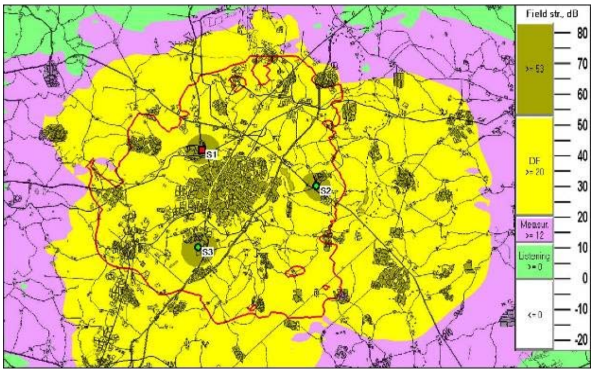
Figure 6.8-4 shows the overall monitoring coverage zones for all three stations. The continuous red contour within the overall direction-finding coverage zone shows the boundary of the triangulation-based location coverage zone, as described in § 4.7.3, which corresponds to the overlapping direction-finding coverage zones from at least two stations. As can be seen from Fig. 6.8-4, the location coverage zone in this case is markedly smaller than the overall direction-finding coverage zone, in line with the general theory set forth above.

The location coverage template described in § 4.7.3.1.4 is portrayed in Fig. 6.8-5 for a 50% probability of finding the sought transmitter within the bounds of the location uncertainty ellipse. Here the red contour describes the boundary of the overall direction-finding zone for all three stations. The key to the boundary values of the various location uncertainty subzones, which are presented in different colours, is to be found in the palette on the right-hand side of the figure.

As can be seen from Fig. 6.8-5, the stations are sited in such a way as to enable the location of category I transmitters throughout the city and its immediate suburbs. A larger part of the city and its immediate suburbs are served with a location uncertainty in the range 0.2-0.4 km (subzone shown in brown); however, there are two “spots” in which the location uncertainty lies in the range 0.1-0.2 km (subzones shown in turquoise). In full accordance with the theory (see § 4.7.3.1.4), these “spots” occur where the bearing lines from stations ***S1*** and ***S3*** intersect at angles close to 90°. Towards the periphery of the overall location coverage zone, the location uncertainty values rise to 0.6-0.8 km (subzone shown in dark yellow). Within the bounds of the template there are a number of small “spots” shown in white, denoting areas which, with the given relief and selected parameters, are served neither by location nor by direction finding, as can also be seen from Fig. 6.8-4.

FIGURE 6.8-4

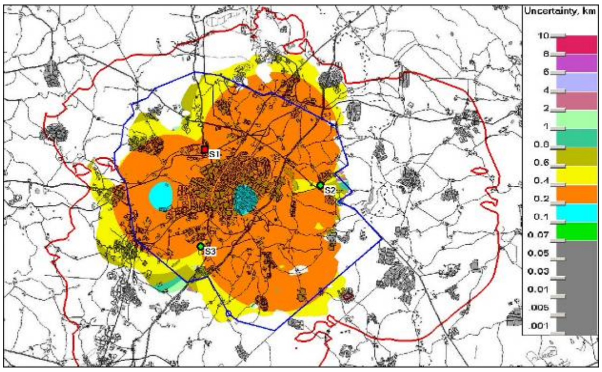
Overall monitoring coverage zones with the three stations, S1 – S3



Spectrum-6.8-04

FIGURE 6.8-5

Location coverage template with the three stations, S1 – S3



Spectrum-6.8-05

Let us assume that the blue contour in Fig. 6.8-5 represents the boundary of an administrative district lying within the area of responsibility of the city in question. Using appropriate software it is possible to calculate numerical values for the location coverage of that district in the subzones with different location uncertainty ranges. This data is shown in Table 6.8-2, where it can be confirmed that a transmitter of category I can be located on 87% of the delineated district area. This area can be further divided into 4 categories, in accordance to the computed location uncertainty, allowing to obtain an uncertainty between 0.2 and 0.4 km in 74% of the considered area.

By comparing Figs 6.8-3 and 6.8-5 it can be seen that station ***S1*** alone provides listening and signal characteristic measurement within the bounds of the entire location coverage zone formed by the three stations ***S1*** – ***S3***. It can therefore be fully equipped and attended, with the other two being unattended automatic direction finders. However, in the interests of greater reliability, one of these two stations may also be fully equipped although left unattended.

TABLE 6.8-2

Statistics for location uncertainty subzones

Location uncertainty ranges (km)	Percentage of surface area of delineated district	Cumulative distribution of percentage values
0.07-0.1	–	–
0.1-0.2	2	2
0.2-0.4	74	76
0.4-0.6	9	85
0.6-0.8	2	87
0.8-10	–	87
	Total	87

In practice, it may very well turn out that the hilltops on which it would otherwise be desirable to locate the antennas of fixed monitoring stations are already occupied by the antennas of powerful transmitters, for example broadcasting, making it necessary to identify alternative station siting options that meet the requirements set forth in § 2.6.1.4 in respect of the protection of such stations from powerful emissions. This can easily be done by repeating the calculations for the site plans of other potential station locations. Providing calculations for several site plans it is possible to choose the best station configuration meeting desired set of requirements.

In cases where it is planned to provide blanket monitoring coverage over fairly large areas, requiring a large number of stations, the corresponding network planning may be carried out on the basis of the theory of regular networks, as described in Report ITU-R BS.944. This approach allows for the establishment of a network with large distances between stations in rural areas and smaller distances within cities or extensive industrial areas where there is a higher density of monitored transmitters and where the bearing uncertainty is considerably greater on account of reflections from buildings and metallic structures. Where the area in question already has something approaching a regular network of fixed monitoring stations, the existing stations will preferably be "inscribed" into the newly planned network.

Such a network, with a variable monitoring station density, is set up on the basis of cells in the form of equilateral hexagons, which in turn are made up of six elementary equilateral triangles, as described in Report ITU-R BS.944, with the stations being sited at all of the network nodes, as shown in Fig. 6.8-6. This figure clearly demonstrates how the elementary triangles of the primary network can be successively subdivided into four smaller equilateral triangles with the distances between stations being $\boldsymbol{L}/2$, $\boldsymbol{L}/4$, $\boldsymbol{L}/8$, and so on. Evidently, in large cities and industrial areas the distances between fixed monitoring stations can in practice be as small as $\boldsymbol{L}/8$ = 7.5 km, or even $\boldsymbol{L}/16$ = 3.75 km.

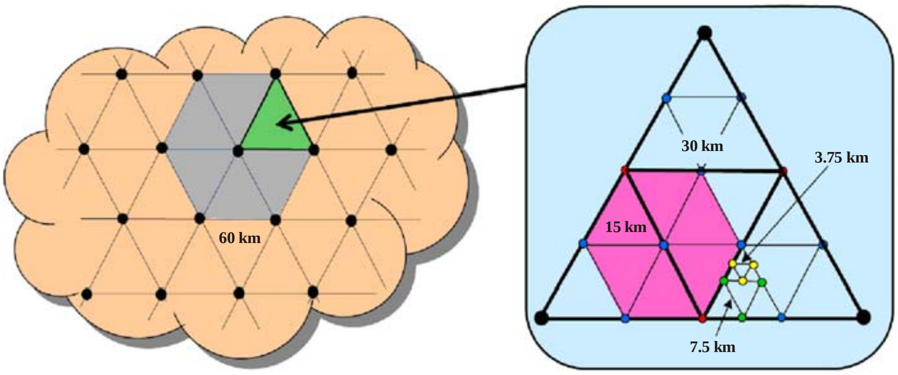
In such a network of variable-density monitoring stations, any fixed station located at a given point may be considered as belonging to the existing or future variable-density regular blanket monitoring network with an uncertainty not exceeding 2.17 km. This facilitates the "insertion" of the existing stations into the new large network.

The calculations for the VHF/UHF frequency bands, performed in accordance with the approach described in [Krutova *et al*., 2009], show that under normal terrain conditions the maximum distance $\boldsymbol{L}$ between the fixed stations in the primary network may be $\boldsymbol{L_m}$ = 60 km where category III monitored transmitters are concerned. Taking such a primary network as the point of departure, it is possible to calculate its parameters with respect to category I-III monitored transmitters, as well as the parameters of the nested areas of the network with inter-station distances of 30 km, 15 km and 7.5 km for all three categories of transmitters. The conditions for performing the calculations are given in [Krutova *et al*., 2009]. The results of the calculations are summarized in Table 6.8-3.

From Table 6.8-3, it can be seen that in a primary network where $\boldsymbol{L_m}$ = 60 km, the location coverage is achieved only for category III transmitters.

FIGURE 6.8-6

Theoretical regular network



Spectrum-6.8-06

TABLE 6.8-3

Calculated data in respect of homogeneous monitoring networks at 450 MHz

L (km)	Category	Coverage zone statistics (%)				Location uncertainty statistics
		Listening	Measure-ment	Direction finding	Location	
60	I	94 – 100	50 – 69	26 – 36	0	-
	II	100	100	98 – 100	64 – 88	0.6-0.8 km: 0-2% 0.8-1.0 km: 20-34% 1.0-2.0 km: 22-33% > 2.0 km: 15-21%
	III	100	100	100	98 – 100	0.6-0.8 km: 1-3% 0.8-1.0 km: 33-50% 1.0-2.0 km: 47-62% > 2.0 km: 0-2%
30	I	100	97 – 100	77 – 88	8 – 15	0.2-0.4 km: 0-3% 0.4-0.6 km: 2-6% 0.6-0.8 km: 2-4% > 0.8 km: 4-7%
	II	100	100	100	100	0.2-0.4 km: 3-6% 0.4-0.6 km: 82-88% 0.6-0.8 km: 8-13% > 0.8 km: 0-1%
15	I	100	100	100	95 – 96	0.1-0.2 km: 0-1% 0.2-0.4 km: 80-85% 0.4-0.6 km: 4-7% > 0.6 km: 6-7%
	II	100	100	100	100	0.1-0.2 km: 0-1% 0.2-0.4 km: 99-100% > 0.4 km: 0-1%
7.5	I	100	100	100	100	0.07 – 0.1 km: 1-2% 0.1-0.2 km: 97-98% 0.2-0.4 km: 0-1% 0.4 km: 0 %

The predominant location uncertainty values are 0.8-1.0 km (33-50% of the land area) and 1-2 km (47-62% of the land area). In the case of category II transmitters, a direction-finding coverage of 98-100% is achieved, making it easier to seek for such transmitters using mobile monitoring stations. However, location by means of fixed stations covers only 64-88% of the land area. In the case of category I transmitters, direction finding covers only 26-36%, and at no point in the network is location provided. Thus, a primary network of fixed stations where $\boldsymbol{L_m}$ = 60 km provides practically no monitoring of low-power category I transmitters with low antennas, and presents major limitations when it comes to the location of category II transmitters.

A considerable improvement can be achieved to the technical characteristics of the network or relevant segment thereof by reducing the distance between stations from 60 to 30 km, although this will entail at least a twofold increase in the cost of constructing the network or relevant segment. Full location coverage of the land area is already ensured for category II transmitters with predominant location uncertainty values in the range 0.4-0.6 km (82-88% of the land area). However, where category I transmitters are concerned, 100% direction-finding coverage of the land area is not yet ensured, while the coverage rate for location by fixed stations amounts to no more than 8-15%.

From this it can be concluded that even networks where $L = L_m/2$ = 30 km do not ensure effective direction finding or location for category I transmitters.

One hundred per cent direction-finding coverage for category I transmitters is ensured by networks or network segments where $L = L_m/4$ = 15 km, when 95-96% of the land area also has location coverage with predominant location uncertainty values in the range 0.2-0.4 km (80 – 85% of the land area).

Even better technical characteristics are achieved by networks or network segments where $L = L_m/8$ = 7.5 km, in which case 100% location coverage is obtained for category I transmitters with predominant location uncertainty values in the range 0.1-0.2 km (97-98% of the land area).

However, this is achieved by means of a considerable increase in the number of fixed monitoring stations, and hence in the volume of expenditure for implementation of the network, but at the same time the requirements are lower in terms of the number of mobile monitoring stations.

The data in Table 6.8-3 can be used to optimize the configuration of the network being deployed, having regard to the tasks to be fulfilled and existing and planned resources available.

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6.9 Measurement uncertainty

6.9.1 Introduction

The terms "uncertainty", "error" and "accuracy" are often used but not always in a correct way. For every measurement made, a value is obtained that may differ from the true value. If the true value could be known then the error could be expressed as the difference between the measured value and the true value. Depending on the process and equipments used for the measurement, raw results are only an estimate of the real value to measure.

Since the true value is unknown, we can only speak about an uncertainty associated with a measured value. The absolute uncertainty is a quantity expressed in the same unit as the measured value itself and describes an interval into which the true value falls with a given probability.

The relative uncertainty is the quotient of the absolute uncertainty and the best possible estimate of the true value.

The lower is the uncertainty the higher is the accuracy, that is, however, difficult to quantify.

6.9.2 Overview and definition of measurement uncertainty

Applying a procedure measurement, with equipment set, in a controlled environment does not produce the same result for each sample measurement.

This characterises the variability of the measurement. This variability may be due to the uncertainty of the equipment test, to the operator, to the measurement environment or to other aspects. To evaluate the real result, it is necessary to specify this variability.

Basically, the result may be characterized by an average value and a standard deviation interval. This characterizes the uncertainty. Two different approaches to express uncertainty are commonly used. These two types are designed as Type A and Type B. They do not refer to the nature of the uncertainty contributor but as a method of estimating which lead to the assessment of the uncertainty.

A **Type A** uncertainty estimate is an estimate derived from the statistical analysis of experimental data. This estimate should not be identified as "random" components of uncertainty. The average of n samples is usually taken into account and the variability of the result is characterised by the standard deviation. Common probability distributions are detailed in § 6.9.3. The Type A is dedicated to the evaluation of the standard uncertainty.

A **Type B** uncertainty estimate is used when the uncertainty cannot be evaluated statistically. The estimate is based on past experience, on data available in Handbooks or extracted from calibration reports. The Type B is used to assess **the standard uncertainty, the combined standard uncertainty and the expanded uncertainty.**

In practice, the Type A is used as a reckoning of raw results and the Type B is based on the analysis of results and influence factors in the measurement.

The combined standard uncertainty is the standard uncertainty of the result of a measurement when that result is obtained from the values of a number of other quantities, equal to the positive square root of a sum of terms, the terms being the variances or covariances of these other quantities weighted according to how the measurement result varies with changes in these quantities.

The expanded uncertainty is quantity defining an interval about the result of a measurement that may be expected to encompass a large fraction of the distribution of values that could reasonably be attributed to the measurand.

Practical aspect of these definitions is detailed in § 6.9.4.

To summarize, the uncertainty of a measurement is expressed according to two parameters which are defined as:

– an average value,

– a standard deviation.

In addition a confidence level might be provided (for example, the value and the interval are true with a probability of 95%).

Taking into account all parameters of each element of the measurement process and reckoning uncertainties lead to provide a value and an interval which include the real value with a certain confidence level. The aim is to carry out measurement comparable and reproducible. The reproducibility of a measurement is essential to improve the confidence in a measurement.

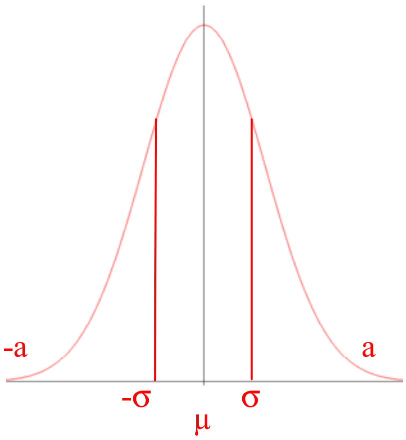
A full consideration of all identifiable source of uncertainty contributes to valid results compare to a theoretical study. The uncertainty explains and justifies observed differences in results. Nevertheless, a special care should be taken during measurement, a systematic bias could occur. One way to avoid such situation is to carry out inter-comparison measurement with other measurement team and/or other measurement chain in order to compare, to improve, to adjust and/or to correct procedure and measurement setup.

6.9.3 Common distribution functions to express uncertainty

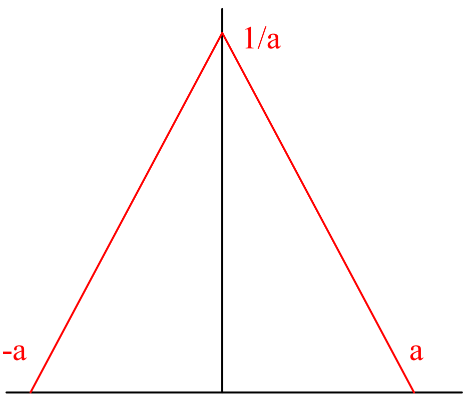
The variability of a set of values may be described with probability distributions. The most common mathematical functions used to express measurement uncertainty are summarized in Table 6.9.1.

TABLE 6.9-1

Summary of probability distributions

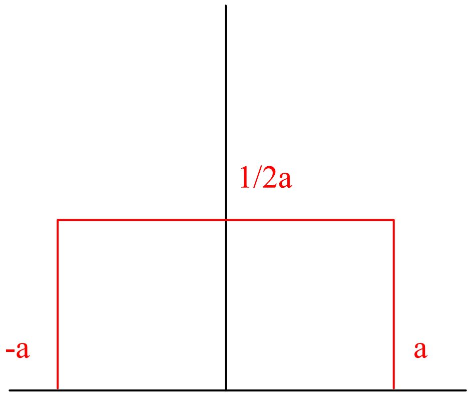
Normal distribution		
	Mathematical function $f(x;\mu,\sigma)=\frac{1}{\sqrt{2\pi}\sigma}e^{-\left[\frac{(x-\mu)^2}{2\sigma^2}\right]}$ μ is the average value σ is the standard deviation	Standard deviation For a confidence interval of 68% $\sigma = a$ For a confidence interval of 95% $\sigma=\frac{a}{2}$ For a confidence interval of 99.7% $\sigma=\frac{a}{3}$

In a set of readings, this Normal or Gaussian distribution is the most used for repeated observations which varies around an average value.

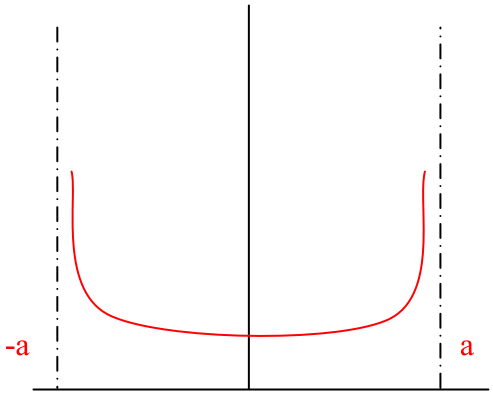
Triangular distribution		
	Mathematical function $f(x)=\begin{cases}\frac{(x+a)}{a^2} & for -a\le x\le 0\\ \frac{(a-x)}{a^2} & for\ 0\le x\le a\end{cases}$	Standard deviation $\sigma=\frac{a}{\sqrt{6}}$

The minimum and the maximum values of this distribution are known.

TABLE 6.9-1 (*end*)

Rectangular or uniform distribution		
	Mathematical function $f(x) = \frac{1}{2a}$	Standard deviation $\sigma = \frac{a}{\sqrt{3}}$

The particularity of this function is that the probability of obtaining any values between [–a; a] is 1. All values are equally probable.

U-shape distribution		
	Mathematical function $f(x) = \frac{1}{\pi\sqrt{a^2 - x^2}}$ for $-a < x < a$	Standard deviation $\sigma = \frac{a}{\sqrt{2}}$

6.9.4 Application

The measurement uncertainty for a monitoring station should be evaluated for those measurements addressed in the following sub-clauses, taking into consideration each of the quantities listed there. The standard uncertainty $u(x_i)$ in decibels and the sensitivity coefficient c_i shall be evaluated for the estimate x_i of each quantity.

The combined standard uncertainty $u_c(y)$ of the estimate y of the measured is calculated as a weighted root sum square (r.s.s.):

$$u_c(y) = \sqrt{\sum_i c_i^2 \; u^2(x_i)} \qquad (6.9\text{-}1)$$

The expanded measurement uncertainty for a monitoring station U_{ms} is calculated as:

$$U_{ms} = 2 \, u_c(y) \qquad (6.9\text{-}2)$$

and should be stated in the measurement report.

NOTE 1 – The coverage factor k = 2 yields approximately a 95% level of confidence for the near-normal distribution typical of most measurement results.

This coverage factor is used to express the level of confidence as assumed in § 6.9.3 on the description of normal distribution.

Principally compliance or non-compliance with a regulatory limit can e.g. be determined in the following manner using one of the following two approaches:

– *1st approach:*

measurement uncertainty U_{ms} as small as possible (V_{meas} is the measured value):

For the operator of a radio service: Compliance with a limit occurs if $V_{meas} + U_{ms}$ complies with the limit.

For the regulator: Non-compliance with a limit can be demonstrated if $V_{meas} - U_{ms}$ does not comply with the limit.

– *2nd approach:*

measurement uncertainty U_{ms} should not exceed a recommended maximum uncertainty U_{rec}:

If U_{ms} is less than or equal to U_{rec} then:

– compliance occurs if no measured value exceeds the limit.

– non-compliance occurs if any measured value exceeds the limit.

For the operator: if U_{ms} is greater than U_{rec} then:

– compliance occurs if no measured value, increased by ($U_{ms} - U_{rec}$), exceeds the limit.

– non-compliance occurs if any measured value, increased by ($U_{ms} - U_{rec}$), exceeds the limit.

For the regulator: if U_{ms} is greater than U_{rec} then:

– compliance occurs if no measured value, decreased by ($U_{ms} - U_{rec}$), exceeds the limit.

– non-compliance occurs if any measured value, decreased by ($U_{ms} - U_{rec}$), exceeds the limit.

6.9.5 Example of an uncertainty calculation

Measurement of field strength (E) in a fixed or mobile monitoring station in the frequency range 30 to 3 000 MHz is one of their tasks.

The measured E is calculated as:

$$\begin{aligned} E = {} & V_r + L_c + AF + \\ & + \delta V_{sw} + \delta V_{sel} + \delta V_{nf} + \delta M + \delta AF_f + \delta AF_h + \delta A_{dir} + \delta A_{cp} + \delta A_{bal} + \delta SR \end{aligned} \tag{6.9-3}$$

The uncertainty of E is calculated from the uncertainties of the terms on the right-hand side by adding their squares and then calculating the square root of the sum (see Table 6.9-2).

TABLE 6.9-2

Values of input quantities for about 30 MHz to 3 000 MHz

(to be calculated for each individual antenna, polarization and subrange)

Input quantity	**Refer to note**	X_i	**Uncertainty of x_i** (dB)	**Uncertainty of x_i** Pr Dist; k	$u(x_i)$ **(dB)**	c_i	$(c_i\, u(x_i))^2$ **(dB)**
Receiver reading	(1)	V_r	±0.1	$k = 1$	0.10	1	0.01
Attenuation: antenna-receiver	(2)	L_c	±0.1	$k = 2$	0.05	1	0.0025
Antenna factor	(3)	AF	±2.0	$k = 2$	1.00	1	1.00
Receiver corrections:							
– Sine wave voltage	(4)	δV_{sw}	±1.0	$k = 2$	0.5	1	0.25
– Receiver selectivity	(5)	δV_{sel}	–0.5	Rectangular	0.28	1	0.0784
– Noise floor proximity	(6)	δV_{nf}	±0.5	$k = 2$	0.25	1	0.0625
Mismatch: antenna-receiver	(7)	δM	+0.9/–1.0	U-shaped	0.67	1	0.4489

TABLE 6.9-2 (*end*)

Input quantity	**Refer to note**	X_i	**Uncertainty of x_i**		**$u(x_i)$ (dB)**	c_i	**$(c_i\, u(x_i))^2$ (dB)**
			(dB)	**Pr Dist; *k***			
Antenna factor corrections:							
– AF frequency interpolation	(8)	δAF_f	±0.3	Rectangular	0.17	1	0.0289
– AF height deviations	(9)	δAF_h	±0.5	Rectangular	0.29	1	0.0841
– Directivity difference	(10)	δA_{dir}	±0.5	Rectangular	0.29	1	0.0841
– Cross-polarization	(11)	δA_{cp}	±0.9	Rectangular	0.52	1	0.2704
– Balance	(12)	δA_{bal}	±0.3	Rectangular	0.17	1	0.0289
Partial sum							2.3487
Shadowing and reflections:							
Shadowing	(13)	δSR_1	±1.0	Rectangular	0.56	1	0.3136
Reflections	(14)	δSR_2	±4.0	Triangular	1.63	1	2.6569
Total sum							5.3192
Combined uncertainty $u_c(y) = \sqrt{\sum_i c_i^2\ u^2(x_i)}$							2.3063
Expanded combined uncertainty (k = 2)							4.6126

Comments on the estimates of input quantities (first column of Table 6.9-2)

The uncertainty associated with an estimate x_i of an input quantity in Table 6.9-2 is the largest uncertainty considered likely within the frequency range covered by this table, provided that it is consistent with accuracy of the measurement specified in Recommendation ITU-R SM.378. Superscripts to input quantities refer to the numbered comments below. The expanded uncertainties are to be compared to the values of U_{rec}.

The assumptions which led to the values in Table 6.9-2 may not be appropriate for a particular monitoring station. When a monitoring station evaluates its expanded measurement uncertainty U_{ms} then it must consider the information available on its particular measuring system, including equipment characteristics, the quality and currency of calibration data, the known or likely probability distributions, and measurement procedures.

A monitoring station may find it advantageous to evaluate its uncertainties over subdivisions of the frequency range, particularly if a dominant input quantity varies significantly over that range.

Notes from the second column of Table 6.9-2:

The following Notes are intended to provide some guidance to monitoring stations confronted with data or situations different to those assumed here.

(1) Receiver readings will vary for reasons, which include measuring system instability, receiver noise, and meter scale interpolation errors. The estimate of V_r is the mean of many readings, with a standard uncertainty given by the experimental standard deviation of the mean.

(2) An estimate of the attenuation uncertainty L_c of the connection between the receiver and the antenna, was assumed to be available from a calibration report, along with an expanded uncertainty and a coverage factor.

(3) An estimate of the free space antenna factor *AF* was assumed to be available from a calibration report, along with an expanded uncertainty and a coverage factor.

(4) An estimate of the correction δV_{sw} for receiver sine-wave voltage accuracy was assumed to be available from a calibration report, along with an expanded uncertainty and a coverage factor.

Comment: If a calibration report states only that the receiver sine-wave voltage accuracy is within a given tolerance (±2 dB), then the estimate of the correction δV_{sw} should be taken as zero with a rectangular probability distribution having a half-width of 2 dB.

(5) δV_{sel} takes into account the uncertainty due to limited resolution bandwidth of the measuring receiver or spectrum analyzer including the uncertainty of any correction factor to compensate for the effect of limited resolution bandwidth. E.g. an RMS detector is used for the measurement of a CDMA signal with a measurement bandwidth of 10% of the occupied bandwidth. In this case the correction factor will be 10 dB and the uncertainty of this correction factor is in the order of 0.5 dB in case of a ±10% bandwidth tolerance.

(6) Depending on the distance of the transmit antenna the noise floor of a measuring receiver may or may not be sufficiently far below the input voltage that its effect is negligible on measurement results.

(7) In general, the antenna will be connected to port 1 of a two-port network whose port 2 is terminated by a receiver of reflection coefficient Γ_r. The two-port network, which might be a cable, attenuator, attenuator and cable in tandem, or some other combination of components, can be represented by its S-parameters. The mismatch correction is then:

$$\delta M = 20\ \log_{10}\left|(1-\Gamma_e S_{11})1-\Gamma_r S_{22}) - S_{21}^2\Gamma_e\Gamma_r\right| \tag{6.9-4}$$

where Γ_e is the reflection coefficient seen looking into the output port of the antenna when it is set up for field-strength measurement. All parameters are with respect to 50 Ω.

When only the magnitudes, or extremes of magnitudes, of the parameters are known, it is not possible to calculate δM, but its extreme values $\delta M^{\pm}$ are not greater than:

$$\delta M^{\pm} = 20\ \log_{10}\left[(1 \pm \left(|\Gamma_e||S_{11}| + |\Gamma_r||S_{22}| + |\Gamma_e||\Gamma_r||S_{11}||S_{22}| + |\Gamma_e||\Gamma_r||S_{21}|^2\right)\right] \tag{6.9-5}$$

The probability distribution of δM is approximately U-shaped, with width not greater than $(\delta M^+ - \delta M^-)$ and a standard deviation not greater than the half-width divided by $\sqrt{2}$.

For field-strength measurements, an antenna specification of VSWR ≤ 2.0:1 was assumed, implying $|\Gamma_e| \le 0.33$. It was also assumed that the connection to the receiver was a well-matched cable ($|S_{11}| << 1$, $|S_{22}| << 1$) of negligible attenuation ($|S_{21}| \approx 1$), and that the receiver RF attenuation was 0 dB, for which the VSWR ≤ 2.0:1 implies $|\Gamma_r| \le 0.33$.

The estimate of the correction δM was zero with a U-shaped probability distribution having width equal to the difference $(\delta M^+ - \delta M^-)$.

Comment: The expressions for δM and $\delta M^{\pm}$ show that increasing the attenuation of the well-matched two-port network preceding the receiver can reduce mismatch error. The penalty is a reduction in measurement sensitivity.

For some antennas at some frequencies, the VSWR may be much greater than 2.0:1.

Precautions may be needed to ensure that the impedance seen by the receiver complies with the specification of VSWR ≤ 2.0:1 when a complex antenna is used.

(8) When an antenna factor is calculated by interpolation between frequencies at which calibration data are available, the uncertainty associated with that antenna factor depends on the frequency interval between calibration points and the variability of antenna factor with frequency. Plotting calibrated antenna factor against frequency helps visualise the situation.

The estimate of the correction δAF_f for antenna factor interpolation error was zero with a rectangular probability distribution having a half-width of 0.3 dB.

Comment: At any frequency for which a calibrated antenna factor is available, the correction δAF_f does not need to be considered.

(9) The height dependence of antenna factor for a complex antenna will differ from that for a dipole antenna, which has been considered for the given amount of uncertainty. The estimate of the correction δAF_h was zero with a rectangular probability distribution having a half-width evaluated from the behaviour of biconical and log-periodic antenna factor with height.

(10) The responses of a complex antenna in any direction must be considered relative to the direction of the main lobe for which the antenna factor has been measured.

The correction δA_{dir} was zero with a rectangular probability distribution having the appropriate width.

Comment: A non-zero estimate of δAdir with reduced uncertainty could be evaluated from the known pattern of the measuring antenna, and applied as a function of frequency and angle of incidence.

(11) The cross-polarization response of a dipole antenna can usually be considered to be negligible. The estimate of the correction δA_{cp} for cross-polarization response of a log-periodic antenna was zero with a rectangular probability distribution having a half-width of 0.9 dB, corresponding to the CISPR16-1 cross-polarization response tolerance of –20 dB.

Comment: If a dipole is used as the measuring antenna the correction δA_{cp} is negligible.

(12) The effect of an unbalanced antenna is greatest when the input coaxial cable is aligned parallel to the antenna elements. The estimate of the correction δA_{bal} for antenna unbalance was zero with a rectangular probability distribution having a half-width evaluated from the performance of commercially available antennas.

(13) Effects of shadowing may be considerable in cases of fixed monitoring stations.

The estimate of the correction δSR_1 was zero with a rectangular probability distribution having a half-width of 1 dB as an example. It is difficult to estimate the shadowing effect of e.g. a building.

(14) Effects of reflections may be reduced by field-strength averaging with antenna height variations and variation of the vehicle position in cases of mobile monitoring stations.

References

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ISO [1993] *International Vocabulary of Basic and General Terms in Metrology*. 2nd Edition, ISBN 92-67-01075-1.

ISO [1993] *Guide to the Expression of Uncertainty in Measurement*. ISBN 92-67-10188-9.

ISO/IEC Guide 98-1:1995 – Guide for the expression of uncertainty in measurement (GUM).

TAYLOR, B. N. and KUYATT, C. E. [September, 1994] Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results. United States Department of Commerce Technology Administration, National Institute of Standards and Technology, NIST Technical Note 1297.

6.10 Antenna processing and spatial diversity

6.10.1 Introduction

Although antenna processing and spatial diversity have been used for the past 30-40 years, implementation of the technology has been primarily in communication devices. RF enhancements and reduced processing has largely developed these techniques in the last few years, allowing an improvement in the amount of data that can be transmitted, as well as minimize fading problems and interference on the same frequency.

Spectrum monitoring can also benefit from the use of such techniques to adapt monitoring systems to new technologies and new transmission schemes. Development of wide band wireless cellular systems and flexible spectrum applications lead to a more and more complex radio electric environment, and in some cases these technologies.

Antenna processing can improve the performance of technical monitoring functions such as interference diagnosis and signal separation. Characterization and identification of transmitters, detection and identification of interferers, multipath determination, direction finding and location (angle of arrival (AOA) determination and/or from time of arrival (TOA)/time difference of arrival (TDOA) determination), and other factors can be optimized.

Spectrum monitoring in difficult and complex monitoring environments can benefit from the application of such techniques, in the following situations:

1. urban areas and mountainous locations. For such situations, shadowing by obstacles, flat and selective fading, multipath reflections, etc. are very frequent;
2. re-use of frequencies for:
   – e.g. single-frequency network (SFN) digital TV;
   – e.g. cellular networks;
3. implementation of dynamic spectrum allocation and convergence where the simultaneous use of several radio-communication networks lead to radio transmitters sharing in the same frequency bands.

In this context, antenna processing, thanks to its ability to separate the transmitters and the propagation paths is of particular interest.

6.10.2 Antenna processing and spectrum monitoring

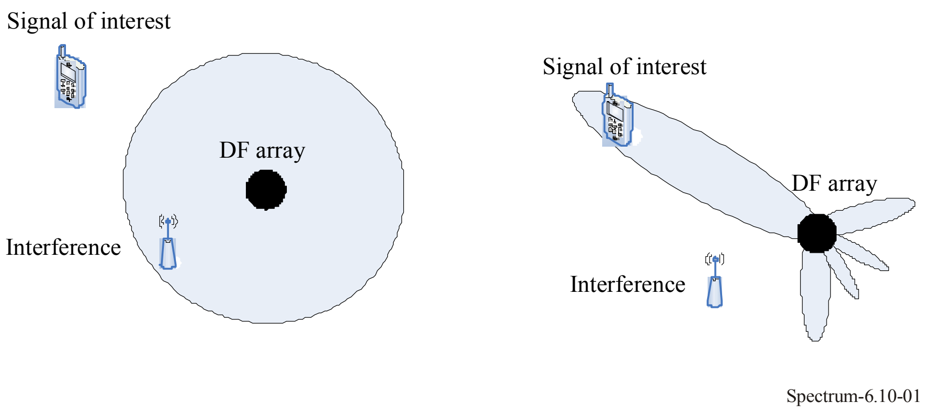
The main purposes of antenna processing are interference cancellation, transmitter separation, sensitivity optimization and multipath effects cancellation (mainly the case of frequency fading).

Interference cancellation: antenna filtering favours one transmitter direction and rejects the interference signal. Then the transmitter of interest can be demodulated and measured under optimal conditions.

Transmitter separation: the antenna filtering can separate several signals at the same frequency. Then the transmitters can be demodulated and identified.

FIGURE 6.10-1

Example of antenna processing: the sensitivity is improved by creation of a beam and the interference is cancelled

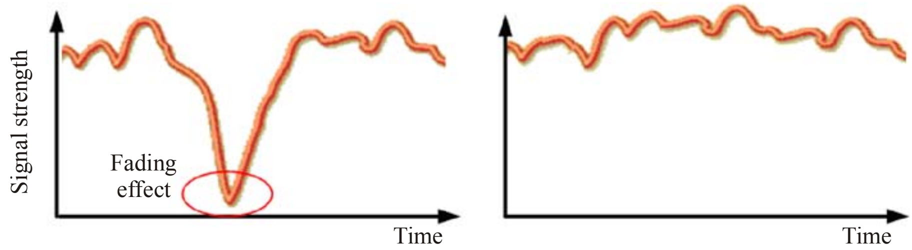


Sensitivity optimization: the antenna filtering implements a formation of digital beam towards the desired signal, thus improving sensitivity.

Fading cancellation: the result of multipath effects is random signal fades as the reflections destructively (or constructively) superimpose on one another, which effectively cancels part of the signal energy for brief periods of time. The goal of antenna filtering is to lower these effects by using the spatial diversity offered by multiple antenna processing.

FIGURE 6.10-2

Example of a signal without antenna processing: A deep fading prevents the receiver to demodulate. In the right figure, the fading effect is reduced by antenna processing and spatial diversity



Spectrum-6.10-02

All these functionalities are important to improve monitoring tasks, such as interference analysis or transmitter identification in a complex environment.

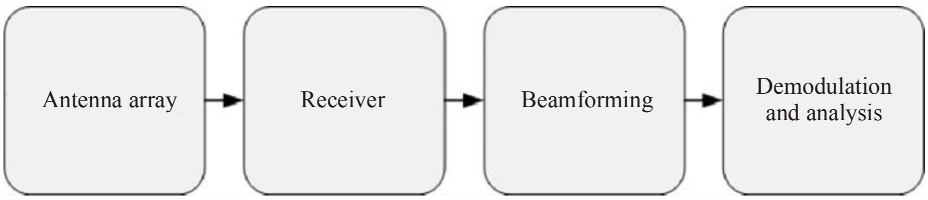
Antenna processing and spatial diversity are based on the use of multi antenna arrays associated to coherent receivers. It is then easy to implement these functions to be used simultaneously into a multi channel correlative interferometer or advanced resolution direction finders without any hardware upgrade but only with additional software.

6.10.3 Antenna processing principles

Antenna processing adapts the receiver to the local radiofrequency environment by the use of real time modification of the antenna radiation pattern with a main lobe focusing towards the transmitter of interest.

FIGURE 6.10-3

Schemes of an antenna processing system



Spectrum-6.10-03

A typical antenna processing systems is composed of:

– multiple antenna elements (one antenna array);

– multiple receivers including coherent processing;

– signal processing algorithms that vary the way in which those elements are used as a function of operational scenario;

– output processing for each of the selected incoming signal, like demodulation, spectral analyze or identification.

6.10.3.1 Antenna arrays and receiver

Use of multiple antennas has several advantages compared with the use of a single antenna. The first one is the exploitation of the spatial diversity which provides enhanced system reliability by minimizing fading of the signals. The second one is beamforming, which focuses energy and thereby provides a better signal to an intended user.

6.10.3.2 Beamforming

Two types of antenna processing techniques can be defined, conventional beamforming and adaptive beamforming. Conventional beamforming implements several fixed beam patterns. A decision is made to select the appropriate beam. Adaptive beamforming allow the antenna to steer the beam to any direction of interest while simultaneously eliminating interfering signals.

6.10.3.2.1 Antenna filtering or conventional beamforming

A beamformer array generates a single-channel signal from multiple antennas signals by filtering the individual signals (adaptive filters) and adding them together, i.e. combining the signals linearly with frequency-dependent weights in amplitude and phase. For a given weighting function, the spatial response of such a beamformer can be described by an antenna pattern showing the dependence of array gain on direction.

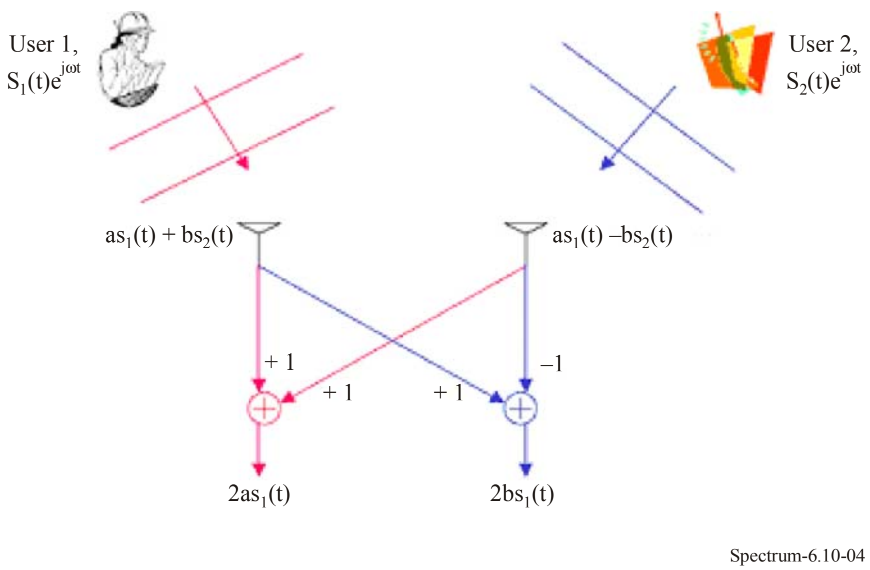
The figure above shows a simple scenario for conventional beamforming: from an antenna array receiving the "User1" signal and the "User2" signal; the algorithm provides two results by applying different weights to the incoming signals.

6.10.3.2.2 Adaptive antenna or adaptive beamforming

Adaptive beamforming takes advantage of interference (or other signals present at the level of the antenna array) to change the directionality of the array. The phase and amplitude of the signal from different antennas is combined in such a way that the pattern of radiation is optimized for the desired signal.

FIGURE 6.10-4

Example of a simple scenario with a 2-antenna array



Adaptive array methods can be classified according to the criteria used for selecting weights to combat a given interference structure and the algorithms used for changing the weights in time. Among the more useful weight-selection criteria are noise-cancellation, eigenvector decomposition and constrained beamforming which is closely related to the known direction minimum-variance and maximum-likelihood criteria. Noise cancellation uses an interference-only signal to remove correlated interference from a target-plus-interference signal. Eigenvector decomposition can be used to estimate the directions of signal arrivals and cancel all but one of the signals.

6.10.3.3 Demodulation and analysis

When the adaptive antenna algorithms have been applied to the input signal of the array, the signal may be demodulated and analyzed in order to identify the transmitter.

Thanks to the use of adaptive antennas, the SNR or SINR is improved and the overall gain is higher since the power on each receiving antenna is coherently combined.

Diversity gain results when independent channels exist between the transmitter and receiver such that the likelihood of all channels experiencing a deep fade simultaneously is greatly reduced.

6.11 Required documentation

For effective work of the monitoring station a collection of relevant documentation and software should be available at a station.

Documentation is also needed for better understanding and application of this Handbook on Spectrum Monitoring.

Documents can be stored in digital format, to save place and to ease their exploration. The following §s comprise a set of such kind of documents and software.

6.11.1 Basic and general international documents

The basic document covering the use of the radio-frequency spectrum is the ITU Radio-Regulations (RR).

The RR, as a principal instrument of the international radio-regulatory arrangement, are based on the use of two main concepts:

– frequency allocations to mutually compatible radiocommunication services operating in specific parts of the spectrum;
– voluntary or obligatory regulatory procedures (for coordination, notification and recording) that are adapted to the allocation structure.

The RR are developed, revised and adopted by World Radiocommunication Conferences (WRC) and published by ITU. According to RR Article 20 (Service publications and online information systems) (WRC-07) the following publications are issued by ITU and may be included in the monitoring stations documentation:

List I – *The International Frequency List.*

List IV – *List of Coast and Special Service Stations.*

List V – *List of Ship Stations and Maritime Mobile Service Identity Assignments.*

List VIII – *List of International Monitoring Stations.*

List VIII A – *List of Stations in the Space Radiocommunication Services and in the Radio Astronomy Service.*

Manual for Use by the Maritime Mobile and Maritime Mobile-Satellite Services.

However, the RR are oriented mainly towards those matters that have a global or regional character, and in many areas there is a place for making special arrangements on a national, bilateral or multilateral basis.

6.11.2 Minimum documentation that should be available at monitoring stations

Table 6.11-1 contains the minimum documentation, which should be available at monitoring stations.

It has to be adopted to the individual tasks of the monitoring station and to the structure of whole monitoring system.

TABLE 6.11-1

Minimum documentation which should be available at monitoring stations

International	National
ITU BR International Frequency Information Circular (IFIC) on DVD-ROM(1) Regional frequency plans Radio Regulations(1) Bilateral and regional agreements ITU List VIII (List of International Monitoring Stations)(1) ITU List IV (Coast Stations and Special Service Stations)(1) ITU List V (Ship Stations *and Maritime Mobile Service Identity Assignments*)(1), (3) ITU-R Recommendations(4) Handbook on Spectrum Monitoring(1) Handbook on National Spectrum Management	National frequency allocation table National frequency assignments (data base) National laws and ordinance acts Maps (or digital maps) of different scales(2) Road maps and city maps(2) User manuals and service manuals for all equipment Telephone dictionary of the own organization and other important numbers Public telephone dictionary, or other access Work instructions Case documentation(5)

(1) These documents should be available at least at HF monitoring stations.

(2) Maps are required at the station and in each vehicle.

(3) Information contained in this List can also be obtained via the Internet-based ITU-MARS (Maritime Mobile Access and Retrieval System), (http://www.itu.int/ITU-R/go/mars).

(4) ITU-R Recommendations are to be used as a reference. Nevertheless, the essentials can be transformed into measurement instructions.

(5) As already indicated in § 2.2.5, the documentation of past cases can be taken as a reference.

6.11.3 ITU-R Recommendations

ITU-R Recommendations constitute a set of recommended technical and operating standards for radiocommunications. They are the result of studies undertaken by Radiocommunication Study Groups.

The ITU-R Recommendations are approved by ITU Member States. Except for those incorporated by reference in the Radio Regulations (Vol.4), their implementation is not mandatory; however, as they are developed by experts from administrations, operators, the suppliers and other organizations dealing with radiocommunication matters from all over the world, they enjoy a high reputation and are implemented Worldwide.

ITU-R Recommendations are divided into Series according to the subjects they cover, as follows:

BO Satellite delivery

BR Recording for production, archival and play-out; film for television

BS Broadcasting service (sound)

BT Broadcasting service (television)

F Fixed service

M Mobile, radiodetermination, amateur and related satellite services

P Radiowave propagation

RA Radio astronomy

RS Remote sensing systems

S Fixed-satellite service

SA Space applications and meteorology

SF Frequency sharing and coordination between fixed-satellite and fixed service systems

SM Spectrum management

SNG Satellite news gathering

TF Time signals and frequency standards emissions

V Vocabulary and related subjects

The ITU-R Recommendations and Reports are published and available on the ITU web pages: (http://www.itu.int/rec/R-REC) and (http://www.itu.int/pub/R-REP). They are also published twice a year on a DVD-ROM.

6.11.4 Radiocommunication SG 1 Recommendations and Reports

Those are the developed ITU-R Recommendations and Reports related to Spectrum Management. They contain essential information to monitoring stations.

See (http://www.itu.int/rec/R-REC-SM) for the Recommendations and (http://www.itu.int/publ/R-REP-SM) for the Reports.

NOTE – The latest versions of Recommendations and Reports should be used.

6.11.5 ITU-R Handbooks

As well as ITU-R Recommendations, ITU-R Handbooks are a set of technical and operational texts, based on ITU-R Recommendations and Reports, for radiocommunications with more practical features. They are also the result of studies undertaken by Radiocommunication Study Groups. They are revised and published every several years as and when the necessity arises. The relevant ITU-R Handbooks for monitoring tasks are as follows:

SG 01 **Spectrum management**

– Computer-aided Techniques for Spectrum Management (CAT), (http://www.itu.int/pub/R-HDB-01).

– National Spectrum Management, (http://www.itu.int/publ/R-HDB-21).

– Handbook on Spectrum Monitoring (see Note 1).

– Supplement to Handbook on Spectrum Monitoring (see Note 1).

NOTE 1 – Superseded by the current version of the Handbook on Spectrum Monitoring.

SG 03 **Radiowave propagation**

– Curves for Radiowave Propagation over the Surface of the Earth, (http://www.itu.int/pub/R-HDB-13).

– Ionosphere and its Effects on Radiowave Propagation, (http://www.itu.int/publ/R-HDB-32).

– Radiometeorology, (http://www.itu.int/publ/R-HDB-26).

– Radiowave Propagation Information for Predictions for Earth-to-Space Path Communications, (http://www.itu.int/publ/R-HDB-27).

– Terrestrial land mobile radiowave propagation in the VHF/UHF bands, (http://www.itu.int/publ/R-HDB-44).

– Radiowave propagation information for designing terrestrial point-to-point links, (http://www.itu.int/pub/R-HDB-54).

SG 04 **Satellite services**

– Satellite Communications – Fixed Satellite Service (FSS), (http://www.itu.int/publ/R-HDB-42).

SG 05 Terrestrial Services

– Compatibility between the Broadcasting Service in the Band of about 87-108 MHz and the Aeronautical Services in the Band 108-137 MHz, (http://www.itu.int/publ/R-HDB-12).

– Digital Radio-Relay Systems, (http://www.itu.int/publ/R-HDB-24).

– Land Mobile (including Wireless Access) Volume 1: Fixed Wireless Access, (http://www.itu.int/pub/R-HDB-25).

– Land Mobile (including Wireless Access) Volume 2: Principles and Approaches on Evolution to IMT-2000/FPLMTS, (http://www.itu.int/publ/R-HDB-30).

– Land Mobile Handbook (including Wireless Access) – Volume 3: Dispatch and Advanced Messaging Systems, (http://www.itu.int/publ/R-HDB-47).

– Land Mobile Handbook (including Wireless Access) – Volume 4: Intelligent Transport Systems, (http://www.itu.int/publ/R-HDB-49).

– Migration to IMT-2000 Systems – Supplement 1 to the Handbook on Deployment of IMT-2000 Systems, (http://www.itu.int/publ/R-HDB-46).

SG 06 Broadcasting service

– DTTB Handbook – Digital terrestrial television broadcasting in the VHF/UHF bands, (http://www.itu.int/publ/R-HDB-39).

– HF Broadcasting System Design, (http://www.itu.int/publ/R-HDB-33).

– LF/MF system design, (http://www.itu.int/publ/R-HDB-38).

SG 07 Science services

– Selection and Use of Precise Frequency and Time Systems, (http://www.itu.int/publ/R-HDB-31).

– Satellite Time and frequency Transfer and Dissemination, (http://www.itu.int/pub/R-HDB-55).

6.11.6 Relevant ITU-R software

Over the past few years, a growing number of administrations have requested engineering software to support their national and international frequency management activities. The programs are submitted by participants in the work the Radiocommunication Study Groups or by the Radiocommunication Bureau.

A detailed description of available computer programs, which might be of interest to radio spectrum management, is accessible electronically through the ITU Web site (http://www.itu.int/).

Examples of programs are:

1. ACP: Antenna Coverage Program.
2. IDWM: ITU Digitized World Map (IDWM) and Subroutine Library.
3. MSAM: Microcomputer spectrum analysis models, (http://ntiacsd.ntia.doc.gov/msam/).
4. Calculation of Ground Waves, (http://www.itu.int/ITU-R/go/rsg3-software-ionospheric).
5. *SMS4DC* a Spectrum Management System for Developing Countries.
6. MARS Maritime Mobile Access and Retrieval System the most up-to-date data registered in the ITU master Ship station database, (http://www.itu.int/ITU-R/go/mars).
7. GLAD GLobal Administration Data System: an online data retrieval-system and a central repository of ITU-R common information concerning administrations and geographical areas, (http://www.itu.int/ITU-R/go/glad).

Furthermore databanks and computer programs on radiowave propagation can be found at: http://www.itu.int/ITU-R/go/sg3-dtbank-dbsg3.

6.11.7 Internet Web sites

The World Wide Web (WWW) Internet addresses represent Web locations that have information relating to various aspects of spectrum monitoring and spectrum management.

The Web should be considered an important source of monitoring and management information, with useful software that may be downloaded, as well as a way to interact within national spectrum management organizations and with other monitoring organizations via electronic mail and other documentation.

Table 6.11-2 lists Internet World Wide Web sites that are relevant to readers which have interest in radio monitoring:

TABLE 6.11-2

Internet World Wide Web sites relevant to radio monitoring

Subject	Description/WWW address
ITU Global Directory	Administration's Contact Information: www.itu.int/GlobalDirectory/
ITU Radiocommunication Bureau	Homepage: www.itu.int/ITU-R/go/rhome
ITU Monitoring database	Monitoring database: www.itu.int/ITU-R/go/terrestrial-monitoring
ITU Spectrum management/monitoring	Study Group documents: www.itu.int/ITU-R/go/rsg1
ITU-R Recommendation	www.itu.int/publ/R-REC
ITU-R Handbooks	www.itu.int/publ/R-HDB
Engineering	International Engineering Consortium (IEC): www.iec.org/
	Institute of Electrical and Electronic Engineers (IEEE): www.ieee.org/
	IEEE Antennas and Propagation Society: www.ieeeaps.org/
	IEEE Instrumentation & Measurement Society: www.ieee-ims.org
	IEEE Broadcast Technology Society: www.ieee.org/organizations/society/bt/index.html
	Fraunhofer Institute, Germany: www.iis.fraunhofer.de/en/index.jsp
	Dutch Electronics and Radio Society: www.nerg.nl
	International Amateur Radio Union: www.iaru.org
Regional Organizations	Asian-Pacific Telecommunity (APT): www.aptsec.org
	European Conference of Postal and Telecommunications Administrations (CEPT): www.cept.org
	European Communications Office: www.ero.dk
	Inter-American Telecommunications Commission (CITEL): http://portal.oas.org/Portal/Topic/CITEL/AcercanbspdenbsplanbspCITEL/tabid/379/language/en-US/default.aspx
	Arab Spectrum Management Group (ASMG): www.asmg.ae
	African Telecommunication Union (ATU): www.atu-uat.org/
	Regional Commonwealth in the Field of Communications (RCC): www.rcc.org.ru

TABLE 6.11-2 (*end*)

Subject	Description/WWW address
National Organizations	Agence Nationale des Fréquences, France: www.anfr.fr
	Federal Communications Commission, USA: www.fcc.gov
	Federal Network Agency, Germany: www.bundesnetzagentur.de
	Industry Canada: www.strategis.gc.ca/spectrum
	Ministry of Communications, Israel: www.moc.gov.il/140-en/MOC.aspx
	Monitoring Earth Station, Leeheim, Germany: http://www.bundesnetzagentur.de/cln_1932/EN/Areas/Telecommunications/TechnicalTelecomsRegulation/SpaceRadioMonitoringStadion/SpaceRadioMonitoringStation_Basepage.html
	National Communications Authority, Hungary: www.nhh.hu
	National Telecommunication Agency, Brazil: www.anatel.gov.br
	U.S. National Oceanic and Atmospheric Administration radio user's page: www.ngdc.noaa.gov/mgg/topo/globe.html
	Communications Research Centre (CRC), Canada: www.crc.ca
	National Research Council, Canada: www.nrc.ca
	Ukrainian State Centre of Radio Frequencies and Supervision for Telecommunications: www.ucrf.gov.ua
	Solar terrestrial activity report (solar Flux/A index chart): www.solen.info/solar/
	Central Radio Management Office (CRMO), Republic of Korea: www.crmo.go.kr/en
Scientific Agencies	U.S. National Science Foundation: www.nsf.gov
	Committee on Radio Astronomy Frequencies: www.craf.eu/
	Institute for Telecommunication Sciences: www.its.bldrdoc.gov

ANNEX 1
TO THE HANDBOOK

MONITORING SYSTEM PLANNING AND TENDERS

Page

A1 Topics to be considered by Regulatory Authorities before issuing a tender

A National Radio Regulatory Authority has to interpret and implement the provisions of the ITU RR, which have the force of international treaty. It has also to implement the national statutory provisions of the national laws and the Rules framed there under, relating to radiocommunications. Compliance of the provisions of the authorisations/ licenses by various wireless users spread all over the country has also been enforced. Monitoring Organization is the field Organization of the national Authority providing practical data as relevant for spectrum management including control and regulation of wireless networks with a view to ensuring interference-free operations of all networks.

The Monitoring Organization is entrusted with all necessary responsibilities for effecting coherent and extensive usage of radiocommunications in the country. Following aspects relate to planning, coordination and regulation of the spectrum in the national context:

a) optimising the utilisation of radio spectrum by following the latest international standards and practices for spectrum management and wireless monitoring functions;

b) utilisation and protection of orbit/frequency resource for national satellite and other space systems by publishing, notifying and registering national system with ITU and ensuring continued protection from new systems of other countries;

c) identifying the spectrum need for new wireless networks, and assigning to them suitable frequency(ies), power, bandwidth, emission, hours of operation, and other technical parameters with appropriate operational, regulatory and administrative provisions;

d) authoring the installation and operation of wireless stations by specifying all the necessary technical and operational parameters like frequency of operation, power, emission, hours of operation, etc.;

e) establishing regulations, technical parameters and standards governing the use of each frequency band or specific frequency by stations of different radio services, having regard to current international regulation and agreements;

f) undertaking special coordination work for use of radio systems/ equipments in special situations such as natural calamities, etc.;

g) maintaining and updating all information on authorized radiocommunication systems such as frequencies, locations of stations, power, call signs etc.

Radio Monitoring supports all these functions as it is an important part of spectrum management process. It plays a significant role in the planning, engineering, electromagnetic compatibility and in ensuring compliance with licensed/authorized parameters. In fact the monitoring is known as eyes and ears of spectrum management.

The other Chapters of this Handbook on Spectrum Monitoring provide many detailed descriptions of all types of monitoring stations, equipment and procedures. This Annex provides an overview about what sort of planning, studies and procedures are required when developing either a nation-wide monitoring system or a fixed or mobile monitoring station.

Radio frequency spectrum is to be used equitably, economically, efficiently and rationally. Appropriate frequency repeatability is therefore required to be ensured. Adoption of appropriate equipment and monitoring system required to be ensured.

A2 General overview of a tender process

When a national administration decides to create its nationwide monitoring system, a new local monitoring station, or just like take a single mobile measuring system, the work of the established project for the execution of the assigned goal is dividable into three stages (see Fig. A1-1):

Preparation stage: Planning

− Concept for a radio monitoring system.

− Feasibility study.

− Business Plan.

- System planning.
- Specifications for the systems.

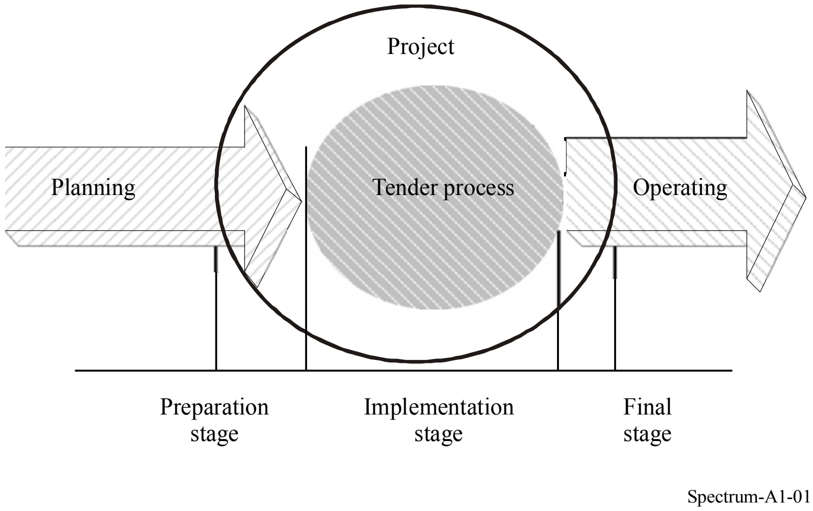
Implementation stage: Tender process

- Invitation to start public purchase tender (consideration of the competence of the bidders, viewpoints of the disqualification for fulfilment of contract).
- Invitation for bids (including clarification to the bidders).
- Submission of proposals by the bidders.
- Evaluation of received proposals (request for clarifications inclusive).
- Decision for award of contract.
- Signature and entry into force of the contract.

Final (termination) stage: Acceptance procedure, operation

- Factory, provisional and final acceptance procedures.
- Training, maintenance and spare parts supply.
- Starting up of the operation.

FIGURE A1-1



A3 Preparation stage: planning

This section describes the various stages, which may lead to a tender process for a complete new monitoring system or part(s) of it, resulting finally to the procurement of equipment.

In case only a part of an existing monitoring system or an individual piece of equipment need to be replaced, some of these stages are not needed.

In case a complete new monitoring system is needed a number of fundamental requirements are to be worked out in order to come to a monitoring system which responds to the monitoring need of the regulatory body, available budget, etc.

The following stages are described:

- Concept for a radio monitoring system.
- Feasibility study.
- Business Plan.

− System planning and design.

− Development of specifications for the system.

A3.1 Concept for a radio monitoring system

As described in Chapter 1 of this Handbook, Spectrum Management is described as the overall process of regulating and administering use of the radio frequency spectrum. The goal of spectrum management is to maximize spectrum efficiency and minimize interference. Rules and regulations, based on relevant legislation, form a regulatory and legal basis for the spectrum management process. Databases of information, including details of all authorized users of the spectrum, provide the administrative and technical basis for the process. Analysis of the information in these databases facilitates the spectrum management process resulting in decisions for spectrum allocations, frequency assignments, and licensing. Amongst others spectrum monitoring provides the necessary means to maintain the integrity of the spectrum management process and can be defined as a process of observing the radio frequency spectrum and reporting on its use.

In defining the operational concept, the following elements need to be addressed:

− Automation of data management and spectrum monitoring process, with appropriate computer software. The computer software and equipment for spectrum monitoring activities are specialized. Consequently provision of adequate materials would be essential for these activities.

− Augmentation of automated spectrum monitoring, radio noise surveys, and direction finding facilities, both in the fixed and mobile modes (capabilities up to 3 GHz).

− Specialized monitoring facilities for microwave and other higher frequency bands and for specialized services up to 50 GHz or above.

− Augmentation of satellite monitoring facilities for geostationary (GSO) and non-geostationary (non-GSO) satellite systems.

− Structure of the organization (staff) and its interaction with other organizations particularly by the spectrum management.

− Existing and required infrastructure.

− Training of personnel for institutional competence and capacity building; etc.

These elements are addressed in the following sections.

Once the operational concept has been defined, a cost/benefit analysis should be conducted to assess whether the requirements of the administration would be met in a cost effective way. This is always necessary, no matter whether a new system or the modernization/modification of an existing system is planned.

A3.2 Feasibility study

A3.2.1 The goal of feasibility study

The feasibility study is a fundamental basis of starting a tender process. The study is needed in order to analyze alternatives, study the impact of developments on the future measurement possibilities and find the best solution, including what would be the impact on the spectrum management responsibilities in case one decides not to procure new equipment.

The study should also answer the question on what the achievable advantages of the technical development are for the authority, the information society and the spectrum users?

During the development of technical planning of monitoring measuring devices or systems, one should take into consideration the technical capability, the lifetime and deterioration of the available devices or systems.

In the course of the planning and development of measurement devices or systems, the following items should be specified and taken into consideration:

− Coverage areas of monitoring based on:

  i) responsibilities of the Regulatory Body;

  ii) size of the country;

iii) density of the spectrum usage over the country;

iv) need for other functional elements of the spectrum management process, such as frequency planning, licensing and enforcement departments;

v) responsibility of the monitoring service;

vi) future planned use of radio communication in the country.

– Measurement tasks derived from the regulatory environment.
– Technical specification(s) of the equipment related to the tasks.
– Need for a comprehensive measuring system or for a specially designed measuring system for performing a special type of measurement.
– Number and location of (remote) fixed stations.
– The functions of mobile monitoring units.
– Number and type of mobile units.
– Purchase of a turn-key system or build-up a system from individual components.
– Integration into an existing system or purchase of a stand-alone system.
– Necessity of remote access to the measurement and/or frequency management data bases.
– Degree of dependence from a single supplier.
– Price and follow-up cost.

The depth of feasibility studies and the cost for external contributors should be proportional to the value of the investment.

A3.2.2 Content and structure of the feasibility study

For attainment of the goal of the study, the intended technical purpose, the structure, the implementation procedure, the necessary resources (financial and human), the possible alternatives and the expectable completion date of task must be exactly specified in the study.

The study should specify the topics below in detail:

– Definition of the subject of the study.
– Legal and regulatory environment and analysis of the communications market.
– Definition of the reason and goal of the study:

i) background and justification for the new monitoring system;

ii) structure of monitoring system to be implemented;

iii) (new) tasks for the monitoring service, including frequencie ranges to be covered etc;

iv) existing equipment is out dated and can not fullfill the required measurements;

v) usability and integration of the existing measuring equipment;

vi) to provide the monitoring service with technical state-of-the-art system(s);

vii) to improve the effective and efficient way of working by the monitoring staff;

viii) how many staff is needed to operate a new system;

ix) technical competence needed for the staff;

x) informatics system and data management;

xi) economics calculations.

– Alternatives for the implementation of project.
– Expectable further developments.
– Time schedule for the study.

– Resource planning:
   i) human resource (for the preparatory, implementation and operation stages);
   ii) financial resources (for the preparatory, implementation and operation stages).
– Management of risks:
   i) exploration of risk factors;
   ii) classification of risks;
   iii) analysis of the effects of risks;
   iv) on the bases of analyses, elaborating of the appropriate risk management policy.

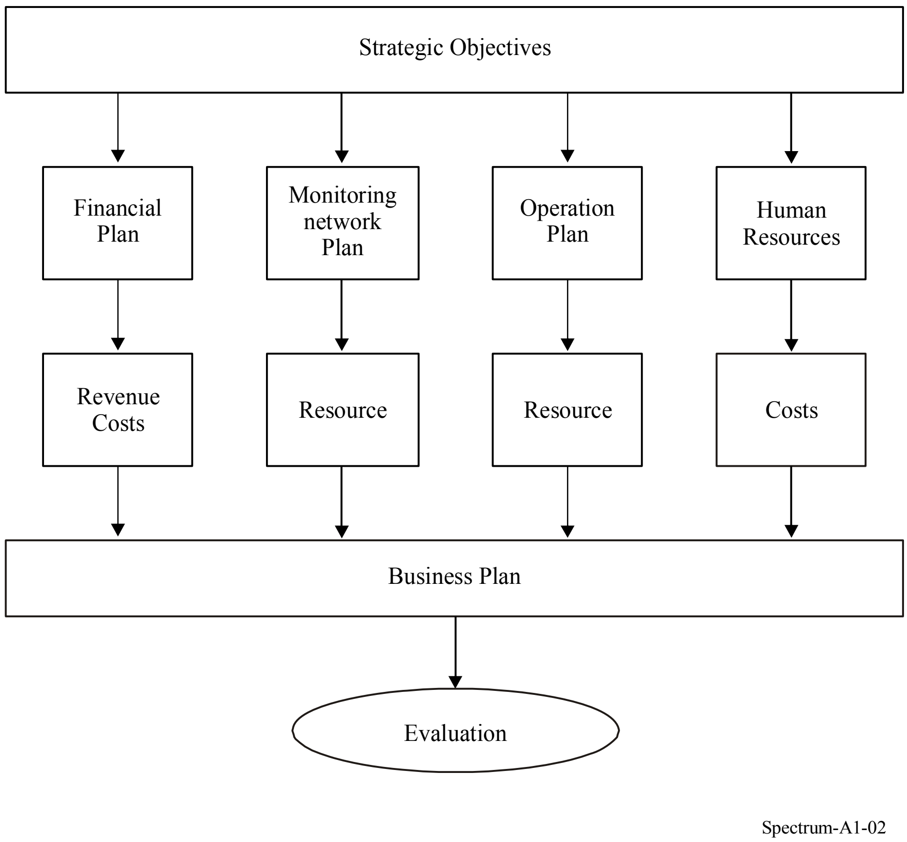
A3.3 Business Plan

A system requirements study is prepared either by the administration or/and by consultants.

A tender may also be necessary in the case of replacement of equipment and in the case that some parts of the process (see Fig. A1-2) have to be modified.

FIGURE A1-2

National management of monitoring business plan



A3.4 System planning and design

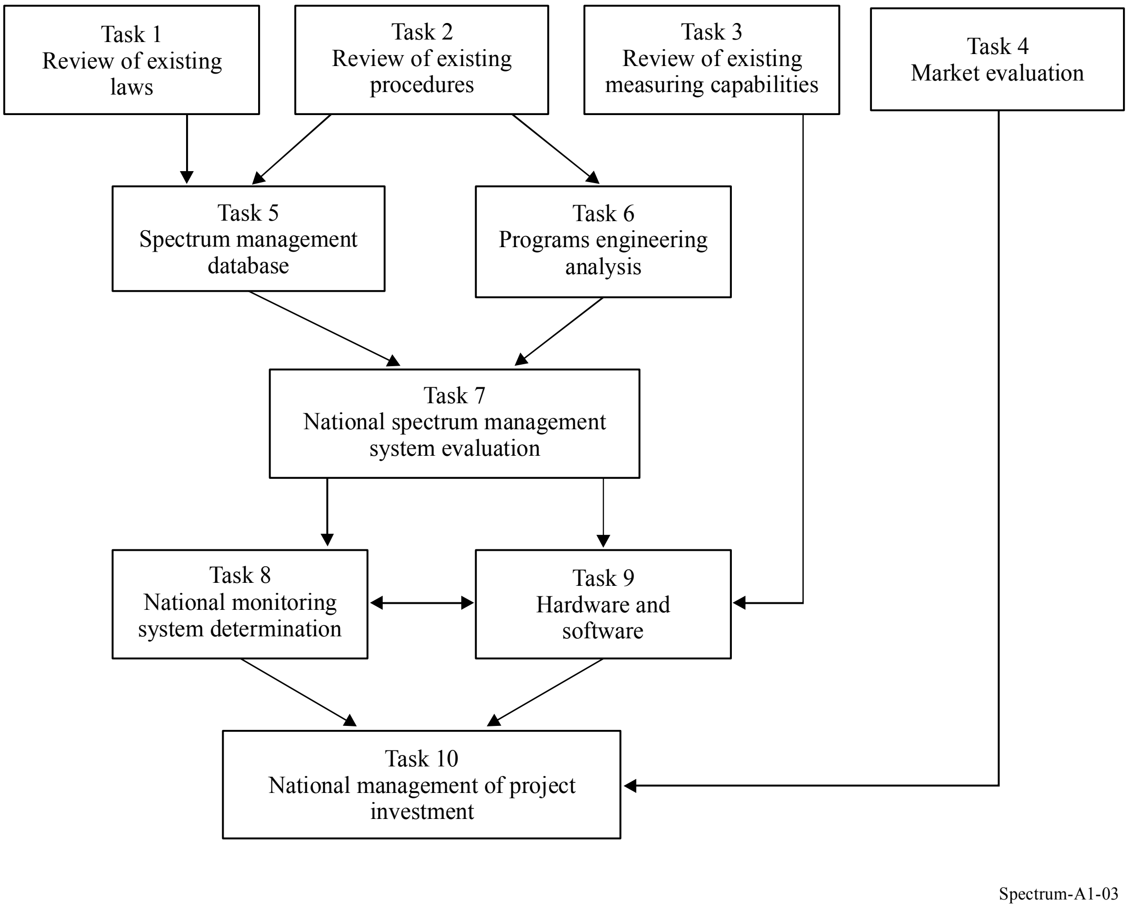
This section proposes a technical approach and a methodology in order to establish a schedule of conditions for the establishment of a national system of spectrum management and monitoring which takes into account the objectives described in the preceding chapters. In the same way, the principle described makes it possible to establish a structure of the management of the spectrum built around basic functions to achieve as described in the ITU-R Handbook on National Spectrum Management.

Some of its functions being able to be gathered or on the contrary subdivided according to the habits, resources of the country considered thus that size of the organization.

Methodology described in Fig. A1-3 is based on 10 different tasks taking into account all legal and technical aspects induced by the management of the spectrum in a worldwide environment.

FIGURE A1-3

National spectrum management and monitoring plan



This model tender assumes that land, building construction and utility (water, sewage, telephone, electricity, fuel, etc.) connection costs are borne by the Agency issuing the tender.

A3.4.1 Review of existing laws and legal aspects

Task 1 will make it possible the Administration to be familiarized with the new laws and existing billing at the regional, world level and governing the use of the spectrum. Of these allied studies to the knowledge of the national law of the country, it could be established an adequate national lawful framework.

A3.4.2 Review of existing procedures and methodologies

This task will have to be taken into account by the persons in charge of the management and the control of the spectrum. It must have reviewed and evaluated the planned organization of the regulator as well as management operations. The framework as well as management operations will have to be taken into account. A framework will have to be devised that suitably harmonizes requests for licences, the attribution and allowance of frequencies as well as the payments related thereto. This information will be used in order to develop a data-processing general system corresponding to the needs for management and control of the spectrum.

A3.4.3 Review of existing measuring capabilities

During the planning phase of development, the capability and suitability of the existing measuring devices must be reviewed. It must be decided, what are those measurement abilities that are sufficient to keep at the present disposal level and what are those that must be improved by the project to satisfy the future measurement demands.

The possible integration of newly purchased equipment to the existing system(s) must be also reviewed.

Additionally the future manpower must be reviewed considering the new measurement tasks.

A3.4.4 Market evaluation

The use and usability of radio spectrum are essential conditions of the function of communications market. Considering that radio spectrum is a limited natural resource, to satisfy all increasing demands of the communications market is only possible by establishment new modulation technologies (e.g., digital changeover) and opening new frequency bands. When planning the development of a spectrum monitoring system, the developers must be fully aware of the long-term spectrum demands of the communications market, the characteristics of new modulation technologies and the new frequency bands waiting for to be opened. Considering the quick development of measuring systems, an effort should be made to avoid the new system to be obsolete, even shortly after its first operation.

A3.4.5 Data base of spectrum management

The spectrum management data base will allow the analysis of the data elements in quantity and quality. This is necessary for an effective management of the spectrum in the country. This implies an analysis of the data as well as average existing paper or electronics and their integration in the new information processing system, which will rationalize the information flow and will ensure its storage. (See Recommendation ITU-R SM.1413 – Radiocommunication Data Dictionary for notification and coordination purposes.)

A3.4.6 Programs engineering analysis

The functionalities and the modules of applications to the engineering necessary are to be determined and should include/understand mainly:

– allowance of the frequencies;
– analyze systems of engineering;
– interference and electromagnetic compatibility;
– calculation of the royalty billing;
– Inspection;
– homologation – approval;
– reports/ratios.

These application software modules must be directly inter-connected with the data base of administrative management. Chapter 8 of the ITU-R Handbook – National Spectrum Management, contains a list of the basic and optional modules required.

A3.4.7 National spectrum management system evaluation and monitoring system determination

In these tasks, the frequency monitoring capabilities and the requirements for an efficient nationwide monitoring system are determined. The need of a regulatory system is ideally require the establishment of both national and regional administrative offices and various types of monitoring stations. In some instances the administrative offices and monitoring stations may be accommodated in the same buildings, but not all monitoring stations will have identical facilities.

Some monitoring stations will be required to monitor only VHF/UHF spectrum whilst others will monitor frequencies below VHF and /or above UHF. The location of unknown transmitters and sources of interference will be a major activity requiring suitable direction-finding capability and this include mobile stations.

The major objectives of the radio monitoring system are to support the primary activities required for national spectrum management, as well as checking for compliance with the regional and worldwide allocations of the International Telecommunications Union (ITU) and those obtained through bilateral agreement. To be effective, the radio monitoring system must cover all the major population centres throughout the country on a continuous basis. The tasks and activities that must be conducted by radio monitoring system, as well as the necessary equipment are described in this Handbook. The documents will consider the establishment of the technical specifications for and operation of a national regulatory monitoring system. These tasks must consider the existing and/or the development of the Frequency Management Data Base and associated planning software packages that will be required to administer policy.

A3.4.8 Hardware and software evaluation

According to the needs for data processing (hardware and software) as well as equipment of vehicle inspection expressed in the conclusions for tasks 5, 7 and 8, the experts dedicated to this task must optimize and/or direct the solutions found as well according to criteria of cost as of maintenance/formation.

A3.4.9 National management of project

At the completion of the network design, the project manager, data engineer and the financial analyst will develop the capital costs and investment requirements for the spectrum monitoring network. It is assumed that a part of the national network can be provided over existing facilities or augmenting the existing capacities. It will be necessary to know the budgetary limitations that the country may impose upon the spectrum program so that a system concept and specification that is within these constraints may be implanted. In the case of a limited budget, the committee would make recommendations on the time phase program that would meet the budget requirements and meet the immediate spectrum monitoring requirements. With this study – Project Investment Brief – the committee prepares a Project Report with tender documents for submission to the national authorities.

A3.5 Development of specifications for the system

A3.5.1 National and regional centres, monitoring stations

Administrations in smaller countries tend to have a national monitoring centre and an appropriate number of fixed and/or mobile monitoring stations, which are controlled directly by the national monitoring centre. Administrations in larger countries may find it desirable to have regional monitoring centres in addition to the national centre. In either case, the national monitoring centre may also include a national spectrum management centre to provide integrated automated management and monitoring of the radio spectrum.

The mobile monitoring stations supplement the network of fixed stations. Practically they have the same measuring capabilities like fixed station, but can be installed easily almost anywhere in the country, accordingly are able to monitor different spots.

In compliance with their functions, certain mobile monitoring stations (vans for interference investigation, coverage measurement, measurement of microwave networks) possess specialized measurement capabilities.

For specifying their types and necessary number, effort should be made to achieve their most optimal building-up and measurement capacity, in the course of planning stage.

In case of mobile stations, the expectable frequency of measurement tasks should be taken as a basis in the first place when specifying their necessary number.

During the planning of measurement system capacity, the necessary number of fixed stations depends on the size and the terrain conditions of the area, as well as the frequency range that must be monitored.

When designing a mobile monitoring station, a compromise must be found between full-scale equipment, budget and limitations on weight and space of the vehicle. Therefore, it must be decided whether a general-purpose vehicle or a specialized vehicle for the certain task should be procured.

The available service network and spare part supplies for the applied vehicles in the country are also important viewpoints.

A3.5.1.1 Organization, number of operator positions and equipment of a monitoring station

The following points will have to be defined:

Control Centre/ Monitoring Station	Organization/Tasks/Means/Interactions
Hierarchical position	National/Regional/Local/Other
Allocation of responsibility	Frequency range (e.g. VLF up to HF and/or V/UHF and/or SHF) Services to be monitored, services areas List of monitoring stations to be directly controlled and mobiles List of dependant lower level control centres
Organization of the work	Existing computer or network architecture (s), software for automation For the number of operator positions, specify: – Operating hours/Numbers of shifts – Hierarchy and share of responsibility between operators – Tasks/Reports/Document follow-up procedures (specify) Archiving methods and means (data, audio, interval …) Reporting means Security concerns and procedures
Work position description	Control all or some of the remote stations functions Program or scheduled automated tasks to run off-line in remote stations Perform location computation and display result Access to database to consult technical file of frequency management (interactivity) Display of geographical information Issue automated reports Expected response time (specify for each task) Maximum number of simultaneous connections with remote stations and type of connections (data, voice-grade or broadcast-sound grade audio …) Maximum number of simultaneous recordings (if done at control centre) Man-machine interface: language(s), operation system and data base.
Interaction with frequency management system	Is a computerized frequency management system available? If yes, which one? Is interaction with frequency management system required? Availability of locally available frequency management database
Geographical Information System (GIS)	Which geographical information system is available under which format for integration? 2-D (road map, administrative map, topographic map), vector and/or raster 3-D (digital terrain model) Coordinates to be used (UTM, geographical ...) scales and resolutions, areas required
Communications	a) Means for operators: – Fax/ telephone/Internet (individual or shared) – E-mail (with work positions, control center(s), station(s), frequency management department etc.) – Radiocommunication means (public, private, HF, VHF/UHF, SHF) b) Means for remote stations or other control centres – Private networks – Private point to multipoint (radio/microwave/PSTN/ISDN/ Analogue or digital leased lines/X25/VSATs, Internet, …) – Speed and bandwidth

A3.5.1.2 Measurement tasks

It should be noted that it is up to the responsibility of every country to decide on the measurement tasks and the related frequency ranges to be covered.

To define the essential measurement equipment characteristics for each operator position, the following points should be specified:

Frequency measurement

– Frequency range.

– Required accuracy; is a central frequency standard available.

– Classes of emission (measurement method).

Field strength, level and power flux-density measurement

– Quantity and methods of measurements at fixed stations, at mobile stations.

– Required accuracy.

– Frequency range.

– Special measurements:

  – Coverage measurements (measurements along a route), measurement of antenna patterns (e.g. by helicopter).

Spectrum occupancy including channel occupancy measurement

– HF emissions, VHF/UHF emissions.

– Technical specifications of channels: bandwidth, spacing, type of modulation.

– Duration of occupancy recording: continuous, time from … to …, special days, repartition of scans.

– Required scanning speed (software).

– Additional information to be recorded (e.g. call sign, automated identification/decoding).

Occupied bandwidth measurement

– β/2 and/or *x*-dB method measurements using spectrum analyser or software.

– Others methods.

Modulation measurement

– Modulation depth.

– Frequency deviation.

– Bit error rate (BER).

– Other quality parameters.

– Constellation diagram.

Direction finding and location measurement

– System concept.

– Type of station: fixed, mobile, transportable, portable and required accuracy.

– Frequency range.

– Location (by triangulation or SSL) digital terrain mapping required.

– Response time.

– Needed space for DF antennA

– Display of bearings on digital maps.

Identification measurement

– Classes of emission.

– Identification (e.g., decoding) of the various transmissions.

– "Fingerprinting"/"Individual transmitter envelope characteristics".

Monitoring of spacecraft emissions e.g.:

– Frequency, bandwidth, power flux-density measurements.

– Determination of orbital positions.

– Occupancy of frequency bands at orbital positions.

Multimedia broadcast e.g.:

– Type terrestrial or satellite.

– Quality of received signal (needs special equipment)/decoding.

Cellular networks to be monitored:

– System parameters in order to identify the type of network.

– Field strength.

– Quality parameters (e.g. RxQual/CIR /BER).

– Additional information (e.g., handover for cellular radio).

– Number of channels.

– Maximum allowable distance between measurement points.

– Maximum distance between the measurement points of the same frequency/channel (valid for all allowed velocities).

– Is a special data evaluation tool needed and is it the intention to combine this system with the mobile monitoring (mapping) system?.

Microwave links including satellite links

Receiving and measuring equipment in the 1 to 50 GHz range for which services? (equipment).

A3.5.2 General equipment specifications

With regard to the elected measurements: to define the equipment allowing these measurements in each monitoring centre, fixed (remote) and/or mobile monitoring station.

a) System concept and architecture centre, station, means of communications, software.

The performance of a monitoring station is directly related to the quality of antennas, receivers or field meters and radio direction-finders.

b) Antennas

To determine the types and the number of antennas for each station with regard to the elected, the following details have to be known measurements.

– Basic questions:

  a) Polarization (diversity) and frequency ranges (sub-ranges).

  b) Approximate distances from the region to be monitored (radius).

  c) Geographic pointing of the antennas (degrees).

  d) Distance between antennas and signal distribution system.

– Signal distribution system:

  a) Frequency range.

  b) Number of receiver connections per antennA

  c) Number of antennas if antenna diversity is required.

  d) Operation of the signal distribution system: manual, semi-automatic or automatic.

– Omnidirectional and dipole antennas:
  a) Active receiving antennas.
  b) Transmitting/receiving antennas.
  c) Air traffic control antennas.
– Directional antennas:
  a) Linearly polarized log-periodic antennas.
  b) Dual-polarized log-periodic antennas.
  c) Dish and feed antennas.

For all antennas: frequency range (from 10 kHz to 50 GHz or further); identification of the antenna types in cooperation with the system supplier.

c) Receivers, Direction – Finders

– Frequency bands.
– Reception channel number.
– Analogue or digital type.
– Manual or automatic control (computers, software).

d) Additional equipment

Certain additional equipment will permit more effective operation of a monitoring station. One example is the reporting equipment: reproduction machines, oscilloscopes audio-video recorders, printers, etc.; or:

– Frequency (10 MHz) and time etalon (rubidium, GPS or GLONASS).
– Air conditioner.

For mobile monitoring:

– Navigation and positioning system (Dead Reckoning system, GPS, GLONASS (or other), or a Complex Navigation system).
– Compass for azimuth determination.

A3.5.3 Monitoring vehicles and devices

The VHF/UHF band mobile monitoring stations shall be designed and supplied housed in a vehicle, and shall be completely equipped with all necessary monitoring equipment, monitoring antennas, modem(s) communication antenna(s), GPS and GPS antenna, interconnecting cables, power supplies, cabinets, racks, mounting hardware, interface devices and terminal blocks to form a complete and working stand alone system, as well as a reliable component that is an integral part in the national spectrum monitoring system. The vehicle can be also equipped with portable measuring instruments for doing Spot Monitoring or exact interference source localization.

In the course of vehicle purchasing the following alternatives must be considered:

– Body of vehicle (van, jeep, passenger car).
– Engine type (petrol, diesel).
– Driven wheels (2 or 4).
– Size and weight.

A3.5.4 Software

The Management system and monitoring system shall contain a significant amount of software to automate data collection, processing, evaluation, and interference analysis tasks.

Using software to save spectrum monitoring results in relational databases and correlating this information with the central database of authorized users will save considerable research time while increases the accuracy.

The monitoring system application system and control software shall be developed in accordance with the ITU-R Recommendations, in particular ITU-R SM.1537, the National Spectrum Management ITU-R Handbook [2005] and the relevant ITU-R Recommendations of the Handbook on Spectrum Monitoring.

Pieces of monitoring application software:

– Digital mapping software.
– Direction finding software (integrated with the mapping software).
– Data base management software.
– Intelligent archive system software.
– Interface software between licensing database and monitoring measurement results.
– Measurement result evaluation software (data filters, post processes and graphically displays of data, automatic reference values and licence database compliance investigation).

The monitoring application program shall be of a user-friendly design, and shall be described in detail in the relevant manuals and guidelines.

A3.5.5 General requirements for the units of monitoring systems

In the technical annex of invitation for tender document the inviter specifies and publishes the measurement tasks, the required equipment and the expected minimal technical requirements.

During the planning of project implementation, the optimal number of fixed, mobile, portable or hand operated measuring systems and the division of the measuring tasks among them must be decided.

For detailed information on the technical requirements for the units of monitoring systems, see the Chapter 3 of this Handbook.

A3.5.6 Specifications for services

A3.5.6.1 Site survey

The location of a fixed radio monitoring system has a very large effect on its efficiency and on the costs that are involved. Siting is governed by geographic, topographic and climatic conditions including local noise and sites must be selected very carefully because this must guarantee the required performance of the overall system.

Generally the user is responsible for site investigations. Documents, results of measurements, topographical maps, etc. must then be made available.

In developing the systems' operational concept the number of individual stations and their tasks will have been decided, and the selection of sites can be made according to the ITU-R Recommendations.

In the HF range sites can be selected by evaluating computerized radio-propagation forecasts, but supplementary measurements should still be carried out on-site.

A3.5.6.2 Telecommunication links and network

– Are telecommunication links between the individual stations to be quoted for? If so, of what kind (physical lines, radio links, microwave)? Will the administration provide them? Are telecommunication lines available?
– What is to be transmitted (voice, music, data)?
– Details of lines: type (public dialling network, dedicated network, dedicated telecom line with interfaces according to ITU-T Recommendations (e.g., V24)), quality (transmission rate in bauds, bits/s), length, system (two-wire, four-wire).
– Details of radio or microwave links: frequency, mode, channel bandwidth and transmit/receive system. If available computers are to be integrated into the system, it is necessary to have details of the type, memory capacity, interface conditions, peripherals and software. A transmitter (or transmitters) shall normally be operated remotely to avoid interference to the monitoring station.

– Details of structure: point-to-point, multipoint-point, ring, star.
– Is masking or encryption called for?

A3.6 Training

In order to make effective use of the monitoring facilities, it is essential that a comprehensive training program be acquired, along the monitoring facilities. The Bidder shall provide suitable training for the staff in the form of classroom training and on-the-job training, either in the country or abroad. There are two components of this training program as listed below:

Factory training is to be provided at the supplier's factory on equipment that is identical to that being purchased by the Administration. The classroom training must include a course on the fundamentals of spectrum monitoring (and spectrum management) by suitably qualified trainers with first-hand experience.

Site training is to be provided at Administration monitoring facilities once the equipment has been installed. Most of the remaining time shall be used for Administration to learn on-the-job increasingly sophisticated monitoring tasks. A final information course shall be provided to show how monitoring information is to be utilized to validate national spectrum monitoring.

For training the number and qualifications of the persons taking part, the location and duration of the training must be discussed. This calls for separate training courses at different levels.

A3.7 Maintenance and repair

The concept for maintenance and repair should under all circumstances be worked out (e.g. what is to be repaired locally, what centrally and what by the manufacturer(s)?)

Stocking of spares, the considerations to be made are as follows:

a) single components;
b) subassemblies (e.g. circuit boards);
c) whole rack-mounts or plug-ins;
d) critical equipment. (Not forgetting the MTBF – Mean Time Between Failures).

It is also necessary to check the time interval for which the stocking is intended (not forgetting the differing MTTRs – Mean Time To Repair).

A3.8 Documentation

Equipment/system documentation is provided in the necessary language(s).

Detailed documentation must be available as part of the project.

A4 Implementation stage: tender processes

A4.1 Specimen of invitation for monitoring tender

Depends on the type of tender procedure, the invitation for monitoring tender is an advertisement, which invites bidders for implementation of a project.

Usually the national laws prescribe its form, the required contents and the applicable rules of the tender procedure.

The invitation for tender gives a brief description on the project background, the scope of work and the duties of bidders and customer.

This may also contain information on site inspections and any dead line for clarifications on the Bidding documents.

The technical requirements of monitoring system are detailed in the enclosure of invitation for tender.

The tender procedures, including the publications are dependent on the national law.

A4.1.1 Invitation for monitoring tender document should include the following:

A4.1.1.1 Guidance part

This section of the bidding documents provides the information necessary for Bidders to prepare and submit responsive bids that meet the Purchaser's requirements. The guidance part describes the critical steps of bid submission, opening and evaluation, and the stipulations of award of contract.

– Availability data of the Purchaser Administration who issued the invitation for tender to supply and install of the new system.

– Summary (of the project).

– Availability (and sometimes the price) of the technical enclosure of invitation document.

– Instruction for the required format and content of the tender document.

  (Filling out the registration form clearly and legibly is very important as it can be assured only for registered applicants that they receive information on any possible modification, amendment or clarification regarding the contents of the tender document.)

– Stipulations of participation and mandatory prequalification (of Bidders) that they have the financial, technical, and production capability necessary to perform the contract and meet the specified qualification criteria:

  i) Certified references (Experience in handling similar contracts with names of former clients).

  ii) Capabilities with respect to personnel, equipment, and construction or manufacturing facilities.

  iii) Financial and economic stability.

  iv) Quality assurance system.

– Manufacturer's authorisations (if manufacturer is other than supplier).

– Queries.

  Bidders requiring any clarification about the present invitation to tender shall submit their queries by fax or e-mail:

  i) Name(s), address and telecommunications means.

  ii) Deadline for Bidders to submit queries in writing (before the pre-bid meeting).

  iii) Deadline of relevant replies from administration is communicated to all registered Bidders.

– Pre-bid meeting (date, time and place of clarification meeting, generally, not less than three weeks prior to the deadline for submission of bids).

The Bidder shall bear all costs associated with the preparation and submission of its bid, and the Purchaser will in no case be responsible or liable for those costs.

– Technical visit to installation sites:

  Two options:

  Option 1: Bidders that so desire may conduct a site survey in order to make sure that the equipment it intends to propose match actual tender requirements. The costs of visiting the site or sites shall be at the Bidder's own expense.

  Option 2: For many tenders, the purchasing administration requires from the bidders a visit to the sites. For each visited site, the administration delivers an official site report signed by both parts. These documents should be supplied with the offer. Failure of a Bidder to make a site visit is a cause for its disqualification.

– Instructions to Bidders

  The bidding documents shall furnish all information necessary for a prospective bidder to prepare a bid for the goods and works to be provided. Bidders are expected to examine all instructions, forms, terms, specifications, and other information in the Bidding documents. Failure to furnish all information or to submit a bid not substantially responsive to the Bidding documents in every respect will be at the Bidder's risk and may result in the rejection of its bid :

i) Submission of proposals:

   a) Address (for submission of bid).

   b) Number of the original and copy tender documents.

   c) Legalize the bid (signed by a person or persons duly authorized to sign on behalf of the Bidder).

   d) Sealing and marking of bids.

   e) Deadline for submission of the bid (any bid received by the Purchaser after the bid submission deadline will be rejected and returned unopened to the Bidder).

   f) Language issues of bid (working language, technical documentation comprising the bid, instruction manuals, software interface, etc.).

ii) Bid formularies.

iii) Prices and currency proposal.

iv) Conformity to international standards and shall meet the latest ITU Recommendations on the subject.

v) Up-to-date design and the use of modern techniques (high standard of performance and reliability).

vi) Delivery.

vii) Guarantees.

viii Specific information to be provided in the proposal.

With regard to national laws and the principles applied by the administration: "Proposals shall contain, but not necessarily be limited, to the following information":

For example:

i) Proposed organization of the work (organizational chart(s), work plan, ...).

ii) Detailed description of the work plan and final products to deliver.

iii) Name and curriculum vitae of all staff assigned to each particular task.

iv) A statement of compliance/non-compliance.

v) Deviations from specifications, in particular if the bidder can prove that the alternative offered will be in all respects as satisfactory and as fully capable of meeting the administration needs as if it conformed fully to the Technical Specifications. The alternative offer must be fully explained.

vi) On-job training. The proposal must clearly indicate: curriculum vitae of the training staff, objectives, target group, desired entrance qualification and number of trainees.

vii) Tender Bond (Tender guarantee, or Bid-Bond).

   In this document the Bidder's bank guarantees that in case its client withdraws from the conditions proposed in its bid within its validity period, the bank pays the amount of the guarantee (generally 2 – 5% of the Bidder's proposed price) to the Purchaser Authority.

viii) Performance Bond (will be required only from the winning Bidder).

ix) Validity of the proposals (must be valid for an identified time period after the deadline date for bid submission prescribed by the Purchaser).

x) The original of the technical and commercial proposals shall be signed by an official legally authorized to enter into contract on behalf of the bidder; generally each page of the original shall be witnessed.

– Evaluation of proposals:

   i) Opening date, time and scene of the sealed proposals.

   ii) Detailed specification of the viewpoints and method for evaluation of bids.

– Disqualification conditions:

i) The offer rejected in case it is incomplete (e.g., Bid Bonds, validity of the offer).

Bids may be rejected in case:

i) After the technical evaluation is shown that one or more of the recommended technical parameters is worse than the minimal requirement in the call for tender document.

Bidders shall be notified of the decision taken, within the indicated date in the tender or the law (by fax, followed by a letter).

A4.1.1.2 Main articles of the contract

– Subject of contract.
– Obligations of the customer.
– Obligations of the bidder.
– Payment conditions (timing and method of payment).
– Guarantee conditions.
– Procedure in case of violation of contract.
– Procedure in case of force major.
– Procedure for debated cases.
– Managing of confidential information.
– Modification of contract.
– Other instructions.

A4.1.1.3 Technical requirements

– Subject of the tender.
– System description.
– Inclusions (what the project will include, like software, infrastructure, services).
– Others inclusions (like warrantee, spare parts, software support and update).
– Minimum technical requirements for each parameter of the system and each measuring instruments.

A4.2 Specimen for proposals of the bidder

A4.2.1 Introduction

– Introduction of bidder and their experiences.
– Advantages of the proposed system.
– How to meet the proposed system to the future need.
– Ability to be integrated into the costumer’s existing system.
– Inclination for taking part in further developments.
– List of proposed sub-contractors.
– Period of validity of bids.

A4.2.2 General technical characteristics

– Performable measurement tasks (e.g., according to the relevant standards).
– Operating frequency range.
– Accuracy of measured data.

A4.2.3 System functions

– Feature characteristics of the system.

Information on how they meet to the technical demands of the tender.

A4.2.4 Method of system implementation

– Denomination of local subcontractors, installation and starting up.

A4.2.5 Technical guarantees

– Period of guarantees (system, software).
– Provision period for spare parts after guarantee term.

A4.2.6 Detailed definitions on:

– Undertaken tasks.
– Presentation of delivered products.
– General system characteristics.
– Technical specifications of each measuring instruments of system.
– Building-up in accordance with requirements.
– Remote and local controlling.
– Data storage and transfer.
– Possibilities on further developments.
– Characteristics of software and integrated with spectrum management.
– Solutions on power supply.
– Types and characteristics of antennas.
– Type(s) and technical data of vehicle(s).
– Health and safety solutions.
– Calibration and self testing.
– Implementation schedule and deadlines of deliveries.
– Expected tasks from customer.
– Training.
– Arranging of controversial matters.
– Etc. (e.g., bid for system and software maintenance contracts).

A4.2.7 Presentation of references

– Financial and economic stability.
– Certified references.
– Quality assurance system.
– Copy of the company registry court document.
– Manufacturer’s authorizations.
– List of approved subcontractors.

A4.2.8 Block diagrams of system

A4.2.9 Price

– The prices lot-by-lot and the total price.
– Terms and conditions of payment.

A4.3 Specimen contract format

The contract is a legally binding exchange of agreement between parties that the law will enforce. Breach of contract is recognized by the law and remedies can be provided.

The contract documents must clearly define the scope of work to be performed, the goods to be supplied, the rights and obligations of the Purchaser and of the Supplier or Contractor.

Introductory provisions

- Definition and addresses of the Contracting Parties.
- Preliminaries to the contract.
- Scope, character and purpose of the contract.
- Terms used in the contract.
- Working language.

Legal status of the parties, their rights and obligations

- Rights and obligations of the Supplier:
  - i) Sub-contracting.
  - ii) Shipping and installation of system and system elements.
  - iii) Guarantees.
  - iv) Repairing and maintenance of system.
  - v) Repairing, maintenance and development of software.
  - vi) Related services.
  - vii) Training related instructions.
- Rights and obligations of the Costumer:
  - i) General instructions.
  - ii) Costumer's right to supervision.
  - iii) Co-operation obligatory.
  - iv) Obligatory of payment.
  - v) Training related obligatory.
- Applicable law and the forum for the settlement of disputes.

Subject of the contract

- Subject of the contract.
- Software and the related rights.
- Provisions relating to the completion of the contract.
- Compliance with statues, laws, regulations, etc.:
  - i) Installation place and date of completion.
  - ii) Method of fulfilment.
  - iii) Date of completion of the contract.
- Procedure of acceptance:
  - i) Factory acceptance prior to the acceptance procedure.
  - ii) General rules for the acceptance procedure of the system.
  - iii) Place of the acceptance procedure.
  - iv) Minutes to be drawn up of the acceptance procedure.
  - v) Acceptance procedure of fixed and mobile stations.

vi) Acceptance of the software and the complete system.

– Packing, shipping and insurance.

– Product upgrades.

– Additional services:

i) Training.

ii) Services to be provided under warranty.

Responsibility for the contracted performance; rules for the impossibility of performance

– Responsibility of the Supplier in case of improper performance:

i) Obligations of the Supplier.

ii) Penalty obligation of the Supplier.

iii) Obligation of the Supplier to remedy the failures.

iv) Warranty obligation of the Supplier.

– The Client's responsibility for the improper performance.

– Impossibility of fulfilment.

Prices and terms of payment

All prices shall include what has been required by the Tender Document.

Fee to be paid for the production, installation of the system as well as the related additional services:

– The total contractual price.

– Payment of the contractual price.

– Additional payment obligations.

Prices shall be quoted excluding taxes, based on national regulations.

Miscellaneous and final provisions

– Obligation of Parties to cooperate, handling of confidential information.

– Settlement of disputes, enforcement of legal rules, governing law.

– Force majeure.

– Amendment to the contract.

– Validity and termination of the contract.

– Other contracts concluded between the Parties.

– Responsible contact persons duly authorized by the Parties.

– Liquidated damages.

– Indemnification.

Annexes to the contract

Annexes to the contract will be based on the procedures from ITU, World Bank or the purchasing administration.

In all cases the Bid will always be annexed to the contract.

A4.4 Evaluation and comparison of proposals and award of contract

For the evaluation and comparison of proposals the purchasing administration needs to follow predefined process of evaluation such as:

– Procedures as defined by the International Telecommunications Union (ITU).

– Procedures as defined by the World Bank.

– Procedures in case the purchasing administration is not bound to the procedures from ITU or World Bank.

A Tender Evaluation committee appointed by the Purchaser authority will evaluate the bids from financial, legal and technical aspects. The evaluation methodology will be defined by the purchasing administration and should be described with all the details in the evaluation report of the Committee.

The proposals submitted by the bidders may be opened in the presence of Bidders' representatives at the stipulated time and place specified in the invitation to bid. Proposal may be rejected if not accompanied by Bid Bond.

During the evaluation the purchasing administration may ask clarifications to the bidders on their offers.

A4.4.1 Procedures as defined by ITU

Evaluation of proposals

– Evaluation group established by ITU or by ITU and the purchasing administration.

– Technical evaluation and commercial evaluation made separately (technical evaluation made first):

i) The technical evaluation should cover the main following points:

a) Measuring receiver, antenna system, workstation, software, optional DF system, Factory Acceptance Test (FAT), delivery, training (see Attachment 1: ITU example of technical analysis of the proposals).

ii) The commercial evaluation should cover the main following points:

a) Price, payment terms & conditions and commercial conditions, legal evaluation (see Attachment 2: ITU example of the commercial and legal evaluations).

iii) Appreciation of technical problems.

iv) Capability.

v) Experience of experts.

vi) Total price.

vii) Incomplete offers shall be rejected.

viii) Confidentiality (no information concerning examination, clarification or evaluation shall be communicated to bidders or any other person).

ix) Bidders shall be notified of decision taken as soon as possible (by fax followed by letter).

Rejection of proposals:

– ITU reserves right to reject any proposal and call for a second tender.

– No obligation to accept the lowest tender.

A4.4.2 Procedures as defined by the World Bank

NOTE 1 – The terminology used is that of the World Bank.

When the World Bank (WB), IBRD or IDA, delivers a loan agreement to one of its Members, the WB supplies the borrower with a set of GUIDELINES named "Proposals Evaluation Report". These guidelines facilitate the borrower proposals evaluation in conformity with the *Directives: Contracts signing financed by IBRD loans or IDA credits – January 1995 (January 1996, August 1996 and September 1997 revisions*), refer to §§ 2.53, 2 and 4 of Annex 1, in particular, (see dbusiness@worldbank.org).

NOTE 2 – According the Directives in § 1.6 and footnote p. 9, some countries are not authorized to profit from the contracts financed by the WB.

NOTE 3 – The State of the borrower can exclude countries or territories from the tender if the borrower can apply the criterion given in § 1.8.

NOTE 4 – The United Union Security Council under United Union Charter Chapter VII can forbid a WB loan close to determined countries.

The Proposals Evaluation Report (PER) describes the procedure for the borrower to evaluate the received offers. Moreover, in all cases, it is of importance to apply the evaluation and request procedures described in the Instructions section of the tender document. The PER includes a letter of advice and its annexes are sent to the WB.

The borrower must examine the evaluation tables included in the Guidelines during the project's preparation in order to determine the staff needs required for the offer's evaluation. The WB can explain in detail the procedure to be followed. The WB encourages the borrower to contract consultants with relevant experience to evaluate the offers relating to complex projects. The consultant's contribution can eventually be financed by the loan if the agreement allows for this (Directives, Annex 1, § 2-C).

The PER includes:

– *Preamble*
– *Forms – usage*
– *Typical forms for evaluation of offers*

Letter of advice:

a) If the project is subject to previous examination from the WB (WB agreement before project awarding decision), the borrower (ministry, organism or service) should send the PER to the WB under cover of a letter of advice. This letter should indicate the evaluation conclusions and supply all complementary information liable to facilitate the WB evaluation.

b) For projects subjected to an *a posteriori* examination procedure by the WB (WB agreement not necessary for project awarding), the evaluation report and a signed copy of the contract should be presented to the WB previous to (or simultaneously) any demand of payment (Directives – Annex 1 and loan agreement).

Table 1 – Identification

Description of the loan agreement, in particular that of cost evaluation and WB evaluation procedure (administrative data).

Table 2 – Evaluation procedures

Tender publications (administrative data).

Table 3 – Proposals delivery and offers opening

In accordance with the Directives, § 2.44, Table 3 gives the date, time, number of offers, offer's validity. If the tender procedure is in two stages (technical and economic) this Table should be supplied for each step. The opening meeting minutes should be addressed to the WB and to each supplier.

Table 4 – Prices of offers (Public lecture)

All the modification of the prices read in public including discounts, options, variants, etc., should be described in Table 4.

Table 5 – Preliminary examination

Conformity with the tender obligations, including technical specifications: The evaluation process should start as early as the offer opening. The preliminary examination forms the subject of identifications and rejections of offers that are incomplete, not admissible or do not correspond to the tender's essential provisions and which consequently should not be evaluated.

This examination should consider the following points:

– Verification: identification of offer's deficiencies.
– Origin criterion.
– Offer guarantee.
– Conformity with tender dispositions and technical specifications.

The evaluation principles are the following:

– The borrower should evaluate the proposals only with regard to the tender obligations and information.

– During the evaluation process, the borrower can ask the suppliers to provide more information on equivocal points or incoherencies noted in their proposals. These demands are presented in writing but the suppliers cannot modify the prices and the type of supplies, work or offered services except for errors in calculation (Directives, Annex 4, § 10). Any price or offer requisites cannot be modified.

Table 6 – Unconditional corrections and discounts

For each supplier, Table 6 gives the offer prices, the corrections (calculation errors), the discounts and the total amount of the offers.

Table 7 – Exchange rate

The exchange rates used for the evaluation are indicated.

Tables 8A and 8B – Currency exchange

According to the currency chosen by the borrower and indicated in the tender, Tables 8A and 8B give the offer's total amount in the borrower's currency.

Table 9 – Additions for omissions, adjustments and currency variations

Table 9 gives the offer's price totals.

– Omissions, mistakes detected in the offers should be balanced by additional prices. (Omitted elements in one offer can be met by the other offers, pricing average.) At the same time, it is possible to refer to external sources such as pricing lists, transport cost scales, etc.

– Adjustments: the tender instructions give the implementation and operation criterion.

The offers, including minor variations with respect to tender instructions, can be considered acceptable if after detailed analysis it is possible to give it a monetary value, which is added to the offer prices, as a penalty, to facilitate comparisons.

The evaluation methodology concerning these factors should be described with all details in the evaluation report and fully in compliance with tender instructions.

Sometimes, the WB authorizes the use of a point system for the supplies purchased. In this case, the adjustments are expressed in points (see Directives, § 2.6.5).

In order to obtain details on offers evaluation by means of a point system, the borrower can obtain the advice from the WB.

Tables 10A and 10B – Priority rights for national supplies and works

If the tender allows a national preference, it is possible to take into account national customs and the preference margin given in the tender provisions.

Table 11 – Final evaluation of offers and contract awarding proposal

Table 11 sums up all the data included in the above Tables (prices at the opening meeting, error corrections, discounts, adjustments) and nominates the tender winner.

Annex I: Instructions for offers evaluation

Annex II: Meeting for offers opening. Information on offers

Annex III: Non-eligible countries

Annex IV: Example of preliminary examination

Annex V: Proposals evaluation Report. Content.

A4.4.3 Procedures in case the purchasing administration is not bound to the procedures from ITU or World Bank

Before the evaluation starts, the evaluation committee will decide which methodology will be used to decide to which Bidder the contract can be awarded. The following methodologies can be used:

– Scoring approach by use of formulas.

– Weighting method.

– Yes/no compliant.

– Compliant combined with the offered prices.

A5 Final (termination) stage: Acceptance procedure

A5.1 Factory acceptance

The provider shall (at its own expense carry out) at the place of manufacture all such tests and/or inspection of the equipment and any part of the equipment as specified in the contract according the factory acceptance documents submitted by the provider amended or not by the Administration (Mutual agreement).

A5.2 Site acceptance test procedure

The provider supplies the site acceptance document(s) to the Administration and shall give a reasonable advance notice of such test and/or inspection and the place and time thereof the project. The tests are carried out to demonstrate that all items of equipment are present; that they are correctly assembled and interconnected; that they function correctly according the technical specifications (visual inspection and technical tests). A final test of the entire system including the communication links should be carried out taking into account the respective responsibilities for the supplies of the Administration and the contractor.

Acceptance of the system is normally followed by a one-year warranty period, during which the provider may be required to maintain a warranty bond. Alternatively, in some administrations, provisional acceptance is given upon successful completion of acceptance test, and at the conclusion of some period (usually the warranty period) final acceptance is given.

A5.2.1 Acceptance (or provisional acceptance in the case of provisional and final acceptance)

Acceptance shall occur in respect of the equipment or any part thereof when:

– the acceptance test has been successfully completed and functional guarantees are met;

– the acceptance test has not been successfully completed or has not been carried out for reasons not attributable to the provider.

Acceptance shall not be withheld if minor discrepancies or problems exist. Rather, acceptance shall occur and the discrepancies and problems shall be noted and corrected during the warranty period.

The following list provides an example of the site acceptance test procedure report’s content concerning a HF/VHF/UHF fixed station:

a) Subject

The document describes the acceptance procedures of a Spectrum Monitoring Station under the terms of the contract.

b) Visual inspection

Operations to be carried out to check the presence of all the items listed on the contractual configuration statement and fill in the configurations and handbooks:

– Antennas systems switching, cables, lightning protection.

– Masts, towers (stays, painting, lightning).

– Inspection of building, wiring, security devices, frames, racks, computers, receivers, energy.

– Software implantation.
– Handbooks of equipment, software and system.
– Marking (equipment homologation).
– Documentation will be controlled and the list of the delivered documents annexed to the acceptance report.

c) Technical tests

– Energy check (main supply and UPS).
– HF/VHF/UHF Direction Finding functions: fixed frequency, scanning, location.
– HF/VHF/UHF ITU Measurements: fixed frequency, frequency scanning, memory scanning.
– Signal analysis.
– Manual and automatic missions: systematic control of transmitters, frequency occupation rate, search of unknown transmitters.
– BITE – Build integrated test equipment.

The result of the tests carried out during acceptance will be consigned in the acceptance test report signed by the Administration and the supplier.

A5.2.2 Final acceptance

In the case of acceptance followed by a warranty period guaranteed by a warranty bond, this section does not apply. In the case of a provisional acceptance followed by a final acceptance, the provisional acceptance certificate signed by both parties, according to the administrative terms specifying the warranty period (generally one year), and after this period the final acceptance certificate is provided.

APPENDIX 1
TO ANNEX 1

ITU example of technical analysis of the proposals

TABLE A1-1

Functional parameters	Specifications	Requirements	COMPANY Y Basic	COMPANY X
Control	Monitoring and supervision of radio signals	Operational functions, for training purposes	COMPLIANT	Option 1: software only – NOT COMPLIANT Option 2: Hardware + software Only Option 2 is considered below
1. Frequency range of monitoring receiver:	Frequency range: 100 kHz – 2.5/3 GHz	The frequency range must include all radio services operated in the bands indicated	COMPLIANT	COMPLIANT with some reservations (see observation on last row)
2. Receiving antennas:	Frequency range: 100 kHz – 2.5/3 GHz	In accordance with the system's characteristics	COMPLIANT	COMPLIANT
3. Operating modes:	Manual and automatic	The system must make it possible to differentiate between manual and automatic monitoring	COMPLIANT	COMPLIANT
4. Measurement of technical signal parameters:	1. Frequency 2. Field strength and power flux-density 3. Bandwidth 4. Modulation percentage (AM) 5. Frequency offset (FM) 6. Spectrum analysis 7. Spectrum occupancy measurements	– Measurements in accordance with ITU-R Recommendations and RR – Real-time and differentiated measurements – Interception, demodulation, recording and analysis of signals – Free determination of the threshold for signal reception	COMPLIANT	COMPLIANT

TABLE A1-1 (*end*)

Functional parameters	**Specifications**	**Requirements**	**COMPANY Y Basic**	**COMPANY X**
5. Demodulation:	CW, AM, FM, SSB, NFM, WFM		COMPLIANT	COMPLIANT
6. Tracking functions:	1. Discrete frequency tracing 2. Frequency tracking by band 3. Discretionary selection of frequency steps	Manual and automatic frequency selection	COMPLIANT	COMPLIANT
7. Data collection:	Storage of measurement results and generation of reports	Interface for connection of peripheral equipment such as printers and PCs	COMPLIANT	COMPLIANT
8. Application software:	1. Man-machine interface: – User-friendly – Clearly identified functions – Frequency spectrum – Easy reading of results – Conversion of units – Visualization of statistical occupancy tables 2. Simulation of the radio direction-finding process 3. Potential growth of the system: – Ability to install radio direction-finding equipment easily – Easy to maintain – Automatic testing – Easy to use – Versatile		COMPLIANT	COMPLIANT

TABLE A1-2

Functional parameters	Specifications	Requirements	COMPANY Y Basic	COMPANY X
Training	1. Course on assembling an installation 2. Course on operation and maintenance 3. Guidance material for training (in printed or electronic form)	Five days for two engineers. Course No.1 will take place at the factory Course No. 2 includes the preventive and corrective maintenance	COMPLIANT	NOT COMPLIANT
Vocabulary of terms, acronyms and abbreviations	Both in English and French	Optional: Spanish	COMPLIANT	COMPLIANT
Power supply	220V ± 5%, 50 Hz		COMPLIANT	Not indicated
Documentation	1 Installation plans 2 Operational and maintenance manuals of both the system and its components	Conceptual diagram of the system Description of systems and equipment Assembling and installation plans Operational acceptance test-run of the station Procedures to carry out detection and correction of system flaws Operational procedures for corrective and preventive periodic maintenance Procedures to locate system breakdowns and repair thereof	COMPLIANT	COMPLIANT
Supply of goods and services	The contractor will assume the responsibility for providing goods and services as established in the respective contracts		*	
Support and spares	Supply of pieces and spare parts (fungibles and non-fungibles) necessary for the maintenance service of the system for a two-year period after the final acceptance of the contract		*	10 years after the final acceptance

TABLE A1-2 (*end*)

Functional parameters	Specifications	Requirements	COMPANY Y Basic	COMPANY X
Factory acceptance test	Verification of technical specifications of the equipment		One ITU specialist, three working days	No indication concerning factory acceptance test
Transportation and delivery	A maximum of [180] days on site, including the responsibility of packing, transportation and installation		*	Four months after the order. Delivery in Geneva
Installation	It is the responsibility of the contractor to install the equipment and carry out all required tests to guarantee the perfect condition and functioning of the system	Installation, testing, integration and operation	*	
Running of provisional tests before acceptance	To test the reliability of the installation and functioning of the system and the equipment		*	
Running of final tests before acceptance	Protocol of acceptance		*	COMPLIANT
Guarantee	Guarantee of quality covering the smooth functioning, material and software for 12 months after the date of final acceptance		*	COMPLIANT

* Note 1 – Compliant according to statements made by COMPANY Y in “compliance list”.

TABLE A1-3

Functional parameters	**Specifications**	**Requirements**	**COMPANY Y Basic**	**COMPANY X**
The insurance responsibility	The contractor signs an insurance policy to cover any risk that can arise until the certificate of provisional acceptance has been issued (covering the period from the moment when the equipment leaves the factory until its provisional installation, where it has been delivered)			
1. Overall presentation of technical part 2. Computer workstation (Item 2 of terms of reference)			1. Very good 2. OK **List of options:** …	1. Poor presentation of the offer and difficulty to find the appropriate/relevant information 2. Workstation: minimum configuration 3. No Factory acceptance test 4. Training: proposal not compliant with the ToR

APPENDIX 2
TO ANNEX 1

ITU example of the commercial and legal evaluations

1 Commercial evaluation – Opening of commercial proposals

1.1 The total opening price of each of the offers as identified by the Evaluation Group is as follows:

Bidders (in alphabetical order)	**Total opening price in USD**
Company X	[999 999.00] – 1st proposal [999 999.00] – 2nd proposal
Company Y	[999 999.00] – basic proposal [999 999.00] – optional proposal

1.2 COMPANY X submitted the most comprehensive commercial proposal. COMPANY Y provided most of the required information in its offers. However, the level of detail (e.g., price breakdown) was not satisfactory and consequently required further clarifications.

1.3 The Total Evaluated Price (TEP) of each of the two offers as identified by the Commercial Evaluation Committee is as follows:

Bidder	**Basic proposal**	**Optional proposal 1**	**Optional proposal 2**
COMPANY X	USD [999 999.00]	USD [999 999.00]	USD [999 999.00]
COMPANY Y	USD [999 999.00]	USD [999 999.00]	–

1.4 No detailed price breakdown was presented by COMPANY Y. Consequently, it was necessary to require a detailed explanation of its overall price in order to complete the commercial evaluation of its proposal. COMPANY X did not provide the complete required information (a detailed price breakdown list of items for Options 1 and 2).

1.5 COMPANY X and COMPANY Y are considerably different in their respective opening prices. In the case of COMPANY X, the most significant difference comes from the fact that the basic proposal contains only training. Consequently, following the recommendation of the TEC., for more details please see TEC's Technical Evaluation Report.

1.6 Prices quoted by … contain a 10% discount of the item total price.

1.7 Price is in USD CIP Geneva (taking into consideration that ITU did not identify the point of destination). ITU needs prices quoted DDU – in accordance with Incoterms 2000 including customary packing (point of destination to be determined). This point has to be clarified during the negotiation contract.

1.8 ***Payment terms and conditions***. Both companies have proposed payment terms. Therefore, payment terms and conditions of the future contract ***need to be negotiated*** with the selected company.

1.9 Both offers include ***commercial conditions***. In the case of contract negotiations with both companies, ITU may discuss all proposed modifications and additional payment conditions of the Contract in accordance with ITU rules and regulations (see for COMPANY X pages ii to jj of Chapter N of the commercial proposal and for COMPANY Y proposal pages kk to ll of Chapter M).

2 Legal evaluation – Compliance with specimen contract format (Part II of Invitation to Tender)

General information	COMPANY X			COMPANY Y	
	1st proposal	2nd proposal	3rd proposal	1st proposal (basic)	2nd proposal
Proposal validity					
Compliance with contract	Yes (α)	Yes	Yes	Yes	Yes
Compliance with technical requirements	Yes	Yes	In addition	No	Yes
Total man/days	5	5	–	–	15
Total working time	7.5 h/day 3-5 days	7.5 h/day 3-5 days	–	9 h/day 2 days	9 h/day 6 days/4 weeks
Price per man/day	9 999.00	9 999.00	–	–	9 999.00
Total man/days	6	6		10	10
Total working time	7.5 h/day 5 days (37.5 h)	7.5 h/day 5 days (37.5 h)		6 h/day 1 day (6 h)	6 h/day 5 days/3 weeks (90 h)
Price per man/day	9 999.00	9 999.00		9 999.00	9 999.00
Elements that may increase the total firm fixed price	None, if items are restricted to items Price Schedule I to III submitted with the offer	None, if items are restricted to items Price Schedule I to III submitted with the offer		Training classroom and equipment not available	Training classroom and equipment not available
Counterpart services the bidder expects will be provided by ITU	Appropriate installation site must be provided	Appropriate installation site must be provided		Set up classroom and make sure necessary training equipment is available	Set up classroom and make sure necessary training equipment is available
Commitment to start and perform work	Effective date of contract	Effective date of contract		Effective date of contract	Effective date of contract
Time of delivery/ conditions	*N* month	*N* month		*M* weeks	*L* weeks
Total firm fixed price in USD					

2.1 α – Concerning the compliance with requirements:

COMPANY X remarks that:

i) The translation of the system software into the French language is offered separately, since all our customers worldwide do accept the software in the English language.

ii) Translation of software into French requires a one-time charge.

iii) The manuals for equipment and training will be provided in French.

iv) Training for preventive and corrective maintenance will be provided, if trainees have engineering degrees and experience.

COMPANY Y second proposal (optional) fully complies with the requirements.

2.2 With regards to the proposed ***Specimen Contract Format***. In the case of contract negotiation with both companies, ITU may discuss all proposed modifications and additions to Specimen Contract Format and payment conditions. The most important concern the following articles:

a) **Substantive law** (compliance with statutes, laws, regulations):

COMPANY X proposes that "all disputes shall be settled in accordance with the terms of the contract and the supplementary agreements, otherwise in accordance with the substantive law in force in the country XYZ without referring to other substantive laws".

This requirement is not in accordance with ITU rules and regulations.

NOTE 1– Declare "comply" with Specimen Contract Format.

b) Arbitration:

COMPANY X proposes that "the attempt shall be regarded as being miscarried, if one of the two parties informs the other party of this fact in writing". If an attempt at settlement has failed, the disputes shall be settled under the Rules of Conciliation and Arbitration of the CCI in [CITY] by three arbitrators... (see page k/k, chapter N of the commercial part) – This article could be negotiated.

c) Factory inspection acceptance and delivery:

See comments/proposal of COMPANY X, paragraph *n,* page *m* of Chapter *N* of the optional proposal.

d) Guarantees:

Both companies give detailed conditions of guarantee and request modifications. Some of the proposed modifications are not in accordance with the ITU standard contract but could be negotiated.

e) *Force majeure:*

COMPANY X suggests modifying this article. See Chapter *N*, page *i/k* "…the event of *force majeure* shall be confirmed by the Chamber of Commerce, ...". Some of the proposed modifications are not in accordance with the ITU standard contract but could be negotiated.

List of the abbreviations used in the Handbook

2G	2nd generation (GSM)
3G	3rd generation (UMTS)
3GPP	3rd generation partnership project
3GPP2	3rd generation partnership project 2
A/D	Analog to digital
ACU	Antenna control unit
ADC	Analogue to digital converter
ADSL	Asymmetric digital subscriber line
AF	Audio frequency
AGC	Automatic gain control
AM	Amplitude modulation
AMDS	Analogue modulation data system
AMSL	Above mean sea level
AOA	Angle of arrival
APD	Amplitude probability distribution
API	Application programming interface
APT	Asian-Pacific Telecommunity
ASIC	Application-specific integrated circuit
ASK	Amplitude shift keying
ATM	Asynchronous transfer mode
ATSC	Advanced television systems committee
AWGN	Additive White Gaussian Noise
BCCH	Broadcast control channel
BER	Bit error rate/ratio
BIT	Built in test
BITE	Built-in test equipment
BLER	BLock error rate/ratio
BPSK	Binary phase shift keying
BR	ITU Radiocommunication Bureau
BR IFIC	ITU BR International Frequency Information Circular
BSS	Broadcasting-satellite service
BW	BANDWIDTH
BWA	Broadband wireless access
C/I	Carrier-to-interference ratio
CAF	Cross ambiguity function
CB	Citizen band
CCDF	Complementary cumulative distribution function
CDMA	Code-division multiple acess
CEPT	European Conference of Postal and Telecommunications Administrations
CIF	Common intermediate format
CIR	Channel impulse response
CISPR	International Special Committee on Radio Interference
CITEL	Inter-American Telecommunications Commission
COFDM	Coded orthogonal frequency-division multiplex
COSPAS/SARSAT	International Satellite System for Search and Rescue
CPICH	Common pilot channel
CPLPA	Circularly-polarized log-periodic antenna
CPM	Continuous phase modulation
CRMO	Central Radio Management Office
CRT	Cathode ray tube
CSV	Comma-separated value

CTCSS	Continuous tone-coded squelch system
CW	Continuous wave
DAB	Digital audio broadcasting
DAM	Dynamic amplitude modulation
DANL	Display average noise level
DDC	Digital down-converter
DECT	Digital european cordless telecommunications
DEM	Digital elevation model
DF	Direction finding/finder
DFT	Discrete fourier transform
DGPS	Differential GPS
DMB-T/H	Digital multimedia broadcasting- terrestrial/handheld
DME	Distance measuring equipment
DQPSK	Differential quadrature phase shift keying
DRM	Digital Radio Mondiale
DSB	Digital sound broadcasting
DSL	Digital subscriber line
DSP	Digital signal processor/processing
DSSS	Direct sequence spread spectrum
DTM	Digital terrain model
DTMB	Digital terrestrial multimedia broadcast
DTMF	Dual tone multiple frequency
DVB-T	Digital video broadcasting – terrestrial
EDGE	Enhanced data rates for GSM evolution
EHF	Extremely high frequency (30 to 300 GHz)
e.i.r.p.	Equivalent isotropically radiated power
ELF	Extremely low frequency (3 to 30 Hz)
EMC	Electromagnetic compatibility
EMF	Electromagnetic field
e.r.p.	Effective radiated power
ETSI	European Telecommunications Standards Institute
EUT	Equipment under test
EVM	Error vector magnitude
FAT	Factory acceptance test
FBO	Frequency band occupancy
FCO	Frequency channel occupancy
FDD	Frequency-division duplex
FDDI	Fiber data distributed interface
FDMA	Frequency-division multiple access
FDOA	Frequency difference of arrival
FER	Frame error rate
FET	Field effect transistor
FFT	Fast fourier transform
FHSS	Frequency hopping spread spectrum
FM	Frequency modulation
FMCW	Frequency-modulated continuous wave
FPGA	Field-programmable gate array
FSK	Frequency-shift keying
FSPL	Free space path loss
FSS	Fixed-satellite service
GFSK	Gaussian frequency shift keying
GIS	Geographic information systems
GLONASS	Global navigation satellite system
GMSK	Gaussian minimum shift keying
GPIB	General-purpose interface bus

GPRS	Global packet radio service
GPS	Global positioning system
GSM	Global system for mobile communications
GSO	Geo-stationary orbit.
GUI	Graphical user interface
HF	High frequency (3 to 30 MHz)
HSDPA	High speed downlink packet access
HSPA	High speed packet access
HSUPA	High speed uplink packet access
I/Q	In-phase and quadrature
IBOC DSB	On channel digital sound broadcast
IBRD	International Bank for Reconstruction and Development
ICAO	International Civil Aviation Organization
ICNIRP	International Commission on non-ionizing radiation protection
IDA	International Development Association
IDWM	ITU Digitized World Map
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IF	Intermediate frequency
IFIC	International Frequency Information Circular
IFL	International Frequency List
IFM	Instantaneous frequency measurement
ILS	Instrument landing system
IMP	Intermodulation product
IN	Impulse noise
IP3	Third order intermodulation product
IRPA/INIRC	International Radiation Protection Association/International non-ionizing Radiation Committee
IS95	Interim Standard 95 (first CDMA-based digital cellular standard)
ISB	Independent sideband
ISDB-T	Integrated services digital broadcasting-terrestrial
ISDN	Integrated services digital network
ISM	Industrial, scientific and medical
ISO	International Organization for Standardization
IT	Information technology
ITS	Institute for Telecommunication Sciences
ITU	International Telecommunication Union
ITU-R	ITU Radiocommunication Sector
ITU-T	ITU Telecommunications Standardization Sector
KCC	Korea Communications Commission
KISA	Korea Internet & Security Agency
LAN	Local area network
LED	Light-emitting diode
LF	Low frequency (30 to 300 kHz)
LHCP	Left-hand circular polarisation
LMDS	Local multipoint distribution service
LNA	Low-noise amplifier
LO	Local oscillator
LoB	Line of bearing
LoS	Line-of-sight
LPA	Log periodic antenna
LPZ	Lightning protection zone
LSB	Lower side band
LTE	Long term evolution
MARS	Maritime Mobile Access and Retrieval System

MER	Modulation error rate/ratio
MF	Medium frequency (300 to 3 000 kHz)
MIFR	Master International Frequency Register
MIMO	Multiple input, multiple output
MMDS	Multimedia distribution service
MMI	Man-machine interface
MMN	Man-made noise
MoM	Method of moments
MPEG	Standards for audio and video compression developed by the Moving Picture Experts Group
MPHPT	Ministry of Public Management, Home Affairs, Posts and Telecommunications (Japan)
MPX power	power of the Multiplex signal
MSK	Minimum shift keying
MSS	Mobile-satellite service
MTBF	Mean time between failures
MTI	Moving target indication
MTTR	Maximum time to repair
MUF	Maximum usable frequency
MUSIC	Multiple signal classification
NASA	National Aeronautics and Space Administration (USA)
NIR	Non-ionizing radiation
NMR	Noise-to-mask ratio
NOAA	National Oceanic and Atmospheric Administration (USA)
NSMS	National spectrum management system
NTIA	National Telecommunications and Information Administration (USA)
NTSC	National Television System Committee
ODA	Official Development Assistance (Japan)
OFDM	Orthogonal frequency division multiplexing
OFDMA	Orthogonal frequency division multiple access
OoB	Out of band
OQPSK	Orthogonal quadrature phase shift keying
PABX	Private automatic branch exchange
PAL	Phase alternate line
PC	Personal computer
PCA	Position of closest approach
P-CPICH	Primary common pilot channel
PCS	Personal communication systems
PDA	Personal digital assistant
PEP	Peak envelope power
pfd	Power flux-density
PHS	Personal handyphone system
PM	Phase modulation
PMR	Private mobile radio
Ppm	Parts per million
PRF	Pulse repetition frequency
PRN	Pseudo-random number
PSD	Power spectral density
PSK	Phase-shift keying
PSNR	Peak signal-to-noise ratio
PSTN	Public switched telephone network
QAM	Quadrature amplitude modulation
QCIF	Quarter common intermediate format
QoS	Quality of service
QP	Quasi-peak
QPSK	Quadrature phase shift keying

RBDS	Radio broadcast data system
RBW	Resolution bandwidth
RCR	Development center for radio systems
RDS	Radio data system
RF	Radio frequency
RHCP	Right-hand circular polarisation
RLAN	Radio local area network
RMTP	Remote monitoring transfer protocol
r.m.s.	root mean square (RMS)
RNSS	Radionavigation-Satellite Service
ROM	Read only memory
RR	Radio Regulations
RRC	Root raised cosine
RSCP	Received signal code power
RTTY	RADIOTELETYPE
S/N	Signal-to-noise ratio
SA	Selective availability
SAR	Specific energy absorption rate
SCA	Subsidiary communication authority
SCN	Single carrier noise
SCPC	Single channel per carrier
SDG	Subjective difference grade
SDH	Synchronous digital hierarchy
SDMA	Spatial-division multiple access
SECAM	Sequential colour with memory
SFN	Single frequency networks
SHF	Super high frequency (3 to 30 GHz)
SIM	Subscriber identity modules
SINAD	Signal-to-noise and distortion
SINR	Signal-to-interference-plus-noise ratio
SIR	Signal to interference ratio
SM	Spectrum management
SMS4DC	Spectrum management system for developing countries
SNR (S/N)	Signal-to-noise ratio
SPD	Spectral power density
SPS	Standard positioning service
SSB	Single side band
SSL	Single station location
SVD	Singular value decomposition
TCA	Time of closest approach
TCP/IP	Transmission control protocol/internet protocol
T-DAB	Terrestrial digital audio broadcasting
TDD	Time-division duplex
TDMA	Time-division multiple access
T-DMB	Terrestrial digital multimedia broadcasting
TDOA	Time difference of arrival
TETRA	Terrestrial trunked radio
THD	Total harmonic distortion
TLE	Two line elements
TOA	Time of arrival
TV	Television
UHF	Ultra high frequency (300 to 3 000 MHz)
UMTS	Universal Mobile Telecommunications System
UPS	Uninterruptible power supply
USB	Upper side band

USNO	United States Naval Observatory
USTTI	United States Telecommunications Training Institute
UTC	Universal Coordinated Time
UTM	Universal Transverse Mercator
UWB	Ultra wide band
VDSL	Very high speed digital subscriber line
VHF	Very high frequency (30 to 300 MHz)
VLF	Very low frequency (3 to 30 kHz)
VOR	VHF omnidirectional range (radio navigation system for aircraft)
VPN	Virtual private network
VQM	Video quality metrics
VSA	Vector signal analyzer
VSAT	Very small aperture terminal
VSB	Vestigial sideband
VSWR	Voltage standing wave ratio
WAN	Wide area network
WGN	White gaussian noise
WHO	World health organization
WiMAX	Worldwide interoperability for microwave access
WLAN	Wireless local area network
WRC	World Radiocommunication Conference
XOR	Exclusive Or
YIG	Yttrium iron garnet

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