EUROPEAN
SCIENCE
FOUNDATION

CRAF Handbook for Radio Astronomy

Committee on Radio Astronomy Frequencies (CRAF)
An ESF Expert Committee

Third edition – 2005

The European Science Foundation (ESF) acts as a catalyst for the development of science by bringing together leading scientists and funding agencies to debate, plan and implement pan-European scientific and science policy initiatives. It is also responsible for the management of COST (European Cooperation in the field of Scientific and Technical Research).
ESF is the European association of 78 major national funding agencies devoted to scientific research in 30 countries. It represents all scientific disciplines: physical and engineering sciences, life, earth and environmental sciences, medical sciences, humanities and social sciences. The Foundation assists its Member Organisations in two main ways. It brings scientists together in its Scientific Forward Looks, Exploratory Workshops, Programmes, Networks, EUROCORES, and ESF Research Conferences, to work on topics of common concern including Research Infrastructures. It also conducts the joint studies of issues of strategic importance in European science policy and manages, on behalf of its Member Organisations, grant schemes, such as EURYI (European Young Investigator Awards).
It maintains close relations with other scientific institutions within and outside Europe. By its activities, the ESF adds value by cooperation and coordination across national frontiers and endeavours, offers expert scientific advice on strategic issues, and provides the European forum for science.

The ESF Expert Committee on Radio Astronomy Frequencies, CRAF, was established in 1988 to coordinate the European efforts for the protection of radiospectrum bands used by the Radio Astronomy Service and other passive applications.

Cover: The 76-m diameter Lovell Telescope at Jodrell Bank Observatory, UK, came into operation in 1957 and has operated continuously since then, 24 hours per day, apart from stoppages for maintenance, painting, repairs, and two major upgrades to the primary reflecting surface. In 2005 the Lovell Telescope took part in pioneering eVLBI observations, in which radio telescopes on different continents are connected via the internet to perform Very Long Baseline Interferometry. Photograph courtesy of Ian Morison, Jodrell Bank Observatory.

CRAF Handbook for Radio Astronomy

Edited by Jim Cohen, Titus Spoelstra,
Roberto Ambrosini and Wim van Driel

Third edition – 2005

EUROPEAN
SCIENCE
FOUNDATION

Preface

The Committee on Radio Astronomy Frequencies, CRAF, was established under the umbrella of the European Science Foundation in 1988 to coordinate European efforts for the protection of the radio frequency bands used by the Radio Astronomy Service and other passive users of the radio spectrum.

Progress in technology, which has made possible all kinds of advanced astrophysical research, now threatens to render this research impossible from the surface of the Earth. Radio transmissions from terrestrial, airborne and space-based stations are proliferating in ever increasing numbers for a multitude of purposes.

The pressure on the authorities to make radio spectrum available for all newly invented applications of radio, e.g. various space systems, high altitude platform stations (HAPSs), digital broadcasting, power line communications, ultra-wide band technology and vehicular short range radar, is tremendous.

This Handbook reviews the needs of the Radio Astronomy Service and the measures required for its continued protection.

The Handbook has been prepared by the Committee on Radio Astronomy Frequencies of the European Science Foundation in Strasbourg, CRAF. It provides a comprehensive review of matters related to spectrum management and the protection of the science of Radio Astronomy against harmful interference. The review is placed within the historical and technological context within which the Radio Astronomy Service operates.

This book is intended for a wide readership. It aims to provide a bridge between the professional radio astronomical community and professional radio spectrum managers with no previous background in astronomy.

Summary

Section 1
Radio Astronomy was first recognised by the International Telecommunication Union, ITU, as a radiocommunication service in 1959. The Radio Astronomy Service has been vigorous in defending its frequency allocations ever since. The “whys” and “hows” of the service are introduced.

Section 2
The Radio Astronomy Service is a passive service. The radio window and passive frequency use are explained. New discussions of Radio Astronomy in space are supplied, and of passive remote sensing of the Earth’s atmosphere.

Section 3
The characteristics of the Radio Astronomy Service are given. Radio astronomical observing techniques are explained.

Section 4
The frequencies used for the Radio Astronomy Service are introduced on two levels: the general considerations and specific considerations, illustrated by tables and detailed comments.

Section 5
Further comments are given on the use of specific frequency bands, expanding on the brief descriptions given in Section 4.

Section 6
The negative impact of human-generated interference on radio astronomical observations is explained and analysed.

Section 7
The question of whether the passive services need absolutely interference-free bands is discussed.

Section 8
The European and worldwide efforts to cooperate within the policy-making and decision-making processes are described.

Section 9
The protection of Radio Astronomy frequencies in the context of international law is explained.

Section 10
A review of some recommendations to improve the radio environment for Radio Astronomy.

Section 11
Details of Radio Astronomy stations and passive remote sensing stations in Europe.

Section 12
Recommended literature.

Appendices
Some useful administrative sections.

Contents

Preface
Summary

1. Introduction

Appendices

Introduction

Radio Astronomy is a young and vigorous science, in which many parts of the universe are being studied and new discoveries are continually being made. Radio observations have transformed our understanding of the universe in just half a century, and captured the public imagination. Quasars, pulsars, the Big Bang and many other phenomena were first revealed by Radio Astronomy.

To continue this advance with all of its potential benefits, it is necessary to operate many observatories with various characteristics and at diverse locations and to be able to observe in a large number of frequency bands. Many countries around the world, including Argentina, Australia, Brazil, Canada, China, France, Germany, India, Italy, Japan, Korea, Mexico, the Netherlands, Poland, Russia, Sweden, the United Kingdom and the USA have made major investments in the development of Radio Astronomy. It is anticipated that this investment will continue and that other countries will soon join major radio astronomical projects. This progress in science can continue only if access to the necessary frequency bands in the radio spectrum is guaranteed in an adequate manner.

This Handbook is concerned with frequency allocations for Radio Astronomy, and the regulatory means necessary for protecting the science from radio frequency interference. The Handbook has been prepared by the Committee on Radio Astronomy Frequencies of the European Science Foundation in Strasbourg, CRAF (see Section 8.2). It aims to provide a bridge between radio spectrum management and Radio Astronomy, so that professional spectrum managers can better understand the needs of Radio Astronomy, and radio astronomers can better understand the regulatory process.

1.1. History of Frequency Allocations to the Radio Astronomy Service

The scientific need for Radio Astronomy to have its own allocated radio-quiet frequency bands was first presented in 1959 to a World Administrative Radio Conference, WARC, a global conference held under the auspices of the International Telecommunication Union, ITU. At that time the general philosophy regarding the frequency-allocation scheme for the benefit of radio astronomical research was:

- that the science of Radio Astronomy should be formally recognised as a radio service in the context of the ITU Radio Regulations (RR);
- that a series of bands of frequencies should be set aside internationally for Radio Astronomy, which should lie at approximately every octave (that is, doubling in frequency) above 30 MHz, each with a bandwidth of about 1% of the centre frequency;
- that special international protection should be afforded to the hydrogen line (1400 - 1427 MHz), the hydroxyl radical (OH) lines (~1.6 GHz; rest frequencies: 1612.231 MHz, 1665.402 MHz, 1667.359 MHz, 1720.530 MHz) and the predicted deuterium line (322 - 329 MHz);
- that some frequency bands should be afforded the highest protection by being reserved exclusively for *passive* use, nowadays specified by Footnote No. **5.340** of the RR, which states that in these bands all emissions are prohibited

At the 1959 WARC, considerable steps were made towards meeting these needs, and at subsequent conferences (with more limited tasks) the growing scientific needs were stated and further steps taken to meet them.

The discovery of discrete cosmic radio sources and most of our current knowledge of their nature and distribution, and of the processes responsible for the radio emission from them, has come through observations of their broadband radiation (continuum spectra). Observations of the intensity of the continuum emission of a radio source need to be made in a number of frequency bands, in order to determine its characteristic "spectrum".

Although the bands made available to the Radio Astronomy Service, in accordance with the Final Acts of the World Administrative Radio Conference for Space Telecommunications (Geneva, 1971) represented a significant improvement over the international allocations made to the Service in 1959 and 1963, they represented only a partial fulfilment of the requirements of the Service: many of the allocated bands had insufficient bandwidth, most of them were shared with other radio services; many applied only to limited areas of the world; and there were large intervals between some of the allocated bands.

At WARC 1979, Radio Astronomy improved its position in the ITU Radio Regulations, and the requirements of the service were given more serious consideration. At frequencies above 20 GHz most requests for allocations were granted. Below 20 GHz the situation was more difficult, because of the requirements of already well-entrenched active services.

One of the results of WARC-79 is Article **29** of the ITU Radio Regulations. It contains a series of frequency assignment provisos for the protection of the Radio Astronomy Service whose impact in practice depends on their implementations by individual national Administrations. It does not, however, contain explicit acceptance of levels of interference detrimental to Radio Astronomy, such as are given in Recommendation ITU-R **RA.769**. Although the foundations of this article are well documented, there is great reluctance within the ITU-R to incorporate it in official regulations because of its impact on the active services.

At the World Radio Conference, WRC, in 1995, however, a footnote (No. **5.208A**) was added to the ITU Radio Regulations on the protection of the Radio Astronomy Service in the bands 150.05 - 153 MHz, 322 - 328.6 MHz, 406.1 - 410 MHz and 608 - 614 MHz from harmful interference according to the threshold levels listed in Recommendation ITU-R **RA.769**. This footnote was inserted in the frequency table for all bands below 1 GHz, which are allocated to the Mobile Satellite Service for operation in the space-to-Earth direction.

A major achievement of WRC-2000 was the re-allocation of most of the frequency bands between 71 and 275 GHz, where the Radio Astronomy Service secured its access to nearly all the spectrum that is useable from the ground through the atmospheric windows in this frequency range. It was gratifying that the Radio Astronomy Service was given primary status in these millimetre-wave bands where it had in fact been making observations without the benefit of formal allocation for many years (see Section 5.6).

Until recently no WARC, WRC, or any other regulatory forum had addressed effective structural solutions to the problems of interference to Radio Astronomy from transmitters operating in frequency bands outside those allocated to the Radio Astronomy Service. Many primary radio astronomy bands are adjacent to bands allocated to airborne or space services (space-to-Earth). The first steps towards addressing this problem were made in Istanbul in 2000, where WRC-2000 introduced new footnotes (Nos. **5.443B**, **5.511A** and **5.551G**) which specify that downlinks of certain specified satellite services shall not exceed radio astronomy interference thresholds in the bands 4990 - 5000 MHz, 15.35 - 15.40 GHz and 42.5 - 43.5 GHz. This was the first time that interference levels for the protection of the Radio Astronomy Service appeared explicitly in the Radio Regulations.

WRC-2000 also set the first general limits on unwanted emissions from satellites. Specifically, WRC-2000 revised Annex **3** of the Radio Regulations which now gives tables of maximum permitted power levels for spurious emissions, including those from satellites**.** The limits apply for all new satellites from 1 January 2003, and will apply to all satellites from 1 January 2012. Three years later, WRC-03 adopted a Resolution on the “Compatibility between the radio astronomy service and the active space services in certain adjacent and nearby frequency bands” (Resolution **739**) which specifies lower thresholds for unwanted emission flux densities from space stations at a radio astronomy station, for particular frequency bands and particular space services.

It has become abundantly clear in recent years how spectral usage by active services close to, or even inside, radio astronomy frequency bands is detrimental to the quality of radio astronomical observations. This growing problem continues to receive considerable attention. The problems mentioned hold in particular for satellite (space-to-Earth) and aeronautical transmissions which contribute significantly to the increase in harmful interference to radio astronomy observations on a worldwide scale.

1.2. Radio Astronomical Requirements

The electromagnetic radiation detected in Radio Astronomy is either emission from atoms or molecules at very specific characteristic frequencies: **line emission;** or it is so-called **continuum emission** of thermal or non-thermal origin, which is very broadband. In both cases the radiation may be polarized. The **polarization** characteristics of the radiation may be of great astrophysical significance, since these are a manifestation of magnetic fields in the radio source or in the intervening medium between the source and the Earth.

Good frequency coverage, high spectral resolution, high spatial resolution and high time resolution are (besides state-of-the-art technology) essential for radio astronomical research.

- **Good frequency coverage** is very important for the study of the spectral characteristics of continuum emissions, since these are clues to the emission mechanism and therefore are direct “finger prints” of the physical conditions within the radio source.

Wide frequency coverage is essential for polarization studies, since, because of the magneto-ionic characteristics of the interstellar medium, the angular direction of linear polarization varies in proportion to the inverse square of the frequency. Therefore, observations at three or more unequally spaced frequencies are needed to separate the polarization characteristics due to the magnetic properties intrinsic to the radio source from those of the interstellar medium. To achieve this good frequency coverage, bands spaced at intervals of about an octave in frequency are normally required.

- **High spectral resolution** is crucial to analyse the kinematics within a radio source, as manifested through its Doppler-shifted line emission. A resolution of 1 Hz per MHz corresponds to a velocity resolution of 300 metres per second.
- **High spatial resolution** is essential for the study of the detailed structure of radio sources. Very high spatial resolution (e.g. 10^{-6} of a radian) can be achieved by the technique of VLBI (see below and Section 3.7).
- **High time resolution** is important to study time variations in radio sources. These variations can be as short as microseconds (in the case of pulsars).

For over three decades astronomers have been linking together radio telescopes located many thousands of kilometres apart, thereby creating interferometer systems with very long baselines. This technique, known as **Very Long Baseline Interferometry, VLBI**, has proved invaluable in studying the structure of very distant radio sources (see Section 3.7). VLBI arrays are sensitive to the fine structure in the radio source. The angular resolution achieved is of the order of λ/D radians, where λ is the wavelength and D is the largest distance between the radio telescopes. Extremely high angular resolutions can be achieved with intercontinental baselines, and many countries have collaborated in the global development of this technique (e.g., Australia, Canada, China, Finland, France, Germany, India, Italy, Japan, the Netherlands, Poland, South Africa, Spain, Sweden, Ukraine, the United Kingdom and the USA).

The baselines available to the global VLBI network have been extended by the launching of a dedicated space-VLBI antenna. Baselines of up to three times the Earth’s diameter have led to improved higher angular resolution images (see Section 3.8). From such studies astronomers have found, among other significant results, that the enigmatic quasars, the most powerful radio sources in the universe, show intricate small-scale structures associated with their central “engine”.

The technique of VLBI also has many practical applications, such as studies of continental drift, the rotation rate of the Earth, polar wandering, latitude determination and earthquake prediction. Such experiments are able to determine intercontinental distances with accuracies of a few centimetres.

For VLBI experiments to succeed, telescopes in several different countries must observe together simultaneously on exactly the same frequency, without interference. *Thus it is essential that the same frequency bands be allocated to the Radio Astronomy Service and be protected worldwide*.

1.3. Aim of this Handbook

In this Handbook we state the views and needs of the Radio Astronomy Service for the protection of the science of Radio Astronomy in Europe.

There is continuing need for review and updating of the allocations of frequencies for Radio Astronomy. Despite the extension of radio techniques to frequencies above 1000 GHz the use of relatively low frequencies still remains very important to Radio Astronomy.

The needs of **continuum observations**, when first stated in 1959, were based largely on the desire to measure the spectra of radio sources over a wide range of frequencies. Since that time two developments have reinforced this need for continuum bands. First, the discovery of pulsars has not only given us new astronomical objects to study but has also provided a unique tool for exploring the properties of the interstellar medium. For these studies continuum bands, particularly those at frequencies below a few GHz, are required. Second, the technique of VLBI requires telescopes in several different countries to observe the same source simultaneously on exactly the same frequency, which in turn requires that the frequency bands be protected worldwide.

The original request of about 1% of the centre frequencies for the bandwidths of the continuum bands has proved to be inadequate. New techniques require **larger bandwidths** to achieve better sensitivity, and hence in some parts of the spectrum bandwidth expansions have been requested.

Since 1959 many thousands of discrete **spectral lines** have been discovered. They are produced by a wide variety of simple and complex atoms, ions and molecules. The protection of these spectral-line frequencies is a difficult task. The frequencies are given by laws of nature and cannot be altered. Some lines have been discovered in frequency bands already allocated to other services.

In some simple cases what is needed is clear; for example, the value of hydrogen-line studies has grown, particularly as more sensitive instruments look further out into space. Because of the general expansion of the universe, the more distant objects have greater recession velocities, and so by the Doppler effect their spectral lines undergo a **redshift** to lower frequencies. This has made it urgent to look for ways to extend the protection of the hydrogen-line to below 1400 MHz.

Some protection is also needed for spectral lines from the more exotic molecular species. This can sometimes be achieved through frequency allocations given by footnotes in the Table of Frequency Allocations of the ITU Radio Regulations. Although spectral lines are intrinsically very narrow in bandwidth, the internal and bulk motions of the molecular clouds cause Doppler shifts of the line frequencies that are received. A minimum protected bandwidth 0.2% of the rest frequency is usually suggested for a spectral line, to allow observations of line emissions Doppler-shifted by up to ±300 kilometres per second (which is typical for sources within the Milky Way).

The frequencies between 2 and 30 MHz are also significant for radio astronomical research, but because of the congestion problems in this range of the spectrum hardly any possibility exists of improving the situation for the Radio Astronomy Service. The development of the new generation radio telescope for low frequencies, the Low Frequency Array, LOFAR, with the goal to "open a new window on sky in the electromagnetic spectrum from ~10 - 240 MHz with unprecedented sensitivity and resolution" illustrates that access to these "low frequencies" remains an important issue for the Radio Astronomy Service.

In 1960 the vulnerability of Radio Astronomy to **interference** was documented by the former International Radio Consultative Committee, CCIR, of the ITU. The early estimates have been refined and improved (although they have in fact proved to be remarkably accurate) and are published in Recommendation ITU-R **RA.769**. It is important to find ways to protect the radio astronomy bands from adjacent band interference from air- and space-to-ground transmissions. In some cases it may be possible to increase the radio astronomy band allocations at the same time that the adjacent band interference problem is solved (e.g. at 2690 and 5000 MHz through a modification of allocations to the Broadcast Satellite Service and the Microwave Landing System, respectively).

CRAF proposes that the frequency bands allocated to the Radio Astronomy Service be afforded protection to the levels given in Recommendation ITU-R **RA.769**. Within these bands the total spectral power flux density, spfd, produced by services in other bands should not exceed these recommended levels.

2.

Nature of the Radio Astronomy Service

2.1. The Radio Astronomy Service is a "Passive" Service

The use of the radio frequency part of the electromagnetic spectrum is regulated by an international body which, for historical reasons, is primarily interested in its use for telecommunication rather than for scientific and in particular astronomical purposes. This body is the International Telecommunication Union, ITU. Its Radio Regulations, RR, define and recognise a number of different "radio communication services", such as the broadcasting, aeronautical radionavigation, and mobile services. By means of World Radiocommunication Conferences, WRCs (formerly WARCs), the ITU allocates radio frequencies to the different services. Radio Astronomy is *one such* recognised service but is exceptional in being a **passive** service, that is, a service not involved in transmission but concerned only with the reception of naturally occurring radio waves. Consequently **the intensity of the radio waves received by radio telescopes is**, unlike those of active services, **not subject to human control**. Likewise, the frequencies of astrophysically important radio spectral lines are fixed by laws of nature and cannot be controlled. Furthermore, the spectral lines from distant objects are redshifted to lower frequencies because of the expansion of the universe, so the frequency of reception depends on the distance of the source.

All the active services operate in bands that are also occupied by signals of cosmic origin. Generally they suffer no noticeable interference from these signals, because artificial transmitters produce power flux densities at the Earth's surface that are many orders of magnitude stronger than the power flux densities from cosmic sources.

In the early days of the development of radio, receivers were not sufficiently sensitive to detect the natural emissions of cosmic origin, and for that reason the sole usefulness of the radio spectrum was perceived to be for communications. Thus its apportionment fell into the hands of bodies having communications as their main concern.

With the development of more sensitive radio receivers, it became possible to view the universe through the "radio window". As a result of much ingenuity, modern radio telescopes have now been developed to such an exquisite degree of sensitivity that they closely approach the theoretical limit of what is physically possible. So today, radio waves of cosmic origin, that are perhaps as little as one millionth of the intensity of those used by other radio services, are routinely observed by the telescopes of the Radio Astronomy Service.

2.2. The Radio Window

The radio spectrum is a unique natural resource. It offers possibilities that are of great importance to humankind because it enables wireless communication. It also offers astronomers a dramatic view of the universe through the "radio window", the range of radio wavelengths over which the Earth's atmosphere is transparent.

Electromagnetic waves that travel at the speed of light were predicted theoretically by J. C. Maxwell (1831-1879) in 1873. H. Hertz (1857-1894) demonstrated the existence of these waves experimentally in 1888. G. Marconi (around 1900) pioneered the exploitation of these radio waves for economic and social use: our radio spectrum was born.

Radiocommunications and Radio Astronomy have always been closely associated. T. A. Edison in collaboration with A. E. Kennely, who first predicted the existence of the ionosphere, tried to detect radio waves from the Sun (1890). The experiment might well have succeeded but for the ionosphere itself. They were probably using detectors for very long wavelengths of many kilometres. The father of Radio Astronomy was K. G. Jansky, a telecommunications engineer. While investigating noise levels in long distance communication links at 10-metre wavelength, Jansky discovered cosmic radio noise, the radio counterpart of starlight (1932). He found that this so-called "background noise" peaked in the direction of the centre of the Milky Way.

To Jansky, cosmic radio waves were just a form of interference to communications systems. Today, by contrast, radiocommunication systems have grown to become sources of interference that set serious limitations to Radio Astronomy.

Radio techniques advanced very rapidly during the Second World War, particularly due to the development of radar. The beginnings of Radio Astronomy were thus rooted in the technology of radiocommunications and radar. In the course of its evolution, Radio Astronomy has in turn led to advances in communications through the development of low-noise amplifiers in receiver systems and of large steerable antennas which later proved vital for space communications. Today however, we find ourselves more in competition than cooperation with radio and radar, where the use of the radio window is concerned.

2.3. What Radio Astronomy Offers to Society

Like every science, Radio Astronomy, its results and techniques, serve the progress of other sciences in particular and humankind in general. This has been recognised by the award of three Nobel prizes. Radio Astronomy has long-term cultural and scientific returns. Words such as "quasar"," pulsar", and "black hole" have entered everyday use. Large radio telescopes have become local landmarks and even national icons for science. But Radio Astronomy also provides more tangible benefits, among which we may mention:

- the development of *very-low-noise receivers* (with wide applications), over a large frequency range, with noise temperatures as low as 1 Kelvin per GHz;
- the study of the *thermography of the body* by use of millimetric radio techniques (~45 GHz);
- the *detection of cancers* at centimetre wavelengths (~10 GHz) with modern radiometers and using a method of mini-aperture synthesis (interferometry);
- computerised *X-ray tomography* techniques employ methods originally developed for mapping radio sources;
- the *detection of forest fires* by their microwave radiation;

- the development of *radio sextants* for marine navigation, allowing accurate determinations of positions at sea even on overcast and rainy days;
- the *forecasting of earthquakes* by very long baseline interferometric, VLBI, measurements of fault motion by a determination of the apparent positions of small radio sources;
- the determination of many geophysical parameters such as *continental drift, polar wandering, latitude measurements*, and *variation in the Earth's rotation*, with the use of connected elements and VLBI techniques;
- experimental verifications of Einstein's *General Theory of Relativity* and the phenomenon of gravitational lensing using radio interferometry;
- verification of the existence of gravitational waves, and precise confirmation of Einstein's *General Theory of Relativity*, from timing measurements of binary pulsars;
- testing *theories of the origin of the universe*, and determining the age of the universe, using observations of the 3 K background radiation, the relic of the primeval fireball or Big Bang;
- measuring the temperature of the Earth's atmosphere and the distribution of water vapour and impurities such as carbon monoxide by *passive, remote-sensing technique;*
- monitoring of *weather* by using radiometers;
- using radio astronomy spectroscopy at mm-wavelengths to survey the *ozone layer and environmental pollution;*
- discovery of the *ozone hole*;
- *training of people* going on to all kinds of positions in daily life.

3.

Characteristics of Radio Astronomy

Since the discovery of cosmic radio waves by Jansky in 1932, the science of Radio Astronomy has expanded enormously. Many new types of astronomical object have been discovered and investigated by radio methods and many important discoveries have been made.

Whereas "optical astronomy" observes and studies the light waves from hot objects such as stars, celestial radio waves come mainly from material between the stars, including cool clouds of gas and dust, and high energy electrons in ordered motion. Radio astronomers study many of the same celestial objects as do optical astronomers, but radio measurements often reveal unexpected new aspects. In addition, radio astronomers have discovered new classes of objects and quite unexpected forms of activity. The universe provides a laboratory in which matter can be studied over a wide range of physical conditions, the extremes of which cannot now or even in the foreseeable future be reproduced on Earth. Extremes of density, temperature, and pressure and unusual chemical compositions can all be found at places in the universe that are under study by astronomers.

Some of the sources of radio waves studied by astronomers are believed to be at the very furthest limits of the currently known universe; and because they are so far away, the radio waves have been travelling for many billions of years. They tell us about the condition of the universe a very long time ago. Beyond the last identifiable objects is the cosmic microwave background radiation, the relic of the Big Bang in which our universe was formed. Closer to home, there are large sections of our Milky Way Galaxy that cannot be seen by optical astronomers because light is blocked by clouds of interstellar dust; radio waves can penetrate these dust clouds, enabling us to study the whole of our Galaxy and beyond to other galaxies that were previously hidden behind the Milky Way.

Characteristics of cosmic radio emissions

The spectrum of the celestial radio waves reaching the Earth has a broad continuum, which covers the whole range of frequencies that can penetrate the Earth's atmosphere, together with a large number of spectral lines of atoms, ions and molecules, each line being confined to a quite narrow frequency range. Due to Doppler shifts produced by motions of the emitting material, spectral line emissions may be shifted in frequency or broadened in frequency.

Continuum emission

Many interactions between ions and electrons, or between electrons and cosmic magnetic fields, produce radio pulses of varying amplitude and narrowness. The superposition of a large number of such events in an object in space produces continuum emission. Such emissions can arise through several different mechanisms. Analysing the mixture requires observations to be made at multiple frequencies. Strategically located frequency allocations to the Radio Astronomy Service make it possible to establish the general characteristics of the emission from the source, to estimate the mix of emission mechanisms, and thence determine the conditions in the source.

The radio continuum arises from two principal types of mechanism:

- "Thermal" emission, the intensity of which is proportional to the physical temperature, observed mainly in an ionised gas of unbound electrons and protons, but also in solids such as the planets, or our Moon, or even our own body.

- "Non-thermal" emission is characteristic of the majority of the radio sources (such as radio galaxies, quasars, pulsars and supernova remnants). This radiation is generated by high-energy particles in the presence of magnetic fields. The non-thermal radiation produced by highly relativistic electrons is called synchrotron emission. The synchrotron process generally produces a radio spectrum with a negative slope of ~0.8 in the log frequency versus log flux density plane. Hence these non-thermal sources have higher radio fluxes at lower radio frequencies. Additionally, some non-thermal sources contain compact components where the electrons have higher energies, and the radio spectrum is flat or even inverted.

Non-thermal emission usually bears the imprint of the magnetic field in which it is generated. Many non-thermal radio sources show weak polarization of their emission, from which it is possible to estimate the magnetic field and electron density within the source. The polarization is further modified by the magnetic fields and charged particles through which the radio waves propagate to Earth. The plane of linear polarization undergoes Faraday rotation by an amount that depends on the frequency. Observations at several widely spaced frequencies are needed to disentangle the various effects. The need for exclusive bands every octave is clearly indicated in the case of polarization studies.

At sufficiently low frequencies self-absorption in an emitting source causes a decrease in the flux density (Figure 1). This cut-off occurs at different frequencies for sources with different physical parameters, such as the strength of the magnetic fields at the source. It is imperative to establish the low-frequency spectra of such sources in order to study their physical properties.

The low-frequency range also has a great importance in the observations of both the thermal and non-thermal diffuse radiation in our Galaxy. Such observations give information on the high-energy particles in our Galaxy and on their distribution, and also on the hot ionised plasma in the plane of the Galaxy. In particular, the ionised interstellar clouds

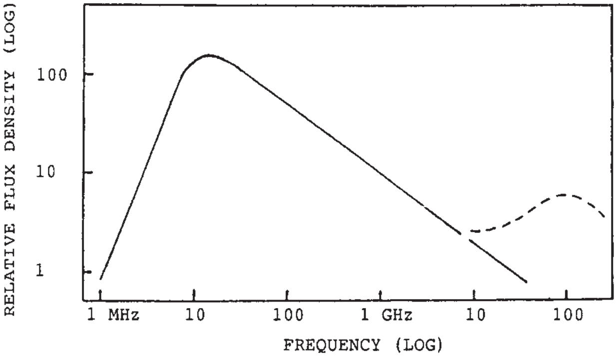

Figure 1: Spectrum of a "typical" non-thermal radio source, showing a low frequency cut off below 10 MHz, plus a "compact" high frequency component (dashed) found in some sources.

can be studied at low frequencies, where their spectra approximate that of a black body. Several hundred such galactic clouds appear approximately as black bodies at frequencies below ~100 MHz. Such spectral observations can be used directly to compute the physical parameters of the radiating clouds particularly their temperatures.

Another interesting and important class of objects are the pulsars. Pulsars are now understood to be highly condensed neutron stars that rotate with a period of the order of 1 second. They are produced by the collapse of the cores of very old stars during a catastrophic supernova explosion. The most rapidly rotating pulsars have millisecond periods which are extremely stable, rivalling the best laboratory clocks. The radio spectra of pulsars indicate a non-thermal emission mechanism, perhaps of synchrotron type. Observations have shown that pulsars are generally strongest at frequencies in the range from ~50 to 600 MHz; hence most pulsar observations are being performed at such frequencies.

The discovery and the study of pulsars during the last decades have opened up, unexpectedly, an important new field in physics, that of the state of highly condensed matter. The study of neutron stars with densities of the order of 10^{17} kg/m^3 and magnetic-field strengths of 10^8 Tesla, has already contributed immensely to our understanding of the endpoint of stellar evolution and has brought us closer to understanding the enigmatic black holes (which are supposed to be the most highly condensed objects in the universe). Observations of binary pulsars have verified the existence of gravitational radiation at the level predicted by Einstein’s General Theory of Relativity. Low frequencies are indeed important for pulsar observations.

Spectral line emission

The space between the stars is not empty, but filled with rarefied gas and dust. In some places cold dense clouds of this material are collapsing to form new stars and planets. In other locations, stars are interacting with this medium, heating it and enriching it through mass loss. In an average galaxy, this “interstellar medium” makes up a significant fraction of the total mass. It contains the material for new stars and the ashes of old ones. The study of this material is a major branch of astronomy. Radio spectroscopy provides a means of investigating regions of space that are too cold, dark or rarefied to radiate visible light or infrared radiation.

Energy changes in the atoms, ions and molecules of interstellar material produce radio emissions at discrete frequencies, which are characteristic of the materials producing them and their environments. In addition, if the clouds are moving as a whole or the material within them is in motion, Doppler shifts change the frequencies measured at the Earth. The result is that by observing these “spectral line emissions”, it is possible to measure the composition of the interstellar medium, the amount of material, its chemistry, and how it is moving.

One of the most widely observed spectral lines occurs at a wavelength of 21 cm, i.e. 1 420.4057 MHz, arising from neutral (un-ionised) hydrogen atoms in the interstellar gas. The hydrogen 21 cm line is the single most important spectral line studied by radio astronomers (see Section 5.3). Thousands of spectral lines have now been detected from other atoms, ions and molecules in the interstellar medium. Lines have been detected from several atomic species and their isotopes, and from a large number of molecules.

The study of spectral lines allows us to investigate the chemistry and kinematics within star-forming clouds of gas and dust. Spectral lines have now been detected from more than 100 different molecular species in interstellar space. Many of these are organic molecules, and some are quite complex. These discoveries have raised interesting questions about the way in which these complex entities have been built up and the way in which further development may have led to the spores of life, as a possibly widespread phenomenon. Astronomers now study astrochemistry, in which they attempt to trace out the development of a chain of chemical compounds by searching for the appropriate spectral lines. To study the physical conditions inside a molecular cloud, or in different portions of the cloud, it is necessary to compare the relative strengths of lines from different molecules, or of different transitions from the same molecule. In some cases, a set of lines can be studied from a particular type of molecule, involving different isotopes of one or more of the constituent atoms (hydrogen, oxygen, or nitrogen); these studies can give valuable information on the relative densities of the various isotopes and thus indirectly on the general evolution of the chemical elements. The relative significance of particular lines depends very much on the kind of study for which they are used. However, to understand the chemical and physical conditions properly, it is necessary to intercompare a large number of lines.

The locations in the radio spectrum of these lines are dictated by nature. In seeking frequency allocations to the Radio Astronomy Service, attempts have been made to cover the main spectral lines, such as the 1 420.4057 MHz spectral line from interstellar atomic hydrogen, with enough bandwidth to cover the most likely range of Doppler shift, and to cover the band requirements for continuum observations, while keeping the requests to a reasonable level. This has required, of necessity, various compromises.

One such compromise includes attempts to observe outside allocated frequency bands in cases where there are large Doppler shifts (such as those in which sources lying far beyond our Galaxy).

Radio sources

In the *solar system*, the *Sun*, an ordinary star to which we are exceptionally close, has always been an object of great interest to radio astronomers. The slowly varying component of solar radio emission has been found to provide one of the best indicators of the variation of solar activity over the Sun’s 11-year sunspot cycle. In addition, intense and rapid bursts of solar emission are providing greater understanding of what happens on the Sun during active periods and the way the Sun influences events in the Earth’s atmosphere and ionosphere. Besides the Sun and the *planets* (e.g. Jupiter and Saturn), *comets* are also the subject of radio astronomical research. The study of comets is of increasing importance, since they may offer clues to the origin of the solar system.

Radio Astronomy has provided new information about the early and late stages of the *“life” of stars*, stages that are important in the evolutionary process but that are not well understood. Strong and localised sources of radiation in spectral lines of the hydroxyl and water molecules are found in the shells of objects that appear to be in the process of becoming stars. Some compact sources of thermal continuum radiation, which are embedded in dense clouds of dust, also seem to be *protostellar objects*. Certain giant *molecular clouds* have in fact been shown to be the main breeding grounds of new stars. Such clouds can be studied only by radio methods.

At the other end of the stellar life cycle, radio astronomers study *supernova remnants*, the material blown out from massive stars in giant explosions at the end of their lives as stars. Radio astronomers have also discovered the very dense and compact neutron stars which are the residue left behind after a supernova explosion. A *neutron star* is observed in the form of a *pulsar*, a pulsating radio source, which emits narrow beams of radiation as it rotates with a very regular period of about a second.

Many *distant galaxies* are abnormally strong emitters of radio waves. These “radio galaxies” are the subject of many investigations in an attempt to discover the source of their enormous radio energy and the circumstances of the explosive events that seem to have occurred in many of them.

Intrinsically, the most powerful radio sources are the *quasars*, which are compact objects emitting radio energy at a prodigious rate. A quasar is believed to be the nucleus of a galaxy that is usually too distant for anything but the bright central core to be seen. The radio technique of Very Long Baseline Interferometry, VLBI, enables the central “engine” to be studied with resolutions as small as tens of microarcseconds. Superluminal expansion motions (apparently faster than the speed of light) have been measured. These superluminal motions indicate that the radio emission comes from highly relativistic beams of plasma. The study of quasars involves fundamental physics, in the continuing attempt to understand these exotic sources of energy.

Apart from quasars, the *nuclei* of some other classes of *galaxies* show great activity and unusual energy production. Even the nucleus of our own Galaxy is a small-scale version of an active galaxy, and this can best be studied by radio methods.

The history of Radio Astronomy has produced a remarkable and increasing rate of major unexpected discoveries. In the last few decades, radio astronomers have made fundamental new discoveries in physics and have brought us closer to understanding the nature of the universe. The rapid rate of discoveries in Radio Astronomy will surely continue. It is to the advantage of all humankind to assure such progress in part by protecting radio frequency bands for the Radio Astronomy Service.

3.1. Radio Astronomy and Electromagnetic Compatibility

Astronomy is interested in the entire electromagnetic spectrum

Different physical processes produce electromagnetic radiation at different frequencies. Telescopes exist for all parts of the spectrum. The natural limitations to ground-based Radio Astronomy are set by the ionosphere which becomes opaque below 3 MHz and the absorption due to various molecular constituents of the atmosphere at frequencies higher than 350 GHz.

Alien circumstances compared to active services

The radio signals used in active services are modulated to carry information and the power levels are set high enough to produce the required signal-to-noise ratio. In the Radio Astronomy Service the user has no control over the transmitted signal. The transmitted power cannot be varied to improve detectability. So we need to avoid absolutely the intentional use of the passive bands by transmitters of active users. Radio astronomical spectral lines are not tuneable. Their frequencies are set by the nature of the particular atom, ion or molecule and by the physical conditions within the emitting region. Radio Astronomy receives cosmic noise, it is an analogue service. The signals are extremely weak, i.e. **60 dB below** receiver noise (as is the current state-of-the-art technology). For normal radiocommunications **20 dB above** receiver noise is usual. Astronomers can control the electromagnetic environment only at the receiver and this creates a potential incompatibility with active spectrum use.

The radiation received is usually Gaussian noise

Careful study of the intensity of the radiation as a function of frequency, position, polarization and its variation with time can give details on the nature of the source.

Receiver bandwidth

There are two major goals:

- broadband: detection of continuum emission from thermal as well as non-thermal extraterrestrial radio sources. In this application the sensitivity is improving with increasing bandwidth.
- narrowband: in use for spectral line studies, i.e. of the Doppler-shifted line emission, which informs us about the kinematics within extraterrestrial radio sources.

Equipment

The equipment is continuing to be improved with greater sensitivity and better angular resolution. System temperatures of 10 - 20 K for cm-wavelengths and angular resolutions of milliarcseconds are obtained in daily practice.

3.2. Radio Astronomical Observations

Celestial radio sources emit electromagnetic radiation at all frequencies in the entire electromagnetic spectrum. Very often the emission at frequencies other than radio frequencies is so weak that these objects can be studied only by Radio Astronomy. The frequency dependence of the emitted intensity depends fundamentally on the physical conditions, kinematics, and distribution of matter and its characteristics within the radio source. This frequency dependence is conditioned by the mechanism generating the radiation. The intensity of emitted radiation can be constant as a function of time for a certain frequency, but the frequency dependence can also show temporal variations (for instance, due to violent events within the radio source).

The intensity of the received radiation can be constant in time, but can also show variations at all possible time scales ranging from many years to fractions of a millisecond. Flux variations may arise from intrinsic variability in the source (for example, regular pulses from pulsars, or irregular outbursts from interacting stars and active galactic nuclei), or from propagation effects (such as interstellar and interplanetary scintillations). Also other parameters such as the structure of radio sources often show temporal variability. Of course this is not known a priori, hence the radio astronomical observations need to be stable as a function of time. This stability puts requirements on the equipment and also on the interference levels that can be tolerated within the frequency bands used.

Given the characteristics of the celestial radio sources, high spectral, high spatial and high time resolution are necessary for radio astronomical observations (see Section 1.2). Furthermore, good frequency coverage is essential since the dependence of the intensity of the radio source as a function of frequency is the “finger print” of the nature of the radio source.

To analyse the spectral characteristics within the receiver bandwidth (which can range from a kHz to several GHz) observations are usually done with many frequency channels in parallel (up to several thousand is quite common). The extremely weak signals received on Earth can be detected only if the sensitivity is adequate. Usually the sensitivity of a radio astronomy receiver is –60 dB below the sensitivity used in telecommunication receivers. Furthermore, high dynamic range in the final results is important to investigate weak features around strong radio sources. A dynamic range of 50 dB is state-of-the-art. Sensitivity levels of a few microJanskys are currently achievable (1 microJansky corresponds to 10^{-32} Wm^{-2} Hz^{-1}). To achieve these high quality results both large bandwidth and long observing times are needed. This is only possible when the EMC environment does not generate harmful interference within the observing bandwidth and during the integration time (which can be up to several days). Since characteristics of radio sources can vary on time scales of days to many years, the observations should be repeatable with at least the same quality over these time intervals.

For the reasons outlined, radio astronomical measurements are particularly vulnerable to interference from transmitters of active services

3.3. Radio Astronomical Techniques – Continuum Observations

3.3.1. Single Dish Observations

Radio astronomical observations may employ stand-alone instruments, such as single dish telescopes, or a combination of instruments, as a radio interferometer.

Single dish telescopes have dimensions ranging from a metre to 100 metres for fully steerable dishes such as the Effelsberg 100–m dish in Germany, and up to 300 metres for dishes that can cover only a very limited area of the sky, such as the Arecibo fixed dish in Puerto Rico.

Figure 2 shows a map of the Milky Way at 408 MHz made over several years using the 76–m Lovell Telescope at Jodrell Bank in the UK, the Effelsberg 100–m telescope in

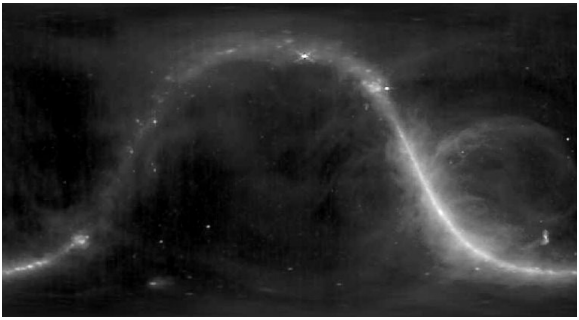

Figure 2:
An all-sky map of continuum emission at 408 MHz from the Milky Way, plotted in celestial coordinates. The bright spots are discrete radio sources lying inside and beyond our Galaxy (Haslam et al.1982). Copyright: MPIfR Bonn.

Germany, and the Parkes 64–m telescope in Australia. The angular resolution or half-power beamwidth of the image is 0.85 degrees (about 1.6 times the diameter of the Moon). The map was made using many scans across the sky, assuming that the background radiation and receiver noise varied slowly with time during the course of each scan. The map shows the large-scale structure of the radio emission from the Milky Way, but most of the discrete sources appear point-like: their intrinsic angular sizes are much less than the radio telescope beamwidth.

A single dish measurement of an unresolved point source usually involves a comparison between the radio power measured in the direction of the source and the mean power measured towards a number of nearby comparison or reference regions. In this way the strength of the emissions, their polarization, and the variation of these properties with frequency may be determined. It is implicitly assumed that the source and the environment in which the measurements are made do not vary during the course of the measurement. Variability over weeks, months or years may also be monitored. Some sources, such as pulsars and the Sun, produce emissions that vary more rapidly. They therefore require special observing techniques.

3.3.2. Antenna Array Observations

Single dish measurements are limited by their angular resolution. Radio astronomers use radio interferometers to measure the structure of radio sources on very fine angular scales down to a fraction of a milliarcsecond. An array of two or more antennas has a field of view roughly equal to the half-power beamwidth of one of the individual antennas making up the array, and an angular resolution or beamwidth equal to that of an equivalent aperture with the dimensions of the whole array. Each pair of antennas in the array is sensitive to a range of angular scales. If there are enough antennas in the array, many angular scales can be measured simultaneously, and images can be produced in a single operation or “snapshot”. Most arrays, however, use the rotation of the Earth to sample the radio source from different directions, in the technique called “aperture synthesis”. For linear arrays with moveable antennas, such as the Synthesis Radio Telescope at Westerbork in the Netherlands, about twelve 12-hour observations are needed, using different antenna spacings, to collect enough information to make the best

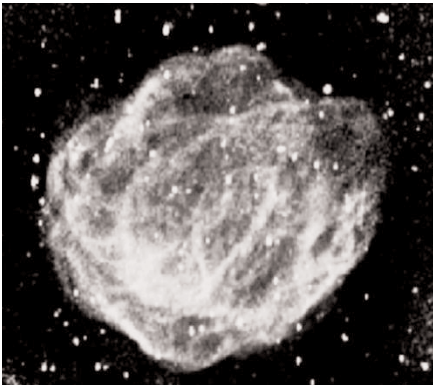

Figure 3:
Radio image made using a synthesis telescope at 1.4 GHz. It shows the rapidly expanding remnant produced by a supernova explosion. The object is about 10 000 light years away, and, if it were visible to our eyes, it would look bigger than the full Moon. The background dots are not stars; they are distant radio galaxies and quasars. Figure courtesy of Ken Tapping, Dominion Radio Astrophysical Observatory, Canada.

image; each day the antennas have to be moved to new positions. In assessing the impact of unwanted emissions, the average half-power beamwidth of the individual array antennas should be used, since this is the size of the patch of sky the array can “see”. The synthesised beam pattern for the final image is determined in the data processing.

An example of a radio map made in this way is shown in Figure 3.

Different combinations of instruments are used in radio interferometry. In Europe, radio interferometers located on a single site and operating at metre and centimetre wavelengths are located in Cambridge (United Kingdom), in Nançay (France) and in Westerbork (the Netherlands). An interferometer operating at mm-wavelengths is located on the Plateau de Bure (France). Such connected element interferometers achieve the angular resolution equivalent to a “single dish” instrument with the diameter of the whole array, which is several km, for the examples mentioned.

Long baseline interferometry, where the array is of order 100 km across, is carried out in the United Kingdom, using the Multi-Element Radio Linked Interferometer Network MERLIN, operated by Jodrell Bank Observatory. Optical fibre connections will replace the radio links in 2005. MERLIN achieves the angular resolution of a (hypothetical) single dish 218 km in diameter.

On a continental or worldwide scale telescopes are combined in Very Long Baseline Interferometry, VLBI (see Section 3.7). VLBI is a very special kind of radio astronomical technique and puts particular constraints on the protection of radio astronomy frequency bands.

Radio astronomical observations can be done in a single frequency band or in several frequency bands simultaneously. Furthermore, telescopes can move from one frequency band to another within time scales as short as 1 minute. The choice of frequency is based on the astronomical requirements, physics of the celestial radio source and the characteristics of the instrument used. This implies that, in practical matters of frequency management, one must assume that *all frequencies allocated to the Radio Astronomy Service are always used.*

3.4. Radio Astronomical Techniques – Spectral Line Observations

3.4.1 Single Dish Observations

In spectral line observing the bandwidth of the receiver is divided into many frequency channels of equal width that are measured simultaneously, usually via digital signal processing. The number of frequency channels is typically many thousands. The total power measured as a function of frequency contains the wanted power from the spectral line, together with the unwanted contributions from receiver noise, ground radiation, sky background etc. If the unwanted components in the spectrum are constant in time and slowly varying with frequency, it may be possible to estimate their contribution in the vicinity of the spectral line, the so-called "instrumental baseline" by interpolation, and subtract it. This is the total power mode of observing. Radio astronomers also use position switching and frequency switching techniques to subtract the instrumental baseline. In position switching the on-source spectrum is measured together with one or more off-source reference spectra obtained at nearby positions on the sky. The final spectrum is then obtained by subtracting a suitable mean of the reference spectra from the target spectrum. In cases where the spectral line emission is very extended and line-free reference positions cannot be found, radio astronomers can use frequency switching, in which the reference spectrum is obtained by measuring at a different frequency (or frequencies). In all three modes of observing the requirement for stable conditions during the course of the measurement is paramount.

We can conclude that spectral line observations are particularly sensitive to "unwanted" emissions for the degradation they can produce. Any pattern feature of the line can be obscured, distorted or cancelled by interfering signals. The effect is even worse if the interfering signals are multiple, move or vary in time, because the previously described "subtraction" techniques can be invalidated. This difficulty applies principally to the 1400 - 1427 MHz band, which is used to observe emissions from cosmic hydrogen. This is the dominant material in the universe and is detectable all over the sky.

3.4.2. Antenna Array Observations

In the case of spectral line interferometry, separate images are made for each spectrometer channel. After correction for the Doppler shift due to the Earth's motion, each channel corresponds to a range of Doppler velocities in the target source. The final set of maps is termed a "data cube". Three-dimensional display techniques are necessary to study and interpret such data cubes.

Similar concerns about unwanted emissions apply here.

3.5 Calibration

Calibration of single dish measurements is usually achieved by measuring the receiver output when the radio telescope is pointed towards a point source of known spectral flux density. Calibration involving a switchable broadband noise source (or sources) at the receiver input is also usually employed. Calibration of interferometer data is more complex and beyond the scope of this Handbook.

3.6 Criteria for Harmful Interference

The radio astronomical measurement made at the receiver output is an estimate of the mean power available at the port of the receiving antenna. Radio astronomers express this noise power in terms of a noise temperature, which is the temperature at which a matched resistance, placed at the input port of the receiver, would produce the same power at the receiver output as is observed when the antenna is connected. This noise power is $kT_{\mathrm{system}}B$ (in Watts), where k is Boltmann's constant, B is the bandwidth (in Hz), and T_{system} is the system noise temperature (in degrees Kelvin).

The measurement process is complicated by several noise contributions, all of which have similar properties: ground noise, atmospheric noise, and the internal noise of the receiver. Taking them together one can write

$$T_{\mathrm{system}} = T_{\mathrm{receiver}} + T_{\mathrm{atmosphere}} + T_{\mathrm{sidelobes}} + T_{\mathrm{source}},$$

where T_{receiver}, $T_{\mathrm{atmosphere}}$ and $T_{\mathrm{sidelobes}}$ are the unwanted noise contributions from the receiver, the atmosphere in the main beam and any sources (ground, atmosphere, interference, etc.) in the antenna sidelobes, and T_{source} is the wanted contribution from the source in the main beam. In general T_{source} is the smallest term in this equation. The determination of T_{source} consists therefore of measuring the very small change in the average T_{system} when the antenna is pointed at and away from the source (for a point-like source) or during a scan across an extended source. The weakest cosmic sources that can usefully be measured are those that produce, when the antenna is pointed at them, a change in the output of the receiver comparable with the rms noise fluctuations in the detector output, namely

$$\Delta T = \frac{T_{sys}}{\sqrt{\tau B}} .$$

This quantity represents the rms error in a measurement. Since increasing the bandwidth reduces the rms fluctuations in the receiver output, radio astronomers make continuum measurements using the largest bandwidth possible. Note that if part of an allocated band has to be sacrificed to implement a guard band, the measurement error will increase. If x% of the band is lost, an x% increase in the integration time will be needed to retrieve the required sensitivity, which in turn will mean a reduction in efficiency at the observatory of roughly x%.

Recommendation ITU-R **RA.769** tabulates the levels of interference that would, if noise-like, produce additional rms fluctuations in the receiver output equivalent to 10% of the fluctuations in the absence of that interference. In converting this noise temperature to a spectral power flux density at the observatory, it is further assumed that the interfering signals enter through far sidelobes of the radio telescope at 0 dB gain (Recommendation ITU-R **RA.769**).

Radio astronomical measurements are usually expressed in terms of *spectral power flux density*, i.e. power in Watts falling on a square metre of antenna collecting area, per Hz of receiver bandwidth. The actual bandwidth used to make the measurement will be

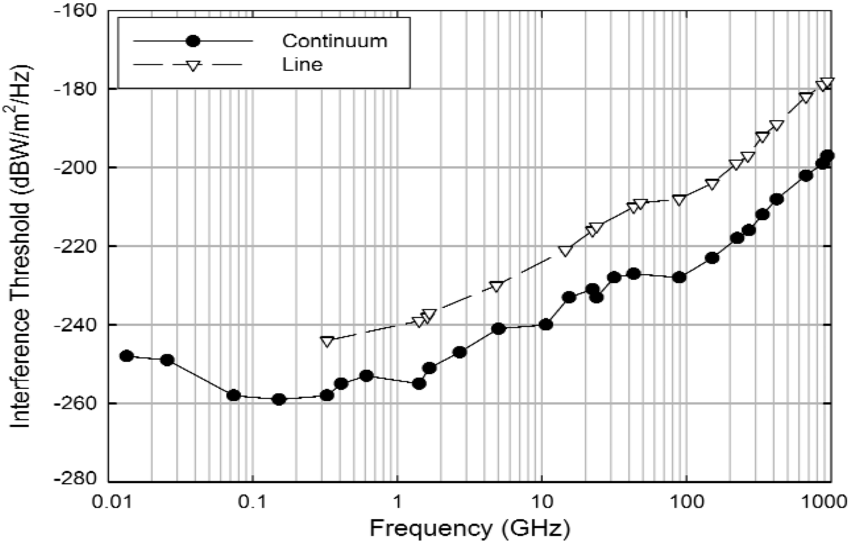

Figure 4: Thresholds of interference versus frequency for radio astronomy spectral line and continuum observations. From ITU-R Recommendation RA.769.

much larger than 1 Hz – generally the entire bandwidth of the frequency allocation in the case of a continuum measurement, or the channel bandwidth in the case of a spectral line measurement. Because of the tiny amounts of power received from cosmic sources, their spectral power flux density is usually specified in terms of the Jansky:

1 Jy = 10^{-26} W m^{-2} Hz^{-1}.

However, for spectrum management purposes, Recommendation ITU-R **RA.769** gives the interference thresholds in units of receiver noise temperature ΔT, in terms of power in the measurement bandwidth, and in terms of spectral power flux density. The spfd thresholds for spectral line and continuum measurements are plotted in Figure 4. 1 Jansky corresponds to –260 dB(W/(m^2Hz)).

3.6.1. Interference to Arrays

It has long been realised that a radio interferometer is less sensitive to radio interference than a single dish telescope. A simple two-element interferometer responds primarily to signals which are correlated at the two telescopes. Interference which is present at only one telescope has a secondary effect on the result (unless it overloads the receiver, destroying its linear transfer function). Furthermore, any interfering signal appearing simultaneously at both telescopes will not in general have the characteristic fringe frequency and delay of a cosmic source. One result of this is that the effective time over which such interference disrupts the measurement is reduced from the time of the complete observation to the mean period of one natural fringe oscillation. For VLBI the nat-

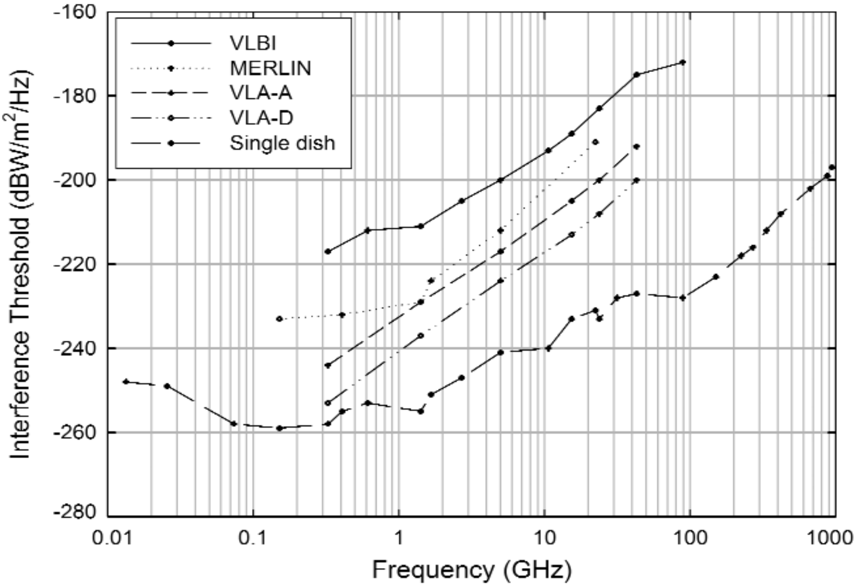

Figure 5. Harmful threshold of interference to radio astronomical continuum measurements shown as a function of frequency for different types of radio telescope. The lower curve applies to total power measurements using a single telescope. Connected element interferometers such as the VLA and MERLIN have a degree of extra immunity against interference which increases with the array size (expressed in wavelength). The curve for VLBI assumes the interfering signal affects only one telescope, in which case the result is independent of the array configuration or size. Adapted from ITU-R Recommendation RA.769.

ural fringe rate is measured in kHz, and so the extra immunity to interference resulting from this effect is considerable. Table 1 lists some representative numbers for VLBI system of 3 000 km baseline. Interference thresholds for VLBI and for radio interferometers of different sizes are compared with the single dish thresholds in Figure 5.

A second effect which occurs is bandwidth decorrelation of broadband interference. Interfering signals at opposite ends of the receiver band will generally have different fringe rates, and this will lead to decorrelation of order

$$\frac{\sin \pi B t}{\pi B t}$$

where B is the bandwidth and t the delay. This means that the effect of the interference is reduced by an amount $-10 \log_{10}(\pi B t)$ dB. The discrimination against interference is strongest when the cosmic source is moving across the interferometer fringes and least when it is moving along a fringe. For VLBI the delay t is sufficiently large that the bandwidth decorrelation factor is also large. Table 1 gives representative values for continuum (B = 2 MHz) and spectral line (B = 1 kHz) measurements.

Table 1: Factors Affecting the Response of a VLBI Array to Interfering Signals

Representative baseline	D = 3 000 km		
Observation time	τ = 40 min		
Wavelength	18 cm	6 cm	1.3 cm
Projected baseline $\upsilon = D/\lambda$	1.7x10^7	5x10^7	22x10^7
Fringe spacing (milliarcsec)	12	4	0.9
*Natural fringe rate $\varpi\upsilon$ (kHz)	1.2	3.6	16.3
Fringe frequency effect $(\varpi\upsilon\tau)^{-1/2}$ (dB)	–32	–35	–38
Representative delay	$t = D/c = 10^{-2}$ sec for all λ		
Representative bandwidth	B = 2 MHz (continuum) 1 kHz (line)		
Bandwidth decorrelation factor (dB) $-10\log_{10}(\pi Bt)$ dB	= –48 dB (continuum) = –15 dB(line)		

Note: Here $\varpi = 7.3 \times 10^{-5}$ Hz is the Earth rotation rate.

Table1 suggests at first sight that VLBI measurements may yield useful results in the presence of relatively strong interference. However there are other factors to be considered. In order to make an accurate measurement of a radio source we must calibrate the amplitude of the fringes. The correlator output is usually in the form of raw cross-correlation coefficients

$$\frac{P_i * P_j}{(P_i^2 P_j^2)^{1/2}} .$$

Any interfering signal present at one site only will effectively add to the receiver noise component of the power P_i, and so will reduce the correlation coefficient. The ITU-R criterion for harmful interference to VLBI measurements is that the interfering signal should add no more than 1% to the receiver noise at a given site (ITU-R Recommendation RA.769). This figure of 1% also corresponds fairly closely to the typical uncertainties in “well calibrated” VLBI data. In practice this 1% limit becomes important before the combined effects of decorrelation given in Table 1.

3.6.2. Conclusions

Radio Astronomy differs from most other radio applications in that the measurements are obtained as averages over long integration times and large bandwidths. In terms of standard radio telecommunications definitions, the available signal-to-noise ratios are very small, usually far less than unity. In addition, radio astronomical observations almost always involve differential measurements of flux density, polarization and/or spectrum at different points in the sky. This needs to be taken into account when addressing interference problems and formulating mitigation measures.

3.7. Very Long Baseline Interferometry, VLBI

Very Long Baseline Interferometry, VLBI, is the technique used for radio astronomical studies requiring the highest angular resolution. A radio interferometer achieves an angular resolution of λ/D radian, where λ is the wavelength and D is the projected separation of the telescopes, as viewed from the radio source. With telescopes separated by intercontinental distances and wavelengths of 1 cm or less, a resolution of less than 1 milliarcsec may be achieved (1 milliarcsec is approximately the angle subtended at the Earth by a person on the Moon). This is the highest angular resolution achieved in any branch of science. The feasibility of extending the technique even further to radio telescopes in space was first demonstrated using the Tracking and Data Relay Satellite System, TDRSS, and space VLBI is now conducted using a dedicated orbiting radio telescope (see Section 3.7).

VLBI is normally used to measure or map sources of very small angular size (milliarcseconds and smaller), or to use known sources to measure changes in the dimensional shape of the antenna array (geophysics research). In this latter case the formal accuracy in the measurements can be a few millimetres over intercontinental distances (usually called *baselines*).

VLBI observations are now conducted regularly at most cm-wave radio observatories around the world. In addition there is a growing global millimetric VLBI network.

3.7.1 VLBI Techniques

VLBI differs from connected-element radio interferometry in several aspects. In a conventional radio interferometer all the receivers at each antenna use a common local oscillator, locked to an accurate frequency standard, to maintain the coherence of the interferometer. Signals from each telescope are brought together, through appropriate delays, to be correlated in real time to produce the interferometer fringes. VLBI is a radio astronomical technique based upon the recording of the amplified cosmic radio emissions in raw form (although downconverted in frequency and then sampled), along with precise timing and reference signals.

In VLBI each observatory relies on its own highly stable atomic frequency standard to maintain coherence by dead reckoning. A hydrogen maser is usually employed, when receiving radio astronomical signals at microwaves (>10GHz) and over hundreds of seconds. The frequency stability required is a few parts in 10^{14}; indeed coherence times are then limited by atmospheric effects and the short-term phase noise of the atomic reference. Coherence times range from 100s at 7 mm wavelength up to tens of minutes at cm wavelengths.

The data from each VLBI station are separately digitised and recorded for subsequent processing. After recording, the signals are brought together at a processing station, where they are synchronised and correlated. In effect, a network of VLBI radio telescopes operates like a single radio telescope using an array of antennas but without those antennas needing to be connected together during the observations. This makes it possible for the array to be very large, with antennas on different continents, or even in space. The recording system used has high sensitivity and is wideband. This so-called MKIV system uses a multichannel tape drive to record up to 512 Mb/s of data on magnetic tape. The MKV system uses computer hard-disc-based recording at 1 GB/s. The feasibility of bringing VLBI data together over the internet, eVLBI, was demonstrated by European and US radio astronomers in 2004.

Another difference from connected-element radio interferometry is the way that VLBI data are processed to make radio maps. Compared with most conventional radio interferometers a VLBI array is very sparse and irregularly filled. Also the absolute phase of the interferometer is virtually impossible to determine. Special mapping techniques have been developed to deal with this situation. Great advances have been made in the last decade in the self-calibration techniques, which make use of redundancy in the data to determine corrections for telescope-dependent errors. If there are three or more telescopes in the array we can construct closure phases of the form

$$\phi_{123} = \phi_{12} + \phi_{23} + \phi_{31,}$$

where ϕ_{ij} is the phase angle on the baseline formed by stations i and j. These closure phases depend only on the structure of the radio source. Instrumental or atmospheric/ionospheric phase errors introduced at any one station will appear twice in the closure phase equation with opposite signs, and so will cancel. For an array of $n>4$ telescopes the number of independent closure phases exceeds the number of telescopes, and so it is possible to solve for the telescope-dependent phase errors. There is a penalty in that the absolute phase information is lost. However this is not a major disadvantage for VLBI as the absolute phase is not known in any case. In a similar way closure amplitudes of the form

$$A_{1234} = \frac{a_{12}a_{34}}{a_{13}a_{24}}$$

may be constructed from the fringe amplitudes a_{ij} on individual baselines, and used to determine telescope-dependent gain errors. The effectiveness of these self-calibration techniques increases as the number of telescopes increases. For an array of n telescopes there are:

$n(n-1)/2$ baselines,
$n(n-1)(n-2)/2$ independent closure phases, and
$n(n-3)/2$ independent closure amplitudes.

Such has been the success of the method that it is now used to process data from connected-element interferometers.

3.7.2. VLBI Frequency Bands

The frequency bands below 50 GHz used regularly for VLBI are listed in Table 2. In most cases they are centred on bands having a primary allocation to Radio Astronomy in at least one ITU region. The degree of protection actually afforded to Radio Astronomy varies considerably from country to country even within a given ITU region (e.g. Section 5.2). The frequency bands used by some of the different VLBI networks are also indicated in Table 2: EVN stands for the European VLBI Network in which 10 radio observatories participate; VLBA stands for the US Very Long Baseline Array network.

Table 2: Frequency Bands Below 50 GHz Used for VLBI

Wavelength (cm)	R.A. Band (MHz) in ITU-R RR	MKIV Band (MHz)	EVN	VLBA	Other
90.0	322.00 - 328.60	315.0 - 335.0	-	-	R
		319.99 - 333.99	X	X	X
50.0	608.00 - 614.00	599.99 - 613.99	X	X	-
21.0	1400.00 - 1427.00	1374.99 - 1430.99	X	-	-
		1385.0 - 1435.0	-	-	R
18.0	1660.00 - 1670.00	1636.99 - 1692.99	X	X	X
		1645.0 - 1695.0	-	-	R
13.0	(2290.00 - 2300.00)	2075.0 - 2325.0	-	-	R
		2214.99 - 2270.99	-	-	DS
6.0	4990.00 - 5000.00	4805.0 - 4855.0	-	-	R
		4956.99 - 5012.99	X	X	*
		5000.0 - 5020.0	-	-	R
		7800.0 - 8700.0	-	-	R
3.6	(8400.00 - 8500.00)	8270.99 - 8326.99	X	X	DS
1.3	22210.00 - 22500.00	22195.0 - 22245.0	-	-	R
		22206.99 - 22262.99	X	X	*
0.7	42500.00 - 43500.00	43178.99 - 43234.99	X	X	+

Notes:

DS	Space Research band used for VLBI, often with NASA dishes.
R	Russian VLBI network
*	Non-standard band for Russian Radioastron space VLBI.
+	Ad hoc sessions.

It will be noticed that the standard VLBI frequency bands for the MK IV recorder usually exceed the bands allocated to Radio Astronomy. Fruitful use of these unprotected sub-bands is possible for reasons discussed in Section 3.7.5.

Two of the bands used are allocated to the Space Research Service for Deep Space transmissions from Space to Earth. VLBI use of these bands has become established through collaborations with NASA. The bands offer the advantage of 64 m-class NASA radio dishes equipped with state-of-the-art cooled receivers and top performance atomic frequency standards.

3.7.3. Mapping Considerations

In Section 3.6.1 we have considered the effect of radio interference on individual measurements of fringe visibility. However the modern trend in VLBI is to use large arrays capable of high quality imaging. “World Array” experiments involving about 20 radio telescopes are beginning to yield high resolution images of a quality similar to that produced by the largest US connected interferometer, the Very Large Array, VLA, in its early years. The quality of the VLBI images is determined by several factors: the number of telescopes, their geographical location, the choice of the receiving frequency and the celestial coordinates of the source being observed – all of which govern the efficiency with which Earth rotation syntheses the large aperture of the array. To be effective, most of the array must be operating most of the time. For an array of 20 telescopes to be fully operational 90% of the time each telescope should be operational 99.5% of the time (assuming the interference events at each site are independent). The ITU-R has adopted 90% of time as its criterion in assessing the likelihood of interference to Radio Astronomy due to unusual propagation effects. The present argument suggests that the 90% of time for VLBI should apply to the whole array, and that a figure of 99.5% would be appropriate for each individual radio telescope. To illustrate the point, an array of 20 telescopes each operating 90% of the time would be fully functional only 12% of the time!

3.7.4. Practical Considerations

The response of a connected-element interferometer to interfering signals has been studied under controlled experimental conditions, and the theory outlined in Section 3.6 has been confirmed. Such a study has not yet been made for VLBI. This is understandable, as VLBI programme committees might not sanction the controlled sabotage of a multimillion dollar international observing facility. If we consider instead the use of existing data we meet new difficulties.

It appears that it would be very difficult to obtain systematic information on radio interference from existing VLBI data. To begin with, the monitoring of radio interference during VLBI experiments varies considerably, and interference at the 1% level might actually pass unnoticed at some sites. The effects of interference only become apparent during the correlation of the data, but that happens some months after the experiment, or even later, during the mapping process. Again it would be difficult to extract exhaustive statistical information. Bad data are usually discarded once identified as such, and there is not yet a systematic procedure for logging this information. It is by now in the hands of scientists whose livelihoods depend on publishing results, not brooding over interference. Nevertheless, there must be a pool of experience and expertise which could be drawn on.

3.7.5. Conclusions

There are factors which give VLBI extra immunity to radio interference compared with a total power system. These factors include the wide separation of the telescopes, the fact that the interferometer responds primarily to signals which are correlated at all telescopes, and the degree of redundancy and parallelism in the data collection which allows data to be edited and corrected in the off-line processing. Partly because of these factors, some VLBI operations are successfully carried out in frequency bands not allocated to Radio Astronomy.

A number of questions deserve further study. For example, we know that astronomers will edit out strong interference, and that the self-calibration techniques will deal with some types of low-level interference. Is there an immediate level at which interference causes more subtle effects in the radio mapping? How should we standardise the logging of interference during VLBI experiments? For example would it be worthwhile to construct automatic interference monitors which could run during VLBI observations? It is clear that a detailed understanding of the effects of radio interference on VLBI in practice, rather than in theory, will require the cooperation of many VLBI scientists at all stages of the experiment from data logging through to correlation and mapping. Can we convince them that it is worth the trouble?

3.8 Space-based Radio Astronomy

Space-based Radio Astronomy is a relatively new field. Because of the absence of atmospheric absorption, space-based Radio Astronomy is invaluable for observing in frequency ranges where ground-based observations can never be made. Several space missions have already been successfully dedicated to Radio Astronomy, as is indicated by the examples in this section.

3.8.1. Space VLBI

The Space Very Long Baseline Interferometry observatory, HALCA, was launched by Japan in February 1997. This satellite has been the main element of the VLBI Space Observatory Programme, VSOP, which is producing high resolution radio images of celestial radio sources. With VLBI, the larger the dimensions of the array of the radio telescopes involved, the finer the resulting angular resolution. The VSOP mission is the first dedicated Space VLBI observatory. By combining observations from the HALCA satellite and ground radio telescopes, the world's astronomers are now able to generate an array of telescopes that is three times the Earth's diameter in extent, and to reap the rewards of improved angular resolution images.

The VSOP mission is a complex international endeavour involving a global network of about 40 radio telescopes, five tracking stations and data processing facilities in Australia, Canada, Japan, the USA, and with participation also of the European VLBI Network and the Joint Institute for VLBI in Europe, JIVE, in the Netherlands.

HALCA's radio telescope is an 8 m Cassegrain type antenna composed of a mesh-surface main reflector. Its orbit is highly elliptical with an apogee height of 21 400 km, a perigee height of 560 km, an inclination angle of 31°, and an orbital period of 6.3 hours. The on-board radio astronomy sub-system includes low-noise receivers for three frequency bands, 1.60 - 1.73 GHz, 4.7 - 5.0 GHz and 22.0 - 22.3 GHz (see also Table 2).

Of crucial importance in the production of VSOP images is the choice of an appropriate weighting scheme since in any given experiment, the antenna with the poorest antenna sensitivity is the HALCA spacecraft. When the appropriate weighting scheme is chosen, VSOP images of moderate dynamic range (≈ 1000:1) can be produced.

In 2005 operations of HALCA ended. Another Space VLBI mission, Radioastron, led by the Russian Academy of Sciences and the Russian Space Agency, is being prepared for launch in the first decade of the twenty-first century.

HALCA and Radioastron represent first generation Space VLBI missions. Their angular resolutions are between 3 and 10 times higher than those of ground-based VLBI systems at the same wavelength. However, they are limited in their scientific productivity by the relatively low sensitivity of the orbital radio telescopes compared to a typical ground-based VLBI radio telescope. The sensitivity of an orbital radio telescope is defined by the size of its antenna and the noise characteristics of its on-board radio astronomy receivers (the diameter for the first Space VLBI telescopes is 8-10 metre as opposed to 25-30 metre for a typical ground-based VLBI telescope).

Space VLBI missions have observed at frequencies as high as 22 GHz, while ground-based VLBI systems routinely operate at frequencies up to 43 GHz (some of them operate at frequencies as high as 220 GHz). There are a number of high-priority scientific objectives which require VLBI observations with an angular resolution roughly 10 times higher than that achievable with ground-based VLBI in the frequency range from 5 to 100 GHz, and with a sensitivity up to 100 times better than that of the current Space VLBI missions.

To address these objectives, a second generation Space VLBI mission is being considered. It will differ from its precursors essentially in two major characteristic: (a) up to two orders of magnitude higher sensitivity; and (b) a broader frequency coverage with an emphasis on the frequency range 5 - 90 GHz. This will require a 25 - 30 metre antenna with an rms surface accuracy of 0.2 mm. Such a mission is currently under study at ESA and NASA.

3.8.2 Single-mode Space Radio Observatories

In 2001, Sweden launched the Odin satellite for both astronomical and atmospheric (aeronomy) research. For atmospheric sounding the spacecraft follows the Earth limb, scanning the atmosphere up and down from 15 to 120 km at a rate of up to 40 scans per orbit (see Section 3.9.3). When observing astronomical sources, Odin is continuously pointing towards the target for up to 60 minutes. The satellite includes optical and radio observing facilities. The radio astronomical research serves particularly the studies of spectral line emissions. Emissions from a large range of molecules are detected by the system.

The main objective is to perform detailed studies of the physics and the chemistry of the interstellar medium by observing emission from key molecular species. Comets, planets, protostars, circumstellar envelopes and nearby galaxies are also studied.

The radio telescope consists of a mirror of 1.1 metre diameter, with a surface accuracy of 10 μm rms. The following frequencies are observed: 118.25 - 119.25 GHz, 486.1 -

503.9 GHz and 541.0 - 580.4 GHz with bandwidth 100 MHz to 1 GHz and a spectral resolution of 0.1 MHz to 1 MHz. The sensitivity of the receiver is 1 K in 1MHz with S/N=5 after 15 min of integration.

Another satellite operating at frequencies between about 100 and 500 GHz is the NASA Sub-millimetre Wave Astronomy Satellite, SWAS, launched on 5 December 1998.

Other space radio observatories include those dedicated to cosmic microwave background research such as COBE, which detected the anisotropy of the cosmic microwave background radiation, and the Wilkinson MAP probe. There are many advantages to placing such radio astronomy stations in one of the Lagrangian points in the gravitational field of the Sun-Earth system around which stable (halo) orbits can be established for spacecraft, namely the L2 point (ITU-R *Handbook on Radio Astronomy*, Chapter 7). At the L2 point the Earth, Sun, Moon and most artificial radio transmitters are concentrated within a small region of sky, so by pointing away from this direction observations of the highest stability can be achieved.

Further developments foreseen in space radio astronomy include the establishment of a radio astronomy station in the shielded zone of the Moon (ITU-R *Handbook on Radio Astronomy*, Chapter 7).

3.8.3. Radio Science with Telecommunication Links across Interplanetary Space

The availability at the big VLBI radiotelescopes of extremely high stability frequency standards and of very low noise receivers has opened the possibility for these stations to participate in Doppler tracking of interplanetary spacecraft. Modern missions carry on-board transponders suitable to retransmit to the Earth the uplink signal, translated to a different frequency band, while preserving phase coherence, even at 8.4GHz and recently 32 GHz. The extremely high spatial resolution achievable by comparing the carrier phases of the up- and downlinks (differential movements as small as a fraction of a millimetre over million kilometres distances have been demonstrated), opens many new research areas. These include the search for experimental evidence of gravitational waves, tests of General Relativity, determination of the masses of the bodies encountered by the spacecraft (the icy satellites, and also Saturn and Titan) by measuring the deflection of the spacecraft trajectory due to their gravitational field, and the analysis of the structure and size distribution of “occulted” bodies (for example the rings of Saturn or the atmosphere of Titan).

This technique has recently shown its power for dramatically improving the navigation accuracy during adverse receiving conditions, for example, when in the conjunction geometry with the Sun, when the radio link is almost aligned with it. The Cassini spacecraft, in particular, has three transponders of such good quality across five frequency bands from 2 to 34 GHz, and has given exciting new results in this field. Further missions are planned for the future: SMART-1, Bepi Colombo, etc. As a by-product, the Cassini observations are the best ever made in separating the different contributions to the up and downlinks due to the solar wind.

3.9. Passive Remote Sensing of the Earth's Atmosphere

The passive frequency bands allocated to the Radio Astronomy Service are also used for other scientific purposes. The following section introduces passive remote sensing of the Earth's atmosphere.

Monitoring terrestrial chemical constituents is essential in the Earth's middle atmosphere, corresponding to the stratosphere and the mesosphere. At altitudes higher than the tropopause (10 - 18 km from the pole to the tropics), ozone molecules play an important role by absorbing the ultraviolet, UV, radiation of the Sun, which is harmful to humankind, flora and fauna, and in general to any terrestrial life if the radiation reaching the ground is sufficiently strong. For more than 50 years, we have imprudently used chlorofluorocarbons (Freons), and allowed them to go up into the stratosphere where they are destroyed by UV radiation, freeing large quantities of chlorine monoxide, the most dangerous destroyer of ozone molecules.

To survey some key components of the atmosphere, various techniques of remote sensing have been developed in the last 20 years using different parts of the electromagnetic spectrum, including UV, optical and infrared spectrometers, lidars (light detection and ranging), and ground-based microwave sensors which have now been operational for many years. The rapid evolution of microwave technology has allowed the development of new instrumentation with lower receiver temperature and improved sensitivity. For the same scientific purposes, satellite-borne microwave experiments have been used for more than 10 years using the technique of Microwave Limb Sounding, MLS, as aboard the Upper Atmosphere Research Satellite, UARS, by NASA from 1991, Odin (Sweden, France, Finland and Canada) from 2001 and more recently Aura/MLS (NASA) in 2004.

3.9.1. Microwave Remote Sensing Radiometry

The microwave remote sensing technique involves making high spectral resolution measurements of optically thin pure rotational lines in atmospheric emission. The frequency range covered is 22 - 1000 GHz, the lower limit being the rotational line of water vapour at 22 GHz. The atmospheric thermal emission is detected by microwave radiometry, which is a passive remote sensing technique, i.e. with no transmitters involved. This microwave technique offers advantages over observations in other spectral regions. The sensitivity to atmospheric aerosol scattering is low and can be neglected in most applications. The thermal emission depends linearly on the temperature but an average profile is sufficient in most cases. Because the measurements are made in emission, observations can be carried out both day and night, and daily time evolution can thus be measured. As rotational transitions are pressure-broadened in the middle atmosphere, this effect permits retrieval of the vertical distribution of the molecular species from the shape of the spectral line.

The retrieval of vertical profiles of the atmospheric molecule concentration requires the use of an inversion process involving a "forward model" which describes the physical relationship between the atmospheric state and the observed quantity, instrumental and spectroscopic parameters, as well as atmospheric parameters (pressure and temperature). Synthetic theoretical spectra are computed, based on an a priori profile of the molecule being considered, followed by an "inversion" code, which uses in most cases the Optimal Estimation Method proposed by C. Rodgers (1990), which provides an estimation of the error budget.

3.9.2. Ground-based Radiometry

In 1989, under the aegis of the World Meteorological Organization, a Network for the Detection of Stratospheric Change, NDSC, was set up in Geneva. The NDSC has six primary stations located in the Arctic, at European middle latitudes, at tropical north and south sites, middle south latitudes and in the Antarctica, as well as a large number of complementary stations distributed around the world. In the primary stations and in some complementary ones, ground-based microwave radiometers are permanently operational to measure ozone, chlorine monoxide, water vapour, nitric acid, carbon monoxide and some other minor atmospheric constituents.

The main frequencies used for these ground-based microwave measurements are 22.235 and 183 GHz for water vapour, 111, 142, 208 and 273 GHz for ozone, 204 and 278 GHz for chlorine monoxide, 201 and 276 GHz for nitrous oxide (N_2O), 203 GHz for hydroperoxyl radical (HO_2), 203.4 GHz for isotopic water vapour ($H_2{}^{18}O$), 206 and 269 - 270 GHz for nitric acid, 115 and 230 GHz for carbon monoxide and 266 GHz for hydrogen cyanide (HCN).

These frequencies are used because of their location in a transparent region of the atmospheric transmission or opacity, as shown in Figure 6, for ground-based measurements below 275 GHz. Figure 7 shows the zenith opacity above that limit (from 275 to 1000 GHz).

3.9.3. Satellite-borne Radiometry

Humankind's influence on the atmosphere of planet Earth has expanded in recent decades from the local scale of urban pollution to the global scale of effects such as the ozone hole. This is also indicated by more and more comprehensive evidence of the enhanced greenhouse effect. Global problems require global monitoring which is provided by experiments located onboard satellites with the ability to scan the atmosphere at altitudes from 10 to 120 km. Microwave experiments working at frequencies higher than 275 GHz are convenient for monitoring a large number of atmospheric molecules which present emission lines in the frequency range 275 - 1000 GHz. Such combined techniques are named Microwave Limb Sounding, MLS. The first MLS experiment was located onboard the Upper Atmosphere Research Satellite launched by NASA in 1991. More recently the Odin satellite was launched on 20 February 2001. It is a Swedish-led project with contributions from France, Finland and Canada. The microwave instrument is the Sub-Millimetre Radiometer, SMR. NASA has recently launched the EOS-Aura satellite having a new MLS experiment, on 15 July 2004. Other projects in the future will include the JEM/SMILES experiment (Superconducting Sub-Millimetre Wave Limb Emission Sounder) to be installed on the Japanese Experimental Module aboard the International Space Station and the

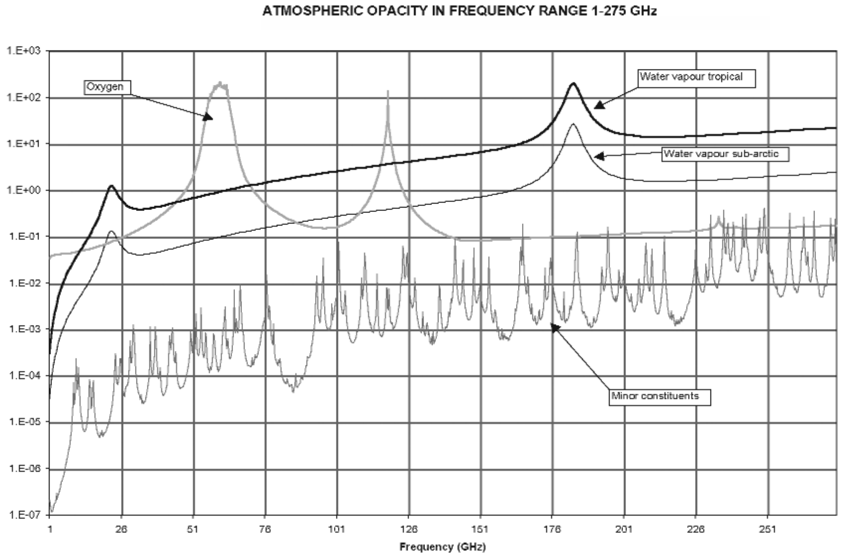

Figure 6. Zenith opacity of the atmosphere between 1 and 275 GHz (ATM code by Pardo, provided by Guy Rochard at Météo-France, CMS, 22302 Lannion, France, Guy.Rochard@meteo.fr).

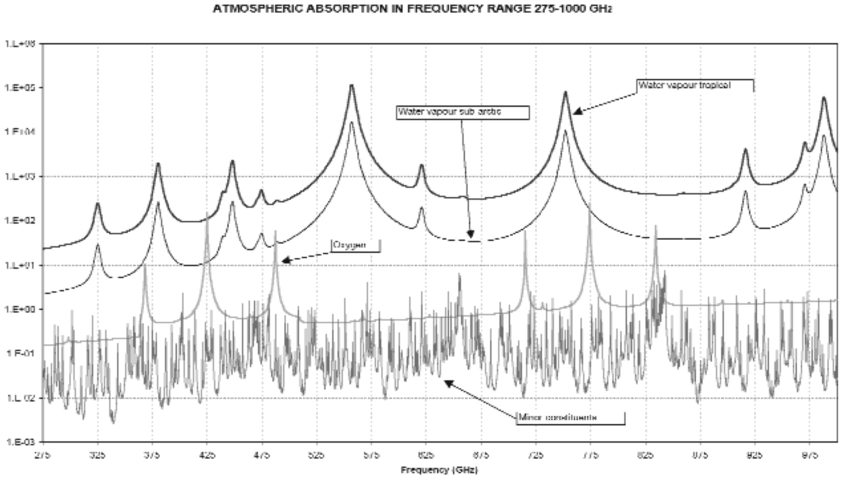

Figure 7. Zenith opacity of the atmosphere between 275 GHz and 1000 GHz (ATM code by Pardo, provided by Guy Rochard at Météo-France, CMS, 22302 Lannion, France, Guy.Rochard@meteo.fr).

Stratosphere-Troposphere Exchange And climate Monitor (STEAM) satellite project for the study of chemical, dynamics and radiative processes in the upper troposphere/lower stratosphere and their relationship with the evolution of the Earth's climate and stratospheric ozone.

Many atmospheric species can be monitored on a global scale during the lifetime of such satellites. Most common are ozone (O_3) and isotopes at a large number of frequencies, chlorine monoxide (ClO) at 347, 501, 575, 612 and 650 GHz, water vapour (H_2O) at 321, 325, 488, 557, 620 GHz and isotopes as $H_2{}^{17}O$ (552 GHz), $H_2{}^{18}O$ (489, 548 GHz), HDO (491 GHz), nitric acid HNO_3 (345, 495, 544, 607, 637 GHz) and many more molecules as CO (346, 576 GHz) and isotopes, BrO (498, 500, 549, 574 GHz), N_2O (502, 552, 578, 628 GHz), NO_2 (570 GHz), HO_2 (569, 577, 580 GHz), H_2O_2 (572 GHz), HCl (625 GHz), H_2CO (577 GHz), HOCl (305, 323 GHz), CH_3Cl (345, 505 GHz). The sulphur dioxide molecule SO_2 (571, 575 GHz) may also be detected after powerful volcanic eruptions such as the Pinatubo event in June 1991.

Data of the measured atmospheric constituents can be assimilated by using model computations in order to get a picture of the constituent distribution over the globe. Such global measurements are important for several scientific goals, such as studying the stratospheric ozone depletion and prediction of recovering, stratosphere/troposphere exchange, upper troposphere-lower stratosphere studies, radiative forcing and effects on the global change of climate.

4.

Radio Astronomy Frequencies

4.1. Considerations on Radio Astronomical Frequency Allocations

Some key-problems of the Radio Astronomy Service are summarised below (here specific frequencies actually refer to frequency bands).

4.1.1. General Considerations

- Strong efforts must be made to protect radio astronomy bands from *adjacent band interference* from air or space-to-ground transmissions. Satellites in geostationary orbits especially cause a significant problem for Radio Astronomy, since they block out certain portions of the sky for long periods. The large number of Low Earth Orbiting, LEO, systems planned and already in orbit act as a curtain which is drawn in front of the field of view of the radio telescopes and closes the radio window. In some cases it may be possible to increase radio astronomy band allocations at the same time that the adjacent band interference problem is solved. Table 3 summarises the potential interference situation from air- or space-to-ground transmissions adjacent to the primary radio astronomy bands.
- The *most important spectral lines* are listed in Recommendation ITU-R RA.**314**. Protection of all of these lines and some others either by footnotes or through an exclusive allocation would be desirable.

  Multitransition observations of some carefully selected molecules (CO, CS, HCN, HCO^+, H_2CO, NH_3) together with theoretical model-fitting is the *only way* to accurately determine the physical and chemical conditions (the distributions of mass, density, temperature, ionisation, and chemical concentration) in the otherwise invisible interstellar and circumstellar molecular clouds. In this way we will better understand the initial conditions for star formation at small as well as large scales (in galactic molecular clouds and in galaxies, respectively) and also stellar evolution processes.

  Observations of the much weaker lines from rarer isotopic variants (isotopomers) of these molecules (^{13}CO, $C^{18}O$, ^{13}CS, $C^{34}S$, $H^{13}CN$, $H^{13}CN$, $H^{13}CO^+$, $HC^{18}O^+$, DCO^+, $H_2{}^{13}CO$) are necessary for the correct interpretation of the main isotopomer lines. Moreover, they provide accurate information on chemical concentrations in the molecular clouds and on stellar nucleosynthesis.
- We expect that *increasing pressure* on the spectrum will in future lead to a *worsening* of *interference* throughout the spectrum, so it is highly desirable to increase the current bandwidth allocations wherever possible in order to preserve the levels of sensitivity at which current research is taking place. In general, a 1-2% bandwidth is the minimum practical allocation; a 5% bandwidth is generally desirable for continuum bands.
- In the last decade radio astronomical studies have demonstrated the presence of ever-more-*complex molecules* in interstellar space. These discoveries have been one of the most fascinating and puzzling developments in the field. The complexity of the largest molecules already exceeds that of simple alcohols or amino acids. It is anticipated that during the next decade still more complex molecules will be

found. Identification of complex molecules requires the detection of a number of characteristic lines.

Complex molecules tend to have many lines distributed through the radio frequency spectrum so no request for protection for specific frequencies is being made here. Rather, the requirement is essentially the same as for continuum studies: a number of relatively wide, well-protected bands. While the same probability that an arbitrary new line will fall in some protected band could be obtained with an appropriate number of narrow bands centred on known lines rather than with a few wide bands, the former bands would be “contaminated” by the relatively strong known lines being protected. Thus, the effort to find new lines would be greatly impeded.

- The continuum bands above *80 GHz* now allocated to the Radio Astronomy Service are particularly useful because they have practical bandwidths and are situated in regions of the spectrum where *atmospheric windows* exist.
- Radio Astronomy observations are very sensitive to *spurious and out-of-band emissions*. They are in particular vulnerable to airborne and satellite transmissions. A major effort to modernise and upgrade engineering standards should be made, especially with regard to unwanted emissions. Modernisation of these standards would be useful to other services as well as to Radio Astronomy.

4.1.2. Specific Considerations

- *Decametric radiation* from the planet Jupiter and solar activity at metric and decametric wavelengths cover a spectrum far wider than the bands allocated to the Radio Astronomy Service. Jupiter is the only radio-planet observable from the ground at decametric wavelengths, and its study is a unique means of developing theoretical models for the radio emissions of all the other planets. The interesting Jovian phenomena can cover the entire spectrum from 3 - 40 MHz. Most solar bursts occur in the frequency range 100 - 3000 MHz continually, and a comprehensive analysis of solar phenomena that are closely linked to the terrestrial environment requires observation frequencies outside the few narrow bands allocated to Radio Astronomy. Solar radio astronomy is an essential tool for solar activity forecasts and especially for the prediction of perturbations caused by the Sun which affect terrestrial radio transmissions.
- There will be strong pressure, internationally, for increased protection of the *322 - 328.6 MHz* band. This band serves both narrowband (or line) and broadband (or continuum) observations, since it includes the hyperfine transition from the cosmological important deuterium atom. As detector technology improves, activity in this band is increasing and as discussed below, there are many valid reasons for such an allocation.
- The *608 - 614 MHz* band has different detailed allocations for each region. The band should be consolidated into a single worldwide exclusive band.
- The *1400 - 1427 MHz* band is the most important band for studies of the hydrogen line and for continuum observations and allocation should be maintained at the

level of ITU RA **5.340**. In bands immediately below this band guidelines should be given to avoid allocations to certain particularly damaging services. This band is used worldwide for Very Long Baseline Interferometry.

- Both the *11-cm (2695 MHz)* and the *6-cm (4994 MHz)* bands are among the important ones for the Radio Astronomy Service, but their bandwidths (0.37% and 0.20%, respectively) are too small relative to their importance to the Service as continuum bands. Virtually all the other continuum bands have at least 1% bandwidths. Proposed national arrangements should partly alleviate this problem.
- *Pulsar research*, a topic of the utmost importance for cosmology and relativity studies, and the subject of one of the recent Nobel Prizes in physics, requires wide band observations in the decimetric range and the lack of a radio astronomy allocation between 614 and 1420 MHz is a serious handicap for pulsar workers.
- Studies of hydrogen, OH or CH lines in highly redshifted radio sources lead extragalactic radio astronomers to observe most of the time outside the allocated bands, which cover only 1% or so of the possible range of observable redshifts.
- These specific considerations imply that a large fraction (sometimes up to 70%) of radio astronomy observations are performed outside the bands allocated to the Radio Astronomy Service, therefore local protection against the power level of surrounding transmitters in all bands and an efficient management of adjacent bands are also urgently needed.

4.2. Table of Frequency Bands Allocated to the Radio Astronomy Service and Adjacent Band Allocations

Table 3 summarises the frequency allocations to the Radio Astronomy Service and the allocations to other services in bands adjacent to radio astronomy bands. It has been extracted from the ITU Radio Regulations. Following the practice in the ITU Radio Regulations, the primary services are indicated by the CAPITAL letters (see also footnotes to Table 3).

Table 3: Summary of Broadcast, Spaceborne and Airborne/terrestrial Allocations Adjacent to Radio Astronomy Bands (status WRC-03)

Status	Allocation ITU RR	RAS[2]	Brdcst[3]	Spaceborne	Airborne/ Terrestrial
	13.26 - 13.36 MHz				AERONAUTICAL[5]
				MOBILE (R)	
1	**13.36 - 13.41 MHz**	PRIMARY			FIXED **5.149**[4]
	13.41 - 13.60 MHz				FIXED/Mobile
	25.21 - 25.55 MHz				FIXED/MOBILE
2	**25.55 - 25.67 MHz**	PRIMARY	**5.149**		**5.149**
	25.67 - 26.10 MHz		PRIMARY		
	30.01 - 37.5 MHz				FIXED/MOBILE
3	**37.5 - 38.25 MHz**	secondary			FIXED/MOBILE
					5.149
	38.25 - 39.986 MHz				FIXED/MOBILE
	72.0 - 73.0 MHz				FIXED/MOBILE
4	**73.0 - 74.6 MHz**	PRIM.R2[6]			FIXED/MOBILE
					5.149
	74.8 - 74.8 MHz				FIXED/MOBILE
	149.9 - 150.05 MHz			MOBILE	
				Earth → space	
				RADIONAVIG.	
5	**150.05 - 153.0 MHz**	PRIMARY			FIXED/MOBILE
				5.149	
	153.0 - 154.0 MHz				FIXED
	315.0 - 322.0 MHz				FIXED/MOBILE
6	**322.0 - 328.6 MHz**	PRIMARY			FIXED/MOBILE
					5.149
	328.6 - 335.4 MHz				AERONAUTICAL
					RADIONAVIG.
	406.0 - 406.1 MHz			MOBILE	
				Earth → space	
7	**406.1 - 410.0 MHz**	PRIMARY			FIXED/MOBILE
					5.149
	410.0 - 420.0 MHz			MOBILE	MOBILE
	470.0 - MHz			PRIMARY	FIXED/MOBILE
				PRIM.R3	
				sec.R2	
8	**608.0 - 614.0 MHz**	PRIM.R2	PRIM.R1/R3		
		sec.R1/R3			
		5.149			
	- 790.0 MHz		PRIMARY		

	1300.0 - 1350.0 MHz				AERONAUTICAL RADIONAVIG. RADIOLOCAT.
				RADIONAVIG. SATELLITE **5.149**	**5.149**
9	**1330.0 - 1400.0 MHz**	notificat. of use		passive	
	1350.0 - 1400.0 MHz				FIXED/MOBILE R1 RADIOLOCAT. **5.149**
10	**1400.0 - 1427.0 MHz**	PRIMARY	**5.340**	PASSIVE **5.340**	**5.340**
	1427.0 - 1429.0 MHz			SPACE OPER. Earth → space	FIXED/MOBILE
	1559.0 - 1610.0 MHz			RADIONAVIG. SATELLITE space → Earth space ↔ space	AERONAUTICAL RADIONAVIG.
	1610.0 - MHz				AERONAUTICAL RADIONAVIG.
11	**1610.6 - 1613.8 MHz**	PRIMARY		MOBILE Earth → space	
	- 1626.5 MHz			**5.149** **5.372** RADIODET.SAT. Earth → space R2 **5.372** Mobile space → Earth **5.372**	
	1656.5 - 1660.0 MHz			MOBILE Earth → space	
12	**1660.0 - 1660.5 MHz**	PRIMARY		MOBILE Earth → space **5.149** **5.376A**	
12	**1660.5 - 1668 MHz**	PRIMARY		PASSIVE **5.149** **5.379A**	Fixed/Mobile
12	**1668 - 1668.4 MHz**	PRIMARY		PASSIVE MOBILE **5.379C** Earth → space **5.149** **5.379A**	Fixed/Mobile **5.149**

12	**1668.4 - 1670.0 MHz**	PRIMARY		METEOROLOG. AIDS MOBILE **5.379C** Earth→space **5.149**	FIXED/MOBILE **5.149**
	1670.0 - 1690.0 MHz			METEOROLOG. AIDS METEOROLOG. SATELLITE space→Earth MOBILE Earth→space	FIXED/MOBILE
	1710.0 - MHz				FIXED/MOBILE
13	**1718.8 - 1722.2 MHz**	secondary **5.385**			**5.149**
	- 1930.0 MHz				
	2520.0 - 2655.0 MHz		SATELLITE **5.413**		FIXED/MOBILE
14	**2655.0 - 2670.0 MHz**	secondary	SATELLITE **5.149** **5.413**	FIXED R2/R3 passive	FIXED/MOBILE **5.149**
14	**2670.0 - 2690.0 MHz**	secondary		MOBILE Earth→space FIXED R2/R3 passive	FIXED/MOBILE **5.149**
15	**2690.0 - 2700.0 MHz**	PRIMARY	**5.340**	PASSIVE **5.340**	**5.340**
	2700.0 - 2900.0 MHz				AERONAUTICAL RADIONAVIG. radiolocat.
	3100.0 - MHz				RADIOLOCAT.
16	**3260.0 - 3267.0 MHz**	notific. of use	**5.149**	**5.149**	RADIOLOCAT. **5.149**
	- 3300.0 MHz				
	3300.0 - MHz				
16	**3332.0 - 3339.0 MHz**	notific. of use	**5.149**	**5.149**	RADIOLOCAT. **5.149**
16	**3345.8 - 3352.5 MHz**	notific. of use	**5.149**	**5.149**	RADIOLOCAT. **5.149**
	- 3400.0 MHz				
	4500.0 - 4800.0 MHz			FIXED space→Earth	FIXED/MOBILE
17-19	**4800.0 - 4990.0 MHz**	secondary			FIXED/MOBILE **5.149** **5.443**

20	**4990.0 - 5000.0 MHz**	PRIMARY		passive	FIXED/MOBILE
			5.149		**5.149**
	5000.0 - 5010.0 MHz			RADIONAVIG.	AERONAUTICAL
				Earth→space	RADIONAVIG.
	5010.0 - 5030.0 MHz			RADIONAVIG.	AERONAUTICAL
				space→Earth	RADIONAVIG.
				space↔space	
				5.443B	
	5030.0 - 5150.0 MHz				AERONAUTICAL
					RADIONAVIG.
	5925.0 - MHz			FIXED	FIXED/MOBILE
				Earth→space	
21	**6650.0 - 6675.2 MHz**	notific. of use		**5.149**	**5.149**
	- 6700.0 MHz				
	10.55 - 10.60 GHz				FIXED/MOBILE
22	**10.60 - 10.68 GHz**	PRIMARY		EARTH EXPL.	FIXED/MOBILE
				(passive)	
				PASSIVE	
			5.149	**5.149**	**5.149**
					radiolocat.
22	**10.68 - 10.70 GHz**	PRIMARY		EARTH EXPL.	
				(passive)	
				PASSIVE	
			5.340	**5.340**	**5.340**
	10.70 - 11.70 GHz			FIXED	FIXED/MOBILE
	14.40 - 14.47 GHz			FIXED	FIXED/MOBILE
				Earth→space	
				Mobile	
				Earth→space	
				space resear.	
				5.504A	
23	**14.47 - 14.50 GHz**	secondary		FIXED	FIXED/MOBILE
				Earth→space	
				Mobile	
				Earth→space	
				5.149	**5.149**
				5.504A	
	14.50 - 14.80 GHz			FIXED	FIXED/MOBILE
				Earth→space	
				Space resear.	
	14.80 - 15.35 GHz				FIXED/MOBILE
				Space resear.	
24	**15.35 - 15.40 GHz**	PRIMARY	**5.340**	PASSIVE	
				5.340	**5.340**
	15.40 - 15.70 GHz			FIXED	AERONAUTICAL

				space→Earth **5.511A**	RADIONAVIG.
	21.40 - 22.00 GHz		SATELLITE R1/R3		FIXED/MOBILE
	22.00 - GHz				FIXED/MOBILE
25	**22.01 - 22.21 GHz**	notific. of use	**5.149**	**5.149**	**5.149**
	- 22.21 GHz				
26	**22.21 - 22.50 GHz**	PRIMARY		EARTH EXPL. PASSIVE **5.149**	FIXED/MOBILE **5.149**
	22.50 - 22.55 GHz				FIXED/MOBILE
	22.55 - GHz			INTER-SATL.	FIXED/MOBILE
27	22.81 - 22.86 GHz	notific. of use	**5.149**	**5.149**	**5.149**
	- 23.00 GHz				
	23.00 - GHz			INTER-SATL.	FIXED/MOBILE
28	**23.07 - 23.12 GHz**	notific. of use	**5.149**	**5.149**	**5.149**
	- 23.55 GHz				
	23.55 - 23.60 GHz				FIXED/MOBILE
29	**23.60 - 24.00 GHz**	PRIMARY	**5.340**	PASSIVE **5.340**	**5.340**
	24.00 - 24.05 GHz			AMATEUR	AMATEUR
	31.0 - 31.3 GHz			space resear.	FIXED **5.543A** MOBILE **5.149**
30	**31.3 - 31.5 GHz**	PRIMARY	**5.340**	PASSIVE **5.340**	**5.340**
31	31.5 - 31.8 GHz	PRIMARY		PASSIVE **5.149**	Fixed/Mobile
	31.8 - 32.0 GHz			SPACE RES. space→Earth	FIXED. RADIONAVIG
	36.0 - GHz			PASSIVE	FIXED/MOBILE
32	**36.43 - 36.5 GHz**	notific. of use		**5.149**	**5.149**
	- 37.0 GHz				
	41.50 - 42.5 GHz		FIXED SATELLITE **5.551H** **5.551I**	FIXED Earth→space **5.551H** **5.551I**	 BROADCASTING Mobile
33	**42.5 - 43.5 GHz**	PRIMARY		FIXED Earth→space **5.149**	FIXED/MOBILE **5.149**
	43.5 - 47 GHz			MOBILE RADIONAVIG.	MOBILE RADIONAVIG.

	47.0 - 47.2 GHz			AMATEUR	AMATEUR
	47.2 - GHz			FIXED Earth → space space ↔ space **5.555A**	FIXED/MOBILE
34	**48.94 - 49.04 GHz**	PRIMARY		**5.340** **5.149**	**5.340** **5.149**
	- 50.2 GHz				
34	**50.2 - 50.4 GHz**		**5.340**	FIXED Earth → space PASSIVE **5.340** **5.555A**	**5.340**
	50.4 - 51.4 GHz			FIXED/Mobile Earth → space	FIXED/MOBILE
35	**51.4 - 52.6 GHz**	**5.556**			FIXED/MOBILE
35	**52.6 - 54.25 GHz**	**5.556**	**5.340**	PASSIVE **5.340**	**5.340**
	54.25 - 58.2 GHz			PASSIVE INTER-SATL.	FIXED/MOBILE
	58.2 - 59.0 GHz	notific. of use			
	59.0 - 64.0 GHz			INTER-SATL.	FIXED/MOBILE RADIOLOCAT.
35	**64.0 - 65.0 GHz**	**5.556**			
	65.0 - 66.0 GHz			EARTH EXPL. SPACE RESEAR.	
	75.5 - 76.0 GHz		BRDCST	FIXED (space → Earth) BRDCST Space research (space → Earth)	FIXED MOBILE
36	**76.0 - 77.5 GHz**	PRIMARY **5.149**		AMATEUR Space research (space → Earth)	RADIOLOCAT. Amateur
36	**77.5 - 78.0 GHz**	secondary **5.149**		AMATEUR Space research (space → Earth)	AMATEUR
36	**78.0 - 79.0 GHz**	secondary **5.149**		Amateur Space research (space → Earth)	RADIOLOCAT. AMATEUR
36	**79.0 - 81.0 GHz**	PRIMARY **5.149**		Amateur Space research (space → Earth)	RADIOLOCAT. AMATEUR
36	**81.0 - 84.0 GHz**	PRIMARY **5.149**		FIXED/MOBILE (Earth → space) Space research	FIXED/MOBILE

36	**84.0 - 86.0 GHz**	PRIMARY **5.149**		FIXED (Earth → space)	FIXED/MOBILE
36	**86.0 - 92.0 GHz**	PRIMARY	**5.340**	PASSIVE **5.340**	**5.340**
36	**92.0 - 94.0 GHz**	PRIMARY **5.149**			FIXED/MOBILE RADIOLOCAT.
36	**94.0 - 94.1 GHz**	secondary		EARTH EXPL. (active) SPACE RES. (active)	RADIOLOCAT.
36	**94.1 - 95.0 GHz**	PRIMARY **5.149**			FIXED/MOBILE RADIOLOCAT.
36	**95.0 - 100.0 GHz**	PRIMARY **5.149**		RADIONAVIG.	FIXED/MOBILE RADIOLOCAT. RADIONAVIG.
36	**100.0 - 102 GHz**	PRIMARY	**5.340**	PASSIVE **5.340**	**5.340**
36	**102.0 - 105.0 GHz**	PRIMARY **5.149**			FIXED/MOBILE
36	**105.0 - 109.5 GHz**	PRIMARY **5.149**		SPACE RES. (passive)	FIXED/MOBILE
36	**109.5 - 111.8 GHz**	PRIMARY		PASSIVE **5.340**	
36	**111.8 - 114.25 GHz**	PRIMARY **5.149**		SPACE SERV. (passive)	FIXED/MOBILE
36	**114.25 - 116.0 GHz**	PRIMARY	**5.340**	PASSIVE **5.340**	**5.340**
	116.0 - 119.98 GHz			EARTH EXPL. (passive) INTER-SATL. SPACE RES. (passive)	
	122.25 - 123.0 GHz			INTER-SATL.	FIXED/MOBILE Amateur
37	**123.0 - 126.0 GHz**	secondary **5.554**		FIXED/MOBILE (space → Earth) RADIONAVIG.	RADIONAVIG.
37	**126.0 - 130.0 GHz**	secondary **5.149**		FIXED/MOBILE (space → Earth) RADIONAVIG.	RADIONAVIG.
37	**130.0 - 134.0 GHz**	PRIMARY **5.149**		EARTH EXPL. (active) INTER-SATEL.	FIXED/MOBILE
37	**134.0 - 136.0 GHz**	secondary		AMATEUR	AMATEUR
37	**136.0 - 141.0 GHz**	PRIMARY **5.149**		Amateur	RADIOLOCAT. Amateur
37	**141.0 - 148.5 GHz**	PRIMARY **5.149**			FIXED/MOBILE RADIOLOCAT.

37	**148.5 - 151.5 GHz**	PRIMARY	**5.340**	PASSIVE **5.340**	**5.340**
37	**151.5 - 155.5 GHz**	PRIMARY **5.149**			FIXED/MOBILE RADIOLOCAT.
37	**155.5 - 158.5 GHz**	PRIMARY **5.149**		PASSIVE	FIXED/MOBILE
	158.5 - 164.0 GHz			FIXED/MOBILE (space → Earth)	FIXED/MOBILE
38	**164.0 - 167.0 GHz**	PRIMARY	**5.340**	**5.340**	PASSIVE **5.340**
	167.0 - 168.0 GHz			FIXED INTER-SATL.	FIXED/MOBILE
39	**168.0 - 170.0 GHz**	notific. of use **5.149**		FIXED (space → Earth) INTER-SATL.	FIXED/MOBILE
39	**170.0 - 174.5 GHz**	notific. of use		FIXED (space → Earth)	FIXED/MOBILE
	174.5 - 174.8 GHz			INTER-SATL.	FIXED/MOBILE
	174.8 - 182.0 GHz			PASSIVE INTER-SATL.	
	182.0 - 185.0 GHz	PRIMARY	**5.340**	**5.340**	**5.340**
	185.0 - 190.0 GHz			PASSIVE	
	190.0 - 191.8 GHz		**5.340**	EARTH EXPL. (passive) SPACE RES. (passive) **5.340**	**5.340**
40	**191.8 - 200.0 GHz**	notific. of use **5.149**		INTER-SATL. MOBILE RADIONAVIG.	FIXED/MOBILE RADIONAVIG.
40	**200.0 - 202.0 GHz**	PRIMARY	**5.340**	PASSIVE **5.340**	**5.340**
40	**202.0 - 209.0 GHz**	PRIMARY	**5.340**	PASSIVE **5.340**	**5.340**
40	**209.0 - 217.0 GHz**	PRIMARY **5.149**		FIXED (Earth → space)	FIXED/MOBILE
40	**217.0 - 226.0 GHz**	PRIMARY **5.149**		FIXED (Earth → space) SPACE RES. (passive)	FIXED/MOBILE
40	**226.0 - 231.5 GHz**	PRIMARY	**5.340**	PASSIVE **5.340**	**5.340**
	231.5 - 232.0 GHz:				FIXED/MOBILE Radiolocation
	240.0 - 241.0 GHz				FIXED/MOBILE RADIOLOCAT.

41	**241.0 - 248.0 GHz**	PRIMARY **5.149**		Amateur	RADIOLOCAT. Amateur
41	**248.0 - 250.0 GHz**	secondary **5.149**		AMATEUR	AMATEUR
41	**250.0 - 252.0 GHz**	PRIMARY	**5.340**	PASSIVE **5.340**	**5.340**
41	**252.0 - 265.0 GHz**	PRIMARY **5.149**		MOBILE (Earth→space) RADIONAVIG.	FIXED/MOBILE RADIONAVIG.
41	**265.0 - 275.0 GHz**	PRIMARY **5.149**		FIXED (Earth→space)	FIXED/MOBILE
42	**275.0 - 1000.0 GHz**	notific. of use **5.565**			

Notes:
1. The band number refers to the numbering used in Section 4.3 of this Handbook.
2. Radio Astronomy Service.
3. Broadcasting service.
4. Footnotes referring to the protection of the Radio Astronomy Service are indicated by number.
5. Primary services are indicated by CAPITAL letters.
6. Status and region indication.

4.3. Comments on Frequency Allocations

This section incorporates CRAF comments on current and requested radio astronomy frequency allocations. These have been arrived at through extensive discussion over many years in the international scientific community.

The CRAF comments are interspersed with remarks on the scientific background to some of the allocations.

The comments are ordered according to increasing frequency.

1. **13.36 - 13.41 MHz:**
2. **25.55 - 25.67 MHz:**
   This band and the preceding band have worldwide shared primary allocations (see also No. **5.149**). These bands are used for observations of decametric radiation from the planet Jupiter and from the Sun.

3. **37.5 - 38.25 MHz:**
   This band has worldwide a secondary allocation (see No. **5.149**). Together with the bands 13.36 - 13.41 MHz and 25.55 - 25.67 MHz this band is very important for research of radiation from Jupiter. Jovian decametric radiation was discovered long after all the decametric frequency bands had been allocated and widely used by active services. The allocations to the Radio Astronomy Service are extremely narrow; how-

ever, the interesting Jovian phenomena can cover the entire spectrum from 3 - 40 MHz. Jupiter is the only radio-planet observable from the ground at decametric wavelengths, and its study is a unique means of developing theoretical models for the radio emissions of all the other planets.

These three bands (13.36 - 13.41 MHz, 25.55 - 25.67 MHz and 37.5 - 38.25 MHz) are also used for solar observations. Also for this research the allocations are extremely narrow, but the interesting solar phenomena can cover the entire spectrum up to 70 MHz. The Sun is the nearest star and its study enables a better understanding of the radio emission mechanisms of all other stars.

The allocation of the band 37.5 - 38.25 MHz was modified only slightly by WARC-79. On a worldwide basis the Radio Astronomy Service has a secondary allocation shared with the Fixed and Mobile Services. In the United States the band 38.00 - 38.25 MHz is shared on a primary basis with the Fixed and Mobile Services. Despite the secondary allocation, this band is often free of interference and is quite useful for radio astronomy.

4. **73.0 - 74.6 MHz:**

This band is used, among other things, for monitoring the interplanetary "weather" structure in the solar wind by an international network of instruments that measure interplanetary scintillation.

5. **150.05 - 153.0 MHz:**

This is a shared primary allocation in Region 1. It falls near the middle of a wide gap in continuum coverage. In the United States, a large amount of interference occurs in this band. A clear continuum band is badly needed between the current 74 and 327 MHz allocations. This band is widely used in the United Kingdom and is a major band for the Giant Metre-wave Radio Telescope, GMRT, in India. Further worldwide consolidation would be most desirable.

This band is also used for pulsar observations and solar observations.

6. **322 - 328.6 MHz:**

This band (see No. **5.149**) is increasingly being used in all regions, because major telescopes are operating or planned on these frequencies to study the structure of radio galaxies. There will be strong pressure, internationally, for increased protection of this band, including especially the avoidance of transmissions from satellites and aircraft.

This band has the desired octave-spacing relation with the 150.05 - 153 MHz and 608 - 614 MHz bands, which is needed for continuum observations and in addition it contains a cosmologically important atomic spectral line: the hyperfine-structure spectral line of deuterium at 327.4 MHz. The relative abundance of deuterium to hydrogen is related to the problems of the origin of the universe and the synthesis of the elements. A determination of the deuterium abundance in the universe will certainly help in defining the most probable theory of the origin and evolution of the universe. Recent ultraviolet observations of deuterium show that its abundance is not uniform, suggesting that studies of its abundance may be of increasing importance.

In Europe the frequency band 322 - 328.6 MHz is used by the Westerbork Synthesis Radio Telescope in the Netherlands and for VLBI applications by radio observatories in France, Germany, Italy, the Netherlands, Poland and the United Kingdom. As detector technology advances, activity in the band is increasing (see Section 5.1).

7. **406.1 - 410 MHz:**
   This is an important band (see No. **5.149**) for radio astronomy, but its usefulness is decreased by interference from balloon-borne transmitters which nominally operate in the band 400.15 - 406 MHz. It would be desirable to reduce the interference potential by lowering the upper limit of this meteorological aids band or by extending the radio astronomy band upwards by a few MHz so that emissions near the lower end of the band could be avoided.

8. **608 - 614 MHz:**
   Various radio astronomy allocations are made nationally within this range, with various degrees of protection, to fit in with local television assignments, one television channel usually being made available for radio astronomy (see Nos. **5.304**, **5.305**, **5.306** and **5.307**). Radio astronomy attaches considerable importance to the maintenance of this allocation since without it, there would be a large gap between the 410 MHz and the 1400 MHz allocations, in one of the most interesting parts of the spectrum. The band is of special value for (worldwide) VLBI observations. It is requested that in those parts of the world in which the allocation to the Radio Astronomy Service is on a temporary basis, greater security can be afforded and radio astronomy given the maximum possible protection from both in-band and adjacent band transmissions. Primary allocations with several MHz in common to all regions are desired (see Section 5.2).

9. **1330 - 1400 MHz:**
   This band is needed for important observations of Doppler-shifted radiation from hydrogen. No. **5.149** (note: No. **5.339**) provides some protection to facilitate observations on more distant sources at those observatories with the largest antennas. Such observations can often be made at frequencies shared with low-power ground transmitters, but high power transmitters especially for radiolocation and any transmitters on aircraft or satellites can cause interference. Especially in Europe this band suffers bad sharing conditions (i.e. by radar). It is hoped that the temporary use for radio navigation (No. **5.338**) will be phased out.

   A worldwide allocation to the Radio Astronomy Service at least from 1370 - 1400 MHz is desired.

10. **1400 - 1427 MHz:**

This is the most important band for studies of the hydrogen line and for continuum observations and should be maintained at the level of No. **5.340**.

The 21 cm line (1420.4057 MHz) of neutral atomic hydrogen is the most important radio spectral line. Since its discovery in 1951, observations of this line have been used to study the structure of our Galaxy and other galaxies. Because of Doppler shifts, the frequency range for observing this emission necessarily ranges from ~1330 to ~1430 MHz (see Section 5.3).

Numerous and detailed studies of neutral hydrogen distribution in our Galaxy and in other galaxies are being made. The data are being used to investigate the state of cold interstellar matter, the dynamics, kinematics and distribution of the gas, the rotation of our Galaxy and other galaxies and to make estimates of the masses of other galaxies.

The 21–cm neutral hydrogen emission is relatively strong and with modern instrumentation it is detectable in all directions in our Galaxy and from a very large percentage of the nearby galaxies.

The band is also used, with the same restriction as for radio astronomy, for a search for emissions from extraterrestrial civilisations (see No. **5.341** and CCIR Report 700).

11. **1610.6 - 1613.8 MHz:**
12. **1660 - 1670 MHz:**
13. **1718.8 - 1722.2 MHz:**

The newest and one of the most exciting branches of astronomy is astrochemistry. This subject involves the study of the OH radical and molecules in space. These observational possibilities started in 1963 when the line emission from OH was detected for the first time at radio wavelengths. This illustrates that radio astronomy can study species which are difficult to obtain in the laboratory.

Today more than 100 different organic and inorganic molecular species have been detected in space. Space chemistry is of vital interest in understanding the formation of stars, planets and life. The OH radical can clearly be identified by observing the principal ground-state-lines at 1665 and 1667 MHz and the "satellite" lines at 1612 and 1720 MHz. The OH lines have been observed both in emission and absorption from several hundred different regions in our Galaxy. One of the most peculiar properties of OH is the extremely narrow and intense emission lines, which are observed in the directions of many interstellar clouds. Such line emissions can originate only from interstellar masers. The study of such phenomena is of great interest in understanding the physical processes for creating maser action. It is possible that such radiation is associated with the formation of protostars and can give us important clues to the initial stages of star formation (see Section 5.4).

Observations of OH maser sources using VLBI have shown that OH sources have apparent sizes that are of the order of 0.01 arcsecond or smaller. These apparent sizes correspond to linear sizes of the order of a few astronomical units (the mean distance between the Earth and the Sun, 150 million kilometres) and suggest an association with protostellar clouds in the process of collapse to form new stars. When the European VLBI telescopes are combined with those in the USA, almost the maximum possible collecting area can be obtained as well as also the maximum angular resolution currently achievable.

Observations of OH and other molecules can also be used for the study of the physical properties of more normal interstellar clouds. With very sensitive instrumentation, OH is detected in external galaxies. This opens new prospects for the study of astrochemistry in other galaxies. OH maser action has also been observed in comets, which stimulates studies of the clues to the origin of the solar system.

An additional interest in OH emission is the study of the relative abundance of the isotopes ^{16}O and ^{18}O. Emission lines from ^{18}OH and ^{16}OH have been detected. Investigations of the isotopic abundances of the elements are crucial to our understanding of the origin and synthesis of the elements in the universe and may assist in our quest for the correct cosmological theory of the origin and evolution of the universe.

Comments on individual OH-bands:

1610.6 - 1613.8 MHz:

The OH line at 1612.231 MHz is characteristic of a special class of astronomical object, the OH-IR sources. The 1612 MHz line is also used in conjunction with the main OH lines in the next higher band. No. **5.149** gives some protection within the band 1610.6 - 1613.8 MHz. This band suffers strong pressure by satellite systems. Better protection is needed, excluding all but transmissions from the surface of the Earth and with an extension of protection to a somewhat wider band of 1610 - 1614 MHz to take account of the larger Doppler shifts now being detected (see also ITU-R Recommendation RA.314**,** Table 1).

1660 - 1670 MHz:

This radio astronomy band is used both for measurements of the OH lines at 1665.402 MHz and 1667.359 MHz and for continuum measurements. The present allocation of the band 1660 - 1660.5 MHz to the Mobile Service may lead to its serious degradation for Radio Astronomy. In addition this band is used for VLBI. Successful use of this band will depend also on the avoidance of interference from meteorological satellites having assignments in the adjacent band (see No. **5.149** and **5.379**). Desired is an allocation for radio astronomy with improved sharing for the total band (See also ITU-R Recommendation RA.314, Table 1).

The sub-band 1668 - 1670 MHz is also allocated to the Mobile Satellite Service. No. **5.379C** sets maximum (aggregate) pfd limits to protect Radio Astronomy in this band. Calculations in preparation for WRC-03 have indicated that within Europe, deployment of stations in the Mobile Satellite Service within about 500 km from a radio astronomy station operating in this band will cause harmful interference to these radio astronomy stations.

1718.8 - 1722.2 MHz:

This band is for observations of the OH line at 1720.530 MHz and protection needs to be improved beyond No. **5.149** by excluding airborne and space transmissions (See also ITU-R Recommendation RA.314, Table 1).

14. **2655.0 - 2690.0 MHz:**

A general consideration for the study of the continuum emission of radio sources is the requirement of sampled observations of these sources throughout a very wide frequency range. Observations at many different frequencies help to define the shape of the spectra of the emission from these sources, which in turn gives information on the physical parameters of the radiating sources such as densities, temperatures and magnetic fields, while they also give information on their lifetimes. The knowledge of these physical parameters is essential for our understanding of the physical processes that produce radio radiation. Many extragalactic radio sources show a “break” in their non-thermal spectrum in the region between 1 to 3 GHz and continuum measurements at ~2.7 GHz are essential to define such a spectral characteristic accurately.

The spectral region 2655.0 - 2700.0 MHz is a good band for continuum measurements partly because the galactic background radiation is low, and also because radio astronomy receivers are of excellent quality and have very low noise at this frequency.

The frequency band 2655.0 - 2700.0 MHz is also useful for galactic studies of ionised hydrogen clouds and the general diffuse radiation of the Galaxy. Since at such frequencies available radio telescopes have adequate angular resolutions (narrow beams, of the order of 10 arc minutes for large telescopes), many useful surveys of the galactic plane have been performed, including the galactic centre, which is invisible at optical wavelengths because of the interstellar absorption by dust particles. The centre of our Galaxy is perhaps its most interesting region and yet it can only be observed at infrared and radio wavelengths, since these wavelengths are not affected by the dust particles in the interstellar space (optical wavelengths are absorbed and scattered by dust particles). The study of the nuclei of galaxies, including the nucleus of our own Galaxy, is emerging as an extremely important and fundamental topic in astronomy. Questions that can be studied in these objects include the state of matter and the possibilities of the existence of black holes in galactic nuclei; the explosive activities and the production of intense double radio sources from galactic nuclei; the influence of galactic nuclei on the morphological structure of galaxies; the formation of galaxies and quasars; and many other and major astrophysical subjects.

An important study at radio wavelengths is the polarization of the radiation that is observed from radio sources. It is often found that radio sources are weakly linearly polarized, with a position angle that depends on frequency. This effect is due to the fact that the propagation medium in which the radio waves travel to reach us is composed of charged particles, electrons and protons, in the presence of magnetic fields. The determination of the degree and angle of polarization gives us information on the magnetic fields and electron densities of the interstellar medium and in certain cases on the nature of the emitting sources themselves. The frequency bands near 2700 and 5000 MHz are vital for polarization measurements.

This band is under pressure by Digital Sound Broadcasting from satellites (which will also endanger the next bands upward). Use of this band for radio astronomy (No. **5.149**) will become impracticable if it is shared with transmissions in the Broadcasting Satellite Service. Exclusive use for radio astronomy to extend the adjacent higher band to a 2% bandwidth is highly desirable, but sharing with services transmitting from the ground only seems feasible (see also next paragraph).

15. **2690.0 - 2700.0 MHz:**

This radio astronomy band needs to be widened, to a total bandwidth of at least 50 MHz preferably by an improvement of the sharing conditions in the band 2655.0 - 2690.0 MHz, and to be protected from interference by satellite transmissions with assignments in adjacent bands (No. **5.340**).

16. **3100.0 - 3400.0 MHz:**

Three molecular lines of the CH molecule have been detected at 3263, 3335 and 3349 MHz. These frequencies are unfortunately only allocated to Radio Astronomy by No. **5.149**, however the study of interstellar CH is considered to be extremely important in understanding the chemistry of the interstellar material. The presence of CH suggests the existence of the molecule CH_4 (methane) which is considered one of the basic molecules for the initial stages of the formation of life.

3260.0 - 3267.0 MHz:
3332.0 - 3339.0 MHz:
3345.8 - 3352.5 MHz:

The protection of these bands (No. **5.149**) for observation of CH is still desired (See ITU-R Recommendation RA.314, Table 1).

17. **4800.0 - 4950.0 MHz:**
18. **4825.0 - 4835.0 MHz:**
19. **4950.0 - 4990.0 MHz:**

The spectral region around 5 GHz has been one of the most widely used frequency ranges in Radio Astronomy during the last decade. Astronomers have made use of this frequency range in order to study the detailed brightness distributions of both galactic and extragalactic objects. Detailed radio maps of interstellar ionised hydrogen clouds and supernova remnants have assisted our understanding of the nature of such celestial objects. These radio maps define the extent and detailed morphology of radio sources and enable us to draw conclusions concerning their structures and dynamics and to derive physical parameters of the sources such as their total masses.

One of the most important uses of the band around 5 GHz is the study of the formaldehyde (H_2CO) interstellar clouds at 4829.66 MHz. The H_2CO line at this frequency is considered to be one of the most important radio lines in the entire spectrum, primarily because it can be detected in absorption in almost any direction where there is a continuum radio source. The distribution of H_2CO clouds can give independent evidence of the distribution of the interstellar material and can help in understanding the structure of our Galaxy. H_2CO has also been observed in absorption against the microwave cosmic 3 K blackbody background radiation. H_2CO lines from the carbon–12 isotopic and oxygen–18 isotope have been detected and studies of the isotopic abundances of these elements are being carried out.

There is a continuing use of the band 4800 - 4950 MHz by radio astronomy in some countries.

The importance of the formaldehyde line at 4829.66 MHz is such that at least a strong footnote is needed (see No. **5.149** and **5.443**) to protect radio astronomy in the band 4825 - 4835 MHz. A wide band (e.g. 4850 - 4890 MHz) is favourable for continuum measurements in this part of the spectrum, chosen to include the formaldehyde line (see ITU-R Recommendation RA.314 Table 1).

The band 4950.0 - 4990.0 MHz is used by radio astronomy as an extension of the next higher band which is too narrow (see No. **5.149** and **5.443**). Protection would be improved if transmission from aircraft could be excluded.

20. 4990.0 - 5000.0 MHz:

This primary (exclusive in Region 2) radio astronomy band is narrow. A much-needed improvement would be to extend the allocation downwards to 4950 MHz by sharing with compatible services. To reduce the risk of interference from aeronautical services above 5000 MHz, exclusion of air-to-ground transmissions from the band 5000.0 - 5010.0 MHz is strongly recommended. This band is used for worldwide VLBI.

21. 6650.0 - 6675.2 MHz:

This band is important for observations of methanol (CH_3OH) (see Section 5.8 Table 6). This transition of methanol is a very powerful cosmic maser found exclusively in regions where massive stars form. It is widely observed in Europe using single dishes, MERLIN interferometry and VLBI.

22. 10.60 - 10.70 GHz:
23. 14.47 - 14.50 GHz:
24. 15.35 - 15.40 GHz:

The frequency band 10 - 15 GHz provides some of the best angular resolutions (~2 arc minutes) using many large and accurate radio telescopes. Many of the non-thermal synchrotron sources are just detectable at higher frequencies, and this frequency range gives us observational information at the highest frequency where these can be detected reliably. This high-frequency range is also important for monitoring the intensity variability of the enigmatic quasars. These objects, which could be the farthest celestial objects that we can detect and which produce surprisingly large amounts of energy, have been found to vary in intensity with periods of weeks and months. Such observations lead to estimates of the sizes of these sources, which turn out to be very small for the amount of energy they produce. The variability of quasars (and some peculiar galaxies) is more pronounced at high frequencies and observations at these frequencies facilitate the discovery and the monitoring of such events. The energy emitted during any one burst from a quasar is equivalent to completely destroying a few hundred million stars in a period of a few weeks or months. We do not yet understand the fundamental physics that can produce such events – observations of the size and variability of these sources are the only ways that can assist us in solving such problems. Observations are now best performed in the frequency range 10 - 15 GHz.

The small sizes of the quasars are revealed from the VLBI observations mentioned earlier. Observations are also being made in the frequency band 10.6 - 10.7 GHz and observations at 15.40 GHz have been successful. The higher frequencies provide us with better angular resolution and enable us to determine more accurately the sizes and structure of quasars.

At 14.4885 GHz an important formaldehyde (H_2CO) line exists, which has been observed in the direction of many galactic sources. Since the line originates from the upper levels of orthoformaldehyde its study gives valuable information on the physical conditions of the interstellar medium, because the excitation energies required to produce the line are different from the energies required to produce the H_2CO line observed at 4829.66 MHz.

Radio astronomy stations on the territory of France, Italy, Spain and the United Kingdom that are operating in the band 14.47 - 14.50 GHz are explicitly protected from interference from the Mobile Satellite Service operating in the band 14.0 - 14.5 GHz.

The importance of the radio astronomy band at 10.60 - 10.70 GHz makes an exclusive worldwide allocation desirable (since it is one of the most valuable bands used for internationally coordinated observations over long baselines). In principle, the use of the exclusive band 10.68 - 10.70 GHz with downward extension with the help of local protection would be adequate. However, observations in the band 10.6 - 10.7 GHz in Europe are degraded by interference from out-of-band emissions of the GDL-6/ASTRA-1D satellites, which provide satellite television broadcasting while operating in the Fixed Satellite Service.

Furthermore, exclusion of aeronautical mobile from the band 10.60 - 10.68 GHz is essential to safeguard this band.

The band 15.35 - 15.40 GHz is an important radio astronomy band in the continuum series and needs to be widened to 15.30 - 15.55 GHz by sharing with compatible services. The possibility of moving it down in frequency to contain the above formaldehyde line near 14.5 GHz has been discussed. A band at least 200 MHz wide would then be sought, so located to avoid the risk of interference from radio navigation satellites below 14.4 GHz. This location would have the advantage of being within a band currently allocated to Fixed and Mobile, rather than the present location between bands available for Space Research (Space-to-Earth) and Aeronautical Radio navigation, which makes an extension of the present band difficult. The Fixed Satellite Service in the lower band is designated as Earth-space and should not be a serious source of interference.

25. **22.01 - 22.21 GHz:**
    This band (No. **5.149**) is used in conjunction with the adjacent band (22.21 - 22.5 GHz) for observations of redshifted H_2O (See ITU-R Recommendation RA.314, Table 1, and Section 5.5).

26. **22.21 - 22.5 GHz:**
    This "H_2O– band" is one of the most important for spectroscopy in radio astronomy (See ITU-R Recommendation RA.314 Table 1, and Section 5.5).

27. **22.81 - 22.86 GHz:**
    This band is used for studies of a non-metastable ammonia line and two lines of methyl formate. Sharing with the other services should be possible in Region 1, when the provisions of No. **5.149** are taken into account. But in Regions 2 and 3 the band is (also) allocated to the Broadcasting Satellite Service. The Radio Astronomy Service will no longer be able to use this band when this service starts operating in this band. Radio astronomers are very much in favour of keeping the status in Region 1 and moreover wish that this allocation should become worldwide (see Section 5.5).

28. **23.07 - 23.12 GHz:**
    This band is of special importance for studies of ammonia lines. The present sharing situation and the provisions of No. **5.149** should be sufficient to provide satisfactory local protection for observatories, but there is a highly interesting methanol maser line immediately above the protected band at 23.121 GHz. Extending the allocation by a small amount to cover this line is considered useful with respect to the increasing active use of this part of the spectrum (see Section 5.5).

29. **23.6 - 24.0 GHz:**
    This exclusive radio astronomy band is the main ammonia band and also important for continuum observations and for observations of a number of other spectral lines (see Section 5.5).

30. **31.3 - 31.5 GHz:**
31. **31.5 - 31.8 GHz:**
    This is a continuum band of sufficient width. The allocations to other services in the band 31.5 - 31.8 GHz should not lead to difficulties. The provisions of Nos. **5.149** and **5.340** should be sufficient to provide satisfactory local protection for observatories.

32. **36.43 - 36.5 GHz:**
    This band is of importance for the search for HC_3N and OH lines. The sharing situation as it is now and the provisions of No. **5.149** should be sufficient to provide satisfactory local protection for observatories.

33. **42.5 - 43.5 GHz:**

The J = 1 → 0 rotational lines of silicon monoxide (SiO) in different vibrational states, at 42.820, 43.122, 43.425 and 42.519 GHz, are the subject of extensive radio astronomy single dish and VLBI measurements. The lines of SiO often indicate maser emission, the mechanism of which is not understood but which extends over a wide range of excitation in the SiO molecule as evidenced by the detection of the v = 3 transition at 42.519 GHz. The protection (incl. No. **5.149**) should be maintained.

34. **47.2 - 50.2 GHz:**

The region between 42.5 and 49 GHz contains important spectral lines of some diatomic and other molecules.

The lines of CS and its less common isotopes $C^{33}S$, $C^{34}S$, ^{13}CS, have been shown to be constituents of both giant molecular clouds and cool dark clouds. Since the J = 1 → 0 transition arises in the lowest possible energy levels of CS, this molecule will become increasingly important in probing cool clouds. Other molecules with detected transitions in this frequency range include H_2CO, CH_3OH and OCS.

The primary allocation of the band 48.94 - 49.04 MHz to Radio Astronomy includes a line of carbon monosulphide (CS) (No. **5.149** and No. **5.340** apply).

35. **51.4 - 59.0 GHz:**

In the bands 51.4 - 54.25 GHz, 58.2 - 59 GHz and 64 - 65 GHz, radio astronomy observations may be carried out under national arrangements (No. **5.340** and No. **5.556** apply).

36. **76.0 - 116.0 GHz:**

Since there is relatively little absorption from atmospheric O_2 and H_2O, the millimetre band between 86 and 92 GHz is perhaps the best high-frequency region for both continuum and line observations of celestial objects. Eighteen molecules have been detected in this frequency range and 25 different isotopic species. These include such simple molecules as SO, SO_2, SiO, SiS, HCN, HCO, HCO^+, HC_3N and HC_2 and such complex molecules as CH_3CH_2OH, CH_3CH_2CN and CH_3OCH_3. The J = 2→1 transitions of SiO fall in this range; SiO is one of the few molecules showing maser emission and the only one showing strong maser emission in an excited vibrational state. HCN, HCO and HCO^+ are vitally important participants in the ion-molecule reactions believed to be important in the formation of many other molecules in the interstellar gas. Furthermore, some molecules have several isotopic species in this range so that isotopic abundance ratios and optical depth effects can be studied. As an example, the basic molecule HCN has the isotopic species $H^{12}C^{14}N$, $H^{13}C^{14}N$ and $H^{12}C^{15}N$ in the 86 - 92 GHz range and all have been observed in the interstellar gas. Also important are isomeric studies (HCN/HNC) with HNC at 90.663525 GHz. It is clear that this region of the millimetre spectrum will remain one of the most used for Radio Astronomy.

86.0 - 92.0 GHz:

This is an important radio astronomy band for continuum measurements and contains several natural lines, two of which are considered of special importance. Transmissions from systems in the Fixed and Mobile Satellite Services in the contiguous band 81.0 - 86.0 GHz are potential sources of interference in the long term.

92.0 - 95.0 GHz:

This band is specifically used for observations of the spectral line of diazenylium (HNN^+) (rest-frequency = 93.17 GHz).

95.0 - 105.0 GHz:

The primary allocation (No. **5.149**) should be maintained for this band. Lines of carbon monosulphide (CS, rest frequency 97.98 GHz), sulphur monoxide (SO, 99.30 GHz) and methyl acetylene (CH_3C_2H, 102.5 GHz) have been identified as being of high priority.

105.0 - 116.0 GHz:

This band is one of the most important bands in the radio frequency spectrum, at least equal in importance to the hydrogen line band 1400 - 1427 MHz. The band contains many spectral lines, in particular the lines of carbon monoxide and its isotopes (CO) at 109.78, 110.20, 112.36 and 115.27 GHz which are not only the most powerful tool in the study of isotope ratios, but are also essential in the study of cool clouds, regions of star formation and structure of our Galaxy and other galaxies. The line at 115.27 GHz is currently given protection by No. **5.340**. Other lines in this band are due to the cyanogen radical (CN), methyl cyanide (CH_3CN), isocyanic acid (HNCO), carbonyl sulphide (OCS) and cyanoacetylene (HC_3N). Very high priority is placed on maintaining the protection of this band.

The discovery of interstellar carbon monoxide (CO) at 115.271 GHz has been of fundamental importance for the subject of astrochemistry. This is primarily because CO is a relatively stable molecule compared with other molecules discovered in the interstellar medium. In fact, CO is the most abundant interstellar molecule after H_2, and is widely distributed in the plane of our Galaxy as well as in a number of other galaxies. These studies have yielded new information on the distribution of gas in spiral galaxies. Allowance for the Doppler shifts characteristics of nearby galaxies is essential.

The isotopically substituted species $^{13}C^{16}O$, $^{12}C^{18}O$ and $^{12}C^{18}O$ have also been detected from many regions in the Galaxy. The molecule CO seems to play an important role in the chemistry of the interstellar medium. The large extent and high abundance of CO may be due to efficient formation mechanisms that remain as yet unknown.

Radio astronomy has invested heavily in this region of the spectrum because of the unique insights spectroscopic studies provide into star formation, interstellar chemistry, the late stages of stellar evolution and the chemical composition of the Milky

Way and other galaxies. Radio astronomical use of frequencies above 100 GHz has increased greatly in the last decades (see Section 5.6).

37. **123 - 158.5 GHz:**
In this frequency range several bands are allocated on a primary basis to radio astronomy and should be maintained for radio astronomy. Bands 300 MHz wide centred on:
140.839 GHz Formaldehyde (H_2CO)
144.827 GHz Deuterated Hydrogen cyanide (DCN)
145.603 GHz Formaldehyde (H_2CO)
146.969 GHz Carbon monosulphide (CS)
150.498 GHz Formaldehyde (H_2CO)
have been identified as having high priority.

38. **164.0 - 167.0 GHz:**
This band is used for continuum observations.

39. **168.0 - 185.0 GHz:**
This band contains useful lines for radio astronomy, for example at 174.6, 174.85, 177.26, 178.4 and 181.2 GHz for which frequency bands are identified in No. **5.149**. It also contains important lines of water at 183.5 GHz and ozone at 184.75 GHz. These lines cannot be observed from the ground, but are accessible from aircraft, balloons and spacecraft.

40. **191.8 - 231.5 GHz:**
Rotational $J = 2 \rightarrow 1$ lines of carbon monoxide (CO) at 219.560, 220.399 and 230.542 GHz need to be observed in conjunction with CO $J = 1 \rightarrow 0$ lines in the band 105 - 116 GHz. This is an important Radio Astronomy requirement and a worldwide primary allocation is currently valid (No. **5.340**).

The frequency band 217 - 231 GHz is in the centre of the highest spectral region at millimetre wavelengths where there is a useful atmospheric window. On each side of the 200 - 300 GHz region atmospheric H_2O absorption makes ground-based observations difficult or impossible.

The IRAM 30-m radio telescope on Pico Veleta in Spain is currently the most sensitive radio telescope in the world at these frequencies. It is anticipated that in the next few years, as instrumental capabilities improve, many additional molecular species will be detected and studied at these high frequencies. Protection is needed for DCN, $^{13}C^{16}O$ and $^{12}C^{18}O$ lines as well as to provide coverage of Doppler-shifted $^{12}C^{16}O$. This band is extremely important for studies of the structure and evolution of galaxies.

41. **241 - 275 GHz:**
This band allocated to the Radio Astronomy Service (No. **5.149**) contains a very important series of spectral lines of the molecules C_2H (262.5 GHz), HCN hydro-

gen cyanide (265.9 GHz), HCO^+, and formalyl (272.0 GHz). Protection should be retained.

42. **275 - 1000 GHz:**
For frequencies above 275 GHz radio astronomy is in need of continuum bands in the atmospheric windows, e.g. around 415 and 500 GHz, bearing in mind the existence of many molecular line frequencies, the relative importance of which will be clarified as work proceeds. Diazenylium (HNN^+) at 279.5 GHz will need protection if allocations are extended to 300 GHz, and $^{12}C^{16}O$ ($J = 3 \rightarrow 2$) at 345.814 GHz if allocations are extended to even higher frequencies (see Section 5.7 and also No. **5.565**).

5.

Radio Astronomical Use of Specific Frequency Bands

5.1. Radio Astronomical Use of the Band 322 - 328.6 MHz

A general argument for one or more low frequency bands is the fact that cosmic radio sources tend to have a great variety of spectral energy distributions. Over a limited frequency range, less than a factor 2, the spectra usually have a power law shape ($S \infty f^{\alpha}$, where S is the flux of the radio source and f is the frequency) but when viewed over a broad range (say from 10 MHz - 100 GHz) spectra undulate and can be very complex. The narrow band spectral index can vary from $\alpha = -2$ to $\alpha = +2$ or more. Even a factor of two in frequency therefore can lead to differences of a factor $2^4 = 16$ in radiated power. The radio spectral index is a very important diagnostic tool for investigating the physical conditions in the source. Young compact sources exhibiting internal absorption (due either to the radiating particles or to thermal ionised gas in the source, or in front of the source) generally have positive spectral indices. Very old relaxed radio sources with low surface brightness usually have (very) negative spectral indices.

The diffraction-limited performance of synthesis telescopes (the Westerbork Synthesis Radio Telescope, the Netherlands; the Very Large Array, USA; MERLIN, UK; and VLBI) working at low frequencies is used to great advantage for surveying large regions of sky and for mapping extended low-brightness regions of emission. Lower frequencies therefore also give a surveying speed advantage over high frequencies which goes as $(\text{frequency})^2$, for the same dish size. Decreasing the dish size to enlarge the field of view is not the solution because this sacrifices sensitivity.

Specific astrophysical problems that can be attacked only at low frequencies are numerous. We mention only a handful:

Galactic radio astronomy

- Total intensity and polarization mapping of the very diffuse, generally low-brightness, galactic non-thermal background emission. At low frequencies the polarization data are sensitive to very small amounts of intervening ionised gas, since the Faraday rotation of the plane of polarization increases as the square of the wavelength.
- Mapping of diffuse emission and absorption of ionised gas in radio recombination lines. These lines are observable at many discrete frequencies but the change from emission to absorption usually occurs in the range around a few hundred MHz.
- There are several classes of sources (flare stars, pulsars) which have very steep spectra which are hard to observe at frequencies above 1 GHz.

Extragalactic radio astronomy

- With the great sensitivity of modern radio telescopes, the 21 cm (1420 MHz) line due to neutral hydrogen is now observable out to large cosmic distances where, due to the expansion of the universe, the line is shifted to lower frequencies. The most distant quasars and radio galaxies have a redshift of seven, which means that neutral hydrogen line is shifted to frequencies of about 180 MHz. Study of the emission and absorption (in the emission spectrum from background objects) therefore enables astronomers to study the gaseous content of the early universe when galaxies were condensing out of the primordial material.

- The radio emission from the oldest parts of spiral galaxies and large radio galaxies is often 10^8 years old or more. The energy losses of the radiating particles cause the spectrum of the radio emission to steepen exponentially, requiring low frequencies to map it. A factor of 2 in frequency often means the difference between a detection or an upper limit.
- A very specific reason for having a low-frequency band in the 327 MHz region is the fact that many arrays have receiver/feed systems optimised/developed specifically for that band, the (historical) reason being that neutral deuterium has its “1420 MHz equivalent” line at 327 MHz. The determination of the deuterium abundance in the universe, and in the Galaxy in particular, is of great importance to cosmology.

Solar research

The band 322 - 328.6 MHz is globally used to monitor the integrated solar radio flux at several stations including stations at Trieste and Nançay in Europe. These observations and the associated alerts are distributed worldwide in support to the forecasting of solar disturbances affecting the Earth environment and human activities (“space weather”).

5.2. Radio Astronomical Use of the Band 608 - 614 MHz

Extraterrestrial radio emission is used in astronomy to study the physical circumstances under which the radiation is generated. These conditions reveal a phase in the evolution of distant galaxies and so this knowledge contributes to a broader understanding of the universe. To completely understand the radiation mechanisms involved, observation of the polarization properties of the radiation is essential. To study the radio structure of extraterrestrial radio sources the wavelength-dependent beamwidth of the mapping instrument is of prime importance for adequate angular resolution.

The band is one of the primary bands used for solar radio astronomy. The total radio solar flux at this frequency is currently monitored by many stations around the world including several stations in Europe. Most of those stations provide real time measurements and alerts in support to the solar activity forecast centres of the International Space Environment Service, ISES. Besides the primary long-term solar radio index at 2.8 GHz, the 608 - 614 MHz band also provides the longest quantitative record of solar activity. This is essential for the understanding of the long-term contribution of changing solar activity to global climate change on the Earth.

5.2.1. Polarization Studies

Very often extraterrestrial radio emission is linearly polarized, because it is produced by relativistic electrons in magnetic fields. The radiation is influenced by magneto-ionic media (outer space and terrestrial ionosphere) on its way to the observer, whereby the polarization characteristics change: the polarization angle varies as the square of the observing wavelength. For an unambiguous determination of this change of polarization angle, observations need to be made at a minimum of three not too widely spaced but unequally separated frequencies. This is of vital importance to determine the intrinsic physical circumstances in the extraterrestrial radio source, in particular the intrinsic polarization angle and hence the magnetic field direction.

The band 608 - 614 MHz is used for measurement of linear polarization of emission from extraterrestrial sources together with the band 322.0 - 328.6 MHz and the band 1400 - 1427 MHz. Using the 611 MHz band, the relative intervals in frequency are 1.9 to 325 MHz and 2.3 (or in frequency squared 3.6 : 5.4), which is a minimum requirement for polarization studies.

5.2.2. Beam Properties

The resolution of diffraction-limited imaging systems (which radio telescopes are) directly depends on the observing wavelength: double the wavelength and you double the beamwidth. For a radio interferometer like the Westerbork Synthesis Radio Telescope (the Netherlands), WSRT, this fact has two major consequences:

- the maximum resolution of the synthesised beam decreases with increasing wavelength;
- the field of view being imaged (determined by the size of the individual interferometer elements) increases with wavelength.

The 611 MHz capability is essential for reasons relating to both of these factors.

In the first place it is necessary to be able to bridge the gap in resolution between 325 and 1413 MHz. Although that constitutes a factor of about 4.5 in linear resolution, it is a difference of nearly 20 times in beam area. For interpretation of many astronomical images the beam area is more relevant than beamwidth. There the more modest jump of a factor 4 - 5 in beam area from 1413 to 611 MHz and from 611 to 325 MHz is about the maximum acceptable.

Astronomical objects vary in size from extremely compact (less than 1 arcsecond) to very extended (many degrees). For the larger objects, mainly features in the Milky Way (various types of diffuse nebulae), the optimum image is obtained when one can match the field of view to the object’s size. Then one obtains the maximum resolution permitted by the physical separation of the interferometer elements combined with a fully sampled image of the object. Loss of the 611 MHz capability would mean for many objects of about one degree angular size that they could only be fully observed at 325 MHz with the consequent loss of resolution and in some cases degradation of image quality due to the presence of four times as many background sources in the field of view.

5.2.3. International Cooperation

Ten European radio observatories participate in the European VLBI Network, EVN.

The VLBI technique enables widely separated (1 000 km and more) radio telescopes to operate together with a consequent huge increase in angular resolution (see Section 3.7). The other major VLBI network is the VLBA in North America. Compared with it, the EVN has the advantage of several very large telescopes, providing high sensitivity. The arguments presented above about angular resolution apply equally to the EVN. An additional factor is that the EVN at 611 MHz has an angular resolution (0.05 arcsecond) very similar to the Hubble Space Telescope, HST. With the EVN at 611 MHz European astronomers have the optimum instrument for producing radio images to match optical data from the Hubble Space Telescope.

5.2.4. Allocation

The frequency allocation of the band 608 - 614 MHz differs in the three ITU regions:

In Region 2 the Radio Astronomy Service has a primary status whereas in Regions 1 and 3 a secondary status is allocated by No. **5.306**. In western Europe the band (called channel 38 in the broadcast band 470 - 790 MHz) has been kept free from strong interference in France, Germany, the United Kingdom and the Netherlands. Without this protection, the research outlined above would be severely hampered or impossible. Not only could the local research programmes not be carried out but also the international cooperation with the VLBI observing technique would be made virtually impossible.

Scientific interest in the use of this band is not expected to diminish with time, quite the contrary. Among the next generation of giant radio telescopes planned by the worldwide astronomical community, it is foreseen that the Square Kilometre Array, SKA, will operate in the frequency band under consideration. SKA will have a collecting area of 1 square kilometre (i.e., about 100 times that of a 100 metre diameter antenna, currently the largest size operational in Europe), distributed over a region some 3 000 km in area. SKA is currently in the planning and R&D phase. It involves several major European radio observatories, and it is planned to be operational by the year 2015. Although its geographical location has not been decided yet, there is a reasonable chance that (parts of) this giant interferometer will be located in Europe.

It should be noted that the new instrument will not replace the currently existing radio telescopes.

5.3. Importance of the Redshifted 21 cm Hydrogen Line

Ninety percent of the atoms in the universe are hydrogen, and most of them are in the ground state. Since its discovery in 1951, the 21 cm line (1420.4057 MHz) of neutral atomic hydrogen, HI, has served astronomy as the most critical tracer of the spatial structure in the Milky Way Galaxy, as an indicator of both redshift and the potential for star formation in other galaxies, and as a probe of the intergalactic conditions at early epochs in the history of the universe. Improvements in antenna, receiver and spectrometer technology have allowed the number of extragalactic HI measurements to grow by more than a factor 50 in the last decade, and the volume of the universe accessible to

21 cm HI line research is expected to expand further with future developments.

Because the universe is expanding, more distant objects appear to be moving away from us with increasingly high velocities. Because of the Doppler effect, this motion away from Earth causes the 21 cm line radiation from a distant galaxy to be shifted from its rest frequency of 1420.4057 MHz to lower and lower frequencies (longer wavelengths). The amount of this frequency shift – referred to as “redshift” – is an indicator of the distance to the emitting source. For example, 21 cm line radiation typically is received from galaxies in the nearest cluster of galaxies, the Virgo cluster, at frequencies around 1415 MHz; from the Perseus supercluster of galaxies at 1400 MHz; and from the Coma cluster of galaxies at 1388 MHz.

These 21 cm line redshifts have provided the distance measures to more than 10 000 galaxies already and have contributed significantly to our understanding of large-scale structure in the galaxy distribution, which itself holds vital clues to the history of the early universe. Most of these galaxies emit 21 cm line radiation so that it is received at Earth in the frequency range from 1330 to 1420 MHz, but recent technological advances have opened up the range even down to 1300 MHz for routine studies. Furthermore, since radio waves travel at the speed of light and the rate of expansion of the universe is known, the frequency shift also provides an indication of the time in the past at which the radiation was emitted. For large redshifts, this “look-back” time is a significant fraction of the age of the universe. Thus astronomers can use the redshifted hydrogen line to study the time evolution of the universe. For example, the 21 cm line absorption detected in the spectrum of a quasar in 1991 at 323 MHz (redshifted into the deuterium band) tells about physical conditions in the universe more than 10 billion years ago!

Hydrogen line research in the frequency range from 1.0 to 1.4 GHz holds special promise because of advances currently being made in radio astronomy technology. The volume of the universe probed by the redshifted hydrogen line shifted to 1 GHz spans 6 billion years in the age of the universe. Over this time interval, galaxies and clusters of galaxies have evolved significantly. Note that the Sun and Earth are estimated to be roughly that old. It is critical to our understanding of the evolution of the universe to be able to study galaxies and their environments over such look-back times.

As we look out to larger distances and back to earlier epochs, the Doppler shift carries the 21 cm hydrogen line outside the frequency range protected for radio astronomy. Because of the importance of UHF for many vital services and commercial enterprises, radio astronomers recognise that such frequencies cannot be excluded from use by active transmitters. Radio astronomers are developing techniques to identify human-generated signals in scientific observations, and reject them, both in real-time and post-detection. This interference excision may be possible if the interference has different time and frequency characteristics from the cosmic 21 cm line radiation. However, because human-generated transmissions are generally much stronger than those arriving from distant extragalactic sources, the regulation of frequency usage and its restriction to well-defined narrow bands is critical so that radio astronomical 21 cm line research can continue. Spurious, wide-band or time-varying signals whose presence cannot be predicted or whose strength saturates radiodetectors will prohibit astronomers from using this unique probe of history and evolution of the universe. Beyond regulation, voluntary cooperation on the part of radio engineers and users to limit unnecessary radiation below 1420.4057 MHz can help significantly to extent humankind’s knowledge of the universe.

5.4. 1.6 GHz OH Emission Lines

5.4.1. OH Megamasers

OH–megamasers radiate in the ground state spectral lines of OH at 18 cm wavelength, primarily in the OH main lines (1665.401 and 1667.358 MHz rest frequency). They are the most powerful maser sources known, with outputs sometimes exceeding 10^{30} W. They occur in the nuclei of infrared-luminous galaxies whose central regions are heavily obscured to optical telescopes by massive clouds of gas and dust. The galaxies are usually violently interacting or merging systems. Megamasers are of great value as a signpost to this rare type of activity, and also because they allow the active nuclei to be studied with sub-arcsecond resolution.

Systematic searches for OH megamasers have been made of candidate galaxies selected from the Infrared Astronomical Satellite, IRAS, catalogue on the basis of their large infrared luminosity or their distinctive infrared colours. More than one hundred megamasers have been found to date. The powerful OH emission can be detected to great distances, prompting speculation that even more powerful gigamasers may exist. The redshifts of the megamaser galaxies take the OH lines well out of the protected band 1660.5 - 1670 MHz. The most distant megamaser presently known is redshifted from 1.667 GHz to 1.315 GHz.

Transmissions from GLONASS and Iridium satellites cause particular disruption to searches for OH megamasers because their signals are nearly always present, and because they cover a wide range of frequency.

5.4.2. Uniqueness of the OH 1612 MHz Band

The band 1610.6 - 1613.8 MHz is used primarily for observations of the OH ground state line at 1612.231 MHz rest frequency. This is one of four hyperfine transitions of OH at 18 cm wavelength. OH is a widespread and abundant molecule which is observed throughout the Galaxy and in other galaxies. Under special conditions one or more of the OH 18 cm lines are greatly enhanced by stimulated emission to give compact maser sources. The OH 1612 MHz maser is the characteristic emission from the so-called OH-IR sources. These are long-period variable stars which are shedding material rapidly and evolving towards the planetary nebula stage. The OH 1612 MHz masers occur in the dusty circumstellar envelope built up as the star loses mass. Observations of the 1612 MHz line give precise measurements of the stellar velocity and the expansion velocity of the envelope; they provide estimates of the mass-loss rate; and using interferometers they enable the structure of the circumstellar envelope to be mapped. Well over one thousand OH-IR sources are currently known. Most have been found by searching candidate infrared sources selected from the IRAS catalogue. Search programmes which are continuing at several observatories are expected to find many thousands more.

OH-IR sources are extremely important because their distances can be determined entirely by radio means. The OH maser emission varies in phase with the infrared emission. However, because of the finite speed of light we see a phase lag between the OH emission from the front and back sides of the circumstellar shell. Measurements of this phase-lag give the linear angular size across the shell. Interferometer measurements give the angular size of the shell. Together the linear size and the angular size give the distance of the star. The technique is of fundamental importance to determining the galactic distance scale. Lengthy monitoring programmes of several years are needed to determine phase-lags. Transmissions from artificial satellites operating in adjacent and nearby frequency bands presently cause harmful interference to measurements of the OH 1612 MHz line worldwide.

5.4.3. Radio Astronomical Use of the OH 1612 MHz Band

The band 1610.6 - 1613.8 MHz is allocated to the Radio Astronomy Service to allow observations of a spectral line of the hydroxyl radical OH which has a rest frequency of 1612.231 MHz. The band has been used for more than 30 years. The increasing astrophysical interest in this spectral line is reflected in the upgrade of the allocation to primary status worldwide at WARC-92. The band is used regularly at 15 radio astronomy sites within Europe. These are listed in Table 6 (see Section 11.1).

The nature of the observations and the amount of use of the 1612 MHz band vary from site to site. Some observatories schedule mainly single telescope measurements (e.g. Nançay, Effelsberg, Yebes and Jodrell Bank). One of the most intensive users of the band is Nançay, which devotes 30% of its observing time to this frequency band. Spectral line observations usually consist of integrations of typically half an hour per source.

All the sites make interferometric observations. The Westerbork Synthesis Radio Telescope array is used for short baseline interferometry. The six radio astronomy sites in England are connected to form a long baseline interferometer MERLIN (the Multi Element Radio Linked Interferometer Network). Finally the European radio telescopes are regularly operated together for Very Long Baseline Interferometry, VLBI. Interferometric measurements usually involve continuous observations of 12 hours or more per source to achieve Earth-rotation aperture synthesis. The European VLBI Network, EVN, currently schedules four observing sessions per year, each of 3 to 4 weeks duration and each covering more than one frequency band. The 1612 MHz band is scheduled frequently but irregularly.

5.4.4. Interference from Satellite Services

At the present time the Russian global navigation satellite system GLONASS is a major source of interference to radio astronomical observations in the band 1610.6 -

1613.8 MHz, throughout the world. Negotiations between the radio astronomy community, represented by the Scientific Commission on the Allocation of Frequencies for Radio Astronomy and Space Science, IUCAF, and the GLONASS Administration, led to a joint experiment in November 1992 which tested new frequency configurations for the GLONASS satellites. These new configurations reduce the level of interference to radio astronomy without compromising the operational capabilities of the navigation system. The GLONASS-IUCAF Agreement, signed in November 1993, sets out a step-by-step plan to reduce the level of interference to radio astronomy. The satellites are now confined to centre frequencies below 1608.75 MHz, and will eventually be confined to frequencies below 1605.375 MHz. The first of a new generation of satellites fitted with filters was launched in 2003. These developments give confidence that a technical solution to the GLONASS interference problem will be achieved.

A second source of interference is the downlink transmission from Iridium satellites, operating in the Mobile Satellite Service, which also have global coverage. Under the auspices of the CEPT Milestone Review Committee, MRC, CRAF and Iridium LCC have negotiated agreements on operational criteria for the Iridium system adequate to protect the radio astronomy service in Europe. These agreements foresee that by 1 January 2006, the Iridium satellite system will comply fully with the criteria to protect the Radio Astronomy Service in the band 1610.6 - 1613.8 MHz, as outlined in ITU-R Recommendation RA.769. The CEPT conclusions are given in CEPT MRC Recommendations 4, 6, 7 and 8. CRAF observed that Iridium LLC did not comply with the agreements, specifically with a work plan, to work towards the goal set for 1 January 2006. Since March 2001, the Iridium satellite system operates under a new operator, Iridium Satellite LLC. It is not yet clear to what extent the new operator will comply with the conditions agreed under the CEPT MRC.

In the upper part of the band 1660 - 1670 MHz, the sub-band 1668 - 1670 MHz is allocated to the Mobile Satellite Service. INMARSAT will use this allocation. However, as explained in Section 4.2, No. **5.379C** sets maximum (aggregate) pfd limits to protect radio astronomy in this band. Calculations in the preparation for WRC-03 have indicated that within Europe, deployment of stations in the Mobile Satellite Service within about 500 km from a radio astronomy station operating in this band will cause harmful interference to the radio astronomy stations.

5.5. Spectral Line Observations in Bands around 20 GHz

In the past radio astronomers tried hard to obtain allocations of frequency bands for a number of spectral lines. The most important spectral lines are contained in Table 1 and Table 2 of ITU-R Recommendation RA.314. Not all these lines received sufficient protection in the ITU Radio Regulations.

The total number of observed spectral lines is far larger. In particular the band from 18 to 30 GHz is densely packed with observed lines. Lovas (1986) recorded a list of 173 transitions within this spectral range, only 37 of which are covered by the four spectral lines that entered the ITU-R Recommendation RA.314. But also many other lines are of continuous interest for the determination of astrophysical parameters of celestial sources. Observations of these lines will become impossible with increasing frequency usage of the bands, especially those which are going to be used for transmissions from satellites to Earth.

Though scientists understand the general limitation for a major increase of frequency allocations for radio astronomy, they claim that for lines outside allocated bands at least occasional experimental observations should remain possible on a long-term basis.

These considerations are especially relevant for many lines in the band 21.5 - 22 GHz, which is already allocated for the Broadcasting-Satellite Service for HDTV in Regions 1 and 3. They also apply to other nearby bands which are allocated for space-to-Earth transmissions. Radio astronomers are willing to give information about preferred bands and sub-bands which should be kept free from satellite transmissions as long as possible.

With regard to the need that experimental observations of special lines should be possible even on a long term, regulations should be provided on the basis of ITU-R Recommendation RA.314**,** which refers to this problem considering: “that astronomers also study spectral lines outside bands allocated to radio astronomy, as far as spectrum usage by other services allows;” and which recommends: “that administrations be asked to provide assistance in the co-ordination of experimental observations of spectral lines in bands not allocated to radio astronomy.”

According to this recommendation, radio astronomers wish to propose arrangements for occasional spectroscopic observations on a time sharing basis such as where such a band is used by the Broadcasting- Satellite Service, agreements could be made for interruption of transmission during certain night hours. Or where such a band is used by the Fixed Service for a down-link from a satellite, the change of transmitter channel usage for a certain time interval could serve for the benefit of radio astronomy.

5.6. Millimetre Wave Astronomy (30 - 300 GHz)

At millimetre wavelengths the non-thermal radiation studied at longer wavelengths becomes weak and the cosmic signals are dominated by thermal radiation from cold material. This is just the long wavelength component of the heat radiation produced by any hot body. For example, the thermal radiation from a room temperature body peaks in the infrared region at around 10 mm wavelength, and is relatively weak in the radio bands. Thermal radiation from cold interstellar clouds at 10 K has a maximum in the sub-millimetre band near 300 µm (1 THz), while the background radiation left over from the Big Bang, at an equivalent temperature of 2.7 K, has its maximum around 1 mm (300 GHz).

In the colder regions of space, matter can exist in molecular form if it is far away from, or shielded from, the intense ultraviolet radiation from hot stars. Each type of molecule radiates at a series of discrete frequencies or spectral lines that are characteristic of the molecule. The relative intensities of the lines emitted by a given molecule depend on the physical conditions such as density and temperature within the emitting region. Thus it is usually necessary to observe several lines of a given molecule in order to estimate the physical conditions. This is also true if one wants to unambiguously identify a molecule, since in general the observed frequency depends on the often unknown velocity of the object under study. Any given line or transition may be obscured by emission from some other molecule. However, by studying the frequencies of several of the emitted spectral lines we can deduce which molecules are present. So, spectroscopy is one of the main tools of the mm-wave astronomer.

Some of the heavier molecules condense to form dust particles which radiate a continuum of frequencies. The study of this continuum radiation is the second tool available to the mm-astronomer. It is much more difficult to deduce the composition of dust particles, as there are few if any characteristic lines which can be used to identify the constituent molecules.

Thus, nature urges mm-astronomers to do spectral line as well as continuum observations. These spectral line observations serve, in particular, a new branch of astronomy: astrochemistry.

The millimetre and sub-millimetre bands offer a unique window through which we can “see” and study these components of the universe which are otherwise invisible. The reasons for this are that they:

- contain over 3 000 radio spectral lines of interstellar and circumstellar molecules;
- are the only bands in which one can detect the emission of cool dust in space;
- are the only bands in which we can detect the emission from dust and molecules in young galaxies at high redshift in the early universe;
- are also the only bands in which one can detect the low-temperature cocoons of protostars, via their dust and molecular-line emission;
- are probably the only bands in which we can derive kinematical information about protoplanetary disks around young stars.

Millimetre-wave astronomy is thus the proper tool to study objects such as comets, planets, interstellar clouds, stellar atmospheres, protostars, protoplanetary disks, galaxies, quasars and intergalactic clouds in which the material is largely molecular. One of the most remarkable discoveries of mm-wave astronomy is that molecules and dust were abundant in the early universe. CO has been detected at a redshift of 4.7, corresponding to a “look back” time of nearly 13 billion years.

The very high density of spectral lines in the millimetre spectrum sets this region of the spectrum apart from that studied at lower frequencies. Sensitive studies of molecular clouds have disclosed up to a hundred lines per GHz. In some sources the spectrum is completely filled by line emission, each line blending with its neighbours. Figure 8 illustrates these results.

As of August 2004 a total of 125 molecular species had been detected in interstellar and circumstellar gas clouds (Table 4). They include stable inorganic and organic molecules such as salt (NaCl), carbon monoxide (CO) and ethyl alcohol (CH_3CH_2OH), reactive molecules such as the strange carbon chains $HC_{11}N$, radicals such as OH, NH_2

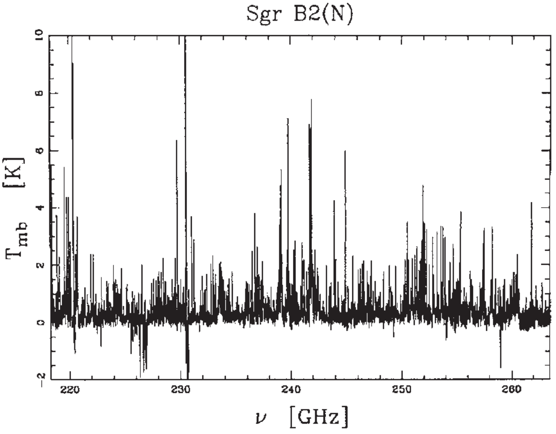

Figure 8: Spectrum taken towards a molecular cloud [Sgr B2(N)] in the direction of the Galactic centre. In this bandwidth of 45 GHz about 1 700 lines have been found. The observation was made with a frequency resolution of 2 MHz by A.Nummelin at the SEST telescope (Chile). The three strongest lines are due to carbon monoxide (^{13}CO and ^{12}CO) and methyl alcohol (CH_3OH). Some lines are seen in absorption (negative features).

Table 4: Molecules Observed in Interstellar and Circumstellar Clouds (as of August 2004)

Diatomic molecules:	AlF AlCl C_2 CH CH^+ CN CO CO^+ CP CS CSi FeO HCl HF H_2 KCl NH NO NS NaCl OH PN SO SO^+ SiN SiO SiS SH
Triatomic molecules:	AlNC C_3 C_2H C_2O C_2S CH_2 CO_2 H_3^+ HCN HCO HCO^+ HCS^+ HOC^+ H_2O H_2S HNC HNO MgCN MgNC N_2H^+ N_2O NH_2 NaCN OCS SO_2 c–SiC_2 SiCN
Four atoms:	c-C_3H l-C_3H C_3N C_3O C_3S C_2H_2 CH_2D^+ HCCN $HCNH^+$ HNCO HNCS $HOCO^+$ H_2CO H_2CN H_2CS H_3O^+ NH_3 SiC_3
Five atoms:	C_5 C_4H C_4Si l-C_3H_2 c-C_3H_2 CH_2CN CH_4 HC_3N HC_2NC HCOOH H_2CHN H_2C_2O H_2NCN HNC_3 H_2COH^+ SiH_4
Six atoms:	C_5H C_5O C_2H_4 CH_3CN CH_3NC CH_3OH CH_3SH HC_3NH^+ HC_2CHO $HCONH_2$ l–H_2C_4 C_5N
Seven atoms:	C_6H c–C_2H_4O CH_2CHCN CH_2CHOH CH_3C_2H HC_5N $HCOCH_3$ NH_2CH_3
Eight atoms:	C_7H CH_3C_3N CH_3COOH CH_2CHCHO CH_2OHCHO $HCOOCH_3$ H_2C_6
Nine atoms:	C_8H CH_3C_4H CH_3CH_2CN $(CH_3)_2O$ CH_3CH_2OH HC_7N
Ten atoms:	CH_3C_5N $(CH_3)_2CO$ CH_3CH_2CHO NH_2CH_2COOH
Eleven atoms:	HC_9N
Thirteen atoms:	$HC_{11}N$

Note: c denotes cyclic molecules, l denotes linear molecules.

and C_2H, and ions like $HCO^+$and $HCCCNH^+$. Many of them are unstable on Earth. Several were discovered in space before being found in the laboratory.

A growing number of organic molecules have been detected that are important for life on Earth, including glycine (NH_2CH_2COOH), the simplest amino acid, detected in 2003 via 27 of its spectral lines. CH_2OHCHO has been found in all three of its isomeric forms, as acetic acid, glycolaldehyde (the first monosaccharide found in space) and methyl formate. There is no consensus as to how such large complex molecules are formed in space. A significant fraction of molecular lines are as yet unidentified and may come from far more complex molecules than any we have identified so far. The new discipline of astrobiology seeks, among other things, to understand the relation of the interstellar molecules to the origin of life.

5.6.1 Techniques of Millimetre-astronomy

Observations at the shorter millimetre wavelengths are increasingly dominated by considerations of the transparency of the Earth's atmosphere. Atmospheric absorption is highest at the transitions of water vapour at about 183 GHz, 325 GHz etc. and oxygen at about 60 GHz, 120 GHz etc. These frequencies are impossible to observe from sea-level and naturally divide the millimetre spectrum into a series of windows. Astronomers therefore speak of the 7 mm, 3 mm, 2 mm, 1 mm etc. windows within which ground-based astronomical observations are possible. This is illustrated by Figure 9. As can be seen, within these windows the effect of atmospheric water vapour is to reduce the transmission at higher frequencies. Millimetre wavelength observatories are generally located at high elevation to reduce as far as possible the quantity of water vapour lying above them. The three curves in Figure 9 represent observing conditions at the very best high altitude sites.

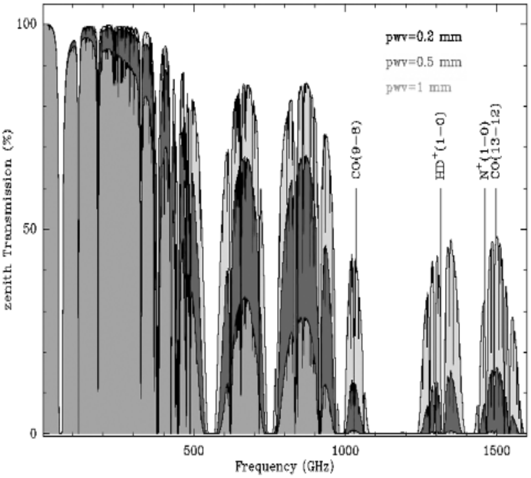

Figure 9:
Zenith transmission of the atmosphere for different levels of atmospheric precititable water vapour, showing millimetre- and sub-mm-wave windows. The upper curve (0.2mm) corresponds to the best transmission on Chajnantor in Northern Chile, the middle curve (0.5mm) corresponds to average transmission on Chajnantor, while the lowest curve corresponds to 1mm. From *Light Pollution: The Global View* (2003), ed. H. Schwarz, p.230, Fig. 3 (Kluwer Academic Publishers), with kind permission of Springer Science and Business Media.

The radio emission from low temperature regions is naturally weak, and very sensitive receivers are necessary for its study. For spectral line observations most observatories use superconducting mixer elements as the first stage of their receivers. These comprise a thin layer of insulating material sandwiched between two superconducting pieces, hence the name “superconductor-insulator-superconductor” (SIS) junctions. For minimum noise these are operated at the temperature of liquid helium. The radio frequency signal and the local oscillator signal are beamed onto the SIS junction using quasioptical techniques. The tunnelling properties of the junctions provide the non-linear element necessary for mixing and translating the radio frequency signal to intermediate frequency for subsequent spectral analysis. Present designs have almost no pre-mixer frequency selectivity so as to permit tuning over a complete atmospheric window with the lowest loss. At any tuning they can examine a slice of spectrum of width typically 500 MHz to 1 GHz. This is usually done by digital autocorrelation spectrometers, filter banks or acousto-optical spectrometers. For continuum observations of dust for example, very sensitive bolometer detectors of wide bandwidth have been developed. These are incoherent detectors, with no local oscillator. To attain the ultimate in sensitivity the bolometer elements are frequently cooled to 0.1 K and their bandwidth is several tens of GHz. Focal plane arrays of up to a 100 such bolometers are in use, providing an instantaneous picture of a section of the millimetre sky.

Such equipment is extremely difficult to protect from interfering signals at nearby frequencies. This vulnerability to interference arises because of the following:

- the equipment sensitivity is extremely high so that only very low levels of spurious or out of band emissions from neighbouring bands can be tolerated. An estimate of these limits is given in ITU-R Recommendation RA769;
- the SIS mixers used by most mm-observatories, need very small local oscillator power. They are thus open to saturation by signals as weak as 1 nanoWatt (–60 dBm), and could be destroyed if the mm-wave telescope were to point directly at a radio transmitter;
- at present there is no technology available to build high Q mm-wave filters of the necessary extremely low loss. Such devices are needed to discriminate against quite legitimate transmissions in adjacent bands. At the high frequencies used in millimetre radio astronomy a given bandwidth corresponds to a much higher Q value than at lower frequencies. There are even serious reasons to doubt that the properties of materials will ever allow adequate filters to be built.
- the IF (intermediate frequency) stages of a mm-wave receiver are vulnerable to interference from powerful transmitters at frequencies far removed from the observing frequency. The IRAM 30-m telescope on Pico Veleta and the SEST telescope in Chile have both suffered interference of this kind from military radar.

As at lower frequencies, single dishes, connected element interferometers and VLBI are all used at millimetre wavelengths. However mm-observatories must be placed at high elevation, frequently on mountain tops, in an attempt to get above the atmospheric water vapour which strongly attenuates mm-wavelength radiation. This has the disadvantage that such observatories often have clear line-of-sight paths extending to hundreds of kilometres, so that they are open to terrestrial interference from a very large area, much larger than for instruments operating at lower frequencies.

Millimetre radio astronomy is now one of the most dynamic fields of astronomy. In Europe we mention the existence of single dish telescopes in Finland, France, Russia, Spain, Sweden, Switzerland and Turkey, with important outstations in Hawaii and Chile. An interferometer array is operating in southern France on the Plateau de Bure. Worldwide plans are going ahead for the investment of several billion dollars in new millimetre facilities. These include a 50 m diameter single dish in Mexico and several large interferometer arrays. The Atacama Large Millimetre Array, ALMA, under construction on the Chajnantor plateau in the Atacama Desert of Northern Chile will comprise 64 × 12 m diameter dishes. ALMA is being built by a global consortium of countries. The site, at an altitude of 5 200 m, is arguably the best in the world for millimetre and sub-millimetre astronomy.

5.6.2. Frequency Protection at Millimetre Wavelengths

It is clear from the preceding sections that the whole of the mm-wave spectrum is full of molecular line emission, each line potentially giving us information which is often unavailable by other means. Many lines are still unidentified and may prove of great interest in the future. The International Astronomical Union, IAU, produces a list of important lines (see Section 5.8) which is an attempt to assign relative scientific priorities, but at best it can only be a guide, as we cannot anticipate future discoveries or needs. The situation becomes even more complex when one takes account of the Doppler shift acting on the radiation from distant objects. Important lines may thus appear at practically any frequency in the mm-bands. The difficulty of devising effective protection of mm-observations is reinforced by the requirement of very large bandwidth needed for continuum studies by bolometer.

WRC-2000 made generous allocations of mm-wave bands to Radio Astronomy, giving astronomers access to most of the atmospheric windows in the frequency range 71 - 275 GHz. Figure 10 compares the allocation status before and after WRC-2000. Most of the useable frequencies now have a primary allocation to radio astronomy. Many of the radio astronomy bands are shared with active services on a co-primary basis. Sharing with active services may be feasible at mm-wavelengths because there are relatively few mm-wave observatories to be protected, and they are usually located in isolated remote sites chosen for their extremely dry atmospheric conditions. The transmitters of the active services are likely to be found at lower altitudes; hence atmospheric attenuation and site shielding may provide the necessary protection to the observatory. The protection of mm-observatories is subject to ongoing investigation. The way mm-observatories will be protected in future may differ from methods used for “classical radio observatories” (i.e. operating at lower frequencies) and may be more like the protection of optical observatories.

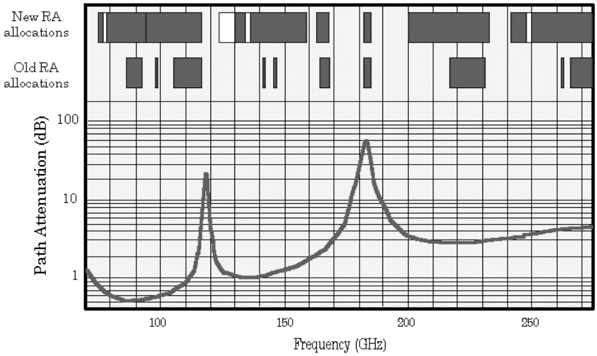

Figure 10: Allocations to the Radio Astronomy Service before and after WRC-2000. The solid curve shows the zenith attenuation of the atmosphere at sea level. Figure courtesy of John Whiteoak, Australia Telescope National Facility.

5.7. Sub-millimetre Astronomy (>300 GHz)

Sub-millimetre astronomy is one of the newest fields in astronomy. Here the cosmic microwave background is at its brightest. This part of the electromagnetic spectrum is also rich in spectral lines from interstellar and circumstellar molecules. The sub-mm region was originally considered to be part of the far-infrared, but sub-mm astronomy is now regarded as part of radio astronomy since the instrumental techniques developed to investigate it have more in common with radio astronomy than with infrared astronomy.

The Earth's atmosphere puts major constraints on ground-based sub-millimetre astronomy, limiting both the sensitivity and the imaging quality of radio telescopes and interferometer arrays. Water vapour, oxygen and other molecules produce attenuation and path delay through the atmosphere, while adding extra noise in the form of their thermal radiation. In addition, the variations in path delay cause fluctuations in the apparent brightness and position of compact radio sources, producing the radio equivalent of "twinkling". Even more than at mm-wavelengths it is essential to choose a high and dry site for a sub-mm telescope. Prime sub-mm sites include Chajnantor in the Atacama Desert of Northern Chile, Manua Kea in Hawaii, and the high regions of Antarctica, especially Dome C. These sites can have as little as 0.2 mm of precipitable water vapour, allowing observations in two atmospheric windows at 1.3 THz and 1.5 THz (see Figure 9) that are the final frontiers of ground-based sub-mm astronomy.

Observations that require extreme stability, or access to frequency bands where the atmosphere blocks radiation severely, are undertaken using instruments on balloons or satellites (see Sections 3.8 and 3.9.3).

The receivers employed are either superheterodyne (phase coherent) receivers using devices such as SIS mixers, or non-heterodyne systems such as bolometers, which are phase incoherent. The greatest sensitivity for continuum measurements comes from non-heterodyne systems that ignore the phase of the electromagnetic wave but simply detect its energy. In a bolometer, incoming radiation raises the temperature of the detector, the temperature rise being measured by a change in the electrical resistance. Bolometric techniques are used from the millimetre band through to the mid-infrared. Bolometers are inherently broad band devices, so filters must be used to select the observing band. The filter bands are usually chosen to match the atmospheric transmission windows. Usually the noise entering from the cosmic source and the atmosphere dominates over the intrinsic noise of the device. As at millimetre wavelengths, bolometer arrays with over one hundred elements are available.

There are no frequency allocations in the sub-mm region of the spectrum. However No. **5.565** of the Radio Regulations lists frequency bands in the range 275 - 1000 GHz that are used for radio astronomy and by other passive services. The footnote urges Administrations to take all practicable steps to protect these passive services from harmful interference until the date when the allocation Table is established in this frequency range. Resolution 950 (WRC-03) allows Administrations to register systems that already operate between 275 and 3000 GHz.

The ITU voted at its Plenipotentiary Conference in 2002 to encourage studies above 3000 GHz, and implicitly broadened its remit to regulate the spectrum without any specific upper limit. These developments are being driven by the growth of laser communications, including satellite communications. Perhaps in the future optical and infrared astronomy may have to operate in a regulated environment.

5.8. Radio-Frequency Lines of the Greatest Importance to Radio Astronomy

At the XXIst General Assembly of the International Astronomical Union, IAU, (Buenos Aires, July 23 - 1 August 1991) the astrophysically most important spectral lines were carefully reviewed. The IAU revised list of spectral lines is reproduced in Table 5. The IAU expressed the need to protect these frequency bands from in-band, band-edge and harmonic emissions, especially from space-borne transmitters. Also included in Table 5 are important spectral lines identified by the IUCAF mm-wave Working Group in preparation for WRC-2000.

Table 5: Radio Frequency Lines of the Astrophysically Most Important Spectral Lines

Substance	Rest Frequency	Suggested Minimum Bandwidth	Notes[1]
Deuterium DI	327.384 MHz	327.0 - 327.7 MHz	
Hydrogen (HI)	1420.406 MHz	1370.0 - 1427.0 MHz	2, 3
Hydroxyl radical (OH)	1612.231 MHz	1606.8 - 1613.8 MHz	3, 4
Hydroxyl radical (OH)	1665.402 MHz	1659.8 - 1667.1 MHz	4
Hydroxyl radical (OH)	1667.359 MHz	1661.8 - 1669.0 MHz	4
Hydroxyl radical (OH)	1720.530 MHz	1714.8 - 1722.2 MHz	3, 4
Methyladyne (CH)	3263.794 MHz	3252.9 - 3267.1 MHz	3, 4
Methyladyne (CH)	3335.481 MHz	3324.4 - 3338.8 MHz	3, 4
Methyladyne (CH)	3349.193 MHz	3338.0 - 3352.5 MHz	3, 4

Formaldehyde (H_2CO)	4829.660 MHz	4813.6 - 4834.5 MHz	3, 4
Methanol (CH_3OH)	6668.518 MHz	6661.8 - 6675.2 MHz	3, 6
Ionized Helium Isotope ($^{3}HeII$)	8665.650 MHz	8660.0 - 8670.0 MHz	
Methanol (CH_3OH)	12.178 GHz	12.17 - 12.19 GHz	3, 6
Formaldehyde (H_2CO)	14.488 GHz	14.44 - 14.50 GHz	3, 4
Cyclopropenylidene (C_3H_2)	18.343 GHz	18.28 - 18.36 GHz	3, 4, 6
Water Vapour (H_2O)	22.235 GHz	22.16 - 22.26 GHz	3, 4
Ammonia (NH_3)	23.694 GHz	23.61 - 23.71 GHz	4
Ammonia (NH_3)	23.723 GHz	23.64 - 23.74 GHz	4
Ammonia (NH_3)	23.870 GHz	23.79 - 23.89 GHz	4
Sulphur monoxide (SO)	30.002 GHz	29.97 - 30.03 GHz	6
Methanol (CH_3OH)	36.169 GHz	36.13 - 36.21 GHz	6
Silicon monoxide (SiO)	42.821 GHz	42.77 - 42.86 GHz	
Silicon monoxide (SiO)	43.122 GHz	43.07 - 43.17 GHz	
Dicarbon monosulphide (CCS)	45.379 GHz	45.33 - 45.44 GHz	6
Carbon monosulphide (CS)	48.991 GHz	48.94 - 49.04 GHz	
Oxygen (O_2)	61.1 (GHz	56.31 - 63.06 GHz	5, 6, 7
Deuterated Water (HDO)	80.578 GHz	80.50 - 80.66 GHz	
Cyclopropenylidene (C_3H_2)	85.339 GHz	85.05 - 85.42 GHz	
Silicon monoxide (SiO)	86.243 GHz	86.16 - 86.33 GHz	
Formylium ($H^{13}CO^+$)	86.754 GHz	86.66 - 86.84 GHz	
Silicon monoxide (SiO)	86.847 GHz	86.76 - 86.93 GHz	
Ethynyl radical (C_2H)	87.300 GHz	87.21 - 87.39 GHz	5
Hydrogen cyanide (HCN)	88.632 GHz	88.34 - 88.72 GHz	4
Formylium (HCO^+)	89.189 GHz	88.89 - 89.28 GHz	4
Hydrogen isocyanide (HNC)	90.664 GHz	90.57 - 90.76 GHz	
Diazenylium (N_2H)	93.174 GHz	93.07 - 93.27 GHz	
Carbon monosulphide (CS)	97.981 GHz	97.65 - 98.08 GHz	4
Sulphur monoxide (SO)	99.300 GHz	99.98 - 100.18 GHz	
Methyl acetylene (CH_3C_2H)	102.5 GHz	102.39 - 102.60 GHz	5
Methanol (CH_3OH)	107.014 GHz	106.91 - 107.12 GHz	
Carbon monoxide ($C^{18}O$)	109.782 GHz	109.67 - 109.89 GHz	
Carbon monoxide (^{13}CO)	110.201 GHz	109.83 - 110.31 GHz	4
Carbon monoxide ($C^{17}O$)	112.359 GHz	112.25 - 112.47 GHz	6
Cyano radical (CN)	113.5 GHz	113.39 - 113.61 GHz	5
Carbon monoxide (CO)	115.271 GHz	114.88 - 115.39 GHz	4
Oxygen (O_2)	118.750 GHz	118.63 - 118.87 GHz	7
Formaldehyde ($H_2{}^{13}CO$)	137.450 GHz	137.31 - 137.59 GHz	3, 6
Formaldehyde (H_2CO)	140.840 GHz	140.69 - 140.98 GHz	
Carbon monosulphide (CS)	146.969 GHz	146.82 - 147.12 GHz	
Nitric oxide (NO)	150.4 GHz	149.95 - 150.85 GHz	5
Methanol (CH_3OH)	156.602 GHz	156.45 - 156.76 GHz	
Water vapour (H_2O)	183.310 GHz	183.12 - 183.50 GHz	7

Carbon monoxide ($C^{18}O$)	219.560 GHz	219.34 - 219.78 GHz	
Carbon monoxide (^{13}CO)	220.399 GHz	219.67 - 220.62 GHz	4
Cyano radical (CN)	226.6 GHz	226.57 - 227.03 GHz	5
Cyano radical (CN)	226.8 GHz	226.37 - 226.83 GHz	5
Carbon monoxide (CO)	230.538 GHz	229.77 - 230.77 GHz	4
Carbon monosulphide (CS)	244.953 GHz	244.72 - 245.20 GHz	6
Nitric oxide (NO)	250.6 GHz	250.35 - 250.85 GHz	5
Ethynyl radical (C_2H)	262.0 GHz	261.74 - 262.26 GHz	5
Hydrogen cyanide (HCN)	265.886 GHz	265.62 - 266.15 GHz	
Formylium (HCO^+)	267.557 GHz	267.29 - 267.83 GHz	
Hydrogen isocyanide (HNC)	271.981 GHz	271.71 - 272.25 GHz	
Dyazenulium (N_2H^+)	279.511 GHz	279.23 - 279.79 GHz	
Carbon monosulphide (CS)	293.912 GHz	292.93 - 294.21 GHz	
Hydronium (H_3O^+)	307.192 GHz	306.88 - 307.50 GHz	
Carbon monoxide ($C^{18}O$)	312.330 GHz	329.00 - 329.66 GHz	
Heavy water (HDO)	313.750 GHz	313.44 - 314.06 GHz	
Carbon monoxide (^{13}CO)	330.587 GHz	330.25 - 330.92 GHz	
Carbon monosulphide (CS)	342.883 GHz	342.54 - 343.23 GHz	
Carbon monoxide (CO)	345.796 GHz	345.45 - 346.14 GHz	
Hydrogen cyanide (HCN)	354.484 GHz	354.13 - 354.84 GHz	
Formylium (HCO^+)	356.734 GHz	356.37 - 357.09 GHz	
Oxygen (O_2)	368.498 GHz	368.13 - 368.87 GHz	
Dyazenulium (N_2H^+)	372.672 GHz	372.30 - 373.05 GHz	7
Water vapour (H_2O)	380.197 GHz	379.81 - 380.58 GHz	7
Hydronium (H_3O^+)	388.459 GHz	388.07 - 388.85 GHz	
Carbon monosulphide (CS)	391.847 GHz	390.54 - 392.24 GHz	
Oxygen (O_2)	424.763 GHz	424.34 - 425.19 GHz	
Carbon monoxide ($C^{18}O$)	439.088 GHz	438.64 - 439.53 GHz	
Carbon monoxide (^{13}CO)	440.765 GHz	440.32 - 441.21 GHz	
Carbon monoxide (CO)	461.041 GHz	460.57 - 461.51 GHz	
Heavy water (HDO)	464.925 GHz	464.46 - 465.39 GHz	
Carbon (CI)	492.162 GHz	491.66 - 492.66 GHz	
Heavy water (HDO)	509.292 GHz	508.78 - 509.80 GHz	
Hydrogen cyanide (HCN)	531.716 GHz	529.94 - 532.25 GHz	7
Carbon monosulphide (CS)	538.689 GHz	536.89 - 539.23 GHz	7
Water vapour ($H_2{}^{18}O$)	547.676 GHz	547.13 - 548.22 GHz	7
Carbon monoxide (^{13}CO)	550.926 GHz	549.09 - 551.48 GHz	7
Water vapour (H_2O)	556.936 GHz	556.37 - 557.50 GHz	7
Ammonia ($^{15}NH_3$)	572.113 GHz	571.54 - 572.69 GHz	7
Ammonia (NH_3)	572.498 GHz	571.92 - 573.07 GHz	7
Carbon monoxide (CO)	576.268 GHz	574.35 - 576.84 GHz	7
Carbon monosulphide (CS)	587.616 GHz	587.0 - 588.20 GHz	7
Heavy water (HDO)	599.927 GHz	599.33 - 600.53 GHz	7

Water vapour (H_2O)	620.700 GHz	620.08 - 621.32 GHz	7
Hydrogen chloride (HCl)	625.040 GHz	624.27 - 625.67 GHz	
Hydrogen chloride (HCl)	625.980 GHz	625.35 - 626.61 GHz	
Carbon monosulphide (CS)	636.532 GHz	634.41 - 637.17 GHz	
Carbon monoxide (^{13}CO)	661.067 GHz	658.86 - 661.73 GHz	
Carbon monoxide (CO)	691.473 GHz	690.78 - 692.17 GHz	
Oxygen (O_2)	715.393 GHz	714.68 - 716.11 GHz	7
Carbon monosulphide (CS)	734.324 GHz	733.59 - 735.06 GHz	7
Water vapour (H_2O)	752.033 GHz	751.28 - 752.79 GHz	7
Oxygen (O_2)	773.840 GHz	773.07 - 884.61 GHz	7
Hydrogen cyanide (HCN)	797.433 GHz	796.64 - 789.23 GHz	
Formylium (HCO^+)	802.653 GHz	801.85 - 803.85 GHz	
Carbon monoxide (CO)	806.652 GHz	805.85 - 807.46 GHz	
Carbon (CI)	809.350 GHz	808.54 - 810.16 GHz	
Carbon monosulphide (CS)	832.057 GHz	829.28 - 832.89 GHz	
Oxygen (O_2)	834.146 GHz	833.31 - 834.98 GHz	
Carbon monosulphide (CS)	880.899 GHz	877.96 - 881.78 GHz	
Water vapour (H_2O)	916.172 GHz	915.26 - 917.09 GHz	7
Carbon monoxide (CO)	921.800 GHz	918.72 - 922.72 GHz	7
Carbon monosulphide (CS)	929.723 GHz	926.62 - 930.65 GHz	
Water vapour (H_2O)	970.315 GHz	969.34 - 971.29 GHz	7
Carbon monosulphide (CS)	978.529 GHz	977.55 - 979.51 GHz	7
Water vapour (H_2O)	987.927 GHz	986.94 - 988.92 GHz	7

Notes:

1. If Note 2 or Note 4 is not listed, the band limits are Doppler-shifted frequencies corresponding to radial velocities of ±300 km/s consistent with line radiation occurring in our Galaxy.
2. An extension to lower frequencies of the allocation of 1400 - 1427 MHz is required to allow for the higher Doppler shifts for HI observed in distant galaxies.
3. The current international allocation is not primary and/or does not meet bandwidth requirements. See Section 4.2, Table 3 and the ITU Radio Regulations for more detailed information.
4. Because these line frequencies are also being used for observing other galaxies, the listed bandwidths include Doppler shifts corresponding to radial velocities of up to 1000 km/s.
   It should be noted that HI has been observed at frequencies redshifted to 323 MHz, while lines of the most abundant molecules have been detected in galaxies with velocities up to 50 000 km/s, corresponding to a frequency reduction of up to 17%.
5. There are several closely spaced lines associated with these molecules. The listed bands are wide enough to permit observations of all lines.
6. This line is not mentioned in Article **5** of the ITU Radio Regulations.
7. These lines are observable only outside the Earth’s atmosphere.

6.

Effects of Radio Frequency Interference on Radio Astronomical Observations

6.1. The Vulnerability of the Radio Astronomy Service

The cumulative effect of various kinds of radio frequency interference has an increasingly negative impact on observational radio astronomy. Why is this? It is because, as a radiocommunication service, Radio Astronomy is a so-called *passive service*, since it only receives radio signals (of natural, cosmic origin), and does not transmit radiation itself: "Radio astronomy**:** astronomy based on the reception of radiation of cosmic origin" (Article **1.13** of the Radio Regulations of the International Telecommunication Union).

The susceptibility of a passive service to interference from electromagnetic waves is greater than that of active services, since a passive service can control only the receiver side of its "communication system" – unlike the active services, which can control both the receiving and transmitting sides of their systems. If, for example, the signal-to-noise ratio in a communication link of an active service is not high enough, the signal power at the transmitter can be increased to obtain the required ratio, whereas in the Radio Astronomy Service the transmitter is set by nature and we can increase the signal-to-noise ratio only by integrating longer or by increasing the sensitivity of our receivers. Furthermore, the frequencies of the spectral lines, or characteristic features in the broadband emissions, are outside our control. This vulnerability is documented in, Report 852 of the CCIR "Characteristics of Radio Astronomy Service and preferred frequency bands" and in the ITU-R *Handbook on Radio Astronomy*.

6.2. Local, Regional and Global Interference

The interference problems experienced at radio astronomical observatories can also be categorised according to the distance of the interfering sources: local, regional and global. Strategic and political aspects of this distance-based categorisation are discussed further in Section 8.

Local problems include things such as nearby industrial workshops, faulty radio equipment, or mobile phone base stations. These local problems require a local solution, for example fixing a faulty transmitter, or establishing a radio-quiet zone around the radio astronomical observatory using local laws (see Section 6.3).

An example of a regional problem is TV broadcasting by adjacent channel or in-channel use of a radio astronomy band, according to a regional broadcasting plan. These problems, which are different for Europe, America, Asia, Africa and Australia, require regional consideration and solutions.

Global problems are potentially the most damaging for Radio Astronomy. Examples are interference caused by satellites and satellite systems, against which no shielding on the ground is possible (see for example Section 5.4.4). Therefore, solutions have to be sought in proper filtering of the transmitters and choice of modulation techniques to reduce spurious and out-of-band emissions (see Sections 6.5 and 7.2). It is also essential to avoid spectrum allocations to active space services adjacent to, or otherwise too close to frequency bands used by the Radio Astronomy Service.

6.3. Radio-Quiet Zones

Great care must be taken in the design and construction of radio telescopes and their associated equipment and electronics to minimise the risk of self-generated interference. Computers and other electronics associated with telescope control, signal processing etc., all radiate at microwave frequencies and have the potential to cause interference unless shielding and other measures are in place. Having established a quiet zone in the observatory grounds, coordinated action is then needed to safeguard the future of the site against outside interference, not only from radio transmitters, but also from electrical or electronic equipment in the vicinity of the observatory. One approach is to establish a radio-quiet zone, an area within which any electrical installation or equipment is subject to control or coordination (not necessarily exclusion).

Most European radio observatories have radio-quiet zones a few kilometres in diameter, implemented at local government level, for example via planning legislation, to control interference from non-radio sources. This is in addition to any national coordination agreements for licenced transmitters. Further details can be found on the CRAF website.

The Atacama Large Millimetre Array, ALMA, in which Europe is making a large investment, is currently under construction (since 2003) in Northern Chile. The first step towards a radio-quiet zone for ALMA was the establishment in 1998 of the Cerro-Chascón Science Preserve, an area about 18 kilometres across that is protected from mining in particular, and from other activities that might interfere with scientific projects. The Science Preserve was established by Chilean Government Supreme Decree No. 185. The second step was taken in 2004, with the passing of Exempt Resolution No. 1055, which provides protection for primary allocated radio astronomy bands, via two zones: a 30–km radius Protection Zone within which no transmitters are allowed in the Radio Astronomy bands used by ALMA, and a 120–km Coordination Zone within which transmitters must be coordinated. The interference limits are taken from ITU-R Recommendation RA.769.

The characteristics of existing radio-quiet zones are now under study within ITU-R Working Party 7D. It is clear from history that such zones are most effective when they are established early.

6.4. The Effect of Broadband Transmissions on Radio Astronomy

In recent years vast improvements in the sensitivity of radio receivers have been achieved, making possible the improvement of existing services and the introduction of new services which are dependent on sensitive receivers for their operation. At the same time new methods of modulation have been introduced, many of which are broadband and even ultra-wideband in nature. Sensitive receivers and broadband and spread spectrum modulation are on a collision course.

All transmitters sending information emit over a finite bandwidth. Most of the emitted energy lies close to the nominal centre frequency and within the allocated band. A small fraction, however, inevitably extends further away from the centre frequency, and outside the frequency band necessary to ensure the transmission of the information at the required rate and quality. These are termed "unwanted emissions." Unless extraordinary precautions are taken, wideband systems will produce significant unwanted emissions far beyond the limits of their allocated bands. This presents a problem for Radio Astronomy.

The existing regulations defining bandwidth, spurious emission and harmful interference were adopted before the widespread use of broadband emission and sensitive receivers developed.

Because of its impact on both Space Research and Radio Astronomy, CRAF has supported the decision made by the WARC-92 to ask the ITU-R Radiocommunications Bureau to study, on a broad basis, the effects of the use by one service of broadband modulation techniques on interference to other services using sensitive receivers and to propose methods to alleviate the problem. Since 1992, these studies have taken place in several ITU-R Task Groups, namely TG1/3, TG1/5, TG1/7 and since WRC-03 in TG1/9 to complete the work. The results are reflected in updates of Recommendation ITU-R SM.329 on spurious emissions and in WRC-03 Resolution **739** on "Compatibility between the radio astronomy service and the active space services in certain adjacent and nearby frequency bands". In spite of the achievements of these Task Groups, CRAF is concerned that the technological developments that could enable the space industry to reduce unwanted emissions in frequency bands used by Radio Astronomy are not always applied. Furthermore, the general limits on unwanted emissions from satellites into passive bands are not mandatory, so there is little incentive for an individual satellite operator to take extra care of passive bands.

6.5 Interference from Space Stations

Interference from satellites is a case of particular importance to the Radio Astronomy Service, because of the global nature of its effects. Radio telescopes in many countries can be affected, no matter how carefully sited they are and how well shielded from terrestrial transmitters. Two scenarios are considered here:

- interference from geostationary satellites
- interference from non-geostationary satellites.

The interference is assumed to come from unwanted emissions of the satellites into frequency bands allocated to the Radio Astronomy Service.

6.5.1. Geostationary Satellites

The interference thresholds to Radio Astronomy are given in Recommendation ITU-R RA.769 in several units. The conversion to spfd values assumes that the radio telescope has 0 dBi gain in the direction of the interfering source. Interference from a geostationary satellite can therefore be assessed in terms of the spfd produced by the satellite at the radio observatory in the relevant frequency band(s). However, as a consequence of the 0 dBi assumption, interference above the levels of ITU-R Recommendation RA.769 will be experienced whenever the gain of the radio telescope in the direction of the satellite exceeds 0 dBi.

In general, it is not considered practicable to suppress the unwanted emissions from satellites to levels low enough to allow a radio telescope to point directly at a satellite without experiencing interference. Each satellite therefore effectively blocks a region of sky whose extent depends on the level of unwanted emissions in the Radio Astronomy band, and on the sidelobe pattern of the radio telescope. Satellite operators can help reduce the sky blockage by controlling unwanted emission levels in the direction of radio observatories. There are also clear advantages to Radio Astronomy in the design of new radio telescopes so as to minimise the gain of sidelobes near the main beam. Unfortunately this can be done only at the expense of reducing the maximum gain of the main beam.

6.5.2. Non-Geostationary Satellites

For coordination of a network of non-geostationary satellites with radio astronomy observatories, the interference is nowadays estimated using the so-called *equivalent power flux density* (epfd) methodology. This methodology was developed by the Satellite Services for assessing mutual interference into each others networks, in a time-varying dynamic situation. The epfd is a direction weighted average of the aggregate interference produced at a radio telescope by a constellation of satellites, taking into account the off-axis discrimination of the radio telescope in the direction of each satellite transmitter, and the beam patterns and pointing directions of the transmitting satellites and the victim radio telescope. The mathematical definition of epfd is given in No. **22.5C1** of the Radio Regulations. Protection of the Radio Astronomy Service is then specified in terms of an epfd level, calculated for specified reference antenna patterns, which must not be exceeded for a given percentage of time. ITU-R Recommendation RA.1513 recommends that “a criterion of 2% be used for data loss to the RAS due to interference from any one network, in any frequency band which is allocated to the RAS on a primary basis.”

Application of the full equivalent power flux density model is complex and time-consuming. Monte-Carlo simulations need to be run for a representative range of observing directions and satellite configurations, and the fractional data loss to Radio Astronomy then needs to be assessed.

It is useful to avoid having to apply the efpd methodology when it may not be necessary. A possible approach is to estimate the spfd of unwanted emissions in the vicinity of the radio observatory under consideration, and compare these with the levels in ITU-R Recommendation RA.769. It would only be necessary to pay more extensive consideration to those cases where the ITU-R Recommendation RA.769 levels are exceeded.

6.5.3. Distribution of Unwanted Emissions within the Radio Astronomy Band

In cases where the width of the radio astronomy band under consideration is larger than the structure of the spectrum of unwanted emissions produced by the transmitter, a suitable working method to ensure that radio astronomical observations will not suffer detrimental interference is that the pfd of unwanted emissions across the entire radio astronomy band shall not exceed the continuum pfd in ITU-R Recommendation RA.769 and within any section of that band of width equal to the designated channel bandwidth for spectral line observations, the pfd of unwanted emissions shall not exceed the value in that ITU-R Recommendation RA.769 for spectral line observations. This method reduces the potential problem of narrow-band interference, and addresses the need for criteria applicable at the band edges.

7.

Does Radio Astronomy need Frequency Bands that are 100% Free of Interference?

7.1. Allocations for Radio Astronomy

The ITU conference WARC 1959 had a special significance for Radio Astronomy for two reasons. First, Radio Astronomy was recognised as a “radiocommunication service”. Second, a series of frequency bands was allocated to the Radio Astronomy Service, as radio-quiet “windows” through which radio astronomers could observe the universe. These bands were reviewed by subsequent conferences, including WARC-92, WRC-95 and WRC-2000. The results are shown in Table 3 (Section 4.2). The fraction of the total spectrum allocated to the Radio Astronomy Service in the ITU Radio Regulations can be summarised as follows:

< 30 GHz:
1.3% primary exclusive for passive frequency use
1.2% primary shared allocations
0.5% secondary allocations

30 - 275 GHz:
16.8% primary exclusive for passive frequency use
38.3% primary shared allocations
5.1% secondary allocations

All frequency bands <275 GHz:
15.1% primary exclusive for passive frequency use
34.2% primary shared allocations
4.6% secondary allocations

The recognition of Radio Astronomy as a service in the same way as broadcasting and mobile communication, was an historic step, as it created a legal basis for Radio Astronomy to seek protection against “harmful” interference. The ITU-R Radio Regulations provide three levels of protection.

1. “Primary” allocations give legal protection from interference, but they are not necessarily exclusive as indicated above.

2. “Secondary” allocations do not give protection from primary users in the same band. Radio services operating in a frequency band in which they have a secondary allocation shall not cause interference to services having a primary allocation in this band, nor can they claim protection from harmful interference from stations of a primary service operating in the band.

3. “Footnotes” draw the attention to the use of a specific band by Radio Astronomy. No. **5.149** urges Administrations to take all practicable steps to protect the Radio Astronomy Service from harmful interference. It notes that emissions from spaceborne or airborne stations can be particularly serious sources of interference to the Radio Astronomy Service.

However, the passive nature of the Radio Astronomy Service needs to be considered here. Radio Astronomy cannot cause interference! Hence secondary allocations are, in practice, the same as mentioning Radio Astronomy in a footnote and provide no legal protection. Thus, in frequency bands in which the Radio Astronomy Service does not enjoy primary status, protection is at the discretion of Administrations that are willing to take the appropriate practical steps to achieve this protection.

The highest level of protection is provided by the exclusively passive bands. No. **5.340** of the Radio Regulations lists frequency bands in which “all emissions are prohibited.” These frequency bands are allocated to the Radio Astronomy Service, the Earth Exploration Satellite Service, EESS, and the Space Research Service, SRS, for exclusively passive use. There are no allocations to active services in these frequency bands. These frequency bands are the most important bands for one or more of the passive services to which they are allocated. The text of the footnote is very short and clear and difficult to misinterpret.

5.340: All emissions are prohibited in the following bands:
- 1400.0 - 1427.0 MHz,
- 2690.0 - 2700.0 MHz except those provided for by No. **5.422,**
- 10.68 - 10.70 GHz except those provided for by No. **5.483,**
- 15.35 - 15.40 GHz except those provided for by No. **5.511,**
- 23.60 - 24.0 GHz,
- 31.3 - 31.5 GHz,
- 31.5 - 31.8 GHz in Region 2,
- 48.94 - 49.04 GHz from airborne stations,
- 50.2 - 50.4 GHz[1],
- 52.6 - 54.25 GHz,
- 86 - 92 GHz,
- 100 - 102 GHz,
- 109.5 - 111.8 GHz,
- 114.25 - 116 GHz
- 148.5 - 151.5 GHz,
- 164 - 167 GHz,
- 182 - 185 GHz,
- 190 - 191.8 GHz,
- 200 - 209 GHz,
- 226 - 231.5 GHz,
- 250 - 252 GHz.

Even an exclusively passive primary allocation of a particular band does not guarantee complete freedom from interference, however, since No. **4.6** of the ITU-R Radio Regulations states that “protection from services in other bands shall be afforded to the

---

1. **5.340.1** The allocation to the Earth Exploration-Satellite Service (passive) and the Space Research Service (passive) in the band 50.2 - 50.4 GHz should not impose undue constraints on the use of the adjacent bands by the primary allocated services in those bands.

Radio Astronomy Service only to the extent that such services are afforded protection from each other".

In practice, Radio Astronomy sometimes has to operate as if it has a secondary allocation worldwide, comprising the whole radio spectrum. And, in fact, many observations are being made outside frequency bands allocated to the Radio Astronomy Service. Hence the question arises: does Radio Astronomy need protected frequency bands that are 100% free of interference?

7.2. Human-generated Radiation from the Sky

Radio Astronomy studies radio sources in the universe and until 1957, when the first artificial satellite, Sputnik, appeared, there were only natural sources. Now there are thousands of artificial satellites of the Earth, of which about 10% are geostationary. Their number is still increasing and it is expected that many satellite networks will be implemented in the coming years. They all contribute to the welfare of humanity and to further development of science and culture. However, there is a price to be paid. With each new satellite launched, another artificial "radio star" appears in the sky. At present these satellites mainly use frequency bands around 137 - 144 MHz, 1.5 - 2.5 GHz, 4 - 6 GHz, 11 - 14 GHz, 20 - 30 GHz and 40 - 50 GHz, but new allocations are sought in all parts of the spectrum, especially for space services. In addition to signals in the allocated frequency bands necessary to perform their functions, these satellites – as well as associated terrestrial transmitters – produce unintended and undesired radiation in neighbouring and even in far remote frequency bands.

Although the constellation of artificial Earth satellites is still very small in comparison with the natural radio sources in the universe, they can make Radio Astronomy measurements on Earth impossible in some regions and at some times. The radiation received from artificial satellites is relatively intense because of their very small distance (in astronomical terms) from the Earth. Many systems currently under development apply mass produced handheld Earth terminals with omnidirectional antennae, like GPS receivers and mobile telephones. They require signal strengths at the receiver more than 10^8 times stronger than astronomical radio sources. Therefore the unwanted emissions from satellites, if they are not well suppressed by technical means, may appear stronger throughout an increasing fraction of the radio spectrum.

If interference to Radio Astronomy is to be avoided, the unwanted emissions from satellites will need to be suppressed by many tens of dB below the general spurious emission limits given in No. **3** of the Radio Regulations. Figure 11 shows a case where this has been successfully done. The unwanted emissions from this broadcasting satellite, that operates only 30 MHz above the passive band 1400 - 1427 MHz, have been suppressed to a level below –260 dB(W/m^2Hz), more than 50dB below the level required in No. **3**. This excellent performance of the satellite even caused doubts about whether the satellite was active or at the correct position, but as Figure 12 shows, the unwanted emissions from the satellite are easily detected in the frequency band 1660 - 1670 MHz that is allocated to Radio Astronomy on a primary basis.

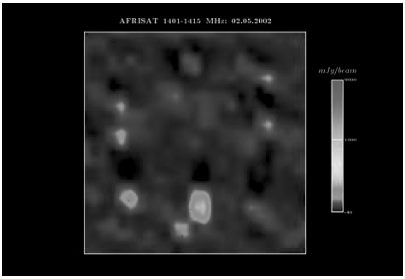

Figure 11: Radio map of the region of sky surrounding a geostationary broadcasting satellite, showing that unwanted emissions from the satellite into the (passive) frequency band 1401 - 1415 MHz are below -260 dB(W/m^{2}Hz). Measurements were made with the Effelsberg 100-m antenna (Klaus Ruf, private communication).

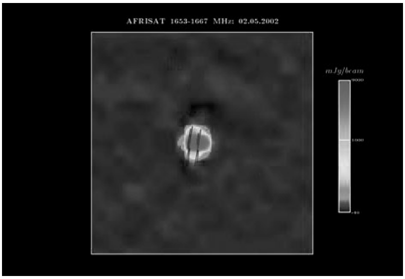

Figure 12: Radio map of the same region of sky plotted in Figure 14, showing that the unwanted emissions from the geostationary broadcasting satellite are easily detected in the frequency band 1660 - 1670 MHz that is allocated to the Radio Astronomy Service on a primary basis, shared with active services. Measurements were made with the Effelsberg 100-m antenna (Klaus Ruf, private communication).

7.3. The Threats to Radio Astronomy

When the ITU recognised Radio Astronomy as a radiocommunication service, it took no account of the fact that this service is a passive service. In the ITU Radio Regulations there is no definition of a passive service, so a distinction between passive and active services is not yet possible.

In spite of the established use of the term “passive” with respect to Radio Astronomy, the wider radio community often fails to grasp its true significance. It is after all quite different to receive a broadcast say +20 dB above the receiver noise level than to detect faint emissions at some –60 dB below the receiver noise after long integration. Consequently the unusual sensitivities obtained in radio astronomical measurements obtained by integration are not always appreciated as the reason for the high vulnerability to interference of this service. Also, the fact that the receivers are often very broadband makes the situation even more difficult. Finally there is the need for accurate calibration of the sensitive instruments, which usually requires an interference-free band.

It is a given fact that the future will see only increasing demands on the use of the radio spectrum by existing or new services.

7.4. Interference Mitigation

Some of the most fundamental problems of physics and the early history of the universe require access to large tracts of the radio spectrum for their solution. Radio astronomers understand that it is unrealistic to request that all this extra spectrum be allocated to the Radio Astronomy Service on a worldwide basis. However, the continuing development of research requires that more and more Radio Astronomy observations will need to be done outside frequency bands allocated to the Radio Astronomy Service. Radio astronomers are, therefore, actively working on the development of interference suppression techniques to enable access to frequency bands where no allocation to Radio Astronomy exists.

This development does not mean that the protection of quiet frequency bands for Radio Astronomy becomes less important: on the contrary, the dynamic occupancy of the radio spectrum implies that Radio Astronomy observations outside the frequency bands allocated to the Radio Astronomy Service can be done only at some price. This price has at least three aspects:

1. much longer observing times are needed because a large fraction of the measurement data is affected by interference and has to be rejected;
2. very intensive and interactive data processing has to be done to extract the astronomical information from the data and separate this from unwanted human-generated transmissions; and
3. proper calibration of the observations and of the instruments may not be possible when the data are affected by interference. (In some cases, however, it is possible to do an approximate calibration using measurements taken in a nearby interference-free passive band.).

Modern interference excision techniques based on digital signal processing can be applied to Radio Astronomy observations, if noticeable interference is present, and particularly when observing outside allocated bands. There is, however, a danger associated with using these potentially useful mitigation techniques, because they may excise the desired signals as well. It has been reported that at one observatory, pulsar emission was detected but rejected as interference, and excised from the data, some years before pulsars were “discovered”. Scientific research is always turning up new discoveries with unexpected properties. Without prior knowledge of the cosmic source and the interferer it can be impossible for mitigation techniques to distinguish between the two. Current research addresses specifically the development of mitigation techniques for radio interferometers: the differences between the interferometer characteristics for a celestial source and a human-generated source contain information that can be used to develop mitigation techniques. Today experiments are being done with mitigation techniques that are able to suppress some interfering signals by a few tens of dB, but not yet to the levels of Recommendation ITU-R RA.769**,** which are considered to be typical interference free levels acceptable to the Radio Astronomy Service.

CRAF is concerned about the argument that is occasionally put forward that passive bands may be used by ultra-wideband, UWB, devices, if the UWB emissions are weaker than some of the permitted levels of unwanted emissions of transmitters operating on other frequencies. Most celestial radio astronomical emissions are intrinsically wideband, and this fact has been one of the powerful tools available to distinguish between natural and artificial signals. Unfortunately, the UWB emissions being proposed today in many ways mimic celestial wideband emission, being weak and noise-like. This makes the task of mitigation against UWB much harder than mitigation against other interfering signals.

7.5. Are Radiation-free Oases Necessary?

From our point of view the obvious answer is **YES**; but let us consider the practical meaning of such an answer under the prevailing conditions. As stated previously, the Radio Astronomy Service (in the sense of the ITU-R definition of a radiocommunication service) is not a single category of radio stations providing a standard service similar to radiocommunication services. Radio Astronomy is a fundamental research science, with no commercial profit, with a wide variety of scientific aims, using different types of extremely highly sophisticated instruments, each having different observing techniques, and different vulnerabilities to interference. Effectively Radio Astronomy is a mixture of different services, with different aims, instruments and different vulnerabilities to interference.

Those radio observations that intrinsically are sensitivity-limited because of very a narrow bandwidth (e.g. spectral line searches) or a very short integration time (e.g. pulsar searches) are especially vulnerable to interference. So too are observations of transient phenomena that will not be repeated, such as the collision of comet Shoemaker-Levi with Jupiter. So too are experiments that require simultaneous observations at many radio observatories for their success. Without interference-free access to the passive bands, Radio Astronomy could not conduct such observations successfully. The situation for other type of observations, such as map-making, may be less severe because the level of sensitivity needed can be obtained by longer integration times provided the celestial radio source does not vary. However many cosmic sources do show intensity variability (which can have any time scale). The practical situation is that the contemporary limits, as recommended by ITU-R studies, are all given for this latter type of observations, not for measurements that are at the limit of what is technically possible.

Nowadays the situation gets even more complex. On the one hand Radio Astronomy really needs radiation-free parts in the spectrum, on the other hand this comes at a time when various new and existing communication services need wider use of the spectrum. Radio Astronomy is evolving more and more from a phenomenological science to astrophysics and astrochemistry, and therefore the requirements for observations increasingly go in the direction of those that are intrinsically limited in sensitivity. The calibration that has to be the basis for quantitative analyses has to be done in an interference-free environment. In practice 10-50% of the observing time of an instrument may be used for calibration.

7.6. Scientific and Cultural Value

Astrophysics goes much further than relating laboratory physics to the stars and galaxies. Through our telescopes and particularly our radio telescopes we have access to physical conditions that are impossible to attain in a laboratory. For example, when the neutron was discovered there seemed no chance of testing the behaviour of a large number of neutrons tightly packed together, yet we now regularly observe pulsars which are stellar remnants consisting only of neutrons. Magnetic fields of some tens of Tesla are available in the laboratory: in the same neutron stars the fields are as large as millions of Tesla. Quasars provide another example of science that cannot be done on the terrestrial scale. High-energy plasma physics on this scale may never be attainable in our experimental fusion reactors, but it may at least be a target to understand and possibly emulate the process on a more domestic scale.

So, astronomy, and especially Radio Astronomy, is not merely providing a description of the universe; it is testing the laws of basic, fundamental physics. The most remarkable of these is the test of the General Theory of Relativity provided by the binary pulsars. General Relativity is concerned with the behaviour of space and time, and the way they are affected by mass. The ideal test-bed is a binary pulsar system, in which an accurate clock – the pulsar itself – moves in orbit around a massive star, its partner in the binary system. The results of the tests confirm in great detail this theory, ruling out several alternatives which were still allowable on laboratory evidence alone. The discovery of the first double pulsar system in 2004 will allow even more sensitive tests of relativity theory in future.

For all humankind, the overwhelming questions of our place in the universe provide a background for our increasingly urgent concern with our place on Earth. It may not be comforting to contemplate the rapid changes in the environment, the explosive growth of world population, and the depletion of our resources, by pacing them against cosmological evolution. It is nevertheless an essential contribution of science to provide a perspective. Radio Astronomy has contributed vitally to cosmology in two areas. First, the realisation that observed sources included the most distant observable objects in the universe. A second vital contribution by Radio Astronomy to cosmology can rank as one of the greatest discoveries ever made. The occasion takes us back to the origins of Radio Astronomy from within the science of radiocommunications. As these techniques moved to even shorter wavelengths, it became again necessary to investigate the natural noise sources which provide the basic limitation to long distance communications. The radio links analysed were between satellites and ground stations with wavelengths in the cm range. Again the pioneering observations were made at Bell Laboratories. The result was the discovery in 1963 by Penzias and Wilson of the Cosmic Microwave Background radiation, CMB.

The cosmic microwave background is the most primitive radiation we can detect. It arose when the universe was a dense expanding fireball less than one million years old. In fact, the CMB is the best experimental evidence of the Big Bang theory. We see the same radiation today redshifted to radio wavelengths. It is a uniform all-pervasive radiation with the spectrum of a black-body of temperature 2.7 K. Radio telescopes detect it as an excess noise contribution to the total receiver noise. It is a very low level noise contribution, compared with “ambient” terrestrial temperatures of about 300 K, and it is inherently very difficult to measure. Because the CMB radiation is almost isotropic over the sky, the excess noise is the same, to within a milliKelvin, wherever the telescope points.

There are also fluctuations of the CMB that are even more difficult to measure. From them we learn about the phenomenology of the very early universe, including the anisotropy of the mass condensation process and subsequent formation of galaxies and clusters of galaxies. This will enable us to discriminate among several cosmological models, which are still allowed on the basis of current knowledge.

Another interesting effect shows that the whole universe is filled with 2.7 K radiation. The so-called Sunyaev-Zeldovich effect predicts a small variation of the spectrum of the 2.7 K radiation, due to the absorption by the very thin and hot gas in clusters of galaxies. The Sunyaev-Zeldovich effect is expected to be best observable in the frequency range between 10 and 100 GHz. It is a sad reflection on progress that this signal could soon become swamped by a local background interference of human-generated emissions produced by spread-spectrum techniques, unwanted sidebands and spurious emissions. In particular it is easy to anticipate that the combined effect of many spread-spectrum transmitters will be to produce a noise floor which will mimic and swamp these ancient signals from the beginning of our universe.

Radio astronomy has become a vital part of international scientific life in many countries. It shows how science can contribute to our culture and to our understanding of our history and our environment. We shall be immeasurably poorer if we use up the remaining quiet portions of the radio spectrum and thereby we lose the ability to look through the radio window at the universe.

8.

Local, Regional and Global Policies

The interference problems in radio astronomical observatories can be divided into different categories according to the distance of the interfering sources. We distinguish problems at a local, regional and a global level (see Section 6.2).

The local problems occur on a scale ranging from the immediate surroundings of the radio astronomical observatory to the borders of the country in which the observatory is located. They can be due to due, for example, to spark-plugs of cars, computers, household equipment (particularly when faulty). They require a local solution such as a radio-quiet zone around the radio astronomical observatory (see Section 6.3).

TV and audio broadcasting by adjacent channel or in-channel use of a radio astronomical reception bands is regarded as a regional problem. These problems are different for Europe, America, Asia, Africa and Australia. They require a regional consideration.

The worst for Radio Astronomy are the global problems, particularly those caused by satellites and satellite systems.

In this section we discuss the different organisations and bodies that radio astronomers need to deal with at all three levels.

8.1. Communication between Radio Astronomy and National Administrations

Active spectrum users, usually originating from broadcast, industry, and telecommunication companies, are one set of partners that radio astronomers have to coexist with in the "electromagnetic society". Another group is the Administrations, whether they be national (of sovereign countries), regional (in Europe bodies such as the CEPT or the European Union) or global (e.g. the United Nations and its organisations, one of which is the ITU). The problem space is illustrated in Figure 13.

Quite often it is experienced that the interests of activities along each of the axes are

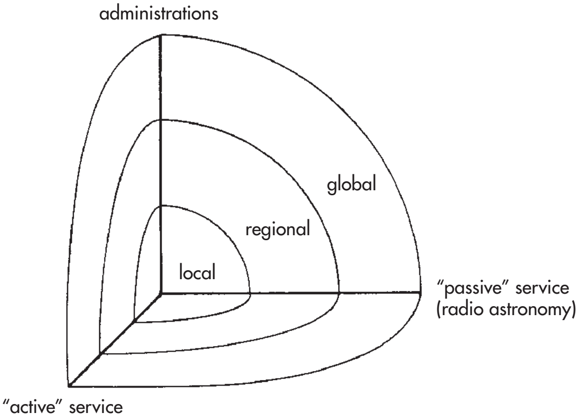

Figure 13: Problem space for frequency management.

orthogonal to each other. This implies that good communications and negotiation fora are mandatory for adequate “living together in the electromagnetic society”.

Since Radio Astronomy is a purely scientific and usually a government-funded activity, it is obvious that communication between Radio Astronomy and the national Administrations must be well organised. This is not least because the national Administrations are the voting members of the World Radio Conferences of the ITU, and at regional European level of the CEPT and the EU. The national Administrations are responsible for implementation of the ITU Radio Regulations and for providing protection where needed.

On the local scale, radio observatories communicate with the local authorities and/or national Administrations and related bodies to alleviate the problems and search for structural solutions within the internationally accepted agreements. The latter is of course mandatory since electromagnetic waves do not stop at country borders. In the USA the need for frequencies and interference protection for Radio Astronomy and passive sensing are coordinated through the Commission on Radio Frequencies, CORF. Established in 1960, CORF is under the aegis of the US National Academy of Sciences. However, it sometimes also addresses regional issues.

On the regional scale in Europe, CRAF coordinates the European efforts for the protection of radio spectrum bands used by the Radio Astronomy Service and other passive applications (see Section 8.2). The Radio Astronomy Frequency Committee in the Asia-Pacific region, RAFCAP, established in 2001, serves a similar purpose in the Asia-Pacific region.

At the global level this work is done by IUCAF, the Scientific Committee on the Allocation of Frequencies for Radio Astronomy and Space Science (under the auspices of Unesco’s International Council of Scientific Unions, ICSU) (see Section 8.3).

8.2. CRAF and its European Role

The Committee on Radio Astronomy Frequencies of the European Science Foundation, CRAF, was founded in 1988 and is made up of representatives of the major radio astronomical observatories in Europe.

An important part of its work is to assist the Scientific Committee on the Allocations of Frequencies for Radio Astronomy and Space Science, IUCAF. This body is a joint commission of the International Union of Radio Sciences, URSI, the International Astronomical Union, IAU, and the Committee on Space Research, COSPAR. These three are amongst the many international scientific unions which, under the International Council of Scientific Unions, ICSU, devolve from Unesco.

According to its Charter and Terms of Reference, the mission of CRAF is to:

- keep the frequency bands used for radio astronomical observations free from interference;
- argue the scientific needs of Radio Astronomy for continued access to and availability of the radio spectrum for Radio Astronomy within the European arena;

- support related science communities in their needs of interference-free radio frequency bands for passive use.

CRAF attempts to coordinate the representations made to the various national and supranational radio regulatory bodies within Europe for the protection of the Radio Astronomy Service. It operates both at an administrative and at a technical level. It is concerned with setting up programmes of interference monitoring and seeks to develop technical means for the protection of radio astronomical observations. It has an educational role in making other, particularly active radio spectrum users, aware of the sensitivity and consequent need for protection of the RAS. This function is fulfilled in part by the publication of this Handbook for Radio Astronomy and a Handbook for Frequency Management, which are intended to be made widely available, particularly to Administrations, system designers and to spectrum managers. Furthermore, CRAF publishes a regular Newsletter, and maintains a website (URL address: http://www.astron.nl/craf).

Since 1 January 1997, CRAF has employed a full time pan-European Radio Astronomy Spectrum Manager.

CRAF is a Sector Member of the ITU Radiocommunication Sector and it has formal observer status within the CEPT.

8.2.1. Actions and Results

CRAF has acted on several fronts to protect the Radio Astronomy Service. Among other things, its work has been to:

- Communicate and cooperate with the appropriate World and European bodies, the ITU, the Radiocommunications Bureau, RB, (before 1993 this was the Comité Consultatif International des Radiocommunications, CCIR) which is the technical committee of the ITU, the International Frequency Registration Board, IFRB (whose activities have also been incorporated in the ITU-R RB since 1993), the Conférence Européenne des Postes et des Télécommunications, CEPT, and its offshoot the European Radiocommunications Office, ERO, to ensure the continued good management of the radio spectrum.
- Participate in ITU-R study activities addressing issues relevant to the protection of Radio Astronomy.
- Correspond with various Administrations and the CEPT concerning the possible use of television channel 38 (608 - 614 MHz).
- Communicate at ministerial level with Administrations concerned on specific spectrum issues, such as MSS deployment at ~1.6 GHz, Short Range Radar developments at ~24 GHz and ~79 GHz, and power line communications. CRAF continues to make representations about such issues to the appropriate authorities.
- Work in close collaboration with IUCAF and with kindred bodies, towards the preparation of a concerted Radio Astronomy position for the various World Administrative Radio Conferences, which are held roughly every three to four years. Despite fears to the contrary, the conference decisions and recommendations

have as a result been often positively favourable to the Radio Astronomy Service. For example, it was agreed to:

- Contribute to the NATO-Committee on the Challenges of Modern Society, CCMS, by investigating the possibilities for more alert administrative control of frequency allocation and management, and possibly obtaining international judicial support. Report No. 213 on The Passive Use of the Frequency Spectrum (published in 1996) of this commission is a result of this effort.
- Draw attention, in various publications of its members, to the effects of human-generated interference on radio astronomical observations.
- Encourage participating Institutes to monitor interference. The Dwingeloo Radio Observatory in the Netherlands maintains a European database on events of harmful interference suffered by European Radio Astronomy observatories. European radio observatories have completed a coherent monitoring campaign to monitor the interference experienced from the Russian global navigation satellites system GLONASS. These observations were of value in negotiations between IUCAF and the GLONASS Administration and led to an agreement between GLONASS and IUCAF on the long-term protection of Radio Astronomy at 1.6 GHz from GLONASS interference.
- Participate in CEPT activities at various levels, including its Working Group FM and various CEPT WGSE project teams.
- Communicate with the CEPT concerning the Detailed Spectrum Investigation, DSI, which the European Radiocommunications Office is carrying out in preparation of a European Common Allocation Table by 2008.
- Negotiate with Iridium LCC on arrangements to protect Radio Astronomy in the band 1610.6 - 1613.8 MHz. This work resulted in Recommendations of the CEPT Milestone Review Committee which contain conditions for the Iridium satellite system to assure Radio Astronomy adequate protection. These conditions are guidance to Administrations for licensing the Iridium system.
- Communicate actively with industry and operators to work towards solutions for compatibility problems:
  - Société Européenne des Satellites in Luxembourg and the German Administration to solve the problem of out-of-band emission from the GDL-6/ASTRA-1D satellite in the Radio Astronomy band 10.6 - 10.7 GHz. The ASTRA satellite, which is operating in a Fixed Satellite Service band, causes harmful interference in the adjacent subband 10.69 - 10.7 GHz. The band 10.6 - 10.7 GHz is heavily used by Effelsberg observatory in Germany. This issue was also extensively discussed with in the CEPT.
  - INMARSAT on the coordination with Aeronautical Earth stations near 1660.0 - 1660.5 MHz.
  - GLOBALSTAR on the coordination with Mobile Earth stations affecting Radio Astronomy operations in the band 1610.6 - 1613.8 MHz.
- Discuss with the Italian Administration the necessary improvement of communication and coordination between itself and the Radio Astronomy Service in Italy.

8.2.2. WRCs and Current Problems

Since 1993 World Radio Conferences, WRCs, are currently held every two to four years. At the WRCs, specific problems concerning frequency allocations are considered at an intergovernmental level. The Radio Astronomy Service being passive, academic and non-commercial, inevitably encounters powerful – especially commercial – interests hungry for spectrum ranged against it. Consolidating and defending its existing allocations is an on-going educational and lobbying exercise. Although CRAF itself is not entitled to send a delegation to these conferences and vote, nevertheless members of CRAF usually attend the meetings as members of the IUCAF delegation or of their national delegations, and contribute in no small measure to the favourable outcomes for the Radio Astronomy Service.

One favourable result of the very last WARC, WARC-92, was the elevation of the status of the Radio Astronomy Service in the band 1610.6 - 1613.8 MHz to CO-PRIMARY worldwide. This band corresponds to one of the transitions of the important OH radical. At present there is interference in this band from out-of-band transmissions from the spread-spectrum signals from the Russian GLONASS satellites. Members of CRAF have assisted IUCAF in technical discussions with the GLONASS Administration in a search for means to enable radio astronomical work to be resumed in this OH band.

Another favourable result at the WARC-92 was that for the first time a WARC recommended that ITU-R study, as a matter of urgency, the spurious emissions from space transmissions in all bands, with a view to specifying spurious and out-of-band emission limits in the ITU Radio Regulations, for the protection of the Radio Astronomy and other passive services. The first such limits were set by WRC-2000.

The WRC-2000 also re-allocated the frequency bands between 71 and 275 GHz with special attention to the passive services. The result was that within the atmospheric windows essentially all frequency bands used by radio astronomers are now allocated to the Radio Astronomy Service.

At WRC-03 an issue was raised concerning FSS feeder links near 1.4 GHz. This issue is of great importance for Radio Astronomy, to which the band 1400 - 1427 MHz is of prime importance. It is expected that WRC-07 will decide on regulations for this matter.

8.2.3. Long-term Problems

One urgent problem, which has not been fully studied by the ITU Radiocommunication Sector, ITU-R, and for which adequate recommendations are still lacking, was touched on earlier. It is the matter of the increasing use of spread-spectrum or CDMA (Code Division Multiple Access) systems. This technique is being introduced into communication systems as a measure to maintain privacy and as a way of mitigating the effect of interference from transmissions of the more traditional kind. It consists of modulating carriers with very rapid non-information bearing modulation which increases the physical bandwidth of the signal to many times that required to convey the meaningful information. It has the effect of spreading the energy of the transmission very thinly over a relatively enormous spectral band. Since the Radio Astronomy Service is routinely concerned with the measurement of signals many orders of magnitude weaker than other services, and often uses large bandwidths to improve sensitivity, this thin spreading of interference which might indeed not be noticed by other services, is totally and immediately devastating in its impact. CRAF is concerned to expose the wrong thinking which is leading to the use of spread-spectrum and to see that its use be subject to regulation and that it be as far as possible eliminated.

The development of Short Range Radar, SRR, at ~24 GHz and ~79 GHz for automobiles is monitoring by CRAF with great concern, most especially since the band 23.6-24.0 GHz enjoys protection under No.**5.340,** which states that all emissions are prohibited in the band. In 2004 regulations were developed in Europe to enable the deployment of SRR at ~24 GHz in spite of this footnote. For the protection of Radio Astronomy an automatic deactivation mechanism is foreseen to switch off SRR devices when they come within a defined separation distance from a Radio Astronomy station operating in the range 22-24 GHz. In the longer term (before 1 January 2014), SRR should move from ~24 GHz to ~79 GHz.

Similar concerns apply to ultra-wideband, UWB, technology more generally. UWB is expected to use bandwidths exceeding several GHz. Currently there are no adequate regulations to address the frequency management issues raised by UWB technology. CRAF is actively participating in the relevant studies at CEPT and ITU-R level.

Looking to the distant future another concern is to preserve the far side of the Moon, which is naturally and permanently screened from terrestrial transmitters, as an interference-free zone for the benefit of future generations of radio astronomers. CRAF is actively seeking to ensure appropriate conventions are adopted now to provide this protection before the region becomes subject to commercial and other interests.

Technological developments within the different active radio services force CRAF to remain alert to their possible impact on the Radio Astronomy Service. This implies that CRAF must adjust its strategy continuously and dynamically in order to cope with these developments.

8.2.4. The European Science Foundation

The European Science Foundation, ESF, acts as a catalyst for the development of science by bringing together leading scientists and funding agencies to debate, plan and implement pan-European scientific and science policy initiatives.

The European Science Foundation is the association of 78 major national funding agencies devoted to scientific research in 30 countries. It represents all disciplines: physical and engineering sciences, life, earth and environmental sciences, medical sciences, humanities and social sciences. The Foundation assists its Member Organisations in two main ways: by bringing scientists together in its scientific programmes, EUROCORES, Forward Looks, Networks and ESF Research Conferences, to work on topics of common concern; and through the joint study of issues of strategic importance in European science policy.

It maintains close relations with other scientific institutions within and outside Europe. By its activities, the ESF adds value by cooperation and coordination across national frontiers and endeavours, offers expert scientific advice on strategic issues, and provides the European forum for science.

8.2.5. Addresses

European Science Foundation

1 quai Lezay-Marnésia, B.P. 90015,
67080 Strasbourg cedex, France
Tel: +33 (0)3 88 76 71 07, Fax: +33 (0)3 88 37 05 32,
Email: mgruber@esf.org

Scientific Secretary for Physical and Engineering Sciences: **N. Williams**

Committee on Radio Astronomy Frequencies, CRAF

Chair: **R. Ambrosini**
Istituto di Radioastronomia C.N.R.,
Via Gobetti 101, 40129 Bologna, Italy
Tel: +39 051-6399361, Fax: +39 051-6399431,
Email: ambrosini@ira.cnr.it

Secretary: **T. A. Th. Spoelstra**
Netherlands Foundation for Research in Astronomy,
P.O. Box 2, 7990 AA Dwingeloo, Netherlands
Tel: +31 521-595100, Fax: +31 521-597332,
Email: spoelstra@astron.nl

Members: **R. Ambrosini**
Istituto di Radioastronomia C.N.R.,
Via Gobetti 101, 40129 Bologna, Italy
Tel: +39 051-6399361, Fax: +39 051-6399431,
Email: ambrosini@ira.cnr.it

R. Bachiller
Observatorio Astronomico Nacional, IGN,
Apartado 1143, E-28800 Alcala de Henares, Spain
Tel: +34 1-885-5060/+34 1-885-5061,
Fax: +34 1-885-5062, Email: bachiller@oan.es

E. Bervalds
Latvian Academy of Sciences,
19 Turgeneva Street, LV-1524 Riga, Latvia
Tel: +371 7228321, Fax: +371 7821153,
Email: berv@acad.latnet.lv

F. Clette
Observatoire Royal de Belgique,
Département de Physique Solaire,
Avenue Circulaire 3, B-1180 Brussels, Belgium
Tel: +32 23730233, Fax: +32 23730224
Email: frederic.clette@oma.be

R. J. Cohen
The University of Manchester, Jodrell Bank Observatory,
Macclesfield, Cheshire SK11 9DL, UK
Tel: +44 1477-571321, Fax: +44 1477-571618,
Email: rjc@jb.man.ac.uk

L. M. dos Santos Rocha Cupido
Centro de Física dos Plasmas, Instituto Superior Técnico,
Avenida Rovisco Pais, 1049-001 Lisbon, Portugal
Tel: +351 234 187877, Fax: +351 234 315885,
Email: cupido@mail.ua.pt

B. A. Doubinski
Scientific Secretary, Scientific Council on Radio Astronomy
of the Russian Academy of Sciences,
Moscow, centre, GSP-3, Marx Avenue 18, Russia
Tel: +7 095-2028286, Fax: +7 095-2038414,
Email: borisd@mail.cplire.ru

I. Fejes
FOMI Satellite Geodetic Observatory,
P.O.Box 546, H-1373 Budapest, Hungary
Tel: +36 27-374-980, Fax: +36 27-374-982,
Email: fejes@sgo.fomi.hu

E. Fürst
Max-Planck Institut für Radio Astronomie,
Radioobservatorium Effelsberg,
D-53902 Bad Münstereifel, Germany
Tel: +49 2257-301-120, Fax: +49 2257-301-69,
Email: p002fue@mpifr-bonn.mpg.de

A. Jessner
Max-Planck Institut für Radio Astronomie,
Auf dem Hügel 69, D-53121 Bonn, Germany
Tel: +49 228-525-127, Fax: +49 228-525-229,
Email: jessner@mpifr-bonn.mpg.de

K. Jiricka
Astronomical Observatory,
25165 Ondrejov, Czech Republic
Tel: +420 204-620154, Fax: +420 204-620110,
Email: jiricka@asu.cas.cz

M. Lindqvist
Onsala Space Observatory,
SE-43992 Onsala, Sweden
Tel: +46 31-7725508, Fax: +46 31-7725590,
Email: michael@oso.chalmers.se

I. Küçük
Erciyes University, Faculty of Arts and Sciences Department
of Astronomy and Space Sciences,
Talas Yolu, 38039 Kayseri, Turkey
Tel: +90 352-437-49-01/33110, Fax: +90 352-437-49-33,
Email: kucuk@erciyes.edu.t

R. P. Millenaar
Netherlands Foundation for Radio Astronomy,
P.O. Box 2, 7990 AA Dwingeloo, Netherlands
Tel: +31 521-595100, Fax: +31 521-597332,
Email: millenaar@astron.nl

C. A. Monstein
Radio Astronomy Group, Institute of Astronomy,
ETH Zentrum, CH-8092 Zürich, Switzerland
Tel: +41 1-632 42 24, Fax: +41 1-6321205,
Email: monstein@astro.phys.ethz.ch

D. Morris
Institut de Radio Astronomie Millimétrique, IRAM,
300 rue de la Piscine, Domaine universitaire de Grenoble,
38406 St-Martin-d'Hères cedex, France
Tel: +33 4 76 82 49 30, Fax: +33 4 76 51 59 38,
Email: morris@iram.grenet.fr

J. P. V. Poiares Baptista
ESTEC,
Postbus 299, 2200 AG Noordwijk, Netherlands
Tel: +31 71-5656565, Fax: +31 71-5654999,
Email: pedro@xe.estec.esa.nl

J. Ritakari
Metsähovi Radio Observatory,
Metsähovintie 114, FIN-02540 Kylmaelae, Finland
Tel: +358 9-2564831, Fax: +358 9-2564531,
Email: jr@kurp.hut.fi

P. Scott
Mullard Radio Astronomy Observatory, Cavendish Laboratory,
Madingley Road, Cambridge CB3 0HE, UK
Tel: +44 1223 337306, Fax: +44 1223 354 599,
Email: paul@mrao.cam.ac.uk

J. B. Usowicz
Toru Centre for Astronomy, Department of Radio Observatory,
Gagarina 11, 87-100 Toru, Poland
Tel: +48 56-62511651, Fax: +48 56-62511651,
Email: ju@astro.uni.torun.pl

W. van Driel
Observatoire de Paris, GEPI,
5 place Jules Janssen, 92195 Meudon cedex, France
Tel: +33 1 45 07 77 31, Fax: +33 1 45 07 77 09,
Email: wim.vandriel@obspm.fr

G. Wannberg
Deputy Director Technical, EISCAT Scientific Association,
Box 812, S-98128 Kiruna, Sweden
Tel: +46 980-79153, Fax: +46 980-79161,
Email: ugw@eiscathq.irf.se

Frequency Manager: **L. Alexe**
Netherlands Foundation for Research in Astronomy,
P.O. Box 2, 7990 AA Dwingeloo, Netherlands
Tel: +31 521-595100, Fax: +31 521-597332,
Email: alexe@astron.nl

Clearing house: **Netherlands Foundation for Research in Astronomy**
P.O. Box 2, 7990 AA Dwingeloo, Netherlands
Tel: +31 521-595100, Fax: +31 521-597332,
Email: spoelstra@astron.nl

NSF liaison officer: **T. E. Gergely**
National Science Foundation, 4201 Wilson blvd, Rm 1045,
Arlington VA 22230, USA
Tel: +1 703-306-1823, Fax: +1 703-306-0525,
Email: tgergely@nsf.gov

WWW homepage **CRAF:** http://www.astron.nl/craf
ESF: http://www.esf.org

8.3. IUCAF and its Worldwide Efforts

At the 1957 General Assembly of URSI the problems of protecting Radio Astronomy were pretty well defined. But radio astronomers could not define specifically what they wanted to do. Actions taken by URSI resulted in representatives of URSI, the IAU and COSPAR attending WARC-59 in Geneva.

In 1960 under the auspices of the International Council of Scientific Unions, ICSU – a Unesco related body – the InterUnion-Commission on the Allocation of Frequencies, IUCAF was formed to continue this work for all three bodies. Its parent organisations are the International Union of Radio Science, URSI, the International Astronomical Union, IAU, and the Committee on Space Research, COSPAR. In 2000, ICSU was transformed into the International Council for Science and IUCAF became the Scientific Committee on the Allocation of Frequencies for Radio Astronomy and Space Science, while retaining its original acronym IUCAF, and remaining under the auspices of ICSU. IUCAF can participate in ITU conferences if it is invited. This holds for a union like the IAU too. At the conferences IUCAF has observer status. IUCAF does not carry out studies as a group, but it invites individuals to do so.

In the 1950s and 1960s many things were different from today: many people recognised the novelty and perspective of the science of Radio Astronomy. And the spectrum was more or less open. The IAU President of the day, Jan Oort, could speak directly to the 1959 WARC on the importance of the hydrogen 21-cm line and secure the first radio frequency allocation for passive use. The first radio molecule, OH, could receive immediate ITU recognition at the Space WARC-63.

Since 1979 there has been a growth of interference from satellites. The radio spectrum has become big business. The possibility of time-sharing has been raised. Radio astronomy has sometimes found itself facing powerful political and economic forces. IUCAF's role has had to grow as a result, although its official mandate remains the same.

The mandate of IUCAF is twofold:

1. to study and coordinate the requirements for radio frequency allocations for Radio Astronomy and space science, and make these requirements known to the national and international bodies responsible for frequency allocations; and
2. to take action aimed at ensuring that harmful interference is not caused to Radio Astronomy or space science, operating within the allocated bands, by other radio services.

9.

The Protection of Radio Astronomy and International Law

The allocation of frequency bands to the Radio Astronomy Service is regulated by the International Telecommunication Union, ITU, in its Radio Regulations, RR. The Radio Astronomy Service has been allocated a number of frequency bands (Table 3).

The status of the allocation can be primary-exclusive for passive frequency use (i.e. Radio Astronomy and other passive applications), primary shared (with active services), secondary, or “notification of use” by footnote urging Administrations to protect Radio Astronomy (No. **5.149**). In practice only a primary allocation has some protection status. When the allocation has a lower status, coordination with the proper Administration is required. The different natures of “active” and “passive” services lead to a compatibility problem, which may result in harmful interference being suffered by the passive service. It should be noted that a passive service can never cause interference. This is in particular a problem for Radio Astronomy, which uses receivers with extremely high sensitivities.

Recognising the need to protect Radio Astronomy observations, the ITU-R has adopted criteria for the protection of Radio Astronomy. These criteria have been documented in ITU-R Recommendation **RA.769** and also published in the *ITU Handbook on Radio Astronomy*. The policies of the national Administrations on frequency management, protection of services, etc., are based on the ITU Radio Regulations, which have the status of an international treaty. The status of other ITU-R documentation is that of “recommendation” or weaker. Usually, a national Administration has published its view on the use of the radio spectrum in a national *Frequency distribution plan*. This plan is only valid for frequency use within the territory of that sovereign State. Because states are sovereign bodies, this national Frequency distribution plan may deviate from the ITU Radio Regulations, but only within the limits explicitly imposed on the international level.

A national Administration gives licences to use part of the frequency spectrum, and when necessary it seeks international coordination. For example, coordination between Radio Astronomy stations operating in the band 608 - 614 MHz (channel 38 according to the Stockholm 1961 Convention) and proposed broadcasting stations was done in a number of countries to enable Radio Astronomy observations in this band.

This licensing, supervision over coordination, frequency distribution and management is a public activity of a state, i.e. dealing with the rules in the relation between the state and its citizens. Coordination itself is subject to the rights and duties of individual legal personalities. This activity is subject to private law.

9.1. Public, Private; Subject, Object

Public actors in the legal sense are *states* and their parts (e.g. a province). Intergovernmental organisations are also counted in this category (e.g. the United Nations Organization). In public law, the legal subjects (see below) make their own rules.

Private actors in the legal sense are individual legal persons: individual people, non-governmental organisations, companies, foundations.

A *legal subject* not only has rights and duties under a particular legal regime, but can also itself act on them. This is not the case for *legal objects*, such as animals, children, or other categories of “disabled” people.

9.2. Going International

International Law deals with the mutual relations between sovereign *states*. States are considered as legal subjects. International law is public law. Individual persons, non-governmental organisations, companies, and foundations under international law are legal objects, not subjects. For example, if a person of one state suffers from a problem in another state, this problem becomes a public case between the states in terms of international law. The abstract idea of *personality* of a state is the leading principle.

A *treaty* rests on an agreement between states as “legal persons”. A treaty has a public status, not a private one.

Non-governmental organisations are private actors (= not public) in the legal sense. In terms of international law, they are legal objects. However, there are also organisations for which the legal status is deduced from the legal status of the actors forming them. Such organisations can be recognised as public actors when they are powerful, e.g. the European Union. Crucial in this respect is the recognition by the states which are not members of that organisation.

Relations between legal person A of country K and legal person B of country L and an event in which both play a role in country M are considered as private cases. Usually the judge in country K and L will refer the case to country M. In that country the case is considered in accordance with local private law.

In international law there are basically two sources of international law: *customary law* and *treaties*. Customary law rests on commonly observed practice. An example is the extent of the territorial waters claimed by a country. If customary law has it at 20 km, that becomes the rule.

A treaty is the result of explicit agreement between states. A treaty is binding only on the treaty-partners, i.e. the states that ratified it. For treaty partners, national law has to follow international law. This is observed in Europe, for example, where the European Union prescribed unification and harmonisation of telecommunication regulations: the national telecommunication laws have to conform to this prescription. Although in practice its role is rather limited, the United Nations Organization (or specifically for telecommunications, in principle at least, possibly the ITU) is potentially the global law-giver.

9.3. Evaluating and Judging

Treaties are developed on the basis of the following principles:

- good faith
- not to do any harm to any partner involved in the treaty.

Events have to be judged and evaluated as to whether they conform to or are in conflict with the law given in a treaty. If a conflict with the international law is observed, sanctions are needed.

However, sanctions are usually extremely difficult; except in a few cases, such as in international policing operations or economic sanctions, they do not exist. Usually the solutions of these problems are the result of political effort.

In terms of telecommunication, checking whether the ITU Radio Regulations are violated, or harmful interference is suffered undeserved, is feasible and is done. But sanctions are usually not possible, unless a private case can be made and referred to action at a national level.

9.4. Protection of Radio Astronomy

On the global scale IUCAF (see Section 8.3) coordinates efforts for the protection of radio spectrum bands used by the Radio Astronomy Service and other passive applications. In Europe, this work is done by CRAF (see Section 8.2). In the USA, radio astronomers have found each other for this work in the Committee on Radio Frequencies of the US National Research Council, CORF, and finally there is the Radio Astronomy Frequency Committee in the Asia-Pacific region, RAFCAP. .

Although IUCAF is an ICSU commission it has no public status. This is because ICSU itself is not a public actor. The UNO and the ITU are public actors in international law. The ITU is a public actor since only sovereign states are full members (= capital-M Member, or Treaty Members).

The same distinction holds at a regional level. The European Science Foundation is not a public actor, nor is CRAF. Note that CORF is a private actor within the USA.

This implies that an agreement between IUCAF or CRAF with an active spectrum user or users (e.g. an MSS operator) has no legal status in terms of international law. Such an agreement has only a private character. Only when such an agreement is used as a model for an agreement between a national Administration and the active frequency user(s) can it obtain a status in international law. An agreement between a radio observatory and an active spectrum user or users has a private status and its legal status depends on the nature of the agreement and national legislation only. A local agreement has no international status.

An example: in 1993 IUCAF and the GLONASS Administration came to an agreement which implied that the GLONASS operations respect the radio astronomical use of the frequency band 1610.6 - 1613.8 MHz in such a manner that the transmission frequencies of the GLONASS satellites will have been moved away out of this band by the year 2005. This agreement has no status in terms of international law by itself. It acquires this status only when it has been taken over by a national Administration as a model for an agreement between this Administration and the Russian one.

What possibilities do radio astronomers have to claim protection at the local, regional or global level? And to what extent?

In close cooperation with national Administrations it may be possible to achieve something, either locally or regionally (via regional public actors) and globally (via global public actors or related organisations, such as the ITU and its sectors).

Radio astronomers request protection against terrestrial interference, Earth-to-space interference, space-to-Earth interference and space-to-space interference. The latter two cases are the most difficult to address and to resolve.

In terms of international law, radio astronomers can refer to treaties to claim protection. The national Administrations play a key role in this respect. In some local situations in which coordination between the Radio Astronomy Service and other services is required or desired, agreements between radio astronomers and active spectrum users can be obtained. These agreements should be reached in good coordination with the national Administration, otherwise radio astronomers undermine their case. Furthermore, these agreements or “memoranda of understanding” should obey the legal principles as given above (see Section 9.3) and conform to the current national and international legislation, i.e. the ITU Radio Regulations. The legal status of such agreements is very limited and absent in terms of international law.

As mentioned above, the ITU Radio Regulations have the status of a treaty, since they are an explicit agreement between states. That is not the end-of-story, particularly when spaceborne systems cause interference to the Radio Astronomy Service. And given the increasing threat from spaceborne systems to Radio Astronomy this requires accurate consideration:

A treaty with a status prior to the ITU Radio Regulations is the 1967 Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and other Celestial Bodies, usually known by its short title, the Outer Space Treaty, OST. This is a United Nations treaty and it is accorded a higher status on the basis of it being formulated within the most fundamental world organisation, and seen as the “Magna Carta” for space. But this interpretation is subject to dispute.

9.4.1. Outer Space Treaty 1967, OST

Some articles of the OST are relevant for the protection of Radio Astronomy:

> **Article I:**
>
> The exploration and use of outer space, including the moon and other celestial bodies, shall be carried out for the benefit and in the interests of all countries, irrespective of their degree of economic or scientific development, and shall be the province of all mankind.
>
> Outer space, including the moon and other celestial bodies, shall be free for exploration and use by all States without discrimination of any kind, on a basis of equality and in accordance with international law, and there shall be free access to all areas of celestial bodies.
>
> There shall be freedom of scientific investigation in outer space, including the

moon and other celestial bodies, and States shall facilitate and encourage international cooperation in such investigation.

Comments to Article I:

This article is supposed to represent the “common interests” principle. The “common interests” principle refers to the theory of the equitable sharing of whatever benefits may be gathered from the exploration and use of outer space – equitably, that is, not only between states operating in outer space, but also taking into account those states not so advanced technologically.

The question as to what “equitable sharing” means in the context of the discussions regarding the utilisation of the geostationary orbit is still a matter of continuing political negotiations between the Treaty members of the ITU. Apart from the utilisation of outer space by the specific category of telecommunication satellites, as regulated in the 1992 ITU Convention, there are other forms of utilisation of outer space not so well covered by international agreements: e.g. remote sensing satellites and direct broadcasting satellites. A customary rule of international law is in development.

The term “exploration” has primarily a scientific meaning. In its turn, “use” is *not* the equivalent of “appropriation” in the legal sense (OST Article II) though it may be so in the scientific sense.

The *rationale* of the provision “... shall be the province of all mankind...” is to aim at equitable sharing of the benefits to be derived from outer space. Outer space is considered to be the “common heritage of mankind”, on the basis of which rule of law the benefits to be gathered from outer space must be equally shared (Reijnen, 1992, p.88).

Article VI:

States Parties to the Treaty shall bear international responsibility for national activities in outer space, including the moon and other celestial bodies, whether such activities are carried on by governmental agencies or by non-governmental entities, and for assuring that national activities are carried out in conformity with the provisions set forth in the present Treaty. When activities are carried on in outer space, including the moon and other celestial bodies, by an international organisation, responsibility for compliance with this Treaty shall be borne both by the international organisation and by the States Parties to the Treaty participating in such organisation.

Comments to Article VI:

This international responsibility applies to states, governmental agencies, non-governmental entities and international organisations alike, and is, in the context of the OST, restricted to national activities in outer space. The topic of “state responsibility” has, from the beginning of discussions on the matter in the UN International

Law Commission, ILC, been located in the field of environmental harm (Reijnen, 1992, p.110).

Non-governmental entities in outer space are defined as those entities which are not funded by and not acting on behalf of their respective governments. Such entities can be private, commercial enterprises, or e.g. scientific communities either of national or international composition. Assuming internal consistency of the UN space treaties, there is evidence that “the appropriate State Party” is the state of *registry* (OST Article V). However, it can also be the state which *launches* or *procures* the launching (OST Article VII). By definition a launching state is a state which launches or procures the launching of a space object, or a state from whose territory or facility a space object is launched. The launching state need not necessarily be the state of registry. Within the context of OST it is considered that a correct assumption might be that the “appropriate State Party” is the state of *nationality* of the non-governmental entity. In the case of a multinational private enterprise it would mean that the various national partners of the multinational private enterprise choose, by common agreement, domicile in one of the constituting partner countries of the enterprise. This stipulation bears evidence of the fact that, in space law as a branch of international law, it is the state that has been accorded a central position, and that, in the matter of the utilisation of outer space, the general principles of international law apply (Reijnen, 1992, p.113f).

Article VII:

Each State Party to the Treaty that launches or procures the launching of an object into outer space, including the moon and other celestial bodies, and each State Party from whose territory or facility an object is launched, is internationally liable for damage to another State Party to the Treaty or to its natural or juridical persons by such objects or its component parts on the Earth, in air or in outer space, including the moon and other celestial bodies.

Comment to Article VII:

This article is, in matters of liability, the counterpart of Article VI on responsibility.

Article VIII:

A State Party to the Treaty on whose registry an object launched into outer space is carried shall retain jurisdiction and control over such object, and over any personnel thereof, while in outer space or on a celestial body. Ownership of objects launched into outer space, including objects landed or constructed on a celestial body, and of their component parts, is not affected by their presence in outer space or on a celestial body or by their return to the Earth. Such objects or component parts found beyond the limits of the State Party to the Treaty on whose registry they are carried shall be returned to that State Party, which shall, upon request, furnish identifying data prior to their return.

Comments to Article VIII:

From the text of this article, the central position of the state of registry in space law is evident. Only in this Treaty does one find the obligation (“shall”) of a state to exert jurisdiction and control over an object launched into outer space if that object is registered in that state’s register (Reijnen, 1992, p.116).

The Declaration of Legal Principles Governing the Activities of States in the Exploration and Use of Outer Space states in its Item 7 in addition:

“The State on whose registry an object launched into outer space is carried shall retain jurisdiction and control over such object, and any personnel thereon, while in outer space. Ownership of objects launched into outer space, and of their component parts, is not affected by their passage through outer space or by their return to the Earth. Such objects or component parts found beyond the limits of the State of registry shall be returned to that State, which shall furnish identifying data upon request prior to return.”

Article IX:

In the exploration and use of outer space, including the moon and other celestial bodies, States Parties to the Treaty shall be guided by the principle of cooperation and mutual assistance and shall conduct all their activities in outer space, including the moon and other celestial bodies, with due regard to the corresponding interests of all other States Parties to the Treaty. States Parties to the Treaty shall pursue studies of outer space, including the moon and other celestial bodies, and conduct exploration of them so as to avoid their harmful contamination and also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter and, where necessary, shall adopt appropriate measures for this purpose. If a State Party to the Treaty has reason to believe that an activity or experiment is planned by it or its nationals in outer space, including the moon and other celestial bodies, would cause potentially harmful interference with activities of other States Parties in the peaceful exploration and use of outer space, including the moon and other celestial bodies, it shall undertake appropriate international consultation before proceeding with any such activity or experiment. A State Party to the Treaty which has reason to believe that an activity or experiment planned by another State Party in outer space, including the moon and other celestial bodies, would cause potentially harmful interference with activities in the peaceful exploration and use of outer space, including the moon and other celestial bodies, may request consultation concerning the activity or experiment.

Comments to Article IX:

States parties to the Treaty have an obligation (“shall”) to undertake appropriate international consultations if any *planned* activity or experiment would cause potentially harmful interference with activities of other states utilising outer space. The formulation entails that, in such cases, the consultations take place *prior* to the *planned* activity or experiment. There is, so far as known, no example in over thirty years of space-flight that such consultation has ever been undertaken. Though that conduct (or lack of it) may be attributed to the absence of experiments deemed sufficiently potentially harmful, the history of space-flight – as far as known – shows many examples of factually harmful activities in space.

In spite of this, there is, neither in general international law nor in space law to be found any norm more specific than the one of Article IX, which obliges states to consult each other prior to the planning of activities in space of a potentially harmful nature.

The last full sentence of Article IX is slightly different: it contains possibly a permission ("may request") not an obligation on, to states to request consultation should the activities or experiment(s) planned by a state party entail potentially harmful interference with similar activities of another state (Reijnen, 1992, p.130f).

9.4.2. Liability Convention 1971

A second specific convention based on the Outer Space Treaty 1967 is the Convention on International Liability for Damage Caused by Space Objects, known by its short title as the Liability Convention 1971. This convention was based in particular on OST Articles VI and VII, as regards international responsibility and liability of states for their national activities in space.

Articles of this Liability Convention relevant for the protection of Radio Astronomy frequencies are:

Article 1:

For the purpose of this Convention:

(a) the term "damage" means loss of life, personal injury or other impairments of health; or loss of or damage of property of States or of persons, natural or juridical, or property of international intergovernmental organisations;
(b) the term "launching" includes attempted launching;
(c) the term "launching State" means:
  (i) A State which launches or procures the launching of a space object;
  (ii) A State from whose territory or facility a space object is launched;
(d) the term "space object" includes component parts of a space object as well as its launch vehicle and parts thereof.

Article 2:

A launching State shall be absolutely liable to pay compensation for damage caused by its space object on the surface of the Earth or to aircraft flight.

Comment to Article 2:

The concept of absolute liability may be supposed to follow that of general international law, as Article III of OST stipulates that states parties to the Outer Space Treaty shall carry on activities in outer space "in accordance with international law" (Reijnen, 1992, p.184).

Article 5.1:

Whenever two or more States jointly launch a space object, they shall be jointly and severally be liable for any damage caused.

Article 5.3:

A State from whose territory or facility a space object is launched shall be regarded as a participant in a joint launching.

9.4.3. Registration Convention 1974

The second specific convention based on the Outer Space Treaty 1967 is the Convention on Registration of Objects Launched into Outer Space of 1974 (known by its short title as the Registration Convention) in particular its Articles VIII, X and XI. These articles deal, respectively, with the obligation of states on whose registry an object is launched into outer space is carried, to retain jurisdiction and control over such object and over any personnel thereof (Article VIII); the opportunity to observe the flights of space objects (Article X); to inform the Secretary-General of the United Nations, the public and the international scientific community, of the nature, conduct, location and results of such activities (Article XI).

On 20 December 1961, the United Nations General Assembly passed Resolution 1721 (XVI), in which it is stated that “the United Nations should provide a focal point for international cooperation in the peaceful exploration and use of outer space”. This Assembly, furthermore,

1. *Calls upon* States launching objects into orbit or beyond to furnish information promptly to the Committee on the Peaceful Uses of Outer Space, through the Secretary-General, for the registration of launchings;
2. *Requests* the Secretary-General to maintain a public registry of the information furnished in accordance with paragraph 1 above;
3. *Requests* the Committee on the Peaceful Uses of Outer Space, in cooperation with the Secretary-General in making full use of the functions and resources of the Secretariat:
   (a) to maintain close contact with governmental and non-governmental organizations concerned with outer space matters;
   (b) to provide for exchange of such information relating to outer space activities as Governments may supply on a voluntary basis, supplementing but not duplicating existing technical and scientific exchanges.

The exchange of data started during the International Geophysical Year in 1959. After 1959, the rocket satellite data centres became the responsibility of the Committee on Space Research, COSPAR, of the ICSU. COSPAR distributes the information via Spacewarn. The Spacewarn Bulletin can be found on the World Wide Web under: http://nssdc.gsfc.nasa.gov/spacewarn/spacewarn.html. The format of the information is given in the Manual 1958 and COSPAR Information Bulletin 1962 (Reijnen, 1992, p.213f).

9.4.4. Additional Comments

Given the increasing threat of harmful interference to Radio Astronomy by transmissions by satellites and that satellites used for international direct broadcasting contribute significantly to this, it is interesting to know that in the *Principles Governing the Use by States of Artificial Earth Satellites for International Direct Television Broadcasting* (1972) it is stated clearly that:

In order to promote international cooperation in the peaceful exploration and use of outer space, States conducting or authorising activities in the field of international direct television broadcasting by satellite should inform the Secretary-General of the United Nations, to the greatest extent possible, of the nature of such activities. On receiving this information, the Secretary-General should disseminate it immediately and effectively to the relevant specialised agencies, as well as to the public and the international scientific community (item 12).

And:

With respect to the unavoidable overspill of the radiation of the satellite signals, the relevant instruments of the International Telecommunication Union shall be exclusively applicable (item 15).

The ITU itself, its Constitution and Convention, and the ITU Radio Regulations are considered "*Related International Agreements*". This implies that international law at its "highest level" should in the context of the current problem be OST, while the ITU documents, treaties and agreements, act as an appendix to this law. Therefore, the ITU Radio Regulations and related documents should be read in the context of OST as far as space applications are concerned.

For the protection of Radio Astronomy frequencies the key articles are *Articles VI and VII of the OST*. It should be noted that in OST "damage" is a generic term and understood in the sense that the victim defines its damage, just like the patient tells the doctor that he has pain (not the other way around). However, the definition of damage is subject to the general interpretation as intended by the drafters and the participating states, subject to reason and ultimately also subject to a decision of a judicial body called upon to judge a particular case.

In the case of Radio Astronomy this may imply that the definition of "harmful interference to Radio Astronomy" and "level of harmful interference to Radio Astronomy" needs to be included in the ITU Radio Regulations (which is at present not the case).

9.5. Consequences

Working on the protection of Radio Astronomy observations, radio astronomers represented by IUCAF, CRAF and CORF, should not only be basing their arguments on the RR and related ITU documentation, but they should be aware of the protection on the basis of the OST. The OST contains no restriction concerning the kind of exploration of outer space, including the Moon and other celestial bodies: this can be done by launching space vehicles, but also done by radio astronomical techniques. It uses the term “exploration” only in a generic way. The same holds for “damage”. However, it is relevant that IUCAF is working on the inclusion of the definition of “harmful interference to the Radio Astronomy Service” in the ITU Radio Regulations. At present this term is not defined.

For IUCAF, CRAF and CORF this situation should be kept in mind and wherever appropriate, Administrations should be made aware of their responsibilities regarding the OST.

10.

Recommendations

Based on the material presented in this Handbook, a number of recommendations should be considered for the protection for the Radio Astronomy Service:

- To protect the bands allocated to the Radio Astronomy Service on a primary basis to the levels given in ITU-R Recommendation RA.769. Explicit reference to this recommendation should be included in the ITU Radio Regulations.

- To adopt a definition of a “passive service” in the ITU Radio Regulations.

- To improve Article 29 of the Radio Regulations in order to make passive frequency use better understood.

- To define in the ITU Radio Regulations the term “detrimental interference”, which is used in ITU-R Recommendation RA.769.

- To improve communication/contact between the radio astronomical institutes and Administrations on the one hand and “industry” on the other hand.

- To pay attention in frequency allocation procedures that detrimental interference is avoided in existing passive bands.

- To avoid “passive” bands being shared with “active” services.

11.

Radio Astronomy and Atmospheric Remote Sensing Observatories in Europe

Table 7 gives the locations of radio astronomy observatories in Europe, and Table 8 gives the locations of atmospheric remote sensing stations. In Section 11.1 the main research programmes are indicated briefly, while the frequency bands used by the Radio Astronomy Service in Europe are listed in Table 8.

Table 7: European Radio Astronomy Observatories

Country	Place	East Longitude	Latitude	Height above sea level (m)	Comment
Austria	Lustbühel	15°29'34"	47°04'03"	483	
Belgium	Humain	05°15'19"	50°11'31"	293	
Czech Rep.	Ondrejov	14°47'01"	49°54'38"	533	
Finland	Metsähovi	24°23'17"	60°13'04"	61	
	Sodankyla	26°37'48"	67°21'36"	197	EISCAT
France	Bordeaux	-00°31'37"	44°50'10"	73	
	Nançay	02°12'00"	47°23'00"	150	
	Plateau de Bure	05°54'26"	44°38'01"	2552	
Germany	Effelsberg	06°53'00"	50°31'32"	369	
	Tremsdorf	13°08'12"	52°17'06"	35	
	Wettzell	12°52'39"	49°08'43"	648	
Greece	Pentele	23°51'48"	38°02'54"	509	
	Thermopyles	22°41'12"	38°49'27"		
Hungary	Penc	19°16'53"	47°47'22"	283	
Italy	Medicina	11°38'43"	44°31'14"	44	
	Noto	14°59'21"	36°52'34"	30	
	Sardinia	09°14'40"	39°29'50"	650	
	Trieste	13°52'30"	45°38'30"	400	
Latvia	Ventspils	21°51'17"	57°33'12"	15	
Netherlands	Borger-Odoorn	06°52'	52°55'	15	
	Dwingeloo	06°23'48"	52°48'48"	25	
	Westerbork	06°36'15"	52°55'01"	16	
Norway	Longyearbyen	16°03'	78°09'		EISCAT
	Ny Ålesund	11°55' 48"	78°55'12"	0	VLBI
	Tromsø	19°13'48"	68°34'12"	85	EISCAT
Poland	Kraków	19°49'36"	50°03'18"	314	
	Toruń	18°33'30"	52°54'48"	100	
Portugal	Espiunca	-08°13'52"	40°59'57"	205	
Russia	Badari	102°13'16"	51°45'27"	832	
	Dmitrov	37°27'00"	56°26'00"	200	
	Kalyazin	37°54'01"	57°13'22"	195	
	Medveziy Ozera	37°57'06"	55°52'06"	239	
	Pushchino	37°40'00"	54°49'00"	200	
	Svetloe	29°46'54"	61°05'	80	

Russia	Zelenchukskaya	41°35'32"	43°49'53"	1000	
	Zimenki	43°57'00"	56°18'00"	200	
Spain	Pico Veleta	–03°23'34"	37°03'58"	2870	
	Robledo	–04°14'57"	40°25'38"	761	
	Yebes	–03°06'00"	40°31'30"	931	
Sweden	Kiruna	20°26'24"	67°52'12"	418	EISCAT
	Onsala	11°55'35"	57°23'45"	10	
Switzerland	Bleien (Zürich)	08°33'06"	47°22'36"	469	
Turkey	Kayseri	36°17'58"	38°59'45"	1045	
Ukraine	Evpatoriya	33°11'	45°11'		
	Kharkov	36°56'30"	49°38'40"	150	
	Lvov	23°49'33"	51°28'32"		
	Odessa	30°16'24"	46°23'51"		
	Poltava	34°49'36"	49°37'57"		
	Simeiz	34°01'00"	44°32'06"	676	
	Zmiev	36°21'20"	49°39'50"		
United Kingdom	Cambridge	00°02'20"	52°09'59"	24	
	Darnhall	–02°32'03"	53°09'22"	47	
	Defford	–02°08'35"	52°06'01"	25	
	Jodrell Bank	–02°18'26"	53°14'10"	78	
	Knockin	–02°59'45"	52°47'24"	66	
	Pickmere	–02°26'38"	53°17'18"	35	

Table 8: European Stations for Atmospheric Remote Sensing

Country	Place	East Longitude	Latitude	Height above sea level (m)	Comment
France	Lannemezan	–00°06'07"	43°02'13"	597	passive
	Pic du Midi	–00°08'42"	42°56'12"	2861	passive
	Sodankyla	26°37'48"	67°21'36"	197	active
Italy	Testa Grigia (Plateau Rosa)	07°42'28"	45°56'03"	3315	passive
Norway	Longyearbyen	16°03'	78°09'		active
	Ny Ålesund	11°55' 48"	78°55' 12"	0	passive
	Tromsø	19°13'48"	68°34'12"	85	active
Sweden	Kiruna	20°26'24"	67°52'12"	418	active and passive
Switzerland	Bern	07°26'19"	46°57'04"	577	passive
	Gornergrat	07°56'	45°59'	3135	passive
	Jungfraujoch	07°59'06"	46°32'51"	3584	passive
	Payerne	06°56'38"	46°48'44"	498	passive

11.1. Main Research in European Radio Astronomy

Austria	
Lustbühel:	• Solar Radio Astronomy
Belgium	
Humain:	• Solar Radio Astronomy
Czech Rep.	
Ondrejov:	• Solar Radio Astronomy
Finland	
Metsähovi:	• Solar Radio Astronomy • Active Galactic Nuclei monitoring • Very Long Baseline Interferometry
Sodankyla (EISCAT):	• Aeronomy
France	
Bordeaux:	• Galactic research (stellar envelopes, interstellar medium) • Near extra-galactic research (molecules, star formation) • Solar system (comets) • Aeronomy and terrestrial atmosphere (H_2O, O_3, ClO)
Lannemezan	• Aeronomy, Earth atmosphere
Nançay:	• Extra-galactic radio astronomy (large scale structure, physics of galaxies) • Galactic research (pulsar timing, circumstellar envelopes) • Cometary research • Solar and planetary radio astronomy (Sun, planets)
Pic du Midi	• Aeronomy, Earth atmosphere
Plateau de Bure:	• Galactic research (circumstellar envelopes, interstellar medium: molecules and dust) • Near extra-galactic research (molecules and dust, star formation) • Solar system (comets) • Aeronomy and terrestrial atmosphere (H_2O, O_3, ClO) • Very Long Baseline Interferometry at mm wavelengths
Germany	
Effelsberg:	• Galactic and extra-galactic radio astronomy • Pulsar research • Very Long Baseline Interferometry • Interstellar molecules
Tremsdorf:	• Solar Radio Astronomy

Italy	
Medicina:	• Very Long Baseline Interferometry: astronomy and geodesy • Pulsar research and pulsar searches • 22 GHz observations of masers • Molecular spectroscopy • Receiver development
Noto:	• Very Long Baseline Interferometry [important node in the geodynamic network] • Technological research on correlators
Testa Griega	• Aeronomy, Earth atmosphere
Trieste:	• Solar Radio Astronomy
Netherlands	
Borger-Odoorn	• LOFAR central core • Galactic and extragalactic radio astronomy • Pulsar and transition research • Low frequency radio astronomy • Epoch of reionization research
Dwingeloo:	• Technological research for radio astronomy instrumentation
Westerbork:	• Galactic and extra-galactic radio astronomy • Pulsar research • Very Long Baseline Interferometry
Norway	
Ny Ålesund:	• Aeronomy, Earth atmosphere, Very Long Baseline Interferometry
Tromsø (EISCAT):	• Aeronomy
Poland	
Kraków:	• Solar radio astronomy
Toruń:	• Very Long Baseline Interferometry
Spain	
Pico Veleta:	• Galactic research (circumstellar envelopes, interstellar medium: molecules and dust) • Very Long Baseline Interferometry at mm wavelengths • Near extragalactic research (molecules and dust, star formation)
Robledo:	• Very Long Baseline Interferometry
Yebes:	• mm-wave spectroscopy of interstellar and circumstellar matter • Very Long Baseline Interferometry

Sweden

Kiruna (EISCAT):	• Aeronomy • Interplanetary scintillation
Onsala:	• Galactic and extra-galactic molecular line radio astronomy • Very Long Baseline Interferometry

Switzerland

Bern:	• Aeronomy, Earth atmosphere
Bleien (Zürich):	• Solar and stellar radio astronomy
Gornergrat:	• Galactic research (circumstellar envelopes, interstellar medium: molecules and dust)
Jungfraujoch:	• Aeronomy, Earth atmosphere
Payerne:	• Meteorology, Aeronomy, Earth atmosphere

Turkey

Kayseri:	• Galactic research (monitoring SiO masers (86 GHz), molecular clouds) • Clusters of galaxies • Pulsars and supernova remnants

United Kingdom

Cambridge:	• Low frequency surveys • Scintillation studies, solar wind • Galactic and extra-galactic radio astronomy • Pulsars • Cosmic microwave background • Long baseline interferometry (MERLIN) • Very Long Baseline Interferometry
Darnhall:	• Long baseline interferometry (MERLIN)
Defford:	• Long baseline interferometry (MERLIN), Very Long Baseline Interferometry
Jodrell Bank:	• Galactic and extra-galactic radio astronomy • Pulsars • Long baseline interferometry (MERLIN) • Very Long Baseline Interferometry
Knockin:	• Long baseline interferometry (MERLIN)
Pickmere:	• Long baseline interferometry (MERLIN)

Table 9: Frequency Bands used by the Radio Astronomy Service in Europe

Band number as used in Section 4	Allocation ITU- RR	Status	Country
1	13.36 - 13.41 MHz	primary/active	F[1], NL[25], UKR
2	25.55 - 25.67 MHz	primary. excl.	F[1], NL[25], UKR
3	37.5 - 38.25 MHz	secondary	F[1], GB[2], NL[25], RUS
4	73.0 - 74.6 MHz	notification of use	F[1], NL[25], RUS
	79.25 - 80.25 MHz	-	F[3], GB[2], NL[25],
	109.0 - 113.0 MHz		CH[4], NL[25], RUS
5	150.05 - 153.0 MHz	primary/active	CH[4], F[3], GB, NL[25], P, PL, RUS
	222.0 - 226.0 MHz	-	CH[4], EC[5], F[3], NL[25], P[23]
	242.0 - 246.0 MHz	-	CH[4], F[3], GB[6], NL[25], P[23]
6	322.0 - 328.6 MHz	primary/active	CH, F[3], GB, I, LT, NL, P, PL, RUS
7	406.1 - 410.0 MHz	primary/active	B, CH, D, F[3], GB, I, NL, PL[7], RUS
	485.0 - 515.0 MHz	-	CH[4], EC[5], P[23], PL[7]
8	608.0 - 614.0 MHz	primary. in R2 secondary in R1/R3	B, CH[4], D, F, GB, I, NL, P[23], PL7, RUS
	926.0 - 934.0 MHz	-	CH[4], CZ[22], F[9], GB[10], PL[7]
	927.0 - 935.0 MHz	-	CH[4], CZ[22], EC[5], F[9], PL[7]
	962.0 - 970.0 MHz	-	CH[4], CZ[22], F[9], GB[6], PL[7]
9	1330.0 - 1400.0 MHz	notification of use	CH[4], CZ[22], D, F, GB, I, NL, PL, RUS, S, TR[24]
10	1400.0 - 1427.0 MHz	primary: passive exclusive	CH[4], CZ[22], D, F, GB, I, NL, PL, RUS, S, TR[24]
	1400.0 - 1800.0 MHz	-	CH[4], CZ[22], RUS, TR[24]
11	1610.6 - 1613.8 MHz	primary/active	CH[4], CZ[22], D, F, GB, I, NL, PL, RUS, S, SP, TR[24]
	1640.0 - 1693.0 MHz	-[8]	CH[4], CZ[22], D, F, GB, I, NL, S, TR[24]
12	1660.0 - 1660.5 MHz	primary/active	CH[4], CZ[22], D, F, GB, I, NL, PL, RUS, S, SP, TR[24]
12	1660.5 - 1668.0 MHz	primary/passive	CH[4], CZ[22], D, F, GB, I, NL, PL, RUS, S, SP, TR[24]
12	1668.0 - 1670.0 MHz	primary/active	CH[4], CZ[22], D, F, GB, I, NL, PL, RUS, S, SP, TR[24]
13	1718.8 - 1722.2 MHz	secondary	CH[4], CZ[22], D, F, GB, I, NL, PL, RUS, S, SP, TR[24]
	2120.0 - 2620.0 MHz	-	CH[4], CZ[22], RUS, TR[24]

	2215.0 - 2240.0 MHz	-[8]	CH[4], CZ[22], NL, SP, TR[24]
	2290.0 - 2300.0 MHz	-[8]	CH[4], CZ[22], D, E, F, GB[3], I, NL, RUS, S11, SP, TR[24]
14	2655.0 - 2690.0 MHz	secondary	CH[4], CZ[22], D, F, GB, RUS, TR[24]
15	2690.0 - 2700.0 MHz	primary: passive exclusive	CH[4], D, F, GB, RUS, TR[24]
16	3260.0 - 3267.0 MHz	notification of use	CH[4], CZ[22], D, F[12], RUS, S, TR24
16	3332.0 - 3339.0 MHz	notification of use	CH[4], CZ[22], D, F[12], RUS, S, TR[24]
16	3345.8 - 3352.5 MHz	notification of use	CH[4], CZ[22], D, F[12], RUS, S, TR[24]
	4300.0 - 4900.0 MHz	-	CH[4], CZ[22], D[13], I[14], TR[24]
17-19	4800.0 - 4990.0 MHz	secondary	D, GB[15], I, NL, RUS[16], S, TR[24]
20	4990.0 - 5000.0 MHz	primary/active	D, F, GB[15], I, NL, S, TR[24]
-	5670.0 - 5790.0 MHz	-	RUS, TR[24]
-	6000.0 - 6100.0 MHz	-[8]	GB, NL, SP, TR[24]
21	6650.0 - 6675.0 MHz	-[8]	D, GB, I, NL, S[11], TR[24]
	8180.0 - 8580.0 MHz	-	SP, TR[24]
	8200.0 - 8700.0 MHz	-	RUS, TR[24]
	8208.0 - 8313.0 MHz	-[8]	F, RUS, TR[24]
	8387.0 - 8443.0 MHz	-[8]	D, GB, I, TR[24]
	8498.0 - 8573. 0 MHz	-[8]	D, GB, I, S, TR[24]
	9600.0 - 9620.0 MHz	-	GB[17], TR[24]
22	9.7 - 10.7 GHz	-	GB[17], TR[24]
22	10.60 - 10.68 GHz	primary/active	D, GB, I, LT, RUS, S, TR[24]
22	10.68 - 10.70 GHz	primary: passive exclusive	D, GB, I, LT, RUS, S, TR[24]
	11.7 - 12.25 GHz	-	D[13], GB, I, TR[24]
	12.25 - 14.25 GHz	-	D[13], TR[24]
	14.5 - 15.5 GHz	-	D[18], GB[19], I, TR[24]
23	14.47 - 14.50 GHz	secondary	D, GB, RUS
24	15.35 - 15.40 GHz	primary: passive exclusive	D, GB, I, RUS, S
25	22.01 - 22.21 GHz	notification of use	D, F, FIN, GB, S, SP
	22.085 - 22.385 GHz	-	RUS, S
26	22.21 - 22.50 GHz	primary/active[8]	D, F, FIN, GB, I, RUS, S, SP
27	22.81 - 22.86 GHz	notification of use	D, F, GB, I, S, SP
28	23.07 - 23.12 GHz	notification of use	D, F, GB, I, S, SP

29	23.60 - 24.00 GHz	primary: passive exclusive	D, F, GB, I, RUS, S, SP
	29.0 - 37.0 GHz	-	S, SP
30	31.2 - 31.5 GHz	notification of use	D, GB, RUS, S[20]
31	31.5 - 31.8 GHz	primary: passive exclusive	D, GB, RUS, S[20]
	35.0 - 37.0 GHz	-	RUS, S
32	36.43 - 36.5 GHz	notification of use	FIN, RUS, S
33	42.5 - 43.5 GHz	prim/active	D, F, FIN, I, RUS, S, SP
	43.5 - 47.0 GHz	-	S, SP
34	47.2 - 50.2 GHz	-[8]	D, S, SP
34	48.94 - 49.04 GHz	primary: shared	D, S, SP
35	51.4 - 54.25 GHz	notification of use	
35	58.2 - 59.0 GHz	notification of use	
35	64.0 - 65.0 GHz	notification of use	
36	76.0 - 77.5 GHz	primary	D, F, S, SP
36	77.5 - 78.0 GHz	secondary	D, F, S, SP
36	78.0 - 79.0 GHz	secondary	F, FIN, S, SP
36	79.0 - 81.0 GHz	primary	FIN, S, SP
36	81.0 - 84.0 GHz	primary	FIN, S, SP
36	84.0 - 86.0 GHz	primary	FIN, S, SP
36	86.0 - 92.0 GHz	primary: passive exclusive	F, FIN, RUS, S, SP
36	92.0 - 94.0 GHz	primary	F, FIN, S, SP
36	94.0 - 94.1 GHz	secondary	F, FIN, S, SP
36	94.1 - 95.0 GHz	primary	F, FIN, S, SP
36	95.0 - 100.0 GHz	primary	F, FIN, S, SP
36	100.0 - 102.0 GHz	primary: passive exclusive	F, FIN, S, SP
36	102.0 - 105.0 GHz	primary	F, S, SP
36	105.0 - 109.5 GHz	primary	F, FIN, S[13], SP
36	109.5 - 111.8 GHz	primary: passive exclusive	F, FIN, S, SP
36	111.8 - 114.25 GHz	primary	F, FIN, S, SP
36	114.25 - 116.0 GHz	primary: passive exclusive	F, FIN, S, SP
37	123.0 - 126.0 GHz	secondary	SP
37	126.0 - 130.0 GHz	secondary	SP
37	130.0 - 134.0 GHz	primary	SP
37	134.0 - 136.0 GHz	secondary	SP
37	136.0 - 141.0 GHz	primary	F, SP
37	141.0 - 148.5 GHz	primary	F, RUS, SP, CH

37	148.5 - 151.5 GHz	primary: passive exclusive	RUS, SP
37	151.5 - 155.5 GHz	primary	RUS, SP
37	155.5 - 158.5 GHz	primary	SP
38	164.0 - 167.0 GHz	notification of use	SP
39	168.0 - 170.0 GHz	notification of use	SP
39	170.0 - 174.5.. GHz	notification of use	SP
39	182.0 - 185.0 GHz	primary	SP, CH
40	191.8 - 200.0 GHz	notification of use	SP, CH
40	200.0 - 202.0 GHz	primary: passive exclusive	SP, CH
40	202.0 - 209.0 GHz	primary: passive exclusive	SP, CH
40	209.0 - 217.0 GHz	primary	SP
40	217.0 - 226.0 GHz	primary	SP
40	226.0 - 231.5 GHz	primary: passive exclusive	F, SP, I
41	241.0 - 248.0 GHz	secondary	F, SP
41	248.0 - 250.0 GHz	primary: passive exclusive	SP
41	250.0 - 252.0 GHz	primary	SP
41	252.0 - 265.0 GHz	primary	SP, I
41	265.0 - 275.0 GHz	primary	D, F, I, SP
42	275.0 - 1000.0 GHz	notification of use	D, F, I, SP

Notes:

1. used frequencies: 10 - 90 MHz
2. Cambridge only
3. used frequencies: 150 - 450 MHz
4. used frequencies 100 MHz - 4 GHz (~ 500 selected channels)
5. frequencies used by EISCAT Scientific Association (EC)
6. used for pulsar work
7. the band 400 - 2000 MHz is used in Poland for solar radio astronomy (channel frequencies are: 650, 810, 980, 1350, 1450 MHz)
8. used for Very Long Baseline Interferometry, VLBI
9. used frequencies: 910 - 950 MHz
10. used for pulsar work/space probes
11. used for VLBI; in Sweden: 2257 - 2313 MHz
12. used frequencies: 3200 - 3500 MHz
13. used for spectral line observations
14. in Italy the band 4700 - 5050 MHz is used
15. 4000 - 8000 MHz: used for MERLIN, spectral line, Very Long Baseline Interferometry, broadband interferometry, cosmic background
16. in Russia: 4600 - 4800 MHz is used
17. cosmic background research
18. in Germany the band 14.2 - 15.2 GHz is used
19. 14.5 - 15.5 GHz: used for cosmic background research
20. in Sweden the band 31.0 - 31.3 is used
21. the band 86.0 - 86.6 GHz is used for Very Long Baseline Interferometry
22. in Czech Rep.: 0.1 - 4.5 GHz is used
23. in Portugal: 150 - 650 MHz is used
24. in Turkey: 1 - 15 GHz is used
25. in the Netherlands: frequencies between 10 and 250 MHz are used by the Low Frequency Array, LOFAR

12.

Recommended Literature

12.1. Protection of Radio Astronomy Frequencies

- M. Bos, 2004, *New dynamic spectrum management: the end of scarcity? - the regulation of ultra-wide band*, Rijksuniversiteit Groningen and Netherlands Radiocommunication Agency.

- R. J. Cohen and W. T. Sullivan III, eds, 2001, *Preserving the Astronomical Sky*, IAU Symposium No.196, Astronomical Society of the Pacific, San Francisco, USA.

- J. E. Flood, C. J. Hughes and J.D. Parsons, 1991, *Radio Spectrum Management*, IEE Telecommunications Series 23, Peter Peregrinus Ltd., London, England.

- H. C. Kahlmann, ed., 1996, *The Passive Use of the Frequency Spectrum*, NATO Committee on the Challenges of Modern Society", Report No.213.

- B. M. Lewis and D. T. Emerson, 2004, *Spectrum Management for Radio Astronomy*, Proceedings of IUCAF summer school, National Radio Astronomy Observatory, Greenbank, USA.

- A. K. Maitra, 2004, *Wireless Spectrum Management – Policies, Practices, and Conditioning Factors*. McGraw Hill, New York, USA.

- D. McNally, ed., 1994, *The Vanishing Universe*, Cambridge University Press, Cambridge, England.

- B. C. M. Reijnen, 1992, *The United Nations Space Treaties Analyzed*, Edition Frontières, Gif-sur-Yvette, France.

- T. A. Th. Spoelstra, ed, 2002, *CRAF Handbook for Frequency Management*, European Science Foundation, Strasbourg, France.

- *United Nations Treaties and Principles on Outer Space*, 1994, Office for Outer Space Affairs, Vienna International Centre, P.O.Box 500, A-1400 Vienna, Austria.

- R. L. White and H. M. White Jr., 1988, *The Law and Regulation of International Space Communication*, Artech House, Boston, USA.

12.2. ITU-R Texts

- *ITU-R Handbook on Radio Astronomy*, 2003, ITU-R Radiocommunications Bureau, Geneva, Switzerland.

12.3. Introduction to Radio Astronomy

- B. F. Burke and F. Graham-Smith, 2002, *An Introduction to Radio Astronomy*, 2nd edn, Cambridge University Press, Cambridge, England.

- F. Graham-Smith, 1974, *Radio Astronomy*, 4th edn, Penguin Books, Harmondsworth, Middlesex, England.

- A. G. Lyne and F. Graham-Smith, 1990, *Pulsar Astronomy*, Cambridge University Press, Cambridge, England.

- G. L. Verschuur, 1987, *The Invisible Universe Revealed - The Story of Radio Astronomy*, Springer-Verlag, Berlin, Germany.

- G. L. Verschuur and K. I. Kellermann, eds, 1988, *Galactic and ExtraGalactic Radio Astronomy*, 2nd edn, Springer-Verlag, Berlin, Germany.

Appendices

Appendix 1. **List of Acronyms**[1]

A

AAC
Aeronautical Administrative Communications

AC/WPBX
Advanced Cordless/Wireless Private Branch Exchange

ADEOS
Advanced Earth Exploration Satellite

ADM
Administrative

ADS
Advanced Digital System

ADS
Automatic Dependent Surveillance (USA)

AeFS
Aeronautical Fixed Service

AeM
Aeronautical Mobile Service

AeM(OR)
Aeronautical Mobile Service (off-route)

AeM(R)
Aeronautical Mobile Service (route)

AeMS
Aeronautical Mobile Service

AeMSS
Aeronautical Mobile Satellite Service

AeMSS(OR)
Aeronautical Mobile Satellite Service (off-route)

AeMSS(R)
Aeronautical Mobile Satellite Service (route)

AeRNS
Aeronautical Radionavigation Service

AeRNSS
Aeronautical Radionavigation Satellite Service

AFSCN
Air Force Satellite Control Network (USA)

ALMA
Atacama Large Millimetre Array

AmS
Amateur Service

AMSAT
Radio Amateur Satellite Corporation (USA)

AMSC
American Mobile Satellite Corporation (USA)

AMSS
Aeronautical Mobile Satellite Service

AmSS
Amateur-Satellite Service

ANFR
Agence National des Fréquences Radioélectriques (F)

ANS
Air Navigation System

AOC
Aeronautical Operational Control

APC
Aeronautical Public Correspondence = TFTS

APCO
Association of Public Safety Communications Officials-International, Inc. (USA)

APT
Asia-Pacific Telecommunity

ARC
Administrative Radio Conference

ARFA
Allied Radio Frequency Agency

ARIA
Advanced Range Instrumentation Aircraft (USA)

ARSR
Air Route Surveillance Radar

ASA
Austrian Space Agency (A)

ASDE
Airport Surface Detection Equipment

ASO
Australian Space Office (AUS)

ATC
Air Traffic Control

ATDRS
Advanced Tracking and Data Relay Satellite

ATDRSS
Advanced Tracking and Data Relay Satellite System

ATN
Amateur Television Network (USA)

ATU
Arab Telecommunication Union

ATS
Air Traffic Services

ATV
Amateur Television (USA)

AVI
Automatic Vehicle Identification

---

[1] Further acronyms can be found at the CRAF website (www.astron.nl/craf)

AVM
Automatic Vehicle Monitoring

AWACS
Airborne Warning and Control System

B

BAPT
Bundesamt für Post und Telekommunikation (D)

BAS
Broadcast Auxiliary Service

BDT
Telecommunication Development Bureau (ITU)

BER
Bit Error Ratio

BIPM
Bureau International de Poids et Mesures

B-ISDN
Broadband ISDN

BNSC
British National Space Centre (UK)

BPSK
Binary phase-shift keying

BS
Base Station

BS
Broadcasting Service

BSS
Broadcasting Satellite Service

BT
British Telecom (UK)

C

CAST
Chinese Academy of Space Technology (CN)

CB
Citizen Band

CCIR
Comité Consultatif International des Radiocommunications (ITU)

CCITT
Comité Consultatif International de Télégraphe et des Télécommunications (ITU)

CCMS
Committee on Challenges of Modern Science (NATO)

CCSDS
Consultative Committee on Space Data Systems

CDMA
Code Division Multiple Access

CENELEC
European Committee for Electrotechnical Standardisation

CEPT
Conférence Européene des Postes et des Télécommunications

CERGA
Centre d'Etudes et de Recherches Géodynamiques et Astronomiques

CGMS
Coordination on Geostationary Meteorological Satellites

CICG
Centre International des Conférences Genève

CIE
Commission Internationale d'Eclairage

CIMO
Commission on Instruments and Methods of Observations (WMO)

CISPR
International Special Commitee on Radio Interference

CITEL
InterAmerican Conference on Telescommunications [similar to CEPT, in America] (Conferencia Interamericana de Telecommunicaciones)

CMTT
Joint Study Group for Television and Sound Transmission

CNES
Centre National d'Etudes Spatiales (F)

CNET
Centre National d'Etudes des Télécommunications (F)

CNIE
Comision Nacional de Investigaciones Espaciales

CNRS
Centre National de Recherches Scientifiques (F)

CODATA
Committee on Data for Science and Technology

COFDM
Coded Orthogonal Frequency Division Multiplex

COMSAT
Communications Satellite Corporation (USA)

COPUOS
UN Committee on Peaceful Uses of Outer Space

CORF
Commission on Radio Frequencies (NRC-USA)

COSPAR
Committee on Space Research

COSPAS
Russian system of Satellite Search and Rescue

COSTED
Committee on Science and Technology in Developing Countries

CPEM
Conference on Precision Electromagnetic Measurements

CPM
Conference Preparatory Meeting (ITU)

CRAF
Committee on Radio Astronomical Frequencies (ESF)

CSA
Canadian Space Agency (CDN)

CSIRO
Commonwealth Scientific and Industrial Research Organization (Australia)

CSTG
Commission for International Coordination of Space Techniques for Geodesy and Geodynamics

D

DAB
Digital Audio Broadcast

DBS
Digital Broadcasting by Satellite

DCS1800
Digital Communication System

DCT
Discrete Cosine Transform Coding

DEC
ERC DECision (CEPT)

DECT
Digital European Cordless Telecommunication System

DFVLR
Deutsche Forschungs und Versuchsanstalt für Luft und Raumfahrt (D)

DG
Drafting Group

DGLR
Deutsche Gesellschaft für Luft und Raumfahrt (D)

DGPS
Differential GPS

DME
Distance Measuring Equipment

DRS
Data Relay Satellite

DRTS
Data Relay and Tracking Satellite

DRTSS
Data Relay and Tracking Satellite System

DSBS
Digital Sound Broadcasting Satellite

DSCS
Defense Satellite Communications System (USA)

DSI
Detailed Spectrum Investigation (CEPT)

DSN
Deep Space Network

DSRR
Digital Short Range Radio

DSSS
Direct Sequence Spread Spectrum

DTI
Department of Trade and Industry (GB)

DW
Deutsche Wetterdienst (D)

E

EARSeL
European Association of Remote Sensing Laboratories

EAS
European Astronomical Society

EBU
European Broadcasting Union

EC
European Community

ECA
European Common Allocation (CEPT)

ECC
Electronics Communication Committee (CEPT)

ECP
European Common Proposal (CEPT)

ECTRA
European Committee for Telecommunications Regulatory Affairs

EDRS
European Data Relay Satellite (ESA)

EDRSS
European Data Relay Satellite System

EES
Earth Exploration Satellite

EESS
Earth Exploration Satellite Service

EFTA
European Free Trade Association

EGC
Enhanced Group Call

EHF
Frequency range 3 - 30 GHz

EIRP
Effective Isotropically Radiated Power

EISCAT
European Incoherent Scatter Scientific Association

ELF
Extremely Low Frequency (< 3 kHz)

EM
Electromagnetic

EMC
Electromagnetic Compatibility

EMI
Electromagnetic Interference

ENG
Electronic News Gathering

EOS
Earth Observation Satellite

EOSS
Earth Observation Satellite System

EPFD
Equivalent Power Flux-Density (dB[W.m^{-2}])

EPIRB
Emergency position-indicating radio beacon

EPP
European Polar Platform

ERC
European Radiocommunications Committee (CEPT)

ERMES
European Radio Message System

ERO
European Radiocommunications Office (CEPT)

ERP
Effective Radiated Power (relative to a half-power dipole)

ESA
European Space Agency

ESF
European Science Foundation

ESOC
European Space Operations Centre

ESR
EISCAT Svalbard Radar

ESTEC
European Space Research and Technology Centre

E-TDMA
Extended Time Division Multiple Access

ETNO
European Public Telecommunications Network Operators' Association

ETSI
European Telecommunication Standards Institute

EUTELSAT
European Telecommunication Satellite Organization

EUMETSAT
European Meteorological Satellite Organisation

EVA
Extra Vehicular Activity

eVLBI
VLBI over the internet

EVN
European VLBI Network

F

FAA
Federal Aviation Administration (USA)

FAGS
Federation of Astronomical and Geophysical Services

FAST
Fundamental Astronomy by Space Techniques Consortium

FCC
Federal Communications Commission (USA)

FDD
Frequency Division Duplex

FDMA
Frequency Division Multiple Access

FEC
Forward Error Correction

FS
Fixed Service

FSK
Frequency Shift Keying

FSS
Fixed Satellite Service

FT
France Télécom (F)

FX
Fixed Service

G

G/T
Ratio of gain to noise temperature

GEMS
Global Environment Monitoring Systems

GEO
Geostationary Orbit

GES
Ground Earth Station

GLONASS
GLobal NAvigation Satellite System (Russia)

GMDSS
Global Maritime Distress and Safety System

GMPCS
Global Mobile Personal Communication by Satellite

GMR
General Milestone Review Committee (CEPT)

GNSS
Global Navigation Satellite System

GOES
Geostationary Operational Environmental Satellite

GPS
Global Positioning System (USA)

GRGS
Groupe de Recherches de Géodesie Spatiale (F)

GSM
Groupe Spécial Mobiles

GSM
Global System for Mobile Communications

GSO
Geostationary Satellite Orbit

GVLS
Global Verification and Location System

H

HAPS
High Altitude Platform Station

HDFS
High Density Fixed Service

HDFSS
High Density Fixed-Satellite Service

HDTV
High Definition TeleVision

HDTP
Hoofddirectie Telecommunicatie en Post van het Ministerie van Verkeer en Waterstaat (NL)

HEO
Highly inclined Elliptical Orbit

HF
High Frequency (frequency range 3 - 30 MHz)

HFBC
High Frequency Broadcasting

HIPERLAN
High Performance Local Area Network

HLC
High Level Commitee (ITU)

I

IAA
International Academy of Astronautics

IAF
International Astronautical Federation

IAG
International Association of Geodesy

IAGA
International Association of Geomagnetism and Aeronomy

IAGC
International Association of Geochemistry and Cosmochemistry

IAMAP
International Association of Meteorology and Atmospheric Physics

IATA
International Air Transport Agency

IAU
International Astronomical Union

IBCN
Integrated Broadband Communications Network

IBS
INTELSAT Business Service

ICAO
International Civil Aviation Organization

ICAS
International Council of the Aeronautical Sciences

ICO
Intermediate Circular Orbit

ICSTI
International Council for Scientific and Technical Information

ICSU
International Council for Science

IDR
Intermediate Data Rate

IEC
International Electrotechnical Commission

IEE
Institution of Electrical Engineers

IEEE
Institution of Electrical and Electronics Engineers

IFL
International Frequency List

IFRB
International Frequency Registration Board

IIASA
International Institute of Applied Systems Analysis

IISL
International Institute of Space Law

ILS
Instrument Landing System

IMASS
Intelligent Multiple Access Spectrum Sharing

IMT-2000
International Mobile Telecommunications-2000 (ITU)

IMO
International Maritime Organization

INMARSAT
INternational MAritime SATellite organization

INPE
Instituto de Psequisas Espaciais

INTA
Instituto Nacional de Tècnica Aerospacial

INTELSAT
International Telecommunications Satellite Organization

IRAM
Institut de Radio Astronomie Millimétrique

IRT
Institut für Rundfunktechnik (D)

ISAS
Institute of Space and Astronautical Science

ISDN
Integrated Services Digital Network

ISL
Inter-Satellite Link

ISM
Industrial, Scientific and Medical Applications

ISO
International Organization for Standardization

ISR
Incoherent Scatter Radar

ISRO
Indian Space Research Organization

ISS
Inter-Satellite Service

ITA
Industrial Telecommunication Association (USA)

ITFS
Instructional Television Fixed Service

ITU
International Telecommunication Union

ITU-D
International Telecommunication Union - Telecommunication Development Sector

ITU-R
International Telecommunication Union - Radiocommunication Sector

ITU-T
International Telecommunication Union - Telecommunication Standardization Sector

IUCAF
Scientific Committee on the Allocation of Frequencies for Radio Astronomy and Space Science

IUGG
International Union for Geodesy and Geophysics

IVS
International VLBI Satellite

IWG
Intersessional Working Group (of the SFCG)

IWP
Interim Working Party (ITU-R)

J

JCMT
James Clark Maxwell Telescope

JEM
Japanese Experiment Module

JEWM
Joint Expert Working Meeting

JIVE
Joint Institute for VLBI in Europe

JIWP
Joint Interim Working Party

JPL
Jet Propulsion Laboratory

JPOP
Japanese Polar Platform

JSS
Joint Surveillance System

JTIDS
Joint Tactical Information Distribution System

L

LAN
Local Area Network

LEO
Low Earth Orbit

LF
Low Frequency (30 - 300 kHz)

LHC
Left Hand Circular

LM
Land Mobile Service

LMS
Land Mobile Service

LMSS
Land Mobile satellite Service

LMST
Light-Weight Multi-Band Satellite Terminal

LOFAR
Low Frequency Array

LPD
Low Power Devices

LSI
Large Scale Integration

M

MAS
Meteorological Aids Service

MAT
Mobile Aeronautical Telemetry

MDS
Multipoint Distribution Service

MERLIN
Multi-Element Radio Linked Interferometer Network (UK)

MES
Mobile Earth Station

MetA
Meteorological Aid Service

METSAT
Meteorological Satellite

MetS
Meteorological Satellite Service

MF
Medium Frequency (300 - 3000 kHz)

MIFR
Master International Frequency Register

MIT
Massachusetts Institute of Technology (USA)

MLS
Microwave Landing System

MM
Maritime Mobile Service

MMARC
Maritime Mobile Radio Conference

MMS
Maritime Mobile Service

MMSS
Maritime Mobile Satellite Service

MOB
Mobile (use in the designation of certain WARCs)

MPIfR
Max-Planck-Institut für Radioastronomie (D)

MRC
Milestone Review Committee (CEPT)

MRN
Maritime Radionavigation Service

MRNS
Maritime Radionavigation Service

MRNSS
Maritime Radionavigation Satellite Service

MS
Mobile Service

MS
Mobile Station

MSS
Mobile Satellite Service

MVDS
Microwave Video Distribution System

N

NAIC
National Astronomy and Ionosphere Center (USA)

NARFA
National Allied Radio Frequency Agency

NAS
National Academy of Sciences (USA)

NASA
National Aeronautics and Space Administration (USA)

NASDA
National Space Development Agency of Japan

NATO
North Atlantic Treaty Organization

NAVSTAR see GPS

NESS
National Environment Satellite Service (of NOAA)

NEST
Nuclear Emergency Search Team (USA)

NFRA
Netherlands Foundation for Research in Astronomy (NL)

NGO
Non-Governmental Organization

NGSO
Non-Geostationary Satellite Orbit

NIST
National Institute of Standards and Technology (USA)

NIVR
Nederlands Instituut voor Vliegtuigontwikkeling en Ruimtevaart (NL)

NNSS
Navy Navigational Satellite System (USA)

NOAA
National Oceanographic and Atmospheric Administration (USA)

NRAO
National Radio Astronomy Observatory (USA)

NRC
National Research Council (USA)

NSF
National Science Foundation (USA)

NTIA
National Telecommunications and Information Administration (USA)

NWS
National Weather Service (USA)

O

OB
Outside Broadcasting

OECD
Organization for Economic Co-operation and Development

OFCOM
Federal Office of Communications (Switzerland)

OFCOM
Office of Communications (UK)

OFDM
Orthogonal Frequency Division Multiplex

OFR
Off Frequency Rejection

OIR
Organisation internationale de radiodiffusion

OQPSK
Offset QPSK

ORB
Orbit (used in the designation of certain WARCs)

OSCAR
Orbiting Satellite Carrying Amateur Radio

OST
Outer Space Treaty (UN)

OTH
Over-the-Horizon

P

PC
Plenipotentiary Conference (ITU)

PCIA
Personal Communications Industry Association (USA)

PCM
Pulse Code Modulation

PCN
Personal Communications Network

PCP
Private Carrier Paging

PCS
Personal Communications Service

PDF
Probability Density Function

PFD
Power Flux Density (dB[W.m^{-2}])

PLC
Power Line Communications

PLT
Power Line Transmissions

PMP
Point-to-multipoint

PMR
Private Land Mobile Radio

POFS
Private Operational Fixed Service

PPARC
Particle Physics and Astronomy Research Council (UK)

PSK
Phase Shift Keying

PSTN
Public Switched Telephone Network

PTT
Post, Telegraph, Telephone (i.e. government ministry for -)

Q

QAM
Quadratic Amplitude Modulation

QPSK
Quadratic Phase Shift Keying

QPSK-C
Quadratic Phase Shift Keying Compatible

R

RA
Radiocommunication Assembly (ITU)

RA
Radio Astronomy Service (ITU)

RADAR
Radio Detecting and Ranging

RAFCAP
Radio Astronomy Frequency Committee in the Asia-Pacific Region

RAG
Radiocommunication Advisory Group (ITU)

RARC
Regional Administrative Radio Conference (ITU)

RAS
Radio Astronomy Service

RAS
Royal Astronomical Society (UK)

RB
Radiocommunication Bureau (ITU)

RD
Radiodetermination Service

RDS
Radiodetermination Service

RDSS
Radio Determination Satellite Service

Rec
Recommendation

RFI
Radio Frequency Interference

RFID
Radio Frequency Identification

RHC
Right Hand Circular

RIN
Royal Institute of Navigation (UK)

RIS
Radiocommunication Information Systems Department (ITU)

RL
Radiolocation Service

R-LAN
Radio Local Area Network

RLS
Radiolocation Service

RN
Radionavigation Service

RNS
Radionavigation Service

RNSS
Radionavigation Satellite Service

RR
Radio Regulations (ITU)

RRB
Radio Regulations Board (ITU)

RSC
Radio Spectrum Committee (EC)

RSPG
Radio Spectrum Policy Group (EC)

RTAGS	Radio Tags
RTT	Road Transport Telematics

S

SARP	ICAO Standards and Recommended Practices
SARSAT	Satellite-Aided Search and Rescue Project
SAT	Satellite
SATCOM	Satellite Communications
SCAR	Scientific Committee on Antarctic Research
SCOPE	Scientific Committee on Problems of the Environment
SCOSTEP	Scientific Committee on Solar Terrestrial Physics
SCPT	Single channel per transponder
SES	Ship Earth Station
SESC	Space Environment Service Center
SETI	Search for Extra Terrestrial Intelligence
SFCG	Space Frequency Coordination Group
SFS	Standard Frequency and Time Signal Service
SFTSS	Standard Frequency and Time Signal-Satellite Service
SGLS	Space-Groundlink Subsystem
SHF	Super High Frequency (3 - 30 GHz)
SITE	Satellite Instructional Television Experiment
SKA	Square Kilometre Array
SMR	Sub-Millimetre Radiometer
SNG	Satellite News Gathering
SO	Space Operation Service
SOS	Space Operation Service
SPAC	Spectrum Planning and Advisory Committee (USA)
S-PCS	Satellite Personal Communications Services
SPFD	Spectral Power Flux Density (dB[W.m^{-2}.Hz^{-1}])
SPS	Spectrum Planning Subcommittee (USA)
SRD	Short Range Device
SRS	Space Research Service
SSB	Space Science Board (of the US NAS)
SSC	Swedish Space Corporation
SSR	Secondary Surveillance Radar
SRR	(Vehicular) Short Range Radar
SWAS	Submillimetre Wave Astronomy Satellite (NASA)

T

TACAN	Tactical Air Navigation System
TAI	Temps Atomique International
TAPC	Terrestrial Aeronautical Public Correspondence = TFTS
T-DAB	Terrestrial Digital Audio Broadcasting
TDD	Time Division Duplex
TDF	Télédiffusion de France (F)
TDM	Time Division Multiplex
TDMA	Time Division Multiple Access
TDRS	Tracking and Data Relay Satellite
TDRSS	Tracking and Data Relay Satellite System
TDWR	Terminal Doppler Weather Radar
TETRA	Trans European Trunked Radio
TFTS	Terrestrial Flight Telephone System = APC
TG	Task Group (ITU)
TSAG	Technical Standardization Advisory Group (ITU)
TTC	Tracking, telemetry, and command
TV	TeleVision

U

UAPT
Union of African Post- and Telecommunication

UHF
Ultra High Frequency (300 to 3000 MHz)

UIC
International Union of Railways

UMTS
Universal Mobile Telecommunication System

UNESCO
United Nations Education, Scientific and Cultural Organization

UNO
United Nations Organization

URSI
Union Radio Scientifique International

UT
Universal Time

UTC
Coordinated Universal Time

UWB
Ultra-Wide Band

V

VGE
Voluntary Group of Experts (ITU)

VHF
Very High Frequency (30 - 300 MHz)

VLA
Very Large Array (USA)

VLBA
Very Long Baseline Array (USA)

VLBI
Very Long Baseline Interferometry

VLF
Very Low Frequency (3 - 30 kHz)

VOR
VHF Omnidirectional Range

VORAD
Vehicle On-Board Radar

VQC
Vector Quatization Coding

VSAT
Very-Small Aperture Terminal

VSOP
VLBI Space Observatory Program

VTS
Vessel Traffic System (radar)

W

WAN
Wide Area Network

WARC
World Administrative Radio Conference (ITU)

WBDTS
Wide Band Data Transmission System

W-HDTV
Wide HDTV

WHO
World Health Organization

WMO
World Meteorological Organization

WP
Working Party (ITU)

WRC
World Radiocommunication Conference (ITU)

WSRT
Westerbork Synthesis Radio Telescope (NL)

WTDC
World Telecommunication Development Conference (ITU)

WTPF
World Telecommunication Policy Forum (ITU)

WTSC
World Telecommunication Standardization Conference (ITU)

WWW
World Wide Web

Appendix 2. **Vocabulary of Special Terms**

Astronomy (general)

abundance (of elements)
relative occurrence of chemical elements in the universe.

astronomical unit (AU)
mean distance between the Earth and the Sun (149.6 million km).

astrophysics
branch of astronomy dealing with physics and chemistry of celestial bodies.

Big Bang
a model of the universe which started with an initial singularity. The Friedmann model of a homogeneous, isotropic universe (composed of adiabatically expanding matter and radiation, as a result of a primeval explosion) is the standard example.

cosmology
theory of the origin, structure and evolution of the universe.

parsec (pc)
distance of a star having a parallax of 1". 1 pc ~ 3.26 light years = 3.1x10^{13} km.

Calibration

redundancy
use of redundant measurement data to remove instrumental effects.

self-calibration technique
calibration of measurement data without use of information external to the observation.

Emission

brightness temperature
the temperature that a black body would have to have to emit radiation of the observed intensity at a given wavelength.

continuum emission
emission produced by the superposition of a large number of interactions between ions and electrons, or between electrons and cosmic magnetic fields, that produce radio pulses of varying amplitude and narrowness (see also: non-thermal emission; synchrotron emission; thermal emission).

equivalent power flux density (epfd)
the sum of the power flux densities produced at a geostationary-satellite system receive station on the Earth's surface or in the geostationary orbit, as appropriate, by all the transmit stations within a non-geostationary-satellite system, taking into account the off-axis discrimination of a reference receiving antenna assumed to be pointing in its nominal direction (Radio Regulations No. **22.5C.1**).

flux
total radiant energy passing through a unit surface into the 2π solid angle of a hemisphere.

flux density
flux of radiation through a unit surface; the strength of an electromagnetic wave, defined as the amount of power incident per unit area. In radio astronomy, the brightness temperature integrated over the solid angle of the source yields the flux density.

flux unit
unit of flux density.

hydrogen spectral line
spectral line of neutral hydrogen (rest frequency: 1420.4057 MHz).

Jansky (Jy)
unit of flux density. 1 Jy = 10^{-26} W m^{-2} Hz^{-1}. Named after K. G. Jansky, who discovered galactic radio waves in 1931.

maser (microwave amplification by stimulated emission of radiation)
The microwave equivalent of a laser, in which photons at the right frequency stimulate an excited atom, ion or molecule to emit further photons at the same frequency, travelling in the same direction. Maser devices are used as amplifiers in some sensitive radio astronomy receivers. Hydrogen masers based on the hydrogen line at 1420.4057 MHz are used as extremely stable clocks in VLBI. Naturally occurring cosmic maser sources are the most intense spectral line sources studied by radio astronomers. Cosmic masers are found in comets, in supernova remnants, and in association with star formation, stellar mass

loss, and active galaxies. The most powerful maser sources known are termed "megamasers".

nonthermal radiation

radiation emitted by energetic particles for reasons other than high temperature of the source. The spectrum of non-thermal radiation is different from that predicted by Plank's law for a blackbody.

propagation effect

change of characteristics of radiation due to the medium through which it propagates (e.g. direction of propagation, effect on polarization characteristics).

redshift

shift of spectral line to lower frequencies due to motion of the emitting object away from the observer.

spectral line

discrete emissions or absorptions in frequency, usually produced by atomic, nuclear, or molecular transitions.

synchrotron emission

electromagnetic emission from relativistic electrons moving in magnetic fields. The acceleration of the particles causes them to emit radiation. A characteristic of such radiation is that it has a strongly polarized power-law spectrum, and the wavelength region in which the emission occurs depends on the energy of the electron e.g., 1 MeV electrons would radiate mostly in the radio region, but GeV electrons would radiate mostly in the optical region.

thermal emission

blackbody radiation; radiation caused by the high temperature of the radiating objects, as opposed to non-thermal radiation, which typically is caused by energetic (not necessarily hot) electrons.

Instrumental parametres

angular resolution

smallest angular distance over which two objects can be observed separately.

bandwidth

range of frequencies over which the measurements are made. The bandwidth is determined either by the radiation itself, which may for instance, be confined to a narrow spectral line, or more usually, by the antenna-receiver system which accepts signals only within a limited frequency range. The receiver is usually designed to have a smaller bandwidth than the radiation itself, so that information about the shape of the source spectrum is not lost through averaging over too great a frequency interval.

diffraction limited

capable of producing images with angular separation as small as the theoretical limit implied by diffraction effects.

dynamic range

ratio of peak intensity to the noise in a dataset (usually expressed in dB).

integration time

used to indicate:

- duration of the observation (often of the order of hours);
- sampling time within the receiver (ranging from microseconds to seconds);
- time over which a series of samples are averaged (ranging from seconds to minutes).

sampling time

time interval during which a received signal is integrated within the receiver before dumping the data to a storage medium.

spatial resolution

angular resolution converted to spatial dimensions.

spectral resolution

minimum frequency separation over which spectral lines can be distinguished separately from each other.

Instrumentation

radio interferometry

the use of two or more antennas in combination as a single instrument with an angular resolution determined by the separation between the antennas.

MERLIN

Multi-Element Radio Linked Interferometer Network (UK)

VLA
Very Large Array (USA)

VLBI
Very Long Baseline Interferometry

EVN
European VLBI Network

eVLBI
VLBI over the internet

space VLBI
VLBI network including space stations

WSRT
Westerbork Synthesis Radio Telescope (NL)

single dish
single paraboloid, cylinder, or other kind of receiving antenna system

Space telescope
Hubble Space Telescope, optical telescope in space

Propagation

Faraday rotation
rotation of the plane of polarization of linearly polarized radiation when the radiation passes though a plasma containing a magnetic field having a component in the direction of propagation.

ionosphere
the region of Earth's atmosphere (80-1000 km) immediately above the stratosphere. The medium is up to about 10% ionised due to the influx of solar UV-radiation.

radio window
the wavelength range between a few millimetres (even sub–mm) and about 30 metres within which Earth's atmosphere is transparent to radiation.

troposphere
lowest level of Earth's atmosphere, from zero altitude to about 15 km above the surface. This is the region where most weather occurs. Its temperature decreases from about 290 K to 240 K.

Protection

active service
radiocommunication service in which transmitter, receiver and the communication channels is under human control.

coordination area
the area associated with an Earth station outside of which a terrestrial station sharing the same frequency band neither causes nor is subject to interfering emissions greater than a permissible level.

coordination distance
distance on a given azimuth from an Earth station beyond which a terrestrial station sharing the same frequency band neither causes nor is subject to interfering emissions greater than a permissible level.

frequency allocation
entry in the Table of Frequency Allocation of a given frequency band for the purpose of its use by one or more (terrestrial or space) radiocommunication services or to the Radio Astronomy Service under specified conditions. This term shall also be applied to the frequency band concerned.

harmful interference
interference which endangers the functioning of radionavigation service or of other safety services or seriously degrades, obstructs, or repeatedly interrupts a radiocommunication service operating in accordance with the ITU Radio Regulations.

level of harmful interference
(for Radio Astronomy)
the interfering signals should produce fluctuations in the detector output which do not exceed 10% of its noise fluctuations.

monitoring
maintaining regular surveillance over the frequency band of interest.

passive service
radiocommunication service in which the operations can be done only by reception of given signals. The user cannot manipulate the transmitter or the communication channel.

protection zone
area associated with an Earth station within which the minimum value of the wanted-to-unwanted signal ratio, usually expressed in decibels, at the receiver input determined under specified conditions, is such that a specified reception quality of the wanted signal is achieved at the receiver output.

Radio Astronomy Service
astronomy based on the reception of radio waves of cosmic origin. It is a passive service, concerned only with the reception of data.

radio-quiet zone
see: protection zone.

separation distance
distance on a given azimuth from an Earth station to the edge of the protection zone.

Radio sources

comet
a diffuse body of gas and solid particles (such as CN, CH, C_2, NH_2, and OH) which orbits the Sun. The orbit is usually highly elliptical or even parabolic (the distance from the Sun ranges from about 1 - 10^4 astronomical units). Comets are unstable bodies with masses on the order of 10^{15} kg whose average lifetime is about 100 passages around the Sun. Periodic comets comprise only about 4% of all known comets. Comets are obviously related in some manner to meteors, but no meteorites from a comet have ever been recovered. Recent observations have established that a comet is surrounded by a vast hydrogen halo.

compact radio source
one whose flux at an intermediate radio frequency is dominated by the contribution of a single bright component less than ~ 1 kilo-parsec across. Compact sources usually exhibit flat X-ray spectra and radio variability.

cosmic microwave background
isotropic radiation first detected in 1964 by Penzias and Wilson at a wavelength of 7.35 cm (equivalent temperature about 2.7 K). It has since been observed at radio and infrared wavelengths from 50 µm to 70 cm. The cosmic background radiation is interpreted as relict from the primeval fireball; it represents a redshift of about 3 000.

discrete radio source
celestial radio source with angular dimensions small compared to the beam of the radio telescope used.

flare star
a member of a class of dwarf stars that show sudden, intense outbursts of energy. It is generally believed that flares in flare stars have certain properties in common: rapid rise to peak light followed initially by a rapid decline and later by a slower phase that occasionally does not return to a pre-flare level within practical monitoring times (several hours). An increase in radio emission is often detected simultaneously with the optical burst.

galaxy
a large, gravitationally bound aggregate of stars and interstellar matter (10^8 - 10^{13} solar masses).

Galaxy
the galaxy to which the Sun belongs.

interstellar medium
in addition to dust, the material in the medium between the stars consist of cold, dense clouds (temperature ~ 50 K, density of hydrogen > 10 cm^{-3}) with radii of a few parsecs and clouds of neutral hydrogen, both immersed in a hot (temperatures > 10^4 K), dilute (density of hydrogen < 0.01 cm^{-3}) intercloud medium. Interstellar matter consists of interstellar gas (99%) and dust (1%).

meteor
a “shooting star” - the streak of light in the sky produced by the transit of a meteoroid through the Earth’s atmosphere.

meteoroid
a small particle orbiting the Sun in the vicinity of the Earth.

millisecond pulsars
pulsar with rotating period as small as 1 millisecond.

nova
a star that exhibits a sudden surge of energy, temporarily increasing its luminosity by as much as 10^4 or more. Unlike supernovae, novae retain their stellar form and most of their substance after the outburst.

neutron star

very small and very dense star, with a diameter on the order of 10 km and densities on the order of 10^{14} g/cm^3. In this condition the neutrons align themselves and, if the star is rotating, this gives rise to a very strong magnetic field of approximately 10^8 Tesla. Electrons injected into this field will spiral and decelerate giving rise to synchrotron radiation. Neutron stars can be found in supernova remnants.

protostar

a stage in the evolution of a young star after it has fragmented from a gas cloud but before it has collapsed sufficiently for nuclear reactions to begin. This phase may take from 10^5 to 10^7 years, depending on the mass of the star.

pulsar

rapidly rotating neutron star which like a lighthouse, radiates a beam which sweeps across the observer at each rotation. The width and shape of the pulse of electromagnetic emission depend on the rotation speed and the angular width of the beam.

quasar

an object with a dominant starlike (i.e. diameter less than 1”) component, with an emission line spectrum showing a large redshift. Many have multiple absorption redshifts; a few have multiple emission redshifts. The light of most if not all quasars is variable over time intervals between a few days and several years, so their diameters must not be much larger than the diameter of the solar system. The energy output of a typical quasar at “cosmological” distance is of the order of 10^{47} ergs per second, which would require a mass of 10^{10} solar masses if it derives its energy solely from nuclear fusion.

radio source

a source of radiation at metre and centimetre wavelengths outside the solar system.

spiral galaxy

a lense-shaped galaxy with luminous spiral arms of gas, dust, and young stars that wind out from its nucleus. Mass range 10^{10} - 10^{12} solar masses. On the average, spiral arms are on the order of 2×10^4 pc long.

supernova

a gigantic stellar explosion in which the star’s luminosity suddenly increases by as much as 10^8. Most of the star’s substance is blown off, leaving behind, at least in some cases, an extremely dense core which may be a neutron star and a pulsar.

Satellite systems

IRAS

Infra-Red Astronomical Satellite

GSO systems

Satellite systems in Geostationary Orbits

HEO systems

Satellite systems in Highly inclined Elliptical Orbits

LEO systems

Low Earth Orbiting Satellite systems in orbits between 150 and 1500 km from the Earth’s surface:

little LEOs: operate at frequencies below 1 GHz;

big LEOs: operate at frequencies above 1 GHz.

MEO systems

Medium Earth Orbiting Satellite systems in orbits between 5 000 and 10 000 km from the Earth’s surface.

Non-GSO systems

Satellite systems in non Geostationary Orbits

Appendix 3. **Keyword Index**

Graphic design: Dans les villes – Strasbourg
Printer: IREG – MAY 2005
ISBN: 2-912049-48-2

EUROPEAN
SCIENCE
FOUNDATION

European Science Foundation
1 quai Lezay-Marnésia, B.P. 90015
67080 Strasbourg cedex, France.
Tel: +33 (0)3 88 76 71 00
Fax: +33 (0)3 88 37 05 32
http://www.esf.org

CRAF Secretariat
Netherlands Foundation for Research in Astronomy,
P.O. Box 2, 7990 AA Dwingeloo, Netherlands.
Tel: +31 521 595100
Fax: +31 521 597332
http://www.astron.nl/craf