Summary

The European Science Foundation's Associated Committee on Radio Astronomy Frequencies, CRAF, was established in 1988 to coordinate European efforts in the protection of radio spectrum bands used by the Radio Astronomy Service and other passive applications.

The development of technology, which has enabled all kinds of advanced astrophysical research, threatens at the same time to render such research impossible from the surface of the Earth. Terrestrial, airborne- and spaceborne transmissions are generated in ever increasing numbers for a multitude of purposes.

The pressure on authorities to make radio spectrum available to all newly developed tools, e.g. RDSS, MSS, HDTV, DBS, APC, S-PCN, is tremendous.

This document reviews the needs of radio astronomy. It is conceptually based on the continuation of the protection of this service.

For the sake of the continuation and progress of the science of radio astronomy, CRAF takes the *starting-point* that frequency protection should be maintained at least at the level the Radio Astronomy Service has enjoyed until now.

This Handbook for frequency allocations in connection with Radio Astronomy has been prepared by the Committee on Radio Astronomy Frequencies (CRAF), an Associated Committee of the European Science Foundation in Strasbourg (see Section 8.2). It provides a comprehensive review of matters related to spectrum management and the protection of the science of radio astronomy against harmful interference. This review is placed within the historical and technological context within which the Radio Astronomy Service operates.

This book addresses a wide readership beyond that of the professional radio astronomy community.

Keyword summary

Chapter 1	Radio astronomy was recognised as an ITU radiocommunication service in 1959. This service has fought for its frequency table allocations ever since. The why's and how's of the service are introduced.
Chapter 2	The Radio Astronomy Service is a passive service. The radio window and passive frequency use are explained.
Chapter 3	The characteristics of the Radio Astronomy Service are given. Radio astronomical observing techniques are explained.
Chapter 4	The frequencies used for the Radio Astronomy Service are introduced at two levels: general considerations and specific ones, illustrated by tables and detailed in comments.
Chapter 5	Detailed comments on the radio astronomical use of specific frequency bands are given to provide background to the brief motivations given in Chapter 4.
Chapter 6	The negative impact of man-made interference on radio astronomical observations is explained and analysed.
Chapter 7	The question of the necessity of absolute interference-free bands for the passive services is discussed.
Chapter 8	The European and worldwide efforts to cooperate within the policy-making and decision-making processes are dealt with.
Chapter 9	The protection of radio astronomy frequencies in the context of international law is explained.

Contents

1. Introduction

This Handbook for frequency allocations in connection with Radio Astronomy has been prepared by the Committee on Radio Astronomy Frequencies of the European Science Foundation in Strasbourg, CRAF (see Section 8.2). It provides a comprehensive review of matters related to spectrum management and the protection of the science of radio astronomy against harmful interference. This review is placed within the historical and technological context within which the Radio Astronomy Service operates.

1.1. History of frequency allocations to the Radio Astronomy Service

Radio astronomy is an active and vigorous science, in which many parts of the Universe are being studied and new discoveries are being made at a rapid rate. To continue this rapid advance with all of its potential benefits, it is necessary to operate many observatories with various characteristics and locations and to be able to observe at many different frequencies. Many countries around the world including Argentina, Australia, Brazil, Canada, China, France, Germany, India, Italy, Japan, Korea, the Netherlands, Poland, Sweden, United Kingdom and the USA have invested in the development of radio astronomy. It is anticipated that they will continue to invest and that other countries will soon start major radio astronomical projects. This progress in science can only continue if the availability of the necessary and important frequencies is adequately guaranteed.

The scientific needs of radio astronomers for the allocation of frequencies were first stated to a World Administrative Radio Conference, WARC, in 1959. These conferences are held under the auspices of the International Telecommunication Union, ITU. At that time the general pattern of the frequency-allocation scheme was

(a) That the science of radio astronomy should be recognised as a radio service in the ITU-R Radio Regulations;
(b) That a series of bands of frequencies should be set aside internationally for radio astronomy, and that these should lie at approximately every octave above 30 MHz and each should have a bandwidth of about 1% of the centre frequency; and
(c) That special international protection should be afforded to the hydrogen line (1400 - 1427 MHz), the OH line (~1.6 GHz; rest frequencies: 1612.231 MHz, 1665.401 MHz, 1667.358 MHz, 1720.533 MHz) and the predicted deuterium line (322 - 329 MHz).

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

The discovery of discrete radio sources and the bulk of current knowledge about their nature and distribution, and of the processes responsible for the radio emission from them, has come through observations of broadband radiation (continuous spectra), made at a limited number of frequencies. Observations of intensity need to be made at a number of frequencies to determine the characteristic "spectra" of sources.

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, represent a significant improvement over the international allocations made to the Service in 1959 and 1963 and are a partial fulfilment of the requirements of the Service.

However, many of the allocated bands have insufficient bandwidths and they are in most cases shared with other radio services; many apply only to limited areas of the world; and there are large intervals between some of the allocated bands.

From WARC 1979 radio astronomy emerged in a much better position in the ITU-R Radio Regulations than it had before. The requirements of the service had been given serious consideration. At frequencies above 20 GHz most requests had been granted. Below 20 GHz the situation was more difficult, because active services already well entrenched had requirements of their own.

One of the results of WARC 1979 is Article 36 of the ITU-R Radio Regulations. It contains a series of frequency assignment proviso's to protect the Radio Astronomy Service. Its detailed impact depends on the implementations by the individual national administrations. There is no explicit acceptance of the levels of harmful interference to radio astronomy as given in ITU-R RA.769-1. Although the validity of this report is well documented, there is great reluctance to incorporate it in the official regulations because of its impact on the active services.

However, at the World Radio Conference, WRC, in 1995 a footnote (FN S5.208A) was added to the ITU-R Radio Regulation saying that radio astronomy should be protected in the bands 150.05 - 153 MHz, 322 - 328.6

MHz, 406.1 - 410 MHz and 608 - 614 MHz to the levels of harmful interference ITU-RRA.769-1. This footnote has been inserted in the frequency table in all bands below 1 GHz which are allocated to the Mobile-Satellite Service for operation in the space-to-Earth direction.

Until now no WARC, WRC, or any other regulatory forum has addressed effective structural solutions to the problems of interference to radio astronomy from transmitters outside the bands allocated to the Radio Astronomy Service. Even now there are a number of primary radio astronomy bands which are adjacent to airborne and spaceborne allocations.

Furthermore, it has become abundantly clear in recent years how spectral usage by active services close to or even in radio astronomy frequency bands is detrimental to the quality of radio astronomical observations. This growing problem received ample attention on several occasions, such as at Colloquium 112 of the International Astronomical Union, IAU, on “Light Pollution, Radio Interference, and Space Debris”, which was held in Washington (August 13 - 16, 1988); the UNESCO-ICSU-IAU exposition in Paris (June 30 - July 2, 1992) and several EMC symposia in Wroclaw. The problems mentioned hold in particular for satellite transmissions which contribute significantly to the growth of 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 frequencies: **line emission**, or **continuum emission** of thermal or non-thermal origin, which is very broad-band. In both cases the **polarisation** characteristics of the radiation are also important and these are an indication of magnetic fields in the radio source.

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 the emissions, since these characteristics are indicators of the emission mechanism and therefore they are direct “finger prints” of the physical characteristics within the radio source. This frequency coverage is essential for polarisation studies, since due to the magneto-ionic characteristics of the interstellar medium the direction of polarisation varies inversely with the square of the wavelength. Therefore, observations at least three different and unequally spaced frequencies are needed to separate the polarisation characteristics due to the magnetic properties intrinsic to the radio source and those of the interstellar medium. To achieve this good frequency coverage, bands spaced at intervals of about an octave in frequency are normally satisfactory.

- **High spectral resolution** is important to analyse the kinematics within the radio source manifested in Doppler shifted line emission.

- **High spatial resolution** is important for the study of the structure of radio sources. Very high spatial resolution can be achieved by the technique of VLBI (see below and section 3.5).

- **High time resolution** is important for the study of the time variations in radio sources. These variations can be as short as milliseconds (as in the case of pulsars).

For more than two decades astronomers have been linking together observations made at radio telescopes many thousands of kilometres apart by recording on fast-running high-density magnetic tape (using very stable oscillators as a reference) and bringing the tapes together so that an interferometer system of several very long baselines is produced. This technique of **Very-Long-Baseline Interferometry, VLBI,** has proved invaluable in studying the structure of very distant radio sources (section 3.5). Extremely high angular resolutions can be achieved. Use has been made of the radio-astronomy bands around 0.3, 0.6, 1.4, 1.6, 5 and 22 GHz for VLBI observations. It is anticipated that international VLBI observations will in the future also make use of the radio-astronomy bands at >22 GHz. Angular resolutions of 0.0003 arcseconds have been achieved with intercontinental baselines and many countries have collaborated in this effort (Australia, Canada, China, Finland, Germany, Italy, the Netherlands, Poland, South Africa, Spain, Sweden, Ukraine, United Kingdom and the USA). Such studies are revealing to astronomers that the enigmatic quasars are composed of intricate structures with many strong localised concentrations of radio emission.

The technique of VLBI has many other 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 this technique, telescopes in several different countries must observe together at exactly the same frequency. *This necessitates that the same bands be protected worldwide.*

1.3. Aim of this document

In this document we restate the views and needs of the Radio Astronomy Service for the protection of the science of radio astronomy in Europe.

There is a continuing need for the reviewing and updating of the allocations of frequencies for radio astronomy. Despite the extension of radio techniques to frequencies over 300 GHz the use of low frequencies remains very important to radio astronomy.

The need for **continuum observations** when first stated in 1959 was based largely on the desire to measure the spectra of radio sources over a wide range of frequencies. Since then two developments have reinforced the need for continuum bands.

The discovery of pulsars has not only given us new astronomical objects to study but has also provided a new tool for exploring the properties of the interstellar medium. For these studies continuum bands, particularly those at frequencies below a few GHz, are most important.

For the technique of Very Long Baseline Interferometry, VLBI, telescopes in several different countries must observe simultaneously at exactly the same frequency; this requires that the same frequency bands be protected worldwide.

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

Since 1959 a large number of **spectral lines** has been discovered. They are produced by a wide variety of simple and complex molecules. The protection of spectral-line frequencies is a difficult task. 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 to objects with greater redshifts. This in turn has made it urgent to look for ways to extend the protection of the hydrogen-line to below 1400 MHz. For many of the molecular species it is difficult to be precise as to their relative scientific importance. Some degree of protection to some lines from the more exotic molecular species continues to be needed by frequency allocations given by footnotes in the Table of Frequency Allocations of the ITU-R Radio Regulations of the International Telecommunication Union, ITU. Although spectral lines occupy a very limited fraction of the whole spectrum, the motions and kinematic characteristics of objects studied in astronomy cause Doppler shifts of these lines. This Doppler shift is mostly to lower frequencies when seen on a cosmological scale, the so-called **redshift** due to the general expansion of the Universe. This redshift can be very large: the 21cm spectral line, excited by interstellar neutral hydrogen, HI, which has a rest frequency of 1420.4057 MHz shifts to frequencies around 300 MHz for distant high redshifted radio sources!

Also, the frequencies between 2 and 30 MHz are significant for radio astronomical research, but due to the congestion problems experienced in this range of the spectrum hardly any possibility exists to improve the situation 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 ITU-R RA.769-1. 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).

We propose that the bands allocated to the Radio Astronomy Service be afforded protection to the level given in ITU-R RA.769-1. Within these bands the 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”, e.g. sound broadcasting, aeronautical radio navigation, mobile telephone, etc. By means of World Radiocommunication Conferences, WRC’s (formerly WARC’s), the ITU allocates radio frequencies to the different services. Radio astronomy is *one such* recognised service but is exceptional in being a **passive** service, i.e. a service not involved in any man-made transmission but only concerned with the reception of naturally occurring radio waves. Consequently **the intensity of the radio waves received by radio telescopes are**, unlike those of active services, **not subject to human control**.

All the active services operate in bands that are also occupied by signals of cosmic origin, but generally they suffer no noticeable interference from these signals, because man-made transmitters emit signals that on reception are several orders of magnitude more powerful than natural signals.

In the early days of the development of radio, receivers were not sufficiently sensitive to detect the natural emission of cosmic origin, and for that reason the sole usefulness of the radio spectrum was perceived to be for communication. Thus its apportionment fell into the hands of bodies with communication 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 phenomenon. It offers possibilities that are of great importance to mankind because it enables wireless communication.

L. Galvani (1737-1798) did his famous frog experiments and discovered the electric current. J.C. Maxwell (1831-1879) predicted electromagnetic waves travelling at the speed of light (1873). H. Hertz (1857-1894) demonstrated the existence of these waves experimentally in 1888. G. Marconi (around 1900) made it possible to employ these radio waves for economic and social use: our radio spectrum was born.

Radio communications 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 wavelengths of many kilometres. Many years later, K.G. Jansky investigated noise levels in order to set a limit to the sensitivity of long distance communication links at 10 meter wavelength. In the process he discovered cosmic radio noise, the radio counterpart of starlight (1932). He found that this so-called "background noise" peaked in the direction of the Milky Way. From these experiments it became clear that the Earth's atmosphere is "transparent" for a certain range of wavelengths, the radio window.

For Jansky cosmic radio waves were a form of interference to communications system in contrast to our present predicament where radio communications have grown to 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 radio communications 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, in particular where the use of the radio window is concerned.

2.3. What radio astronomy offered to the society

Like every science radio astronomical results and techniques serve the progress of other sciences in particular and mankind in general. We may mention

(a) the development of very-*low-noise-receivers* (with wide applications), in a large frequency range, with system temperatures as low as 10 Kelvin.

(b) the study of the *thermography of the body* by use of millimetre radio techniques (~45 GHz).

(c) The detection of *cancer* at centimetre wavelengths (~10 GHz) with modern radiometers and, shortly, using a method of mini-aperture synthesis techniques (interferometric triangulation).

(d) Computerised *x-ray tomography* techniques employ methods originally developed for mapping radio sources.

(e) The detection of *forest fires* by their microwave radiation.

(f) The development of *radio sextants* for marine navigation, allowing accurate determinations of positions at sea even on overcast and rainy days.

(g) 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.

(h) 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.

(i) The experimental verification of Einstein's *General Theory of Relativity* using radio interferometry.

(j) Testing *theories of the origin of the Universe* by observing the 3K background radiation apparently coming from the primeval fireball, the Big Bang.

(k) Measuring the temperature of the earth's atmosphere and the distribution of water vapour and impurities such as carbon monoxide by *passive, remote-sensing techniques*.

(l) Monitoring of *weather* by using radiometers.

(m) Use radio astronomy observations at mm-wavelengths to survey the *Ozone layer and environmental pollution.*

(n) *Training of people* going to all kinds of positions in daily life.

3. Characteristics of radio astronomy

The fact that radio waves can be received from celestial objects, was first discovered by Karl G. Jansky of the Bell Telephone Laboratories in 1932, as a by-product of noise-tests of an early transatlantic radio-communication system. Since then, the science of radio astronomy has expanded to the point where many types of astronomical objects have been studied 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 mainly come from cooler objects, such as the gas between stars or from electrons in ordered motion. Radio astronomers study many of the same celestial objects as do optical astronomers, but in addition they have revealed new classes of objects and discovered quite unexpected forms of activity. Astronomical studies provide a laboratory in which matter can be studied over a wide range of physical conditions, the extremes of which cannot at present 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 waves are stopped by clouds of interstellar dust; radio waves can penetrate these dust clouds, enabling us to study the whole of our Galaxy and other nearby galaxies.

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 atomic and molecular spectral lines, each of which is confined to quite a narrow frequency range.

Continuum emission

The radio continuum arises from two principal mechanisms:

- "Thermal" emission - the intensity of which is proportional to the temperature - is produced in an ionised gas of unbound electrons and protons.

• The majority of the radio sources (such as radio galaxies, quasars and supernova remnants) have a characteristic "non-thermal spectrum". This radiation is generated by high-energy relativistic particles in the presence of magnetic fields, the so-called synchrotron emission. Such a process produces a radio spectrum with a negative slope of ~0.8 in the log frequency vs. log flux density plane. Hence these non-thermal sources have higher radio fluxes at lower radio frequencies. However, at sufficiently low frequencies self-absorption in an emitting source causes a decrease in the flux density (see 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.

This low-frequency range also has a great importance in the observations of both the thermal and non-thermal diffuse radiation in our Galaxy. Such galactic observations provide 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 can be studied at low frequencies, where their spectra approximate that of a black body. Several hundred such galactic clouds appear approximately as blackbodies at frequencies below ~100 MHz. Such spectral observations can be used directly to compute the physical parameters of the radiating clouds, particularly their temperatures.

Fig. 1: Spectrum of a "typical" non-thermal radio source. The dashed line shows the "compact" high frequency component found in some sources.

Another interesting and important class of objects is pulsars. Such objects are now understood to be highly condensed neutron stars that rotate with a period of the order of 1 second. Such objects are produced by the collapse of the cores of very old stars during the catastrophic explosion of their outer stellar parts. The most rapidly rotating pulsars have millisecond periods which are extremely stable, rivalling the best manmade clocks. The radio spectra of pulsars indicate a non-thermal mechanism, perhaps of synchrotron type. Observations have shown that the pulsars are 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 two decades have opened up, unexpectedly, an important new chapter in physics, that of the state of highly condensed matter. The study of neutron stars with densities of the order of 10^{14} g/cm^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 blackholes (which are supposed to be the most highly condensed objects in the Universe). Recent observations of a binary pulsar have verified the existence of gravitational radiation at the level predicted by Einstein's Theory of Relativity. Such low frequencies are indeed important for pulsar observations. The need for exclusive bands every octave is clearly indicated.

Line emission

One of the most widely observed spectral lines occurs at a wavelength of 21cm, arising from neutral atomic (un-ionised) hydrogen in the interstellar gas. The hydrogen 21cm line is the single most important spectral line studied by radio astronomers (Section 5.4). 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 is important to investigate the chemistry and kinematics within radio sources and their structure.

Spectral lines have now been detected from about 100 different molecules 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 might lead to the spores of life, as a possible 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 provide valuable information on the relative densities of the various isotopes and thus indirectly on the general evolution of the chemical elements.

The relative importance of particular lines depends very much on the kind of study for which they are used. However, to understand the chemical and physical condition properly, it is necessary to intercompare a large number of lines.

Radio sources

In the *solar system*, the *Sun*, an ordinary star to which we are exceptionally close, has always been an important object of study by radio astronomers. The slowly varying component of solar emission has been found to provide one of the best indicators of the variation of solar activity over the Sun's 11-year cycle. In addition, the 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. 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 only be studied 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 in comparison with their brightness in an optical telescope. These “radio galaxies” are the subject of many investigations in an attempt to discover the source of their radio energy and the circumstances of the explosive events that seem to have occurred in many of them.

Intrinsically 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 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 important and 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 important discoveries in radio astronomy will surely continue. It is to the advantage of all mankind 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 exists 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

In the Radio Astronomy Service the user has no control over the transmitted signal. The transmitted power can not be varied to improve detection. So we absolutely need to avoid 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 particle, atom 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 communications **20 dB above** receiver noise is usual. Astronomers can only control the electromagnetic environment at the receiver and this creates a potential incompatibility with active spectrum use.

• The radiation received is Gaussian noise

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

• Receiver bandwidth

There are two major goals:

(a) Broadband: detection of continuum emission from thermal as well as non-thermal extraterrestrial radio source. In this application the sensitivity improves with increasing bandwidth.

(b) 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

Equipment with greater sensitivity and better angular resolution is continuing to be improved. System temperatures of 10-20 K for cm-wavelengths and angular resolutions of milliseconds of arc 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 low that these objects can only be studied 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 (implying e.g. 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 scale ranging from many years to milli-seconds. Also other parameters such as the structure of radio sources often show temporal variability. Of course this is not a priori known, which implies that radio astronomical observations need to be stable as a function of time. This stability places requirements on the equipment but also on the interference levels 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 (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 few kHz to several GHz) observations are usually done with many frequency channels (up to several thousand is quite common). This number determines the spectral resolution of the observation. The extremely weak signals received on Earth imply that the sensitivity should be adequate. Usually a 60 dB below receiver noise should be daily standard. Furthermore, high dynamic range in the final results is important to investigate weak features around (for radio astronomy) strong radio sources. An achievable dynamic range of 50 dB is state of the art (see also the cover picture). Sensitivity levels of a few microJansky’s are currently achievable (1 microJansky corresponds to 10^{-32} $Wm^{-2}Hz^{-1}$). To achieve these high quality results long integration times are often needed. This is only possible when within the integration time (which can be up to several days) the EMC environment does not generate harmful interference.

Since characteristics of radio sources can vary at time scales of days to many years, the observations should be repeatable with at least the same quality at these time scales.

3.3. Radio astronomical techniques

Radio astronomical observations are carried out with antennas combined with receivers (usually called radio telescopes) which are either stand-alone instruments, such as single dish telescopes, or a combination of instruments, as in radio interferometry telescopes.

Single dish telescopes have dimensions ranging from a few meters to 100 meters which can point in all directions (Effelsberg, Germany) or 300 meters which can cover only a very limited area of the sky (Arecibo, Puerto Rico). There is a tendency to build larger telescopes since the beamwidth of telescopes of the 25 meters class is usually to wide to obtain sufficient angular resolution.

Combinations of instruments are realised in radio interferometery. In Europe radio interferometers operating at frequencies below about 10 GHz can be found in Cambridge (United Kingdom) and Westerbork (the Netherlands). An interferometer operating at mm-wavelengths is located at Plateau de Bure (France). With such instruments the angular resolution equivalent of "single dish" instruments of the dimensions of the largest distance between the interferometer elements is achieved: which is several km for connected element interferometry.

On a continental or world-wide scale telescopes are combined to form Very Long Baseline Interferometry, VLBI. VLBI is a very special kind of radio astronomical technique and puts constraints on the protection of radio astronomy frequency bands.

Radioastronomical 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 a time span of about 1 minute. The frequency selection is based on the astronomical requirements based on the physics of the celestial radio source and the characteristics of the instrument used. This implies that, in practical matters of frequency management, one has to assume that *all frequencies allocated to the Radio Astronomy Service are always used.*

3.4. Criteria for harmful interference

In general the noise fluctuations ΔT in a radio astronomical measurement of total power are related to the system temperature T, the detector bandwidth β and the integration time τ by the expression

The ITU-R criterion for harmful interference to such a measurement is that the interfering signals should produce fluctuations in the detector output which do not exceed 10% of these noise fluctuations. This is quite different from the popular belief by "communications" that they are allowed to destroy at least 10% of the astronomical data. It is further assumed that the interfering signals enter through far sidelobes of the radio telescope at 0 dB gain (ITU-R RA.769-1).

However it has long been realised that a radio interferometer is less sensitive to radio interference than a total power system. 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 grossly disturbs the receiver). 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 natural fringe rate is measured in kHz, and so the extra immunity to interference resulting from this effect is considerable. Table 2 lists some representative numbers for VLBI system of 3000km baseline.

The 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

where β is the bandwidth and t the delay. 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 2 gives representative values for continuum (β = 2MHz) and spectral line (β = 1kHz) measurements.

Table 2 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

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 is that the interfering signal should add no more than 1% to the receiver noise at a given site (ITU-R RA.769-1). 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 2.

3.5. 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. With telescopes separated by intercontinental distances and wavelengths of 1cm or less, a resolution of less than 1 milliarcsec may be achieved (1 milliarcsec is approximately the angle subtended by a man on the moon). This is the highest angular resolution achieved in any branch of astronomy. The feasibility of extending the technique even further to radio telescopes in space has been demonstrated in the TDRSS experiment and space VLBI missions are currently under development.

VLBI observations are now conducted regularly at most cm-wave radio observatories around the world.

3.5.1. VLBI techniques

VLBI differs from the normal connected-element radio interferometry in several aspects. In a conventional radio interferometer the radio telescopes are linked to a common clock to maintain the coherence of the interferometer and the signals from each telescope are brought together, through appropriate delays, to be correlated in real time to produce the interferometer fringes. This type of operation is not usually possible in VLBI. Originally the problem was purely a technical one, but nowadays it is mainly the cost which prevents satellite links being used. In any case there are two main technical differences between VLBI and conventional radio interferometry. In VLBI each observatory relies on its own highly stable clock to maintain coherence by dead reckoning. For milliarcsecond resolution a hydrogen maser is usually employed. This has a precision of one part in 10^{14} which is adequate; indeed coherence times are then limited by atmospheric effects. Coherence times range from 100s at 7mm wavelength up to tens of minutes at cm wavelengths.

A second difference is that the data from each VLBI station are separately digitised and recorded onto magnetic tape for subsequent processing. Only later are the tapes brought together and the data correlated to produce the interferometer fringes. The recording system used has high sensitivity and is wideband. This so-called MKIV uses a multichannel tape drive to record up to 256MHz of data on magnetic tape.

Another difference with connected-element radio interferometry has evolved in the way 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

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

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.

3.5.2. VLBI frequency bands

The frequency bands used regularly for VLBI are listed in Table 1. 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 (section 5.2). The frequency bands used by the different VLBI networks are also indicated in Table 1: EVN stands for the European VLBI Network in which 10 radio observatories are participating; USA stands for the US Very Long Baseline Array, VLBA, network.

It will be noticed that the standard VLBI frequency bands for the MK III recorder usually exceed the bands allocated to radio astronomy. Fruitful use of these unprotected sub-bands is possible for reasons discussed in Section 3.5.4.

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 been established through collaborations with NASA personnel. The bands offer the advantage of 64m-class NASA radio dishes equipped with state-of-the-art cooled maser receivers.

3.5.3. Mapping considerations

In section 3.4 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 US 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, 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!

3.5.4. 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 3.4 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 multi-million dollar international observing facility. If we consider instead the use of existing data we encounter 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. If interference is noted then there is not yet an agreed system for logging the information (frequency, power, duration etc.). The effects of interference only become apparent during the correlation of the data some months after the experiment, or even later, during the mapping process. Again it would be difficult to extract the 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 from which expertise could be drawn on.

3.5.5. Conclusions

There are factors which give VLBI some 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 VLBI operations are successfully carried out in some unprotected frequency bands not allocated to radio astronomy.

A number of questions deserves 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?

Table 1: Frequency Bands Used for VLBI

Wavelength cm	R.A. Band (MHz) in ITU-R RR		MKIV Band (MHz)		EVN	USA	Other
90.0	322.00	to	319.99	to	x	x	x
	328.60	to	333.99				
50.0	608.00	to	599.99	to	x	x	-
	614.00		613.99				
21.0	1400.00	to	1374.99	to	x	-	-
	1427.00		1430.99				
18.0	1660.00	to	1636.99	to	x	x	x
	1670.00		1692.99				
13.0	(2290.00	to	2214.99	to	-	-	DS
	2300.00)		2270.99				
6.0	4990.00	to	4956.99	to	x	x	*
	5000.00	to	5012.99				
3.6	(8400.00	to	8270.99	to	-	x	DS
	8500.00)		8326.99				
1.3	22210.00	to	22206.99	to	x	x	*
	22500.00		22262.99				
0.7	42500.00	to	43178.99	to	-	-	+
	43500.00		43234.99				

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

Table 2: Factors affecting the response of a VLBI array to interfering signals

Representative baseline observation time	D = 3000 km T = 40 min		
Wavelength λ	18cm	6cm	1.3cm
$\upsilon = D/\lambda$	1.7×10^7	5×10^7	22×10^7
Fringe spacing (milliarcsec)	12	4	0.9
*Natural fringe rate $\varpi_o \upsilon$ (KHz)	1.2	3.6	16.3
Fringe frequency effect $(\varpi_o \upsilon T)^{-1/2}$ (dB)	-32	-35	-38
Representative delay $t = D/c = 10^{-2}$ sec for all λ			
Representative bandwidth	β = 2 MHz (continuum) 1 MHz (line)		
Bandwidth decorrelation factor $\frac{\sin \pi\beta t}{\pi\beta t}$ ($d\beta$) =	-48 dB (continuum) -15 dB (line)		

Here $\varpi_o = 7.3 \times 10^{-5}$ Hz is the Earth's rotation rate.

Fig.2 Thresholds of interference versus frequency for radio astronomy spectral line and continuum observations. From ITU-R RA.769-1.

Fig.3 Harmful threshold of interference to radio astronomical 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 RA.769-1.

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

1. 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 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 to close the radio window. 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. Table 3 summarises the potential interference situation from air- or space-to-ground transmissions adjacent to the primary radio astronomy bands.

2. *Important spectral lines* should have their allocation status improved by the insertion of relatively narrow exclusive bands in the allocation table. This is particularly important in the case of the OH lines (1612, 1665-1667 and 1720 MHz). The suggested bandwidths should be wide enough to cover the expected Doppler range found in our Galaxy. Note that for external galaxies Doppler shifts of about -300 MHz can be observed for both the hydrogen line and the OH lines.

3. The *most important spectral lines* are listed in ITU-R Recommendation RA.314-8. Protection of all of these lines and some others either by footnotes or through an exclusive allocation would be desirable.

   Multi-transition observations of some carefully selected molecules (CO, CS, HCN, HCO+, H_2CO, NH_3) together with theoretical modelfitting 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 on 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, $C^{34}S$, $H^{13}CN$, $H^{15}CN$, $H^{13}CO+$, $HC^{18}O+$, 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 nuclear processing.

4. 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 would be desirable for some of the continuum bands.

5. 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 even more complex molecules and possibly amino acids, will be found. Identification of complex molecules can be made only by detection of a number of 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 a 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.

6. 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.

7. 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

1. *Decametric radiation* from the planet Jupiter and Solar activity at metric and decimetric 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 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 scientifically fundamental solar bursts occur in a frequency range between 100 - 3000 MHz continuously and a comprehensive analysis of solar phenomena that are closely linked to the terrestrial environment require observation frequencies outside the few and narrow bands allocated to radio astronomy. Solar radio astronomy is an essential tool for solar activity prevision and especially for the prediction of perturbations caused by the Sun to terrestrial radio transmissions.

2. There will be strong pressure, internationally, for increased protection of the *322 to 328.6 MHz* band. This band serves both narrow band (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.

3. The *608-614 MHz* band has different detailed allocations for each region. The band should be consolidated into a single world-wide exclusive band.

4. 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 FN S5.340. In bands immediately below this band, guidelines should be given to avoid specific allocations. This band is used world-wide by the Very Long Baseline Interferometry technique.

5. 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 band

have at least 1% bandwidths. Proposed national arrangements should partly alleviate this problem.

6. *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.

7. On *higher frequencies*, 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.

8. 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-R Radio Regulations. According to ITU-R Radio Regulations the primary services are indicated in CAPITAL letters (see also the footnotes to Table 3).

Table 3: Summary of broadcast, spaceborne and airborne/terrestrial allocations adjacent to radio astronomy bands

4.3. Comments on frequency allocations

This section incorporates all 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:** These two bands have a shared primary allocation world-wide (see also FN S5.149). These bands are very important for observations of decametric radiation from the planet Jupiter and from the Sun.

3. **37.5 - 38.25 MHz:** This band has a secondary allocation worldwide (see FN S5.149). 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. Long after all the decametric frequency bands have been allocated and widely

used by active services Jovian decametric radiation was discovered. The allocations to the Radio Astronomy Service are extremely narrow since the interesting Jovian phenomena can cover the entire spectrum from 3 - 40 MHz. Jupiter is the only radio-planet observable from the ground 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, since the interesting solar phenomena can cover the entire spectrum up to 70 MHz. The Sun is the nearest star and its study enables a closer 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 world-wide 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**:
5. **79.25 - 80.25 MHz**: This primary exclusive allocation for the Radio Astronomy Service applies only in Region 2 (before WARC 79 it also applied in Region 3). Observations with the Arecibo 305-m radio telescope may be affected by active use of this band by the Fixed and Mobile Services in Cuba and other countries included in Footnote S5.178. A primary exclusive allocation on a world-wide basis is highly desirable; notification of use is required in Regions 1 and 3 (Footnote S5.149), and in Region 3 (with some exceptions) the band 79.75 - 80.25 MHz is allocated on a primary basis to the Radio Astronomy Service. In the United Kingdom the band 80.5 - 82.5 MHz is used in lieu of the Region 1 allocation 73-74.6 MHz (for historical reasons).

   These bands are used, for example, for monitoring the interplanetary "weather" structure in the solar wind by an international network of instruments.

6. **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 greatly 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 world-wide consolidation would be most desirable.

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

7. **322 - 328.6 MHz**: This band (see FN S5.149) 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, in particular, 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 an 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 ultra-violet 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 will increase (see Section 5.1).

8. **406.1 - 410 MHz**: This is an important band (see FN S5.149) for radio astronomy, but its usefulness is reduced 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 RA band upwards by a few MHz so that emissions near the lower end of the band could be avoided (see Section 5.1).

9. **608 - 614 MHz**: Various RA allocations are made within this range, with various degrees of protection, to fit in with local television assignments, one television channel usually being made available for RA (see FN S5.304, S5.305, S5.306 and S5.307). Radio astronomy attaches considerable importance to the maintenance of this allocation since without it, there would be a large gap between the 410 and the 1400 MHz allocations, in one of the most interesting parts of the spectrum. The band is of special importance for (world-wide) VLBI observations. It is requested that in those parts of the world in which the allocation to Radio Astronomy 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).

10. **1330 - 1400 MHz**: This band is needed for important observations of Doppler-shifted radiation from hydrogen. FN S5.149 (note: FN S5.339) provides some protection to facilitate observations on more distant sources at those observatories with the largest aerials. Such observations can often be made at frequencies shared with low-power ground transmitters, but high power transmitters especially for radiolocation and any transmitters in aircraft or satellites can cause interference. Particularly in Europe this band suffers bad sharing conditions (i.e. by radar). It is hoped that the temporary use of radio navigation (Footnote S5.338) will be phased out.

    A world-wide allocation to Radio Astronomy at least from 1370 - 1400 MHz is desired.

11. **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 FN S5.340.

    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 5.4).

    Numerous and detailed studies of neutral hydrogen distribution in our Galaxy and in other galaxies are being made. Such studies 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, in a search for emissions from extraterrestrial civilisations (see FN S5.341 and CCIR report 700).

12. **1610.6 - 1613.8 MHz**:
13. **1660 - 1670 MHz**:
14. **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. Such 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 molecules in space have been detected. 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 only originate 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 5.3 and 5.4).

    Recent observations of OH maser sources with the powerful technique of Very Long Baseline Interferometry, VLBI, have shown that OH sources have apparent sizes that are of the order of 0.01 arc second or smaller. Such 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 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. Recently, with very sensitive instrumentation, OH has been detected from 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.

Some comments to the different OH-bands:

<u>1610.6 - 1613.8 MHz</u>:
An important OH line used in conjunction with the main OH bands in the next higher band. Footnote S5.149 gives some protection within 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.314-8 table 1).

<u>1660 - 1670 MHz</u>:

This is an important radio astronomy band for measurements of both the OH lines and the continuum. The present allocation of the band 1660 - 1660.5 MHz to the Mobile Service may lead to its serious degradation. In addition this band is used for continuum observations and also for VLBI. Successful use of this band will also depend on the avoidance of interference from meteorological satellites with assignments in the adjacent band (see FN S5.149 and S5.379). An allocation for radio astronomy with improved sharing for the total band is desired (see also ITU-R Recommendation RA.314-8, table 1).

1718.8 - 1722.2 MHz:
This band is for observations of the OH lines associated with those in the band 1660 - 1670 MHz and protection needs to be improved beyond FN S5.149 by excluding airborne and space transmissions (see also ITU-R Recommendation RA.314-8, table 1).

15. **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 can give 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 to 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 such frequencies.

The frequency band 2655.0 to 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 regions of 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 important 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 such 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. Problems 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 polarisation of the radiation that is observed from radio sources. It is often found that radio sources are weakly linearly polarised, 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 polarisation 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 degree of polarisation of radio waves is higher at higher frequencies. The frequency bands near 2700 and 5000 MHz are important bands for polarisation 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 (FN S5.149) will be 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).

16. **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 (FN S5.340).

17. **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 FN S5.149, 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.

<u>3260.0 - 3267.0 MHz</u>:
<u>3332.0 - 3339.0 MHz</u>:
<u>3345.8 - 3352.5 MHz</u>:
The protection of these bands (FN S5.149) for observation of CH is still important (See ITU-R Recommendation RA.314-8, table 1).

18. **4800.0 - 4810.0 MHz**:
19. **4825.0 - 4835.0 MHz**:
20. **4950.0 - 4990.0 MHz**: The spectral region around 5 GHz has been one of the 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 make 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. This 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 - 4810 MHz by radio astronomy in some countries (FN S5.149 and S5.443).

    The importance of the formaldehyde line at 4829.66 is such that at least a strong footnote is needed (see FN S5.149 and S5.443) 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 being located to include the formaldehyde line (see ITU-R Recommendation RA.314-8, 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 FN S5.149 and S5.443). Protection would be improved if transmission from aircraft could be excluded.

21. **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 world-wide VLBI.

22. **10.60 - 10.70 GHz**:
23. **14.47 - 14.50 GHz**:
24. **15.35 - 15.40 GHz**: The frequency band 10 to 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 such 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 means of assisting us in solving such problems. Such observations are now best performed in the frequency range 10 to 15 GHz.

    The small sizes of the quasars are revealed from the VLBI observations mentioned earlier. Such observations are also being made in the frequency band 10.6 to 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 these lines originate from the upper levels of ortho-formaldehyde their study gives valuable information on the physical conditions of the interstellar medium, because the excitation energies required to produce such lines are different from the energies required to produce the H_2CO lines observed at 4829.66 MHz.

Although the importance of the RA band at 10.60 - 10.70 GHz makes an exclusive world-wide allocation desirable (since it is one of the most important bands used for internationally coordinated observations over long baselines) the use of the exclusive band 10.68 - 10.70 GHz with downward extension with the help of local protection seems to be adequate at most observatories. However exclusion of aeronautical mobile from the band 10.60 - 10.68 GHz is essential in order 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 (FN S5.149) is of importance in conjunction with the adjacent band (22.21-22.5 GHz) for observations of redshifted H_2O (see ITU-R Recommendation RA.314-8, table 1) (see 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.314-8, table 1) (see Section 5.5).

27. **22.81 - 22.86 GHz**: This band is of importance 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 FN S5.149 are taken into account. But in region 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 world-wide (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 FN S5.149 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 FN S5.149 and S5.340 should be sufficient to provide satisfactory local protection for observatories.

32. **36.43 - 36.5 GHz**: This band is of importance in the search for HC_3N and OH lines. The sharing situation as it is now and the provisions of FN S5.149 should be sufficient to provide satisfactory local protection for observatories.

33. **42.5 - 43.5 GHz**:
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 SiO 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.

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 $J = 1 \rightarrow 0$ 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.

<u>42.5 - 43.5 GHz</u>:

The lines of silicon monoxide (SiO) at 42.820, 43.122, 43.425 GHz are the subject of RA measurements. Their protection (incl. FN S5.149) should be maintained.

<u>47.2 - 50.2 GHz</u>:
A line of carbon monosulphide (CS). The primary allocation for the band 48.94 - 49.04 MHz (FN S5.149) should be maintained including FN S5.149.

35. **51.4 - 54.25 GHz**:
36. **58.2 - 59.0 GHz**:
37. **64.0 - 65.0 GHz**:
38. **71.0 - 74.0 GHz**:
39. **86.0 - 92.0 GHz**:
40. **92.0 - 95.0 GHz**:
41. **95.0 - 100.0 GHz**: Because 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. Two vibrational states, v = 1 and 0, of the $J = 2 \rightarrow 1$ transitions of SiO fall within 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.

51.4 - 54.25 GHz:
(FN S5.340 and S5.556)

58.2 - 59.0 GHz:
(FN S5.340 and S5.556)

64.0 - 65.0 GHz:
(FN S5.340 and S5.556)

71.0 - 74.0 GHz:
Footnote protection (FN S5.340) should be maintained in a band 150 MHz wide for radio astronomy observations on this formaldehyde line (H_2CO) (rest-frequency = 72.409 GHz).

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 (see SPM Report, Annex 5.2.1.2.2). Transmissions from broadcasting satellites in the contiguous band 84.0 - 86.0 GHz are a potential source of interference in the long term.

92.0 - 95.0 GHz:

Footnote protection should be maintained for this line of diazenylium (HNN^+) (rest-frequency = 93.17 GHz).

95.0 - 100.0 GHz:

The primary allocation (FN S5.149) should be maintained for this line of carbon monosulphide (CS) (rest-frequency = 97.98 GHz) which has been identified as of high priority.

42. **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 tools in the study of isoptope ratios, but are also essential in the study of cool clouds, regions of star formation and the structure of our Galaxy and other galaxies. The line at 115.27 GHz is currently given protection by

Footnote S5.340. Other lines in this band are the cyanogen radical (CN) and lines of methyl cyanide (CH_3CN), isocyanic acid (HNCO), carbonyl sulphide (OCS) and cyanoacetylene (HC_3N). Very high priority is placed on making this band a primary world-wide allocation to the Radio Astronomy Service.

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 and also because CO seems to be very abundant and exists almost everywhere 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 $^{13}C^{18}O$ have also been detected in many regions of 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 is very active 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 activity at frequencies above 100 GHz has been increased greatly in the last decades. By March 1990, hundreds of spectral lines had been detected in the 100 - 200 GHz range; and more instrumentation has become available to study spectral lines in the 200 $\rightarrow$ 300 GHz range (up to frequencies higher than that at which the radio-frequency spectrum is currently allocated). Also at these frequencies numerous lines have been detected.

43. **140.0 - 151.0 GHz**: Primary allocation exists (FN S5.149 and S5.555) and should be maintained for RA 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)

These have been identified as having high priority.

44. **164.0 - 168.0 GHz**: This band is used for continuum observations.

45. **174.0 - 182.0 GHz**: This band contains useful lines for RA at 174.6, 174.85, 177.26, 178.4 and 181.2 GHz for which footnote allocation has been given (FN S5.149).

46. **182.0 - 185.0 GHz**: This band has currently the status of primary allocation the Radio Astronomy Service (shared with SR (Passive)). It contains important lines of water vapour at 183.5 GHz and ozone at 184.75 GHz and the allocation needs to be retained.

    Allocation of 182.0 - 185.0 GHz is proposed for radio astronomy and other passive services. Water, an important constituent of interstellar clouds as well as of the terrestrial atmosphere, has only two radio-frequency lines: at 22.235 GHz and at 183.310 GHz. Both have been detected by radio astronomers, but the former is a maser emission line so only the latter seems to be useful for determining interstellar H_2O abundances. The 183.310 GHz line cannot be observed from the ground but is accessible from airplanes, balloons and spacecraft.

47. **186.2 - 186.6 GHz**: A line of diazenylium which is observed in the Radio Astronomy Service has currently a footnote status allocation (FN S5.149).

48. **217 - 231 GHz**: Lines of carbon monoxide (CO) at 219.560, 220.399 and 230.542 GHz need to be observed in conjunction with CO lines in the band 105 - 116 GHz. This is an important radio astronomy requirement, listed in SPM Report Annex 5.2.1.2.2 and a world-wide primary allocation is currently valid (FN S5.340).

    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 groundbased observations difficult or impossible.

    Large antennas and sensitive receivers at frequencies greater than ~100 GHz are being developed at the present time. 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 $^{12}C^{16}O$. Coverage for $^{12}C^{16}O$ is extended to red shifts of 2000 km/sec, which is in fact a rather modest value. This band is extremely important for studies of the structure and evolution of galaxies.

49. **265 - 275 GHz**: This band allocated to the Radio Astronomy Service (FN S5.149) contains a very important series of spectral lines of the molecules C_2H (262.5 GHz), HCN hydrogen cyanide (265.9 GHz), HCO^+, formalyl (272.0 GHz). Protection should be retained.

50. **Above 275 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 also FN S5.565).

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 small frequency range, less than a factor 2, the spectra usually have a power law shape ($S \propto f^{\alpha}$, 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 (either due to the radiating particles, or due to thermal ionised gas in the sources, 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 and VLBI) working at low frequencies are 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 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 only be attacked at low frequencies are numerous and we mention only a handful:

1. Galactic radio astronomy

- total intensity and polarisation mapping of the very diffuse, generally low-brightness, galactic non-thermal background emission. At low frequencies the polarisation data are sensitive to very small amounts of intervening ionised gas due to the $(\text{wavelength})^2$ dependence of the Faraday rotation of the polarisation plane.

- 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.

2. Extragalactic radio astronomy

- With the great sensitivity of 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 approaching five, implying that neutral hydrogen is shifted to frequencies of about 240 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 part 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 two in frequency often means the difference between detection or upper limits.

- 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 paramount importance to cosmology.

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 polarisation properties of the radiation is essential. To study the radio structure of extraterrestrial radio sources the wavelength dependent beamwidth is of prime importance for adequate angular resolution.

5.2.1. Polarisation studies

Very often extraterrestrial radio emission is linearly polarised, 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 polarisation characteristics change: the polarisation angle varies as the square of the observing wavelength. For an unambiguous determination of this change of polarisation angle, observations need to be done 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.

The 49 cm band (608 - 614 MHz) is used for measurement of linear polarisation of emission from extraterrestrial sources together with the 92 cm band (322.0 - 328.6 MHz) and the 21 cm band (1400 - 1427 MHz). Using the 49 cm band, the relative intervals are from 92 cm to 21 cm wavelength 1.9 : 2.3 (or in squared wavelength 3.6 : 5.4), which is a minimum requirement for polarisation studies.

5.2.2. Beam properties

Making observations with diffraction-limited imaging systems (which radio telescopes are) the resolution directly depends on the observing wavelength: the resolution of such imaging systems depends directly upon the wavelength at which it operates: 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:

1. the maximum resolution of the synthesised beam decreases with increasing wavelength.

2. the field of view being imaged (determined by the size of the individual interferometer elements) increases with wavelength.

The 49 cm 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 21 and 92 cm. 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 beam width. There the more modest jump of a factor 4 - 5 in beam area between 21 - 49 cm and 49 - 92 cm is about the maximum acceptable.

Astronomical objects vary in size from extremely compact (less than 1 arcseconds) 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 49 cm capability would mean for many objects of 0.5' - 1' that they could only be fully observed at 92 cm 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 (1000 km and more) radio telescopes to operate together with a consequent huge increase in angular resolution. The other major VLBI network is 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 49 cm has an angular resolution (0.05 arcsecond) very similar to the Space Telescope, ST. The ST, a major ESA-NASA project to put an optical telescope in space, is likely to set the pace for much astronomical research into the 21st century. With the EVN at 49 cm European astronomers have the optimum instrument for producing radio images to match optical data from the ST.

5.2.4. Allocation

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

In region 2 the Radio Astronomy Service has a primary status whereas in the regions 1 and 3 a secondary status by footnote S5.306 is allocated. In Western

Europe the band (called channel 38 in the broadcast allocated band 470 - 790 MHz) has been kept free from strong interference in France, Germany, the United Kingdom and the Netherlands. Not maintaining this low level of interference means that research as outlined above will be severely hampered. Not only the local research programmes cannot be carried out but also the international cooperation with the VLBI observing technique will be made close to impossible.

5.3. Importance of the redshifted 21 cm hydrogen line

Ninety percent of the atoms in the Universe are hydrogen, and most of those are in the ground state. Since its discovery in 1951, the 21 cm line (1420.4057 MHz) of neutral 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 of 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 with increasingly high velocities away from us. 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 6000 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 - 1420 MHz, but recent technological advances have opened up the range even down to 1300 MHz for routine studies. Furthermore, since radiation travels 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, allowing astronomers to study the time evolution of the Universe. For example, the 21 cm line absorption detected in the spectrum of a quasar recently at 430 MHz tells about physical conditions at an epoch in the history of the Universe some 10 billion years ago!

The 21 cm 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 six 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 man-made emissions in scientific observations both in real-time and at post-detection. Such interference excision is made possible because cosmic 21 cm line radiation often has a characteristic frequency signature. However, because man-made transmissions generally are 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 mankind'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^{29} 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. About thirty megamasers have been found to date. The powerful OH emission can be detected to great distances. 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 18 cm to 21 cm wavelength.

GLONASS transmissions cause particular disruption to searches for OH megamasers because the signals are nearly always present, and because they cover a wide range of frequency (see also Section 5.4.3.5).

5.4.2. Astronomical importance of the OH 1612 MHz band

The band 1610.6 - 1613.8 MHz is used primarily for observations of the OH ground state satellite line at 1612.2 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 variables 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 by mass loss. 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. One thousand OH-IR sources are presently 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 yield many thousands of sources eventually.

OH-IR sources are extremely important because their distances can be determined directly 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 gives the linear angular size across the shell. Interferometer measurements give the angular size of the shell and hence 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 satellites operating in the band 1610-1626.5 MHz under FN S5.366 presently cause harmful interference to measurements of the OH 1612 MHz line world-wide, and prevent the acquisition of useful data during half or more of the observing time.

5.4.3. Problems of sharing between the Radio Astronomy and Mobile-Satellite Services in the band 1610-1626.5 MHz

At WARC-92 the frequency band 1610-1626.5 MHz was allocated to the Mobile-Satellite Services (Earth-to-space) on a primary basis, with a secondary allocation for space-to-Earth transmissions. The band 1610.6-1613.8 MHz was allocated to the Radio Astronomy Service on a primary basis, and Footnote S5.372 states that “harmful interference shall not be caused to stations of the Radio Astronomy Service using the band 1610.6-1613.8 MHz by stations of the Radiodetermination-Satellite and Mobile-Satellite services (No.2904 applies).” Sharing is particularly difficult for radio astronomy, which is a passive service. This document reviews the sharing criteria necessary to protect the Radio Astronomy Service against new mobile services, and considers the sharing problems within Europe.

5.4.3.1. Radio astronomical use of the band 1610.6-1626.5 MHz

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

20 years. The increasing astrophysical interest in this spectral line is reflected in the upgrade of the allocation to primary status world-wide at WARC-92. The band is used regularly at 15 radio astronomy sites within Europe. These are listed in Table 4.

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, Dwingeloo and Jodrell Bank). One of the most intensive users of the band is Nançay, which devotes 50% 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 7 radio astronomy sites in England are connected by microwave links to form a long baseline interferometer MERLIN (the Multi Element Radio Linked Interferometer Network). Finally the European radio telescopes are operated regularly 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 3-4 weeks duration and each covering more than one frequency band. The 1612 MHz band is scheduled regularly but not necessarily in all sessions.

5.4.3.2. Protection criteria

The harmful interference levels for the Radio Astronomy Service are given in ITU-R Recommendation RA.769-1. They depend on the type of measurement being made. For the types of measurements made in Europe in the 1612 MHz band the levels are as follows:-

Single telescope spectral line measurements	-237 dB $Wm^{-2}Hz^{-1}$
Interferometry (Westerbork)	-224 dB $Wm^{-2}Hz^{-1}$
Interferometry (MERLIN)	-215 dB $Wm^{-2}Hz^{-1}$
VLBI	-208 dB $Wm^{-2}Hz^{-1}$

A value of 0 dBi is assumed for the gain of the radio astronomy antenna in the direction of the transmitter (sidelobe level).

5.4.3.3. Sharing considerations

(a) Satellite downlink

The most obvious sharing problem is presented by the satellite downlink in the band 1610-1626.5 MHz. With a direct line-of-sight between the satellite and the radio astronomy antenna the expected power flux densities (pfd) are far in excess of those harmful to radio astronomy. For example the Iridium system is expected to produce an average pfd at the Earth's surface of -163 dB $Wm^{-2}Hz^{-1}$, some 74 dB above the harmful threshold for single telescope spectral line measurements. Thus no transmissions will be possible in the band 1610.6-1613.8 MHz whenever the satellite is above the horizon of an active radio astronomy antenna, if FN S5.372 is to be satisfied. Furthermore, satellite transmissions in the remainder of the band 1610-1626.5 MHz will need substantial filtering if interference from spurious and out-of-band emissions is to be avoided. Such unwanted emissions will need to be well below the pfd of the necessary emissions (e.g. 74 dB below in the case of Iridium). This is a major technical challenge.

(b) Mobile uplink

It is readily shown that frequency sharing is impossible for a mobile transmitter within direct line-of-sight of a radio astronomy site (ITU-R RA.1031). Therefore, some form of geographical and time sharing is necessary. The possibilities for sharing with mobile transmitters were investigated in connection with the Radiodetermination Satellite Service (GEOSTAR in the USA and LOCSTAR in Europe) and were outlined in ITU-R RA.611-2. The Report used the concept of protection zones around radio astronomy sites. This concept, renamed coordination zone, has now been incorporated in the new ITU-R Recommendation on sharing (Draft Recommendation 7D-DG3/1, Geneva 1993).

A coordination zone around a radio astronomy observatory is defined so that the total interference from all mobile transmitters outside the zone does not exceed the harmful interference level, measured at the radio astronomy site. The size of the zone thus depends on the type of radio astronomical measurements being made (Section 3), the number and distribution of mobiles, their e.i.r.p. in the direction of the radio astronomy site, the fraction of time they are active, and the propagation characteristics. Outside the coordination zone mobile users may transmit freely. Inside the coordination zone transmissions must be inhibited unless technical means can be found to avoid harmful interference to the radio astronomy operations.

The radii of the coordination zones calculated in Report 1126 are approximately 100 km for ground-based mobiles and 300 km for airborne mobiles. These numbers are a useful guide to the severity of the sharing problems.

If coordination is to work the mobile user must have some means of determining when a coordination zone has been entered, and some means of reducing the power flux density received at the radio astronomy observatory below the threshold for harmful interference. Two possible solutions have been discussed, although neither system has yet been demonstrated in practice.

In the first solution the mobile user carries position-determining equipment (e.g. a GPS receiver) together with a regularly updated list of the position of those radio astronomy sites currently observing in the 1612 MHz band, and their required coordination zones. Transmissions in the band 1610.6-1613.8 MHz are then inhibited whenever the mobile enters a coordination zone.

In the second solution the radio astronomy observatory has an omnidirectional beacon transmitter in a nearby frequency band. The beacon is activated only when radio astronomical measurements are being made, and the power level of the beacon is related to the size of the coordination zone required. Transmissions from the mobile are inhibited in the band 1610.6-1613.8 MHz whenever the mobile user detects the beacon.

These solutions arose naturally from consideration of the RDSS system, which is fairly sophisticated. It is not clear whether they would be appropriate for the types of mobile now under discussion.

5.4.3.4. Spurious and out-of-band emissions

Mobile transmitters operating in the adjacent band 1613.8-1626.5 MHz could also cause harmful interference to radio astronomy operations through spurious and out-of-band emissions. General limits on unwanted emissions from mobile Earth stations are given in pr ETS 300 254 as -46 dBW in any 100 kHz within the bands 1600-1610 and 1661-1690 MHz, or -96 dBW Hz^{-1}. Mobiles radiating this much power continuously into the radio astronomy band 1610.6-1613.8 MHz would require significant coordination zones, e.g. 30 km in radius. Therefore it is important to ascertain the levels of unwanted emissions from the proposed new mobile transmitters, with a view to tightening the specification. Any reduction in unwanted emissions will reduce the coordination burden.

5.4.3.5. Satellite services

At the present time the Russian global navigation satellite system GLONASS is the major source of interference to radio astronomical observations in the band 1610.6-1613.8 MHz. This is a severe and world-wide problem for radio astronomy, but it is now being dealt with at an international level. Negotiations between the radio astronomy community, represented by the Inter Union Commission on the Allocation of Frequencies, 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. A technical evaluation of the experiment was produced in April 1993 at the meeting of the ITU-R Working Party 7D. The recommendations are that the GLONASS satellites be confined to centre frequencies below the radio astronomy band (≤1608.75 MHz in the first instance, and ≤1605.375 MHz in the second stage), and that as soon as practicable the GLONASS system employs filtering of the satellite transmissions. A political decision is now awaited. These developments should be borne in mind when considering the proposals for sharing with new mobile services.

5.4.3.6. Conclusions

The frequency band 1610.6-1613.8 MHz is used extensively in Europe for radio astronomy (Table 4). The density of radio astronomy sites is particularly high in the United Kingdom and in the Netherlands. The thresholds for harmful interference to the Radio Astronomy Service range from -237 dB $Wm^{-2}Hz^{-1}$ for single telescope spectral line measurements to -208 dB $Wm^{-2}Hz^{-1}$ for VLBI. These low power flux densities illustrate the vulnerability of the Radio Astronomy Service to harmful interference, and the consequent difficulty of sharing the band.

The MSS downlink at 1610-1626.5 MHz presents the most serious threat to radio astronomy operations, as it has the potential to cause world-wide disruption. Frequency sharing will be impossible whenever a satellite is above a the horizon of a radio observatory using the band 1610.6-1613.8 MHz. Indeed satellites transmitting anywhere in the band 1610-1626.5 MHz may be expected to cause harmful interference to the Radio Astronomy Service through their spurious and out-of-band emissions, whenever they are above the horizon, unless the transmissions are heavily filtered. It is not clear whether the necessary filtering can be achieved with current technology.

An initial assessment has been made of the possibilities for frequency sharing with mobile uplinks. It is estimated that coordination distances of approximately 100 km would be necessary for ground-based mobiles, and 300 km for airborne mobiles. Thus in-band sharing may not be a realistic option in some European countries. Mobile uplinks operating in the remainder of the band 1610-1626.5 MHz also have the potential to cause harmful interference to radio astronomy through their spurious and out-of-band emissions, which are not tightly specified at present.

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.314-8. Not all these lines received sufficient protection by the ITU-R Radio Regulations.

The total number of observed spectral lines is by far larger. In particular the band from 18 to 30 GHz is densely packed with observed lines. 173 transitions within this spectral range are recorded in a list by Lovas (1986) only 37 of which are covered by the four spectral lines that entered the ITU-R Recommendation RA.314-8. 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 in bands which are going to be used for transmissions from satellites down 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 statements are especially valid for many lines in the total band 22.5-23 GHz which is already provided for the Broadcasting-Satellite Service, HDTV, in region 2 and 3, but also for other neighbouring bands which may be regarded useful for HDTV and they refer also to allocations for other services with satellite transmissions down to Earth.

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.314-8 which refers to this problem when 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 coordination 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:

In cases, where such a band is used by the Broadcasting- Satellite Service, agreements should be made for interruption of transmission during certain night hours.

In cases, 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. Millimeter wavelength (> 30 GHz) astronomy

At millimetre wavelengths the non-thermal radiation which can be studied at longer wavelengths becomes weak and the cosmic signals are dominated by thermal radiation from cold material. This is just the "long wavelength extension" of the heat radiation produced by any hot body. In principle this is emitted over the whole electromagnetic spectrum from radio wavelengths to gamma rays. For example the thermal radiation from a room temperature body peaks in the infra-red region and is relatively weak in the radio bands. Thermal radiation from cold interstellar clouds has a maximum in the sub-millimetre band and the background radiation left over from the "big bang", at an equivalent temperature of 2.7 K has its maximum at 150 GHz in the 2 mm band.

In the colder regions of space, matter can exist in molecular form if it is far away from the intense ultraviolet radiation from hot stars. The radiation from these molecules occurs at a series of discrete frequencies or spectral lines which are different for each type of molecule. The relative intensities of the lines emitted from a given molecule depend on the physical conditions such as density and temperature within the emitting region. Thus it is frequently necessary to observe several lines, or transitions, of a given molecule. 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 transition may be obscured by emission from some other molecule. However, by studying the frequency 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.

However, 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-radio astronomer. It is much more difficult to deduce the composition of the dust particles as there are few if any characteristic lines which can be used to identify its component 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: *astro-chemistry*.

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

- they are the only bands containing over 1000 radio spectral lines of interstellar and circumstellar molecules;
- they are the only bands in which one can detect the emission of cool dust in space;
- they 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;

- they are also the only bands in which one can detect the low-temperature cocoons of protostars, via their dust and molecular-line emission;

- they are probably the only bands in which we can derive kinematic information about proto-planetary disks around young stars.

Fig.4: Spectrum taken towards a molecular cloud [Sgr B2(N)] in the direction of the Galactic centre. In this section of 45 GHz about 1700 lines have been found. The observation was made with a frequency resolution of 2 MHz by A. Nummelin at the SEST telescope (Chile). The 3 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 insterstellar and circumstellar clouds (as of January 1st, 1997)

Inorganic, stable molecules:

H_2 HCl NH_3 SiH_4 CO H_2O NaCl
CS H_2S KCl NO HNO AlF ALCl
NS N_2O SiO SO_2 NaCN
SiS OCS PN

Organic, stable molecules:

CH_4 C_2H_2 C_2H_4 HCN CH_3CN HC_3N
CH_2CHCN CH_3C_3N CH_3CH_2CN CH_3CCH CH_3C_4H
HNCO CH_3OH CH_3CH_2OH H_2CO H_2CCO
HCCCHO CH_3CHO CH_3OCHO $(CH_2)_2O$
$(CH_3)_2CO$ H_2CS HNCS CH_3SH CH_2NH
NH_2CN NH_2CH_3 NH_2CHO

(not found: acetic acid, urea, glycine)

Reactive molecules:

carbon chains C_2 C_3 C_5
HC_5N HC_7N HC_9N $HC_{11}N$ (?)
H_2C_3 H_2C_4
C_2O C_3O
C_2S C_3S C_5S

linear radicals C_2H C_3H C_4H C_5H
C_6H C_7H C_8H
CH CH_2 (?)
OH NH NH_2
CN C_3N
HCO HCCN H_2CCN
CP SO
SiC SiC_2 SiC_4 SiN
MgNC MgCN

isomers HNC CH_3NC HCCNC HNCCC

cycles c-C_3H c-C_3H_2

ions CH^+ CO^+ SO^+ H_3^+ H_3O^+ $HCNH^+$
$HCCCNH^+$
HCO^+ HCS^+ HN_2^+ HCO_2^+

The detections of CH_2H and $HC_{11}N$ are based on one single rotational transition.

The very high density of spectral lines in the millimetre spectrum sets this part 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 a recent (unsuccessful) search for the simplest amino acid - Glycine - the position of 98 lines was examined, but the density of other lines prevented an unambiguous identification. At such sensitivity the spectrum is completely filled by line emission. This can be seen in the spectrum shown in Figure 4.

As of January 1995 a total of 108 molecular species had been detected in interstellar and circumstellar gas clouds (Table 4). They include stable inorganic and organic molecules such as salt, carbon monoxide and ethyl alcohol, reactive molecules such as the strange carbon chains $HC_{11}N$, radicals such as NH_2, C_2H, and several ions like HCO^+, $HCCCNH^+$. Several were discovered in space before being found in the laboratory. Strangely the aromatic molecules so important for life are absent so far, although searches will doubtless continue.

mm-Wave astronomy is thus the proper tool to study objects like comets, planets, interstellar clouds, stellar atmospheres, protostars, protoplanetary disks, galaxies, quasars and intergalactic clouds in which the material is largely molecular.

5.6.1. Techniques of mm-astronomy

Observations at the shorter millimetre wavelengths are increasingly dominated by considerations of the transparency of the atmosphere. The very molecules under study cause atmospheric absorption. This is highest at the transitions of water vapour at about 22 GHz and oxygen at about 60 GHz, 120 GHz etc. These frequencies are effectively impossible to observe from the ground 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 in which ground based astronomical observations are possible. This is illustrated by Figure 5. As can be seen within these windows the effects of atmospheric water vapour is to give a continuous absorption rising rapidly 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 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. For minimum noise these are operated at the temperature of liquid helium and comprise a thin layer of insulating material sandwiched between two superconducting pieces. Hence the name "superconductor-insulator-super-conductor" junctions (SIS). The tunnelling properties of these 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 to allow 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-optics spectrometers. For continuum observations of dust for example, very sensitive bolometer detectors of wide bandwidth have been developed. To attain the ultimate in sensitivity the bolometer elements are frequently cooled to 0.1 K and their bandwidth is several tens of GHz. "Staring" arrays of up to a hundred such bolometers are now coming into operation and allow an instantaneous picture of a section of the millimetre sky to be "seen".

Fig. 5: Millimetre-wave radio windows

Such equipment is extremely difficult to protect from interfering signals at nearby frequencies, i.e. out-of-band and spurious emissions. While the broadband characteristics of the receivers also imply that often frequencies outside the bands allocated to the Radio Astronomy Service are used.

This problem is because of the following reasons:

1. 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;

2. the SIS mixers used by most mm-observatories, need very small local oscillator power and are thus open to saturation by signals as weak as 1 nanowatt;

3. at present there is no technology available to build high Q radio frequency filters of the necessary extremely low loss needed. 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 such devices to be built.

As at lower frequencies, single dish, connected element interferometers and also VLBI are 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 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, Sweden, Turkey, Russia, France, Spain with important outstations in Hawaii and Chile. An interferomter array is operating in southern France on Plateau de Bure. On a world-wide scale 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 USA plans an array of 40x8 m diameter telescopes, Japan aims for a

50x10 m array and the European countries have their sights set on an array of 50x15 m telescopes.

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 IAU list of important lines (see Section 5.8) 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. Even the few important lines may thus appear at practically any frequency in the mm-bands. This tendency is reinforced by the requirement of very large bandwidth needed for continuum studies by bolometer.

So astronomers need access to the whole of the mm-windows. It is difficult to see how the protection provided by the existing allocations, based on a few important lines and not taking adequate account of Doppler shifts, will be enough in the future as commercial exploitation of the spectrum moves to higher and higher frequency. It is clear that millimetre astronomers can share spectrum with several fixed services, by use of coordination or radio-quiet zones for example. However, this will be impossible in the case of the satellite services. Some careful thought might be necessary to set up “guard” bands around radio astronomy allocations which could be allocated to some of the fixed services which are more compatible with the strict requirements of the Radio Astronomy Service.

The problem of protection of mm-observatories is subject to further investigation. The way mm-observatories are protected 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.

5.7. Footnotes for the Radio Astronomy Service

CRAF would be happy with the status quo of the specification of footnotes for Radio Astronomy in the ITU-R Radio Regulations, in particular if these could be consolidated into four general footnotes as given below:

1. For all cases where band is allocated to Radio Astronomy on a Primary Exclusive basis or to Radio Astronomy on a Primary basis shared with Space Research (Passive) the recommended footnote should read:

A) All emissions are prohibited in the following bands:

25.55	-	25.67	MHz
73.00	-	74.00	MHz
608.50	-	614.00	MHz
1400.00	-	1427.00	MHz
2690.00	-	2700.00	MHz
15.35	-	15.40	GHz
23.60	-	24.00	GHz
48.94	-	49.04	GHz
51.40	-	54.25	GHz
58.20	-	59.00	GHz
64.00	-	65.00	GHz
86.00	-	92.00	GHz
105.00	-	111.00	GHz
217.00	-	231.00	GHz

2. For all cases where the allocation to Radio Astronomy and/or Space Research (Passive) is

a) Primary shared with another service

b) Primary with another service secondary

c) Secondary

d) Secondary by footnote, on a world wide basis or

e) On a world wide basis with no mention of Primary or Secondary the recommended footnote would read:

B) In making assignments to other services to which the following bands are allocated:

13.36	-	13.41	MHz
37.50	-	38.25	MHz
79.25	-	80.25	MHz

150.50	-	153.00	MHz
322.00	-	328.60	MHz
406.10	-	410.00	MHz
608.00	-	614.00	MHz
1330.00	-	1400.00	MHz
1610.60	-	1613.80	MHz
1660.00	-	1670.00	MHz
1718.80	-	1722.20	MHz
2655.00	-	2690.00	MHz
4800.00	-	4990.00	MHz
4990.00	-	5000.00	MHz
10.60	-	10.70	GHz
14.47	-	14.50	GHz

3. Administrations are urged to take all practical steps to protect Radio Astronomy and Space Research (Passive) observations from harmful interference. Space and airborne transmissions present particularly serious sources of interference to these services.

C) In radio astronomy a number of important spectral lines are observed in the bands listed below. Administrations are urged to take all practical steps to protect Radio Astronomy observations from harmful interference. Space and airborne transmissions present particularly serious sources of interference to these services:

3260.00	-	3267.00	MHz
3332.00	-	3339.00	MHz
3345.80	-	352.50	MHz
22.01	-	22.21	GHz
22.21	-	22.50	GHz
22.81	-	22.86	GHz
23.07	-	23.12	GHz
23.60	-	24.00	GHz

4. For all cases where the allocation to Radio Astronomy or Space Research (Passive) is by footnote on a regional basis the recommended footnote would read:

D) In making assignments to other services to which the following bands are allocated:

73.0	-	74.0	MHz
608.0	-	614.0	MHz

Administrations are urged to take all practical steps to protect Radio Astronomy and Space Research (Passive) observations from harmful interference. Space and airborne transmissions present particularly serious sources of interference to these services.

If the above general footnotes are used, the only remaining footnotes will be those dealing with exceptions of various kinds.

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 - August 1, 1991) the astrophysically most important spectral lines have been carefully reviewed. The IAU listed the revision of these spectral lines as 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.

Table 5: Radio-frequency lines of the astrophysically most important spectral lines

6. Effects of man-made interference on radio astronomical observations

6.1. The environment

Man-made interference of various kinds is having an increasing negative impact on observational astronomy.

Why is this?

This is because **Radio astronomy is a passive service**. It means that in the Radio-Regulations of the International Telecommunication Union radio astronomy is defined as a radio service (Article 1, no.14: **Radio astronomy**: astronomy based on the reception of radiation of cosmic origin). The Radio Astronomy Service is defined as a service based on reception. In radio astronomy no signal is transmitted by man and therefore this service is called a **passive** service. The susceptibility of a passive service to interference from electromagnetic waves is larger than that for active services.

In recent years it has become clear that spectrum use by active services close to or even within the bands allocated to the Radio Astronomy Service does occur. For secondary allocations and shared primary allocations this is in agreement with the ITU-R Radio Regulations but detrimental to the quality of the radio astronomical observations. The use of frequency bands with primary allocation exclusively to the Radio Astronomy Service is, apart from being detrimental to the quality of the observations, also not in agreement with the ITU-R Radio Regulations. **The root of the problem is that the Radio Astronomy Service is a passive service**, so it can only control the receiver side of the "communication system", which is different from the active services that control the whole system, transmitters, channel and receiver. The resulting differences are quantitatively related to the numbers that vary with sensitivity, signal to noise ratio, dynamic range, signal power and these differences make active and passive services more or less incompatible. We have therefore a compatibility problem in electromagnetic wave utilisation.

In the realm of communication engineering, communication systems are understood to consist of a transmitter (source), a channel and a receiver (destination) and that in general all these components can be controlled. In most active systems this is the actual situation. If for example the signal to noise ratio in a communication link is not good enough the signal power at the transmitter can be increased.

In radio astronomy we can control neither the transmitter nor the channel: these are set by nature. This results in a increasing vulnerability for interference because of the characteristics of radio astronomy, which are documented in Report 852 of the ITU-R Greenbook II, “Characteristics of Radio Astronomy Service and preferred frequency bands” and the ITU-R *Handbook on Radio Astronomy.*

6.2. Local, regional and global problems

The interference problems in radio astronomical observatories can also be divided into different categories with relation to their distance from the source. Already mentioned are the local problems, that require a **local** solution like for example a radio-quiet zone around radio astronomical observatories.

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

Most damaging for radio astronomy are the **global** problems mainly caused by satellites and satellite systems. No shielding against this threat is possible. Therefore, solutions have to be sought in proper filtering of the transmitters, the use of modulation techniques to reduce spurious and out-of-band emissions, i.e. to avoid spectrum pollution, or by adequate management of the spectrum to avoid allocations to space services adjacent or otherwise too close to frequencies used by the Radio Astronomy Service.

6.3. The effect of broad-band transmissions on radio astronomy

Spurious emissions have been of concern to the ITU since the beginning of radio communications. Initially it was the broad-band nature of spark transmission that made it appear that the number of bands would be severely limited. Fortunately, the tuned circuit and the vacuum tube were invented making it no longer necessary to rely on spark generation for transmitters. Immediately the number of bands available and the potential use of the bands were greatly increased. Shortly thereafter theoretical work was done to show the fundamental relationship between the amount of information per unit time and the required bandwidth. These developments resulted in the more efficient use of the spectrum existing today.

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 broad-band in nature. The sensitive receivers and broad-band modulation are on a collision course.

As with most methods of modulation, broad-band modulation does not cut off sharply at the band edges, but falls off depending on the particular type of modulation and the care exercised in the design of the transmitter. For some types of modulation techniques, the rate of fall-off can be increased by means of well designed filters. The degree to which filtering out of the out-of-band radiation affects the quality of the transmission requires further study. On the other hand, the input bandwidth of a sensitive receiver does not normally fall off sharply at the band edges. Here the rate of cut-off can be increased by the use of filters with not too much effect on the operation of the receiver.

The existing regulations defining bandwidth, spurious emission and harmful interference were adopted before the widespread use of broad-band emission and sensitive receivers occurred.

Because of its impact on both Space Research and Radio Astronomy, CRAF favours that 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 broad-band modulation techniques on interference to other services using sensitive receivers and to propose methods to alleviate the problem. CRAF also favours that the ITU-R reviews the pertinent regulations and propose those changes required on technical grounds to control out-of-band radiation and spurious emissions with the purpose of reducing the occurrence of harmful interference.

7. Does radio astronomy need frequency bands which 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. Firstly radio astronomy was recognised as a "radiocommunication service". Secondly a series of frequency bands was allocated for use by radio astronomy as radio quiet "windows" through which radio astronomers could observe the Universe. These bands were reviewed by subsequent conferences, including the WARC-92 and the WRC-95. The results are shown in Table 3. The fraction of the total spectrum allocated to the Radio Astronomy Service in the ITU-R Radio Regulations can be summarised as follows:

< 30 GHz:
0.7 % primary exclusive for passive frequency use
0.8 % primary shared allocations
1.5 % secondary allocations

30-275 GHz:
3.0 % primary exclusive for passive frequency use
0.5 % primary shared allocations
0.3 % secondary allocations

all frequency bands:
2.2 % primary exclusive for passive frequency use
0.7 % primary shared allocations
0.8 % secondary allocations

The recognition of radio astronomy as a service in the same way as television and mobile communication, was a 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 applications in a frequency band in which they have a

secondary allocation shall not cause interference to services having a primary allocation in this band.

3) "Footnotes" draw the attention to the use of a specific band by radio astronomy and request that "all practicable steps" are to be taken into account to avoid harmful interference to radio astronomy. Footnote S5.149 lists all frequency bands allocated to other services and which are allocated to the Radio Astronomy Service by footnote. This footnote does not only urge administrations to take all practicable steps to protect the Radio Astronomy Service from harmful interference, but it adds that emissions from spaceborne or airborne stations can be particularly serious sources of interference to the Radio Astronomy Service.

However, the passive nature of radio astronomy 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 has no primary status, the factual status is the same as if it has no protection at all (unless administrations are willing to take the appropriate practical steps to achieve this protection).

In practice, however, radio astronomy operates as if it has a secondary allocation world-wide, 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: Does radio astronomy need protected frequency bands, which are 100% free of interference?

Even primary allocation of a particular band does not guarantee complete freedom from interference as ITU-R Radio Regulations state that radio astronomy may seek protection only to the extent that other services are afforded from one another. This degree of protection, which enables active services to operate in practice without loss of quality, is unfortunately sometimes insufficient for radio astronomy. This being insufficient follows from the fact that besides a qualitative "image" of a celestial radio source, the science of radio astronomy needs to perform quantitative analyses. This requires very careful calibration of the instruments in (relatively narrow) interference free environment.

7.2. Man-made 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 humankind and to further development of science and culture. However, there is a price to be paid. With each new satellite launched, another man-made "radio star" appears on the sky. These satellites use at present frequencies in the ranges of around 150 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 intended to perform their missions, 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 time periods. The radiation received from man-made satellites is relatively intense due to their very small distance (in astronomical terms) to the Earth. Many systems currently under development, apply mass produced handheld Earth terminals with omnidirectional antennae, like GPS receivers and mobile telephones. They require signals strengths at the receiver more than 10^8 times stronger than astronomical radio sources. Therefore, even the useless, but unavoidable out-of-band and spurious emissions, even though well suppressed by technical standards, may appear stronger throughout an increasing fraction of the radio spectrum.

7.3. The threats to radio astronomy

Radio astronomy was recognised as a radiocommunication service in 1959. With this recognition it was considered as one of the many communication services, however without recognising that this service is a passive service. In the ITU-R Radio Regulations there is no definition of a passive service, so a distinction between passive and active services was not yet possible. In spite of the established use of the term "passive" with respect to radio astronomy the radio community often fails to grasp its true significance. It is after all quite different to receive a broadcast say +20 dB above noise level than to detect faint emissions at some -60 dB signal-to-noise ratio. Consequently the usual sensitivities used in radio astronomical receivers are seldom appreciated as the reason for the high vulnerability to interference of these receivers. Also the fact that these receivers are often very broad-band makes the situation even more difficult.

It is a given fact that the future will see increasing demands on the use of the radio spectrum by existing or new services. For instance a number of services have already given such indications like (digital) Broadcasting-Satellite Service, Radionavigation-Satellite Service and Mobile Satellite Service.

Even more pressure on the spectrum can be expected from ideas still under study like power from orbit.

7.4. Are radiation free oases necessary?

From the previous paragraphs it is clear that this is not a question that can be answered in a simple way. The answer is **YES**; but let us consider the practical meaning of such an answer under the prevailing conditions. As has been stated in previous paragraphs, the Radio Astronomy Service (in the sense of the ITU-R definition of a radiocommunication service) is not a mere category of radio stations providing a service similar to radiocommuncation services. Radio astronomy is a science, consisting of a wide variety of different scientific aims, different types of instruments each having different observing techniques, and different vulnerabilities to interference, a mixture of different services, with different aims, instruments and different vulnerabilities to interference.

Especially those radio observations that intrinsically are sensitivity limited due to a very narrow-bandwidth (e.g. in the event that spectral line observations are made) or a very short integration time (e.g. in the event of pulsar searches) are vulnerable to interference. Since these kind of observations are done in many of the leading observatories, the answer to the question posed is **YES**. The situation for other type of observations, like map-making may be less severe because the level of sensitivity needed can be obtained by longer integration times if the celestial radio source does not 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 the latter type of observations. Nowadays the situation is becoming 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 in which the various communication services need a wider use of the spectrum. The paramount argument for radiation free parts of the spectrum has to be sought in the quantitatively adequate calibration that has to be carried out.

The reason is that 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 such quantitative analyses has to be done in an interference free environment. In practice 10% to 50% of the observing time of an instrument is used for calibration.

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 which are impossible to attain in a man-made 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: we now regularly observe pulsars which are star remnants consisting of neutrons only. Magnetic fields of some tens of Tesla are available in the laboratory: in the same neutron stars the fields are of millions of Tesla. Quasars provide another example of science that cannot be done on the scale of terrestrial experiments. High-energy plasma physics on this scale may not 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 providing tests for 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 testbed is the binary pulsar, 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.

For all mankind, 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. Firstly the realisation that observed sources included the most distant observable objects in the Universe, the best probes for the theory of the Big Bang. 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 in the science of radio communication. As the techniques of radio communication moved to ever shorter wavelengths, it became necessary once again to investigate the natural noise levels which would provide the basic limitation to long distance communications. The radio links were now between satellites and ground stations and the 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.

The cosmic microwave background is the most primitive radiation mankind can detect. It arose when the Universe was a dense expanding fireball less than one million years old. We see the same radiation today redshifted from optical to radio wavelengths. It is a uniform all-pervasive radiation with the spectrum of a black-body of temperature 2.7 K. It is detected by radio telescopes as an excess noise contribution to the total receiver noise. Because the radiation is almost isotropic the excess noise is the same, to within a milli-Kelvin wherever the telescope points. The signal is inherently very difficult to detect and measure. Even more difficult to measure and as important for our understanding of the early Universe, is the fluctuation of the cosmic background radiation. Through the deviation from isotropy of the 2.7 K radiation we want to learn about the unisotropy 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 “background radiation” is not an illumination of the Universe from the limb, but rather the whole Universe is filled with 2.7 K radiation. Therefore, the so-called Sunjajev-Zeldovich effect predicts the visibility of the 2.7 K radiation in absorption against the more intense black body radiation of the very thin and hot gas in clusters of galaxies. The Sunjajev-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 local background interference of man-made emissions produced by spread-spectrum techniques, unwanted sidebands and spurious emissions. 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 loose 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 with relation to their distance from the interfering source. We distinguish problems at a local, regional and a global scale.

The local problems occur at 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 for example to spark-plugs of cars and household equipment, require a local solution like for example a radio-quiet zone around radio astronomical observatories.

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

The worst for radio astronomy are the global problems mainly caused by satellites and satellite systems.

It is hardly possible for us to imagine a world without any radio, television, telephone and all other kinds of communication systems. All these systems use the electromagnetic spectrum and they use the spectrum in an active way.

This active use means that there is a transmitter generating electromagnetic waves, which travel, and are distributed so that they can be caught by a distant receiver which enables the user to “read” the information modulated on these waves.

This is very different from the characteristics of radio astronomical spectrum use (Section 3).

8.1. Communication between radio astronomy and national administrations

Active spectrum users, usually originating from broadcasting, industry, telecommunication companies, are one partner in the “electromagnetic society”. Another is the administration, whether it be national (of sovereign countries), regional (in Europe bodies such as the CEPT or the European Union) or global (like the United Nations and its organisations). The problem space is illustrated in Figure 6.

Quite often it is experienced that the interests of activities along each of the axis are orthogonal to each other. This implies that good communication and negotiation forums are mandatory for adequate "living together in the electromagnetic society".

Since radio astronomy is a purely scientific and usually a government funded activity, communication between radio astronomers and national administrations should obviously be well organised. This is besides the fact that the national administrations are the voting members of the World Radio Conferences of the ITU. Because of this role they are responsible for proper implementation of the ITU-R Radio Regulations and protection where needed.

At a local scale radio observatories communicate with 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 borders.

Furthermore, the world-wide scale of radio astronomical activity is best served with solutions at the largest possible geographical scale. At a 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 (Section 8.2). At a global scale this work is done by IUCAF, the Inter-Union Commission on the Allocation of Frequencies (Section 8.3).

Figure 6: Problem space for frequency management.

8.2. CRAF and its European role

The Associated 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 Inter-Union Commission on the Allocations of Frequencies for Radio Astronomy and Space Research, 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. 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, so that it is for instance also 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 being fulfilled by e.g. the publication of this Handbook for Radio Astronomy which it is intended to make widely available, particularly to system designers and to Spectrum Managers. Furthermore, CRAF regularly publishes a Newsletter, which is at present only available on the WorldWideWeb (address of homepage: *http://www.nfra.nl/craf*).

Since January 1, 1997, CRAF employs a full time pan-European radio astronomy Spectrum Manager.

8.2.1. Actions and results

CRAF has acted on several fronts to protect the Radio Astronomy Service. Its work has been inter alia 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-RRB since 1993), the Conférence Européenne des Postes et des

Télécommunications, CEPT, and its off-shoot the European Radiocommunications Office, ERO, to ensure the continued good management of the radio spectrum.

- Correspond with the Radiocommunications Agency of the British Ministry of Trade and Industry, DTI, concerning the possible use of television channel 38 (608-614 MHz). As a result channels 35 and 37 have been allocated to television transmitters but in the UK channel 38 is being kept free for radio astronomy.

- Communicate at ministerial level with the Italian authorities to make possible the continued existence of Radio Astronomy in Italy. The regulatory arrangements in Italy are significantly different and significantly less satisfactory than in the rest of Europe, and CRAF fears that the current situation in Italy could easily become the norm throughout Europe unless representations are made to prevent it. For instance despite representations made both by CRAF and the Italian radio astronomers, the proliferation of unregulated private TV networks has made it impossible to protect channel 38 in Italy. At the new radio observatory near Noto in Sicily, the Italian astronomers are suffering impulsive interference in the 1400-1427 MHz hydrogen line band which is supposedly a world-wide passive band allocated exclusively to Radio Astronomy. The interference is clearly out-of-band emission from radar. CRAF is making representations about it 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 recent World Administrative Radio Conference, WARC-92, and the World Radiocommunication Conferences, WRCs, which are held every other year. The conference decisions and recommendations are as a result, and despite fears to the contrary, often positively favourable to the Radio Astronomy Service.

- Have numerous discussions with the French LOCSTAR company concerning various ways of achieving coordination between their proposed Radio Determination Satellite Service, RDSS, planned to occupy the 1613.8-1626.5 MHz band, and the Radio Astronomy Service in the adjacent 1610.6-1613.8 MHz band. The technical problem was how they could reduce their out-of-band emissions to a satisfactory level, and it was exacerbated by their intention to use spread-spectrum modulation. The matter was resolved by LOCSTAR going out of business.

- Contributed 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) by this commission is a result of this effort.

- Drawn attention in various publications of its members to the effects of man-made interference on radio astronomical observations.

- Encourage participating Institutes to monitor interference. The Nançay Radio Observatory in France maintains a European database on events of harmful interference suffered by European radio astronomy observatories. It has been monitoring the interference experienced from the Russian global navigation satellites system GLONASS. These observations have been of value in discussions between IUCAF and the GLONASS administration.

- Participate with various CEPT SE project teams:

  SE17 PT concerning "the compatibility between the MSS uplink and other radio systems in the 1610-1626.5 MHz band". With respect to radio astronomy the report of the project team compared the required separation distances between a radio astronomy observatory and a Mobile Earth Station, using different propagation models taking into account in-band as well as out-of-band emission from the MSS applications.

  SE21 PT concerning Spurious Emissions.

  SE27 PT concerning Terrestrial Digital Video Broadcasting, T-DAB.

  SE28 PT concerning MSS technical standards, operations, and compatibility issues (such as the protection of primary services sharing the band or operating in adjacent bands (Radio Astronomy, MSS,...) and the protection of the Radio Astronomy Service at 5 GHz (second harmonic of the band 2483.5-2500 MHz).

- Communicated with the CEPT concerning the Detailed Spectrum Investigation, DSI, which the European Radiocommunications Office is carrying out in preparation of a Common European Frequency Table by the year 2008.

- Communicated with the 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 operating in the Fixed Satellite Service causes harmful interference in the subband 10.69 - 10.7 GHz. The band 10.6 - 10.7 GHz is heavily used by Effelsberg observatory in Germany.

- Discussed with the Italian administration the necessary improvement of the communication and coordination between this administration and the Radio Astronomy Service in Italy.

8.2.2. WRCs and current problems

Since 1993 World Radio Conferences, WRCs, are held every other year at which specific problems concerning frequency allocations are considered at the inter-governmental 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 recognised by the ITU and was consequently not entitled as such to be at the conference, nevertheless members of CRAF usually attend the meetings as members of the IUCAF delegation or of national delegations, and contribute in no small measure to the favourable outcome for the Radio Astronomy Service.

One favourable result of the last WARC, WARC-92, has been the elevation of the status of the Radio Astronomy Service in the band 1610.6-1613.8 MHz to CO-PRIMARY world-wide. This band corresponds to one of the transitions of the important OH radical. At present this band is interfered because of out-of-band transmissions from the spread-spectrum signals from the Russian GLONASS satellites which have carrier frequencies every 0.5625 MHz from 1602.5625 to 1615.50 MHz. 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 outcome of the WARC-92 was that for the first time a WARC has 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-R Radio Regulations, for the protection of the Radio Astronomy and other passive services, at the next competent WARC.

8.2.3. Long term problems

One urgent problem, which has not been fully studied by the ITU-R Radiocommunications Bureau 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, 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 in exposing 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.

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.

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

8.2.4. European Science Foundation

The European Science Foundation, ESF, is an association of its 62 member research councils and academies and institutions devoted to basic scientific research in 21 countries. ESF brings European scientists together to work on topics of common concern, to coordinate the use of expensive facilities, and to discover and define new endeavours that will benefit from a cooperative approach.

The scientific work sponsored by ESF includes basic research in the natural sciences, the medical and biosciences, the humanities and the social sciences.

The ESF links scholarship and research supported by its members and adds value by cooperation across national frontiers. Through its function as coordinator, and also by holding workshops and conferences and by enabling researchers to visit and study in laboratories throughout Europe, the ESF works for the advancement of European science.

8.2.5. Addresses

European Science Foundation

Dr. H. U. Karow (ESF Scientific Secretary for Physical and Engineering Sciences)

M. Clifford (ESF contact)
1 Quai Lezay-Marnésia
67080 Strasbourg Cedex
France
Tel: +33 3 88 76 71 07
Fax: +33 3 88 37 05 32
Email: pesc@esf.org

Committee on Radio Astronomy Frequencies, CRAF

R. J. Cohen (Chairman)
Nuffield Radio Astronomy Laboratories
Jodrell Bank
Macclesfield, Cheshire SK11 9DL
United-Kingdom
Tel.: +44 1477 571321
Fax: +441477 571618
Email: rjc@jb.man.ac.uk

T.A.Th.Spoelstra (Secretary)
Netherlands Foundation for Research in Astronomy
P.O.Box 2
7990 AA Dwingeloo
The Netherlands
Tel:+31 521 595100
Fax: +31 521 597332
Email: spoelstra@nfra.nl

R. Bachiller
Observatorio Astronomico Nacional
Apartado 1143
28800 Alcala de Henares
Spain
Tel.: +34 1 885 5060/+341 885 5061
Fax: +341 885 5062
Email: bachiller@oan.es

A. O. Benz
Radio Astronomy Group
Institute of Astronomy
ETH Zentrum
80992 Zürich
Switzerland
Tel: +411 632 42 23/1 632 38 13
Fax: +411 262 00 03
Email: Internet: benz@astro.phys.ethz.ch

E. Bervalds
Latvian Academy of Sciences
19 Turgeneva Street
LV-1524 Riga
Latvia
Fax: +371 782 1153
Email: berv@acad.latnet.lv

G. F. Block
ESA, Frequency Management Office
Directorate of Telecommunications
8-10 rue Mario-Nikis
75738 Paris Cedex
France
Tel: +33 1 42 73 73 02
Fax: +33 1 42 73 75 60
Email: gblock@hq.esa.fr

P. Cugnon
Observatoire Royal de Belgique
Ave Circulaire 3
1180 Bruxelles
Belgium
Tel: +32 2 3730302
Fax: +32 2 37 49 822
Email: pierrec@oma.be

B. Darchy
Nançay Observatory
Station de Radioastronomie
18330 Neuvy/Barangeon
France
Tel: +33 2 48 55 18 241
Fax: +33 248 51 83 18
Email: darchy@obspm.fr

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 2028 2286
Fax: +7 095 203 8414
Email: borisd@mail.cplire.ru

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

M. E. Özel
Marmara Research Centre
Space Sciences Department
P.O.Box 21
41470 Gebze-Kocaeli
Turkey
Tel: +90 262 641 2300
Fax: +90 262 641 2309
Email: ozel@mam.gov.tr

J. E. B. Ponsonby
Nuffield Radio Astronomy Laboratories,
Jodrell Bank, Macclesfield,
Cheshire SK11 9DL, England
Tel: +44 1477 571321
Fax: +44 1477 571618
Email: jebp@jb.man.ac.uk

W. Reich
Max-Planck Institut für Radio Astronomie
Radioobservatorium Effelsberg
53902 Bad Münstereifel
Germany
Tel: +49 2257 30112
Fax: +49 2257 30169
Email: wreich@mpifr-bonn.mpg.de

K. Ruf
Max-Planck Institut für Radio Astronomie
Auf dem Hügel 69
53121 Bonn
Germany
Tel: +49 228 525 255
Fax: +49 228 525 229
Email: kruf@mpifr-bonn.mpg.de

A. A. Sanches de Magalhaes
Observatório Astronómico
Prof. Manuel de Barros
Universidade do Porto, Monte da Virgem,
4400 Vila Nova de Gaia
Portugal
Tel: +351 2 782 0404
Fax: +351 2 782 7253
Email: asmagal@oa.up.pt

A. Tlamicha
Astronomical Observatory
25165 Ondrejov
Czech Republic
Tel: / Fax: +42 2-881611
Email: tlamicha@asu.cas.cz

G. Tomassetti
Istituto di Radioastronomia C.N.R.
Via Gobetti 101
40129 Bologna
Italy
Tel.: +39 51 6965041 [Observatory, Medicina]
Fax: +39 51 6965105 / tel: +39 51 6399362 [Bologna]
Fax: +39 51 6399431
Email: tomassetti@astbo1.bo.cnr.it

J. B. Usowicz
Torun Centre for Astronomy
Department of Radio Astronomy
Gagarina II
87-100 Torun
Poland
Tel: +48 56-625 116 51
Fax: +48 56-625 11 651
Email: ju@astro.uni.torun.pl

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

A. Winnberg
Onsala Space Observatory
43992 Onsala
Sweden
Tel: +46 31 772 5527
Fax: +46 31 772 5590
Email: anders@oso.chalmers.se

Frequency manager:

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

Clearing house:

Netherlands Foundation for Research in Astronomy
P.O.Box 2
7990 AA Dwingeloo
The Netherlands
Tel.:+31 521 595100
Fax: +31 521 597332
Email: spoelstra@nfra.nl

WWW home page:

CRAF: http://www.nfra.nl/craf
ESF: http://www.esf.org/craf/ac_01.htm

8.3. IUCAF and its world-wide efforts

At the 1957 URSI meeting the problems of radio astronomy were pretty well defined. But radio astronomers could not define specifically what they wanted to do. By 1959 actions taken by URSI resulted in representatives of URSI, the IAU and COSPAR being sent to the WARC in Geneva.

In 1960 under the auspices of the International Council of Scientific Unions (ICSU) - a UNESCO related body - the Inter-Union-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). IUCAF can participate in ITU conferences if it is invited. This holds for a union like the IAU too. At such conferences IUCAF has observer status. IUCAF does not carry out studies as a group, but it invites individuals to do so.

In the 1960s many things were different from today: many people recognised the novelty and perspective of the science radio astronomy. And the spectrum was more or less open. The Dutch PTT spear-headed radio astronomy in the 1959 WARC with ITU-R documentation.

Since 1979 there has been a growth of space born interferences. The possibility of time-sharing has been introduced. Radio astronomy is at best only equal to the other services, while it does not have any privileges and it can only use specific parts of the spectrum which nobody wants. Often an administration will always lean to what is valuable economically, politically and military.

The mandate of IUCAF is twofold:

1. to study and coordinate the requirements for radio frequency allocations for radio astronomy and space science, and to make these requirements known to the national and international bodies responsible for frequency allocations;

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. To the Radio Astronomy Service a number of frequency bands have been allocated (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, a footnote allocation or "notification of use". 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 nature of an "active" and "passive" service implies a compatibility problem, which may result in harmful interference 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 RA.769-1 and also published in the *ITU Handbook on Radio Astronomy*. The policy of the national administrations on frequency management, protection of services, etc., is based on the ITU-R 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. The sovereignty of a State implies that this national Frequency distribution plan may deviate from the ITU-R Radio Regulations within the boundaries explicitly imposed on the international level. This is due to the fact that the sovereignty of states goes as far as not being in conflict with any obligation under international law. A national administration gives a license to use part of the frequency spectrum and when necessary it demands coordination, e.g. for radio astronomy in the band 606-614 MHz (channel 38 according to the Stockholm 1961 convention) where coordination with broadcast was carried out 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 included in this category (e.g. the United Nations Organisation). 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 the 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 relation between sovereign *States*. States are considered 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 not private status.

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 of which the legal status is deduced from the legal status of the actors forming these organisations. 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 is a value of 20 km, that becomes the rule.

A treaty is the result of explicit agreement between States. A treaty is only valid for the treaty partners, i.e. states who ratified it. For treaty partners, national law has to follow international law. This is for example observed in Europe, 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 UNO (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:

1. Principle of *Good Faith*
2. Principle *Not to do any Harm to any Partner involved in the treaty*

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

However, sanctions are usually extremely difficult. Except in a few cases, such as an international police force or economic sanctions, they do not exist. Usually the solutions to these problems are the result of a political effort.

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

9.4. Protection of radio astronomy

At a global scale IUCAF (*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 (*Section 8.2*). While in the US it is the Committee on Radio Frequencies of the US National Research Council, CORF.

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 scale. The European Science Foundation is not a public actor, nor is CRAF. Note that CORF is a private actor within the US locally.

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 status in international law. An agreement between a radio observatory and an active spectrum user or users has private status and its legal status depends on the nature of the agreement and national legislation only. A local agreement has no international status.

For example, in 1992 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 gets 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? 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 are the most difficult to address and to solve.

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 (*Section 9.3*) and conform to the current national and international legislation, i.e. the ITU-R Radio Regulations. The legal status of such agreements is very limited and absent in terms of international law.

As mentioned above, the ITU-R Radio Regulations have the status of a treaty, since it is an explicit agreement between States. That is not the end-of-story, particularly when space-borne systems cause interference to the Radio Astronomy Service. And given the increasing threat from space-borne systems to radio astronomy this requires accurate consideration:

A treaty with a status prior to the ITU-R Radio Regulations is the *Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and other Celestial Bodies*, OST. This is a UNO treaty. A principally higher status for the OST is considered also on the basis of its character of being formulated within the most fundamental world organisation, the UNO, as "Magna Charta" for "Space". But this interpretation is subject to dispute.

9.4.1. Outer Space Treaty - OST

Some OST articles 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 co-operation 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 orbits 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, for example 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 *ratio* 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 OST, restricted to national activities in outer space. The topic of “state responsibility” has, from the beginning of the 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. Assuring inner 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 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 co-operation 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 an activity or experiment *planned* 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 spaceflight 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 specflight - 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") to, not an obligation of, 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

A second specific convention based on the Outer Space Treaty 1967 is the Liability Convention 1971, in particular on its articles VI and VII, as regards international responsibility and liability of States for their national activities in space.

Articles of this *Convention on International Liability for Damage Caused by Space Objects* 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

The third specific convention based on the Outer Space Treaty 1967 is the *Convention on Registration of Objects Launched into Outer Space of 1974*, 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 (art. VIII); the opportunity to observe the flights of space objects (art. 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 (art. XI).

On December 20, 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 co-operation 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 co-operation with the Secretary General and making full use of the functions and resources of the Secretariat:

   (a) to maintain close contact with governmental and non-governmental organisations 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 co-operation 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-R 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-R 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 *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-R 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 base their arguments on RR and related ITU documentation, but should be aware of the protection on the basis of OST. 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 by radio astronomical techniques. It only uses the term "exploration" in a generic way. The same holds for damage. However, it is considered relevant that IUCAF works on the inclusion of the definition of "harmful interference to the Radio Astronomy Service" in the ITU-R Radio Regulations. At present this term is not defined properly.

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

10. Recommendations

Based on the material presented a number of recommendations can be proposed. In order to improve on the protection for the Radio Astronomy Service the following could be considered:

- To define in the ITU-R Radio Regulations the terms "harmful interference to radio astronomy" and "level of harmful interference to radio astronomy".
- To protect the bands allocated to the Radio Astronomy Service to the level given in ITU-R RA.769-1. Explicit reference to ITU-R RA.796-1 should be included in the ITU-R Radio Regulations.
- To adopt a definition of a passive service in the ITU-R Radio Regulations.
- To improve Article 36 (S29 according the VGE proposal) of the Radio regulations in order to make passive frequency use better understood.
- To improve communication/contact between the radio astronomical bodies and administrations [and related bodies] on the one hand and "industry" on the other hand.
- To pay attention in frequency allocation procedures that existing passive bands should not be touched.
- To avoid that "passive" bands should be shared with "active" services.
- To create more "Primary exclusive Passive" bands.

11. Radio astronomy observatories in Europe

Table 6 gives the locations of all radio astronomy observatories in Europe. In section 9.1 the main research program is indicated briefly.

Table 6: European radio astronomy observatories

Country	Place	East Longitude	Latitude	Height	Comment
Belgium	Humain	05°15’19"	50°11’31"	293	
Czechia	Ondrejov	14°47’01"	49°54’38"	533	
Finland	Metsäëhovi	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	
	Potsdam	13°03’54"	52°22’48"	100	
	Stockert	06°43’24"	50°34’12"	435	
	Tremsdorf	13°08’12"	52°17’06"	35	
Greece	Pentele	23°51’48"	38°02’54"	509	
Italy	Medicina	11°38’43"	44°31’14"	44	
	Noto	15°03’00"	36°31’48"		
	Trieste	13°52’30"	45°38’30"	400	
Latvia	Riga	24°24’00"	56°47’00"	75	
Netherlands	Dwingeloo	06°23’48"	52°48’48"	25	
	Westerbork	06°36’15"	52°55’01"	16	
Norway	Tromsø	19°13’48"	68°34’12"	85	EISCAT
Poland	Kraków	19°49’36"	50°03’18"	314	
	Torun	18°33’30"	52°54’48"	100	
Portugal	Vila Nova de Gaia	-08°35’18"	41°06’30"	232	
Russia	Pulkovo	30°19’36"	59°46’24"	75	
	Zelenchukskaya	41°26’30"	43°39’12"	2100	
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	Gebse-Kocaeli	29°26’52"	40°47’06"	200
Ukraine	Simeis	34°01’00"	44°32’06"	676
	Kharkov	36°56’00"	49°38’00"	150
United Kingdom	Cambridge	00°02’20"	52°09’59"	24
	Chilbolton	-01°26’13"	51°08’40"	92
	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
	Wardle	-02°35’46"	53°06’45"	51

11.1. Main research in European radio astronomy

Belgium

Humain:
- Solar Radio Astronomy

Czechia

Ondrejov:
- Solar Radio Astronomy

Finland

Metsäëhovi:
- Solar Radio Astronomy
- Active Galactic Nuclei monitoring
- Very Long Baseline Interferometry

Sodankyla (EISCAT):
- Aeronomy

France

Bordeaux:
- Galactic research (stellar envelopes, interstellar medium)
- Near extragalactic research (molecules, star formation)
- Solar system (comets)
- Aeronomy and terrestrial atmosphere (H_2O, O_3, ClO)

Nançay:
- Extragalactic radio astronomy (large scale structure, physics of galaxies)
- Galactic research (pulsar timing, circumstellar envelopes)
- Cometary research
- Solar and planetary radio astronomy (Sun, planets)

Plateau de Bure:	• Galactic research (circumstellar envelopes, interstellar medium: molecules and dust) • Near extragalactic 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 extragalactic radio astronomy • pulsar research • Very Long Baseline Interferometry • interstellar molecules
Stockert:	•
Tremsdorf:	• Solar Radio Astronomy
Italy	
Medicina:	• Very Long Baseline Interferometry: astronomy and geodesy • pulsar research and pulsar searches • at 22 GHz observations of masers • molecular spectroscopy • receiver development
Noto:	• Very Long Baseline Interferometry [important node in the geodynamic network] • technological research on correlators.
Trieste:	• Solar Radio Astronomy
Netherlands	
Dwingeloo:	• Study of neutral hydrogen in the Galaxy and extragalactic systems
Westerbork:	• Galactic and extragalactic radio astronomy • pulsar research • Very Long Baseline Interferometry
Norway	
Tromsø (EISCAT):	• Aeronomy

Poland

Kraków:	• Solar radio astronomy
Torun:	• 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
Onsala:	• Galactic and extragalactic molecular line radio astronomy • Very Long Baseline Interferometry

Switzerland

Bleien (Zürich):	• Solar and stellar radio astronomy

Turkey

Gebse-Kocaeli:	• Galactic research (monitoring SiO masers (85 GHz), molecular clouds) • clusters of galaxies • pulsars and supernova remnants

United Kingdom

Cambridge:	• operating frequencies: 38, 81, 151, 327, 408, 610, 1413, 1612, 1665, 1720 MHz, 2.7, 5.0, 15.4, 22.3 and 23.8 GHz.
Chilbolton:	• MERLIN network: 151, 408, 1413, 1612, 1665, 1720, 5000 MHz, 22.3 and 23.8 GHz
Darnhall:	• MERLIN network: 151, 408, 1413, 1612, 1665, 1720, 5000 MHz, 22.3 and 23.8 GHz

Defford:	•	MERLIN network: 151, 408, 1413, 1612, 1665, 1720, 5000 MHz
Jodrell Bank:	•	operating frequencies: 151, 240, 327, 408, 610, 930, 1413, 1612, 1665, 1720, 2300, 2700, 4830, 5000 MHz, 8.3, 10.7, 12.2, 22.3, 22.8, 23.1 and 23.8 GHz
Knockin:	•	MERLIN network: 151, 408, 1413, 1612, 1665, 1720, 5000 MHz, 22.3 and 23.8 GHz
Pickmere:	•	MERLIN network: 151, 408, 1413, 1612, 1665, 1720, 5000 MHz, 22.3 and 23.8 GHz
Wardle:	•	MERLIN network: 81, 151, 240, 327, 408, 610, 930, 1413, 1612, 1665, 1720 MHz

The radio bands are used for the following studies in the United Kingdom:

37.75 - 38.25 MHz:	CLFST all sky survey (interferometry)
80.5 - 82.5 MHz:	Scintillation studies, solar wind, mapping of radio sources
150.05 - 152.0 MHz:	MERLIN continuum band, mapping radio sources, CLFST all sky survey, pulsars.
326.5 - 328.6 MHz:	Very Long Basline Interferometry, pulsars, deuterium spectral line
406.1 - 410.0 MHz:	MERLIN continuum band, mapping radio sources, pulsars
606 - 614 MHz:	Pulsars, Very Long Baseline Interferometry, future: MERLIN continuum band
1350 - 1400 MHz:	Redshifted hydrogen line from distant galaxies
1**400 - 1427 MHz:**	Hydrogen line studies of galaxies and the Milky Way, MERLIN continuum band, mapping radio sources, pulsars, Very Long Baseline Interferometry
1610.6 - 1613.8 MHz:	Hydroxyl (OH) spectral line studies, MERLIN spectral line band, Very Long Baseline Interferometry
1660 - 1670 MHz:	Hydroxyl (OH) spectral line studies, MERLIN continuum and spectral line band, Very Long Baseline Interferometry, pulsars

1718.8 - 1722.2 MHz:	Hydroxyl (OH) spectral line studies, MERLIN spectral line band, Very Long Baseline Interferometry
2670 - 2700 MHz:	Continuum band, mapping radio sources, pulsars, future: MERLIN continuum band
4825 - 4835 MHz:	Formaldehyde (H_2CO) spectral line studies
4990 - 5000 MHz:	MERLIN continuum band, Very Long Baseline Interferometry, mapping radio sources, cosmic microwave background studies, pulsars
10.6 - 10.7 GHz:	Continuum band, cosmic microwave background studies
14.47 - 14.5 GHz:	Formaldehyde (H_2CO) spectral line studies
15.35 - 15.4 GHz:	Continuum band, mapping radio sources, cosmic background studies
22.21 - 22.5 GHz:	MERLIN spectral line and continuum band, water (H_2O) spectral line studies
22.81 - 22.86 GHz:	Ammonia (NH_3) spectral line studies
23.07 - 23.12 GHz:	Ammonia (NH_3) spectral line studies
23.6 - 24 GHz:	MERLIN continuum band, ammonia (NH_3) spectral line studies
31.3 - 31.5 GHz:	Continuum band, cosmic microwave background studies
42.5 - 43.5 GHz:	planned silicon monoxide (SiO) spectral line studies, possible future MERLIN spectral line band, planned Very Long Baseline Interferometry band
48.94 - 49.04 GHz:	planned carbon monosulphide (CS) spectral line studies

Table 7: Frequency bands used by the Radio Astronomy Service in Europe

12. Recommended literature

12.1. Protection of Radio Astronomy Frequencies

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

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

D. McNally, editor, 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 Cedex, 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, 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", 1995, ITU-R Radiocommunications Bureau, Geneva, Switzerland.

12.3. Introduction to radio astronomy

F. Graham-Smith, 1974, "Radio Astronomy", 4th edition, 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, editors, 1988, "Galactic and Extra-Galactic Radio Astronomy", 2nd edition, Springer-Verlag, Berlin, Germany.

13. List of acronyms

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)
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
AVM	Automatic Vehicle Monitoring
AWACS	Airborne Warning and Control System
BAPT	Bundesamt für Post und Telekommunikation (D)
BAS	Broadcast Auxiliary Service
BDT	Telecommunication Development Bureau (ITU)
BER	Bit Error Ratio
BIH	no longer exists; formerly: Bureau International de l'Heure
BIPM	Bureau International de Poids et Mesures
B-ISDN	Broadband ISDN
BMFT	Bundesministerium für Forschung und Technologie (D)
BMPT	Bundesministerium für Post und Telekommunikation (D)
BNSC	British National Space Centre (GB)
BPSK	Binary phase-shift keying
BS	Base Station
BS	Broadcasting Service
BSS	Broadcasting Satellite Service
BT	British Telecom (GB)
CAST	Chinese Academy of Space Technology (CN)
CB	Citizen Band
CCIR	Comité Consultatif International des Radiocommunications (ITU)
CCITT	Comité Consultatif International de Télégraph et des Télécommunications (ITU)
CCMS	Committee on Challenges of Modern Science (NATO)
CCSDS	Consultative Committee on Space Data Systems
CDMA	Code Division Multiple Access
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 Committee on Radio Interference
CITEL	Inter-American 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 la Recherche Scientifique (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 Organisation
CSTG	Commission for International Coordination of Space Techniques for Geodesy and Geodynamics
DAB	Digital Audio Broadcast
DBS	Digital Broadcasting by Satellite
DCS	Defense Communications 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- end 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
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)
EARSeL	European Association of Remote Sensing Laboratories
EAS	European Astronomical Society
EBU	European Broadcasting Union
EC	European Community
ECA	European Common Allocation (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 to 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
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 Operation Center
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
EVN	European VLBI Network
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
FPLMTS	Future Public Land Mobile Telecommunication System (= UMTS)
FS	Fixed Service

FSK	Frequency Shift Keying
FSS	Fixed Satellite Service
FT	France Télécom (F)
FX	Fixed Service
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
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
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 to 30 MHz)
HFBC	High Frequency Broadcasting
HIPERLAN	High Performance Local Area Network
HLC	High Level Committee (ITU)
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 of Scientific Unions

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
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	Inter-Union Commission on Frequency Allocation 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)
IZMIRAN	Institute of Terrestrial Magnetism, Radio Research and the Ionosphere (Russia)
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
LAN	Local Area Network
LEO	Low Earth Orbit
LF	Low Frequency (30 to 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
LPD	Low Power Devices
LSI	Large Scale Integration
MAS	Meteorological Aids Service
MAT	Mobile Aeronautical Telemetry
MDS	Multipoint Distribution Service
MERLIN	Multi-Element Radio Linked INterferometer (GB)
MES	Mobile Earth Station
MetA	Meteorological Aid Service
METSAT	Meteorological Satellite
MetS	Meteorological-Satellite Service
MF	Medium Frequency (300 to 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)
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
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)
NRAL	Nuffield Radio Astronomy Laboratories (GB)
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)
OB	Outside Broadcasting
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
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}])
PMR	Private Land Mobile Radio
POFS	Private Operational Fixed Service
PSK	Phase Shift Keying
PSTN	Public Switched Telephone Network
PTB	Physikalisch-Technische Bundesanstalt (D)
PTT	Post, Telegraph, Telephone (i.e. government ministry for -)

QAM	Quadratic Amplitude Modulation
QPSK	Quadratic Phase Shift Keying
QPSK-C	Quadratic Phase Shift Keying Compatible
RA	Radiocommunications Agency (GB)
RA	Radiocommunication Assembly (ITU)
RA	Radio Astronomy Service (ITU)
RADAR	Radio Detecting and Ranging
RAG	Radiocommunication Advisory Group (ITU)
RARC	Regional Administrative Radio Conference (ITU)
RAS	Radio Astronomy Service
RAS	Royal Astronomical Society (GB)
RB	Radiocommunication Bureau (ITU)
RD	Radiodetermination Service
RDS	Radiodetermination Service
RDSS	Radio Determination Satellite Service
Rec	Recommendation
RFI	Radio Frequency Interference
RHC	Right Hand Circular
RIN	Royal Institute of Navigation (GB)
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	ITU-R Radio Regulations (ITU)
RRB	Radio Regulations Board (ITU)
RTAGS	Radio Tags
RTT	Road Transport Telematics
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
SERTC	Science and Engineering Council (GB)
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 to 30 GHz)
SITE	Satellite Instructional Television Experiment
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
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
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 (= FPLMTS)
UNESCO	United Nations Education, Scientific and Cultural Organization
UNO	United Nations Organization
URSI	Union Radio Scientifique International
UT	Universal Time
UTC	Coordinated Universal Time

VGE	Voluntary Group of Experts (ITU)
VHF	Very High Frequency (30 to 300 MHz)
VLA	Very Large Array
VLBA	Very Large Baseline Array
VLBI	Very Long Baseline Interferometry
VLF	Very Low Frequency (3 to 30 kHz)
VOR	VHF Omnidirectional Range
VORAD	Vehicle On-Board Radar
VQC	Vector Quatization Coding
VSAT	Very-Small Aperture Terminal
VTS	Vessel Traffic System (radar)

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

14. 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 = 3.1×10^{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.
• **flux**	total radiant energy passing through a unit surface into the 2π solid angles 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) A device that utilizes the natural oscillation of an atom or molecule to amplify electromagnetic radiation. Molecules are pumped into a metastable upper state by incident radiation of broad frequency via upper states that connect to the metastable state. They are then stimulated downward by radiation of a certain frequency connecting the metastable and ground states. When a bound electron in the metastable state is hit by emitting a photon of the right frequency, the electron can return to a lower state by emitting a photon of exactly the same frequency as the incident photon. In this process it will emit the photon in exactly the same direction in which the incident photon is scattered, which means that the photons move off precisely in phase. If each hits another electron in the same state, there will be four photons in phase, etc., leading to an intense beam of coherent radiation.
- **nonthermal radiation** radiation emitted by energetic particles for reasons other than high temperature of the source. The spectrum of nonthermal 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 polarisation 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 accelaration of the particles causes them to emit radiation. A characteristic of such radiation is that it has a strongly polarised 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 nonthermal radiation, which typically is caused by energetic (not necessarily hot) electrons.

Instrumental parameters:

- **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 expresses in dB).
- **integration time** — used to indicate:
  a) duration of the observation (often of the order of hours)

	b) sampling time within the receiver (ranging from microseconds to seconds)
	c) time over which a series of samples are averaged (ranging from seconds to minutes)
• **sampling time**	time interval during which 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**	a system of two antennas separated by a certain distance and having two outputs joined together at the input of a receiver.
MERLIN	Multiple Element Radio Link INterferometer (U.K.)
VLA	Very Large Array (U.S.A.)
VLBI	Very Long Baseline Interferometry
EVN	European VLBI Network
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 polarisation of linearly polarised 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% ionized due to the influx of solar uv-radiation.

- **radio window** — the wavelength range between a few millimeters (even submm) and about 30 meters within which Earth's atmosphere is transparant 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 control by man.
- **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 wich a terrestrial station sharing the same frequency band neither causes nor is subject to interfering emissions greater than a permissable 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 a radionavigation service or of other safety services or seriously degrades, obstructs, or repeatedly interrupts a radiocommunication service operating in accordance with the ITU-R 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, i.c. over the frequency band of interest.

• **passive service**	radiocommunication service in which the operations can only be done by reception of given signals. The user cannot manipulate the transmitter nor 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 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^{18} g 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 mm to 70 cm. The cosmic background radiation is interpreted as relict from the primeval fireball; it represents a redshift of about 3000.

- **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 preflare 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 cols, 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 light 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 meter and centimeter 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 $2x10^4$ 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

- **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 5000 and 10000 from the Earth's surface.

15. Keyword index

IREG Strasbourg - 7/1997 - Dépôt légal: août 1997 - N° d'ordre: 971790