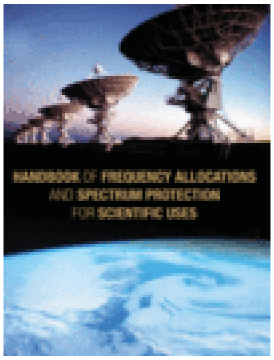

Handbook of Frequency Allocations and Spectrum Protection for Scientific Uses

Panel on Frequency Allocations and Spectrum Protection for Scientific Uses, Committee on Radio Frequencies, National Research Council

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THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine

HANDBOOK OF FREQUENCY ALLOCATIONS AND SPECTRUM PROTECTION FOR SCIENTIFIC USES

Panel on Frequency Allocations and Spectrum Protection for Scientific Uses

Committee on Radio Frequencies
Board on Physics and Astronomy
Division on Engineering and Physical Sciences

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Preface

This handbook was developed by the National Research Council's Panel on Frequency Allocations and Spectrum Protection for Scientific Uses, a panel whose membership was drawn predominantly from the Committee on Radio Frequencies (CORF). The volume sets forth the principles adopted by the panel for the allocation and protection of spectral bands for services using the radio spectrum for scientific research. The purposes of the handbook are as follows:

- To document the panel's positions on spectrum issues,
- To guide spectrum managers and spectrum regulatory bodies on science issues,
- To serve as a resource for scientists on spectrum regulation for research, and
- To provide information to other spectrum users on the concerns of the scientific users of the spectrum.

Among the resources used to prepare this handbook were the following: Radio Astronomy Handbook of the International Telecommunication Union (ITU);[1] the "Redbook" of the National Telecommunications and Information Administration[2] (NTIA) (please note that the panel used the NTIA Redbook as of 2005; it is suggested that readers check the NTIA Web site, listed below, for the latest allocations and regulations); and the handbooks for radio astronomy and frequency management from the European Science Foundation's Committee on Radio Astronomy Frequencies (CRAF). Because

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[1] International Telecommunication Union, *ITU Handbook on Radio Astronomy,* 2nd Ed., Geneva, Switzerland, 2003.

[2] National Telecommunications and Information Administration, *Manual of Regulations and Procedures for Federal Radio Frequency Management (Redbook),* May 2003 edition, revised January 2006, available at http://www.ntia.doc.gov/osmhome/redbook/redbook.html.

radio-frequency regulations, regulatory footnotes, and frequency allocations are subject to change, readers are advised to check the ITU, NTIA, and Federal Communications Commission Web sites, listed below, for the latest information.

Further information on frequency management for scientific uses can be found at the following Web sites:

- Committee on Radio Frequencies (CORF) of the National Research Council: www.nationalacademies.org/corf;
- International Telecommunication Union: www.itu.org;
- Scientific Committee on Frequency Allocations for Radio Astronomy and Space Science (IUCAF) of the International Council for Science: www.iucaf.org;
- Federal Communications Commission: www.fcc.gov;
- National Telecommunications and Information Administration: www.ntia.doc.gov/osmhome/redbook/redbook.html;
- National Radio Astronomy Observatory Spectrum Management: www.cv.nrao.edu/~hliszt/RFI/RFI.htm;
- Geoscience and Remote Sensing Society of the Institute of Electrical and Electronics Engineers' Frequency Allocations in Remote Sensing (FARS) Committee: http://www.grss-ieee.org;
- Committee on Radio Astronomy Frequencies (CRAF) of the European Science Foundation: www.astron.nl/craf; and
- National Science Foundation Electromagnetic Spectrum Management (ESM): http://nsf.gov/funding/pgm_summ.jsp?pims_id=5654.

This handbook was edited and updated between its release in prepublication form and this final published form.

Acknowledgments

This handbook grew out of materials presented and ideas expressed in the report *Views of the Committee on Radio Frequencies Concerning Frequency Allocations for the Passive Services at the 1992 World Administrative Radio Conference*.[1] The efforts of previous and current members of the National Research Council's Committee on Radio Frequencies (CORF) in compiling that document are gratefully acknowledged.

The development of the handbook spanned several years, and the panel thanks the past members of CORF for their contributions to this effort. The panel received invaluable assistance from spectrum managers Tomas Gergely of the National Science Foundation and Charles Wende of the National Aeronautics and Space Administration (retired), whose detailed knowledge and insight were an essential resource. The panel also received substantial help from A. Richard Thompson, National Radio Astronomy Observatory (retired), and John Kiebler, former consultant to CORF. Finally, special thanks are extended to former CORF member T.B.H. Kuiper for his extensive work on the early draft of the handbook.

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[1] National Research Council, *Views of the Committee on Radio Frequencies Concerning Frequency Allocations for the Passive Services at the 1992 World Administrative Radio Conference*, National Academy Press, Washington, D.C., 1991.

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Bernard F. Burke, Massachusetts Institute of Technology,
Martha P. Haynes, Cornell University,
Michael J. Marcus, Marcus Spectrum Solutions,
John M. Osepchuk, Full Spectrum Consulting, and
Charles D. Wende, National Aeronautics and Space Administration (retired).

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Albin J. Gasiewski, University of Colorado at Boulder. Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents

APPENDIXES

Summary

The electromagnetic spectrum is a vital part of our environment. Yet-to-be-discovered knowledge is encoded in the spectrum of radiation that is arriving at Earth from the depths of the universe. For example, the cosmic microwave background, pulsars, and binary pulsars were respectively discovered by Nobel Prize-winning radio astronomers Arno Penzias and Robert Wilson; Antony Hewish; and Russell A. Hulse and Joseph H. Taylor, Jr. Radio astronomers Aleksander Wolszczan and Dale Frail discovered the first extrasolar planets. Other radio astronomers study a wide range of subjects, from the era before the first stars formed to the dynamics of our own Sun. Closer to home, our understanding of Earth's land masses and oceans, its biosphere, the many layers of the atmosphere, and the space around Earth is essential to humanity's safety and well-being. Some radio-frequency measurements of these natural phenomena have immediate economic benefits; others underlie our view of what we are and of our place in the cosmos. The spectrum is therefore a resource to be used wisely now and to be protected for future generations.

The Panel on Frequency Allocations and Spectrum Protection for Scientific Uses arrived at several key considerations related to scientific use of the spectrum. They are in the areas of scientific impact, sensitivity, stewardship, requirements, and opportunity and challenge:

- *Scientific impact*—Radio-frequency measurements of natural phenomena provide essential information with broad scientific and economic impacts.
- *Sensitivity*—Receive-only ("passive") measurements of weak natural signals in a broad range of frequencies must be made with extreme sensitivity.
- *Stewardship*—The extreme sensitivity required makes it essential to maintain protected allocations and also to properly manage use of the spectrum near the protected allocations.
- *Requirements*—Dedicated passive allocations exist only in a limited number of bands. There is need for protection of some bands essential to scientific and societal interests that are not now protected.

- *Opportunity and challenge*—The receive-only services can sometimes take advantage of uncongested spectra not allocated to them. Increasing congestion may deny this capability in the future.

By its very nature, research uncovers new and often unexpected pathways for studying our terrestrial environment and the universe. It is important to recognize that the passive services are always "starved" for sensitivity.[1] The signal-to-noise ratio is limited only by the sensitivity of the receiving instruments and the noise in the environment; passive services do not have the option of increasing the "signal" from the source. If the instruments are to achieve their theoretical limit, the environment must not be contaminated.

This handbook contains practical information regarding the use of the radio spectrum for scientific research. In Chapter 1, the regulatory bodies and issues are described. Chapter 2 discusses the relevant scientific background necessary to an understanding of the issues with spectrum management. Chapter 3 lists the science service spectrum allocations in the United States and their uses. Chapter 4 discusses issues related to spectrum protection.

In addition, the report has a number of appendixes. Appendix A offers National Telecommunications and Information Administration definitions concerning interference. Appendix B provides examples of footnotes to science services allocations. Appendix C lists important International Astronomical Union (IAU) spectral lines below 300 GHz. Appendix D lists important IAU spectral lines above 300 GHz. Appendix E presents selected Federal Communications Commission rules and regulations. Appendix F lists International Telecommunciation Union recommendations pertaining to radio astronomy, space applications, and meteorology. Appendix G lists Earth science passive sensor needs above 71 GHz. Appendix H examines the use of 0 dBi for sidelobe gain in calculations of interference in radio astronomy. Appendix I lists selected acronyms from the text.

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[1] The passive services are those for which the signal is produced by nature and the applications are receive-only.

1

Radio-Frequency Regulation

1.1 SCIENTIFIC FREQUENCY PROTECTION GOALS

The Panel on Frequency Allocations and Spectrum Protection for Scientific Uses calls attention to the statement of task of the National Research Council's Committee on Radio Frequencies[1] (CORF): namely, to advise U.S. government agencies on the needs for spectrum protection and allocation for scientific research. Scientific research that uses the radio spectrum would benefit from U.S. radio-frequency managers working with those of other Administrations[2] at future World Radiocommunication Conferences (WRCs) to improve the spectrum access for the Radio Astronomy Service (RAS) and the Earth Exploration-Satellite Service (EESS). (In addition to the RAS and EESS, other services are also used by scientists. (See Table 1.1.) It is important that World Radiocommunication Conferences in which the RAS and EESS are not explicitly considered do not change the radio regulations in ways that would be deleterious to these services.

Protecting bands allocated to the science services from emissions spilling over from adjacent bands is a critical part of ensuring the vitality of the science. Yet-to-be-discovered knowledge about the universe is encoded in the spectrum of radiation that arrives at Earth. The spectrum is therefore a resource to be protected for future generations, which will develop the technology to detect and decode this information.

The science services are protected both by frequency allocations and by some special geographic restrictions on other users, such as the geographic restriction in the National Radio Quiet Zone that includes the National Radio Astronomy Observatory's facility in Green Bank, West Virginia. Such protection is needed because in some science service bands, radio emissions from airborne and spaceborne transmitters exist very close to the atomic and molecular spectral line frequencies—for

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[1] CORF is a standing committee of the National Research Council operating under the auspices of the Board on Physics and Astronomy. For more information on CORF, see its Web site at www.nationalacademies.edu/corf.

[2] An "Administration" is a foreign body that negotiates in international matters.

TABLE 1.1 Science Services

Service	Abbreviation	Description of Service
Earth Exploration-Satellite Service	EESS	Remote sensing from orbit, both active and passive, and the data downlinks from these satellites
International Global Navigation Satellite System (GNSS) Service	IGS	Accurate position and timing data
Meteorological Aids Service	MetAids	Radio communications for meteorology, e.g., weather balloons
Meteorological Satellite Service	MetSat	Weather satellites
Radio Astronomy Service	RAS	Passive ground-based observations for the reception of radio waves of cosmic origin
Space Operations Service	SOS	Radio communications concerned exclusively with the operation of spacecraft—in particular, space tracking, space telemetry, and space telecommand
Space Research Service	SRS	Science satellite telemetry and data downlinks, space-based radio astronomy, and other services

example, in the bands allocated for observations of hydroxyl (OH) between 1660 and 1668.4 MHz. In recent years, this difficulty has grown greatly in importance, particularly with the introduction of higher-powered space transmitters and the use of spread spectrum modulation techniques. Because the radio astronomy and remote sensing sensitivities to interference are so great and because terrain shielding (the use of geographical features to block radio signals of certain frequencies) cannot be employed, it is most difficult to avoid interference from the sidebands of some spaceborne transmitters, even though their central transmitting frequencies may lie outside the radio astronomy bands. Furthermore, additional geographic restrictions are going to be difficult or impossible to obtain in the United States.

1.2 REGULATORY STRUCTURES

Radio regulations are formulated at several levels and involve a plethora of acronyms (see Appendix I). At the international level, the Radiocommunication Sector of the International Telecommunication Union (ITU-R) formulates regulations through World Radiocommunication Conferences and recommendations through the work of its various study groups.

Much of the work of the ITU-R takes place through its study groups, which are further organized into working parties and task groups. These deal with specific areas or problems and provide studies of questions concerning technical and procedural aspects of radio communications. Study Group 7 has responsibility for use of the spectrum for scientific research (the science services): remote sensing systems are the concern of Working Party 7C (WP7C), and radio astronomy is the concern of Working Party 7D (WP7D). The other services under Study Group 7 are as follows: WP7A, time and frequency standards; WP7B, space research and Earth exploration-satellite services (mostly communications). The services involved provide support of interest and use to the scientific community. The International Council of Scientific Unions (ICSU) that operates under the aegis of the United Nations Educational, Scientific, and Cultural Organization (UNESCO) provides additional input from the scientific community through the Scientific Committee on Frequency Allocations for Radio Astronomy and Space Science (IUCAF). IUCAF is sponsored by three international scientific unions: the International Astronomical Union (IAU), the International Union of Radio Science (URSI), and the Committee on Space Research (COSPAR).

The work of the ITU-R results in an extensive system of formal documents that includes the following:

- *Questions*—which specify the subjects to be studied within the study groups;
- *Recommendations and Reports*—which record the conclusions from these studies; and
- *Regulations*—which are adopted by adhering Administrations and have treaty status. Footnotes may provide additional information, and often provide protection to particular services on a primary or secondary basis.

Each recommendation must be approved by all administrations within the ITU-R before being brought into force, and thus the recommendations are widely regarded as authoritative. Final discussion and acceptance of International Radio Regulations occurs at World Radiocommunication Conferences, meetings that now take place approximately every 3 to 5 years.

The relationship among national and international radio regulatory and advisory bodies with respect to the Radio Astronomy Service and the Earth Exploration-Satellite Service is complicated. See Figures 1.1 and 1.2, which depict the connections among many of these agencies and their relationship to one another both nationally and internationally.

Within the United States, non-federal-government use of the spectrum is regulated by the Federal Communications Commission (FCC). Federal government use is regulated by the National Telecommunications and Information Administration (NTIA), which is part of the U.S. Department of Commerce. Most, if not all, spectrum use for scientific research is under shared federal government/non-federal-government jurisdiction. Many federal agencies have spectrum-management offices—for example, the Department of Defense (DOD), National Aeronautics and Space Administration (NASA), and the National Science Foundation (NSF). The Interdepartment Radio Advisory Committee (IRAC) is a standing committee that advises NTIA with respect to the spectrum needs and use by departments and agencies of the U.S. government.

The U.S. administration has set up national-level study groups, working parties, and task groups that mirror those that operate within the ITU-R. For example, U.S. Working Party 7C (U.S. WP7C), part of U.S. Study Group 7, develops U.S. positions and draft documents concerning remote sensing (U.S. WP7D does so for the RAS). These documents are reviewed by the United States International Telecommunication Advisory Committee (ITAC) and, if approved, are forwarded by the U.S. Department of State to the ITU-R as input for international meetings.

In the United States, radio astronomers, EESS scientists, and others who use the passive and active bands for scientific research can interact with the system of spectrum management through CORF and U.S. WP7C and WP7D, all of which hold meetings that are open to the public. They can also communicate with the spectrum-management offices of the NSF and NASA, the FCC (through public proceedings and ex parte comments, described at http://www.fcc.gov/ogc/admain/ex_parte_factsheet.html) and NTIA, and with members of IUCAF.

As indicated above, CORF is a committee of the National Research Council—the operating arm of

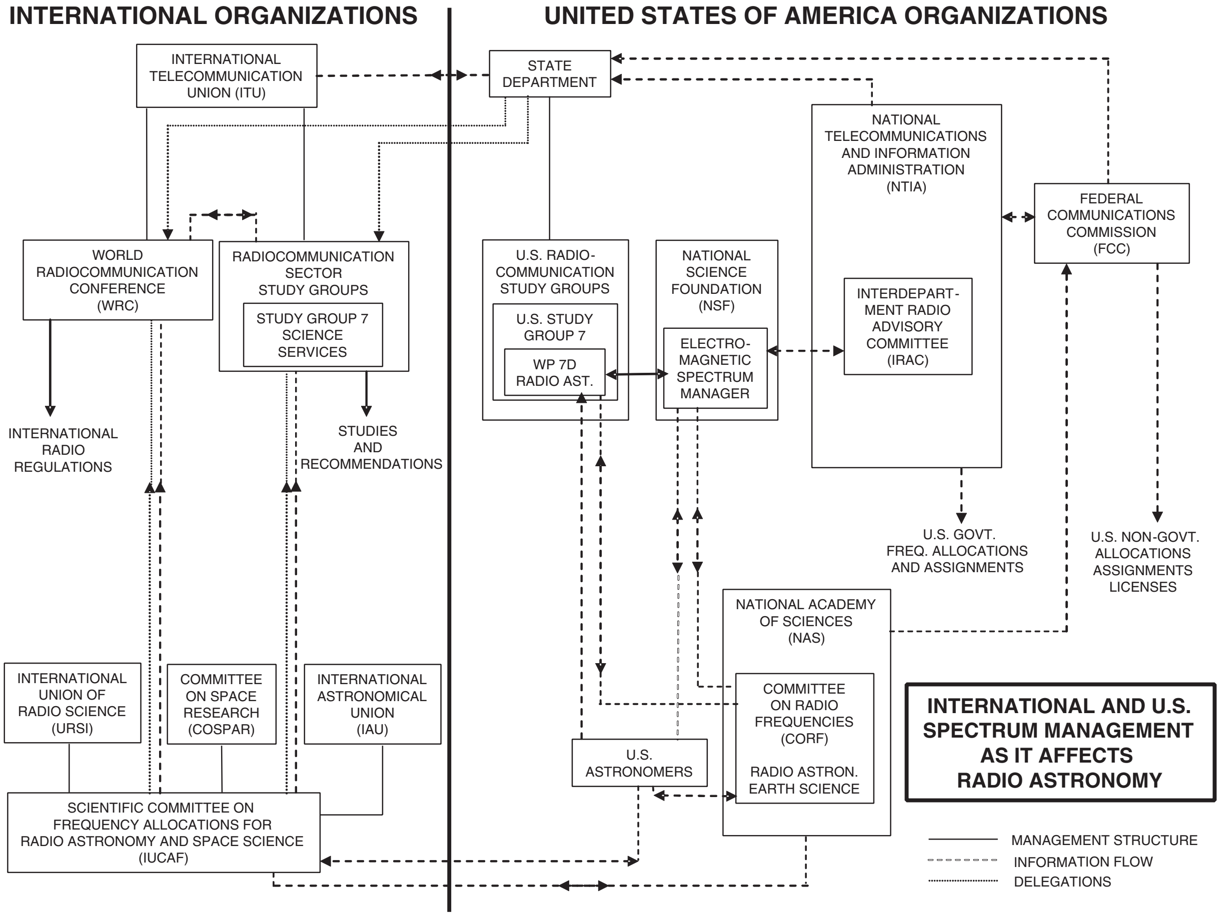

FIGURE 1.1 The diagram depicts the complex relationship among the national and international radio regulatory bodies for the Radio Astronomy Service.

the National Academy of Sciences, which is a private, nonprofit organization chartered by the U.S. Congress. CORF serves as a link between the radio astronomy and remote sensing communities and the spectrum-management offices at the NSF, NASA, and the National Oceanic and Atmospheric Administration (NOAA). CORF participates in public proceedings of the Federal Communications Commission.

1.3 RADIO ASTRONOMY SERVICE

The scientific needs of radio astronomers for the allocation of frequencies were first addressed at the World Administrative Radio Conference (predecessor of the WRC) held in 1959 (WARC-59). Astronomers proposed the following:

- That the science of radio astronomy should be recognized as a service in the radio regulations of the ITU,

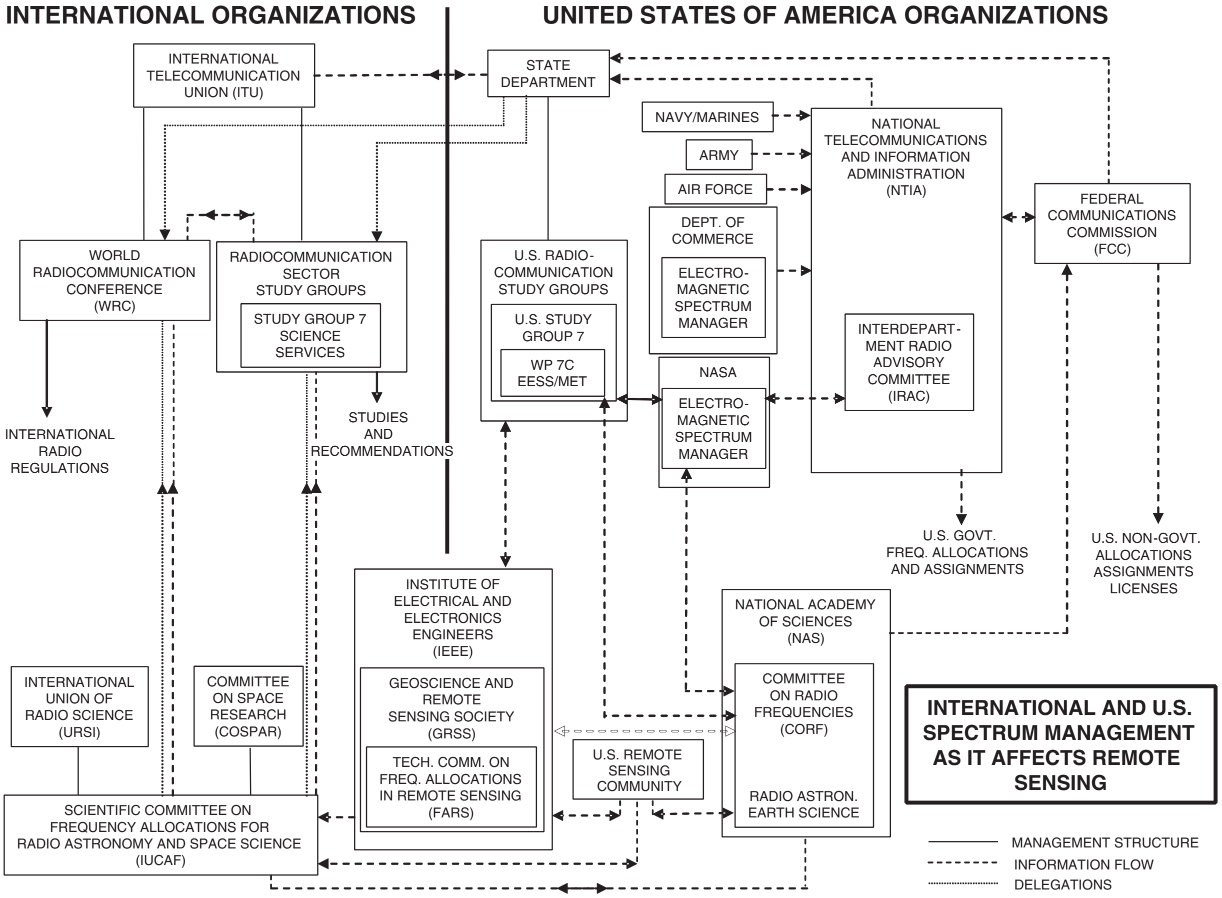

FIGURE 1.2 The diagram depicts the complex relationship among the national and international radio regulatory bodies for the Earth Exploration-Satellite Service.

- That a series of bands of frequencies should be set aside internationally for radio astronomy—these should lie at approximately octave intervals above 10 MHz and should have bandwidths of about 1 percent of the center frequency, and
- That special international protection should be afforded to the hydrogen (H) line (1400-1427 MHz) and to the predicted deuterium (D) line (322-328.6 MHz).

By the end of WARC-59, considerable action had been taken to meet these needs. The Radio Astronomy Service (RAS) was established, and the first frequency allocations were made for this new service. At subsequent conferences, growing scientific needs were recognized and further steps were taken to meet them. For example, the discovery of many new interstellar molecular lines in the radio spectrum led to new frequency allocations and footnote protection. Radio astronomy research now extends into the millimeter and submillimeter wavelength bands, which are now recognized in new allocations and footnotes to the allocation table.

At the World Radiocommunication Conference in 2000 (WRC-2000), the spectrum allocations above 71 GHz were revised, and a number of new allocations to the RAS were made. WRC-2003 was held in Geneva, Switzerland, June 9 to July 4, 2003. There were more than 2,200 delegates, 17 of whom were radio astronomers. Out of a total of 50 agenda items, 10 were of interest to radio astronomers. Most of these involved allocations to satellite downlinks, adjacent or close to radio astronomy allocations.

1.4 EARTH SCIENCE SERVICES

The Earth Exploration-Satellite Service was established at WARC-71. Frequencies were allocated for the transmission of environmental data from space to Earth in order to accommodate the needs of satellite programs such as Landsat, which utilize passive sensors operating in the visible part of the electromagnetic spectrum. Today, the EESS also includes meteorological services—primarily communications, such as the Meteorological Satellite Service (MetSat) and the Meteorological Aids Service (MetAids). Frequencies were first allocated to the EESS and the Space Research Service (SRS) for use by spaceborne active and passive microwave sensors at WARC-79. That WARC made more than 50 allocations for spaceborne microwave sensors: 10 for active sensors and more than 40 for passive sensors.

By 1997, there was a need to improve the regulatory environment for spaceborne microwave sensors. Spectrum requirements for passive sensors had been refined in the 18-year interval between 1979 and 1997, particularly in the unique 50-70 GHz region where measurements in the vicinity of oxygen absorption lines are used to determine atmospheric temperature profiles for use in weather forecasts and climate studies. Also, time had shown that the secondary footnote allocations made for active microwave sensors in 1979 were of little use in preventing new allocations from being made to other services—allocations that could (and did) cause active sensors to be unusable owing to interference.

At WRC-97, passive remote sensing bands between 50 and 60 GHz were realigned. Most active remote sensing bands were upgraded to primary allocations. In the EESS communications area, the 8025-8400 MHz band was upgraded to a primary allocation, and a new wider-bandwidth space-to-Earth allocation was obtained at 26 GHz.

At WRC-2000, the passive bands above 71 GHz were realigned, and the top of the range was extended from 275 GHz to 1 THz via a footnote. The 18.7 GHz passive band gained protection, as did civilian Global Positioning System (GPS) bands.

At WRC-2003, an active band at 437 MHz was allocated, and the active sensing band at 5.3 GHz was expanded in bandwidth from 210 to 320 MHz, but at the cost of losing protection against outdoor radio local area networks at the low end. Of particular concern, up/down communication links near the 1.400-1.427 GHz passive band were given a provisional secondary allocation pending further study and a report to WRC-2007. Note that any emissions in this band are explicitly prohibited by international footnote 5.340.

1.5 ANCILLARY SERVICES

Ancillary services support science and are in fact essential to the operation of spacecraft, observation, and the retrieval of data. While some of these services (i.e., communications) are incorporated within the science services, they are clearly indispensable, and their importance should be recognized.

1.5.1 The Space Research and Space Operations Services

The Space Research Service and the Space Operations Service (SOS) need to be protected and managed in order to enable the community to operate its spacecraft and to retrieve data taken by them. Without these bands, spaceborne science cannot be carried out.

The SRS covers the communications services necessary for spacecraft launch and for data communications with spacecraft. The most prominent network supporting near-Earth missions related to both Earth science and space science is the NASA Deep Space Network (DSN), an international network of antennas operated by the Jet Propulsion Laboratory for NASA. The DSN supports interplanetary spacecraft missions and radio and radar astronomy observations for the exploration of the solar system and the universe. The network also supports selected Earth-orbiting missions.

The SRS also includes communications for space radio astronomy (space very long baseline interferometry) using antennas in Earth orbit. The spacecraft transmit the data to ground stations for processing and analysis.

1.5.2 Frequency, Time, and Position Systems

The Standard Frequency and Time Signal-Satellite Service, as well as navigational systems used by the science community, provide position data needed for measurements of motions of Earth's crust and glaciers as well as for navigation of our spacecraft. They also sometimes support intrinsic scientific uses in addition to navigational purposes—for example, measurements of general relativity.

These systems provide timing virtually anywhere on Earth, orders of magnitude more accurate than any other system. GPS provides timing with an accuracy that can be exceeded only by having an atomic clock located in a laboratory.

The International Global Navigation Satellite System (GNSS) (IGS), formerly the International GPS System, is a voluntary federation of more than 200 worldwide agencies that pool resources and permanent navigation satellite station data to provide the highest-quality data and products in support of Earth science research, multidisciplinary applications, and education. Currently the IGS includes two GNSSs—GPS and the Russian Global Navigation Satellite System (GLONASS)—and intends to incorporate future GNSSs, such as Europe's Galileo system. The IGS is primarily used by the EESS for spacecraft position and timing information in support of remote sensing. There are also experimental scientific uses of IGS for radio science and bistatic radar.

2

The Scientific Background

2.1 RADIO ASTRONOMY

The discovery of radio emission from celestial objects was made by Karl Jansky of the Bell Telephone Laboratories in 1932 as a by-product of studies of system and thermal noise in radio-communication systems. Since this initial discovery, radio astronomers have made many important discoveries, including several recognized by the awarding of Nobel Prizes (Box 2.1). The science of radio astronomy has grown remarkably, becoming a major tool of modern astronomy and astrophysics.[1]

Many scientifically important parts of the spectrum have been protected for astronomical research. With the discovery of new astronomical objects and the development of better equipment and techniques, radio astronomers regularly use frequencies from the lowest allocated radio astronomy band at 13.36-13.41 MHz to frequencies above 1000 GHz. However, much needs to be done to protect the current allocations and to meet the needs of modern research. Following are areas of particular importance:

- *Many of the currently allocated bands have insufficient bandwidths.* Originally, given the technology available to radio astronomy, bandwidths of approximately 1 percent of the center frequency were adequate. With modern technology, more bandwidth is essential for high-sensitivity measure-

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[1] For background information from technical papers regarding the technical capabilities of the Radio Astronomy Services, see the following: D.R. DeBoer and D.C.J. Bock, “The Allen Telescope Array: Splitting the Aperture,” *IEEE Microwave Magazine*, Vol. 5, No. 2, pp. 46-53, 2004; A. Lecacheux, A.A. Konovalenko, and H.O. Rucker, “Using Large Radio Telescopes at Decametre Wavelengths,” *Planetary and Space Science,* Vol. 52, No. 15, pp. 1357-1374, December 2004; and A.R. Thompson, J.M. Moran, and G.W. Swenson, *Interferometry and Synthesis in Radio Astronomy,* 2nd Ed., May 2001.

BOX 2.1
Nobel Prizes Awarded for Contributions Made by Radio Astronomers

2006—John C. Mather and George F. Smoot for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation which trace the fluctuations responsible for all the structures seen in the universe.

1993—Russell Alan Hulse and Joseph Hooton Taylor, Jr., for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation.

1978—Arno Allan Penzias and Robert Woodrow Wilson for their discovery of cosmic microwave background radiation.

1974—Sir Martin Ryle and Antony Hewish for their pioneering research in radio astrophysics: Ryle for his observations and inventions, in particular of the aperture synthesis technique, and Hewish for his decisive role in the discovery of pulsars.

ments, which depend on averaging for noise reduction.[2] The Doppler shift of spectral lines that is due to the expansion of the universe also necessitates going outside of these allocated bands.

- *Most bands are shared with active services.* Obvious strong signals of terrestrial origin can often be excised from collected data, but weak signals defy editing and may therefore by more pernicious, contaminating long-term wideband averages without being apparent in individual data.
- *The radio astronomy bands are not adequately protected from transmissions in adjacent bands.* This is particularly a problem with orbiting transmitters, because their modulation techniques are often inefficient and terrain around observatories does not provide shielding.
- *Some allocations apply to limited areas of the world, providing no protection at all in other areas.*
- *There are large intervals between some of the allocated bands.* In order to determine the spectral distribution of radio source emission, bands were assigned to radio astronomy at approximately octave intervals.

The frequency range of radio astronomy observations now extends above 3 THz (with measurement of the 3438 GHz transition of ^{13}CO and the detection of the 13→12 transition of CO at 1497 GHz), blurring the distinction between radio astronomy and infrared astronomy. With the advent of Earth-to-space telecommunications near 1 μm wavelength (300 THz) and the need to regulate for avoiding interference with optical observatories, the distinction between different kinds of astronomy will eventually vanish from the regulatory perspective. Use of the radio spectrum for communications and other commercial purposes developed first at the lower frequencies (longer wavelengths) because the technol-

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[2] Radiometric noise reduction is achieved by increasing the number of effective samples, which means increasing the product of the time spent observing the source and the bandwidth of these observations. Increasing the time spent observing the source is limited by practical considerations, such as amplifier stability and atmospheric variability, which drives the need for wide bandwidths.

ogy required is generally simpler and less expensive. However, during the past several decades, continuing improvements in technology have allowed the extension of use to millimeter and shorter wavelengths (higher frequencies). Hence, the longer wavelengths were filled up first, and only now are commercial interests beginning to move to millimeter wavelengths. Interference has always been a serious issue at the long wavelengths, but the problem is moving to shorter wavelengths as these become used more extensively.

2.1.1 The Radio Spectrum

Radio emissions arise under conditions that are different from those which produce visible radiation. The light waves studied by optical astronomers originate from such objects as stars and circumstellar nebulae. Celestial radio waves, however, come from diverse environments, including the primordial fireball of the big bang, the cold gas between the stars, electrons spiraling in the magnetospheres of neutron stars, and relativistic jets from black holes. Radio astronomy is also sensitive to processes at work in the universe that are not accessible to observations at other wavelengths, and the study of the universe at radio wavelengths often reveals new classes of objects. Moreover, the study by radio astronomers of the same celestial objects that optical astronomers study provides fresh insights into the physical processes that are not probed at other wavelengths.

Astronomical studies provide a laboratory in which matter can be seen over a wide range of physical conditions, the extremes of which cannot now or in the foreseeable future be reproduced on Earth. Extremes of density, temperature, pressure, and unusual chemical compositions can all be found at various places in the universe and are under close study by astronomers.

2.1.2 Types of Radio Emission

The spectrum of the celestial radio waves reaching the surface of Earth contains a broad continuum that covers the whole range of frequencies that can penetrate Earth's atmosphere, together with a large number of atomic and molecular spectral lines, each of which is confined to a narrow frequency range.

2.1.2.1 Radio Continuum

The discovery of radio sources and the bulk of current knowledge about their nature and distribution and about the processes responsible for the radio emission from them have come through observations of the continuum radiation. Continuum observations consider the broad variation of emission with frequency (see Figures 2.1 and 2.2). Individual measurements are made with broadband detectors that span tens to hundreds of megahertz and are therefore sensitive to interference over a large range of frequencies, from meter to millimeter wavelengths (tens of hertz to hundreds of gigahertz). The radio continuum arises from three principal mechanisms, all of which have major application in the study of astronomical objects:

- Blackbody radiation emitted by all objects according to their physical temperature,
- Free-free emission produced in an ionized gas of freely colliding electrons and protons with an intensity proportional to the temperature of the electrons, and
- Nonthermal emission mostly produced by the *synchrotron process*, in which very high speed electrons spiral around magnetic-field lines. This mechanism is found in the disks of normal galaxies, in

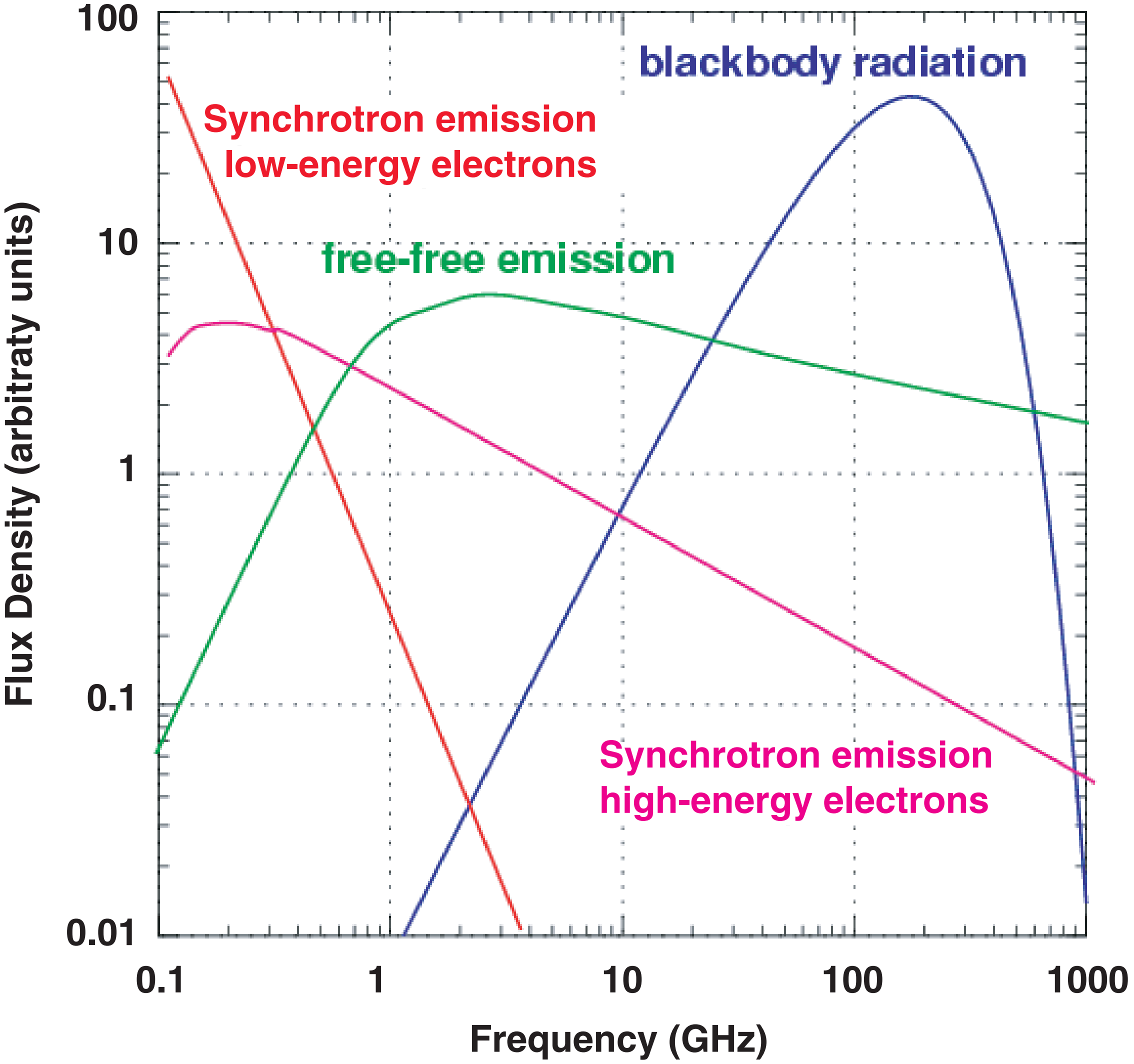

FIGURE 2.1 Continuum spectra produced by various emission mechanisms.

the remnants of supernova explosions, and in unusual types of galaxies known as radio galaxies and quasars.

Observations of continuum intensity determine the characteristic spectra of sources, but because the distribution of continuum radiation with frequency is relatively smooth, observations of this kind do not need to be made at specific or closely adjacent frequencies. Radio-frequency bands spaced at intervals of about an octave of the spectrum are normally satisfactory.[3] The spectrum (strength) of continuum

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[3] Although the roughly octave spacings of the radio astronomy bands provide adequate sampling intervals for smoothly varying continuum sources, some sources, for example planetary atmospheres, have broad spectral features that require observations at frequencies more closely spaced than factors of two.

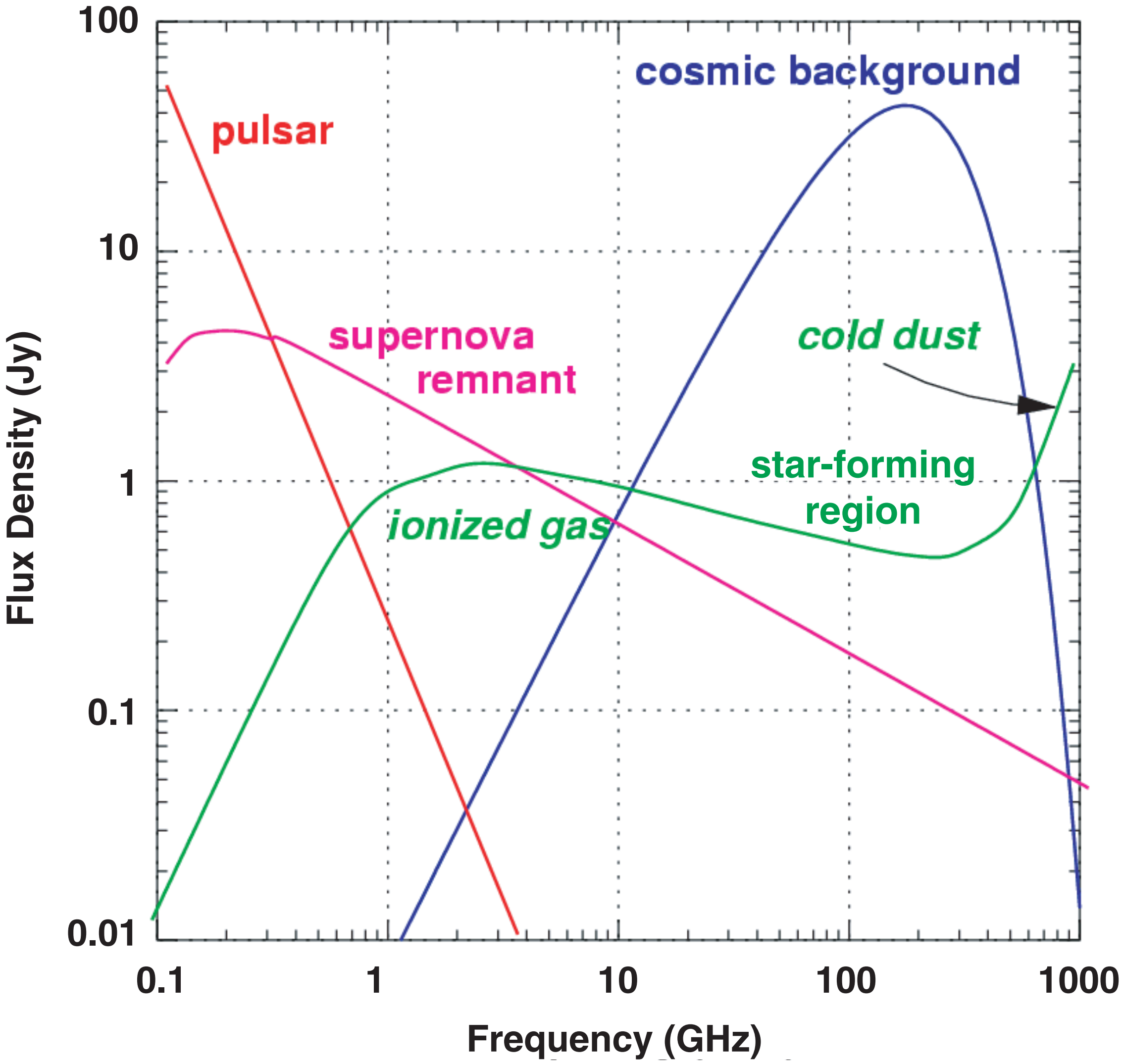

FIGURE 2.2 Spectra of typical continuum radio sources. The flux levels shown correspond to the strongest known sources. A jansky (Jy) is 10^{-26} W m^{-2} Hz^{-1}.

radiation varies only slowly with frequency, so one can use a wide receiver bandwidth and obtain the same signal level across the band. Using a wide signal bandwidth allows high sensitivity to be obtained because the Gaussian noise is averaged down more efficiently. The signal-to-noise ratio obtained is proportional to the square root of the bandwidth. Bandwidths of some hundreds of megahertz or more are commonly used for single antennas, arrays such as the Very Large Array (VLA), and very long baseline interferometry (VLBI). Also, the radio emission from very distant sources such as quasars and radio galaxies is generated largely by the synchrotron mechanism, which does not give rise to radio lines (i.e., it is over a continuum of frequencies).

VLBI relies heavily on the continuum bands, and, in general, observations of the most distant radio sources made by any radio astronomy instruments depend on continuum radiation. Observations of spectral lines, however, are only possible in physical conditions that allow the existence of atoms or molecules, mainly the interstellar medium and the outer envelopes of stars.

Continuum bands, particularly those at frequencies below 3 GHz, are also valuable for the study of pulsars (see §3.2.6).

2.1.2.2 Spectral Lines

Spectral line radiation is emitted when an atom or molecule changes energy levels. The radiation is emitted at a specific frequency and thus results in a line in the radio spectrum (Figure 2.3). Radio techniques allow spectral lines to be observed with very high frequency resolution that cannot be attained by techniques commonly employed at other wavelengths. As a consequence, many experiments, including the fundamental detection of new molecular species, can only be carried out in the radio part of the spectrum.

Each type of atom and molecule has its own unique set of spectral lines. The radio spectral lines of atoms arise from hyperfine transitions or electron recombination. One of the most fundamental and widely observed lines occurs at 1420 MHz; it arises from neutral (nonionized) atomic hydrogen. Studies of this line provide an important tracer of the most abundant element in the universe within the interstellar clouds in the Milky Way and other galaxies. Molecular lines typically come from changes in the

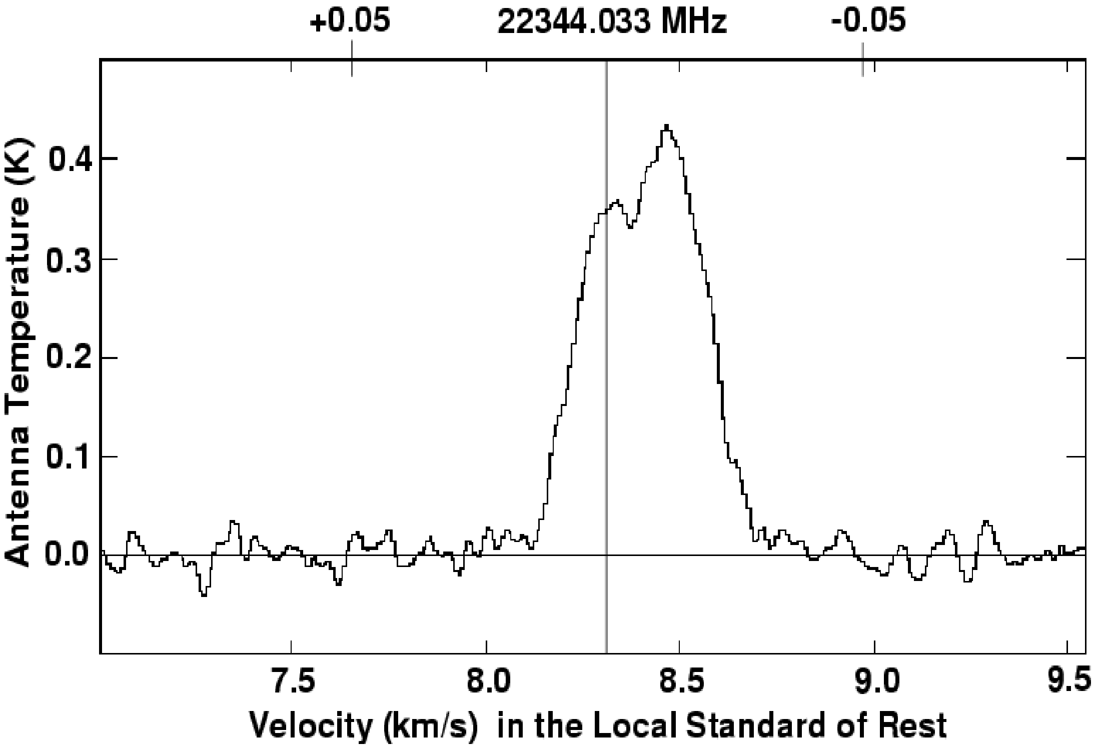

FIGURE 2.3 Spectral line emission from the molecule CCS in molecular cloud B335. From T. Velusamy, T.B.H. Kuiper, and W.D. Langer, "CCS Observations of the Protostellar Envelope of B335," *Astrophysical Journal,* Vol. 451, pp. L75-L78, 1995. Courtesy of the authors.

rotational energy of the molecule. Studies of the abundant carbon monoxide (CO) molecule at 115, 230, and 345 GHz provide fundamental information about the nature and distribution of the densest forms of the interstellar medium.

Many spectral lines from a variety of atomic species and from a large number of molecules have been found in interstellar space and in the atmospheres of stars, planets, and comets. The explosion in the discovery of new species has led to the development of a new and exciting branch of astronomy: astrochemistry. The study of astrochemistry emphasizes the synthesis of interstellar molecules and the evolution of dense interstellar gas, including its role in the formation of stars and later stages of the lives of stars. Since planets form as a by-product of star formation, knowledge of interstellar chemistry and the origins of molecular species is vital to an understanding of the early planetary chemistry and the origin of life. Spectral lines from over a hundred different molecules have now been detected in interstellar clouds (Table 2.1). Many of these are quite complex organic molecules, which raises questions about how far interstellar chemical evolution progresses toward creating the chemical precursors of life and how widespread the phenomenon of life might be in the universe.

With a better understanding of interstellar chemical evolution, it has also become possible to use the relative strengths of lines of certain molecules to determine the physical and chemical conditions in interstellar clouds and circumstellar envelopes. Thus, some specific molecular lines have proved to be exceptionally valuable diagnostic tools that require special attention. Appendixes C and D in this handbook respectively list the spectral lines below and above 300 GHz considered by the International Astronomical Union (IAU) to be the ones most important to astronomy (as of 2005) and, if they lie in an allocated band, their protection status is listed. In addition to the value of some molecular lines as diagnostic tools, since molecular transitions occur throughout the electromagnetic spectrum, observations of transitions of interstellar molecules at all frequencies improve our understanding of the physical nature and composition of the interstellar medium. For this reason, it is important that all spectrum users take all practical steps to minimize pollution of the spectrum with unnecessary emissions.

Observing spectral lines also allows astronomers to study kinematics and to determine distance from the shifting of the lines due to the Doppler shifts of the line centers arising from relative motion of the emitter and observer. In addition, the width of the lines provides important information about the physical conditions in and surrounding the emitting source and about motions within the source.

2.1.3 Sources of Radio Emission

Some of the sources of radio waves are believed to be at the farthest limits of the known universe. Because these sources are so far away, the radio waves have been traveling for many billions of years and thus provide information about the condition of the universe a very long time ago (see Figure 2.4).

The evolution of tiny fluctuations in the density of the universe into galaxies and clusters of galaxies is one of the most exciting research areas in modern astrophysics. The existence of the density fluctuations was revealed by NASA's Cosmic Background Explorer (COBE) mission and imaged by its Wilkinson Microwave Anisotropy Probe (WMAP) mission (see Figure 2.5), both satellites operating at radio frequencies. While the WMAP results are from a space mission, ground-based and balloonborne cosmic microwave background (CMB) experiments continue to play vital roles in the study of the small-scale structure of the CMB and its polarization. Radio astronomy serves as the best way to study the CMB, which has yielded a remarkable picture of the initial evolution of the universe (see Figure 2.6).

Studies are just beginning of the epoch of re-ionization (EoR), during which radiation from the first generation of stars and galaxies (re)ionized the universe (see Figure 2.7). Observations of neutral

TABLE 2.1 Astrophysical Molecules, Grouped by Number of Atoms, Found in Interstellar Clouds of Various Sorts

Number of Atoms[a]											
2	3	4	5	6	7	8	9	10	11	12	13
H_2	C_3	c-C_3H	**C_5**	C_5H	C_6H	CH_3C_3N	CH_3C_4H	CH_3C_5N?	HC_9N	$CH_3OC_2H_5$	**$HC_{11}N$**
AlF	C_2H	l-C_3H	C_4H	l-H_2C_4	CH_2CHCN	$HCOOCH_3$	CH_3CH_2CN	$(CH_3)_2CO$			
AlCl	C_2O	C_3N	C_4Si	C_2H_4	CH_3C_2H	CH_3COOH?	$(CH_3)_2O$	NH_2CH_2COOH?			
C_2	C_2S	C_3O	l-C_3H_2	CH_3CN	HC_5N	**C_7H**	CH_3CH_2OH	CH_3CH_2CHO			
CH	CH_2	C_3S	c-C_3H_2	CH_3NC	$HCOCH_3$	**H_2C_6**	HC_7N				
CH^+	HCN	C_2H_2	CH_2CN	CH_3OH	NH_2CH_3	**CH_2OHCHO**	C_8H				
CN	HCO	CH_2D^+?	CH_4	CH_3SH	c-**C_2H_4O**	CH_2CHCHO					
CO	HCO^+	HCCN	HC_3N	HC_3NH^+	**CH_2CHOH**						
CO^+	HCS^+	$HCNH^+$	HC_2NC	HC_2CHO							
CP	HOC^+	HNCO	HCOOH	NH_2CHO							
CSi	H_2O	HNCS	H_2CHN	C_5N							
HCl	H_2S	$HOCO^+$	H_2C_2O	HC_4N							
KCl	HNC	H_2CO	H_2NCN								
NH	HNO	H_2CN	HNC_3								
NO	MgCN	H_2CS	SiH_4								
NS	MgNC	H_3O^+	H_2COH^+								
NaCl	N_2H^+	NH_3									
OH	N_2O	**SiC_3**									
PN	NaCN	C_4									
SO	OCS										
SO^+	SO_2										
SiN	c-SiC_2										
SiO	CO_2										
SiS	NH_2										
CS	**H_3^+**										
HF	**SiCN**										
SH	**AlNC**										
FeO(?)	SiNC										

NOTE: Molecules in boldface type have been found in Comet 1995 O1 Hale-Bopp. H_2O^+ and C_2H_6 are seen in the comet, but not in interstellar clouds. The latest data can be obtained from Dr. Alwyn Wootten, National Radio Astronomy Observatory, http://www.cv.nrao.edu/~awootten/; accessed March 1, 2006.

[a] A lower-case "c" indicates a cyclic structure; a lower-case "l," a linear structure; and a "?," a tentative identification.

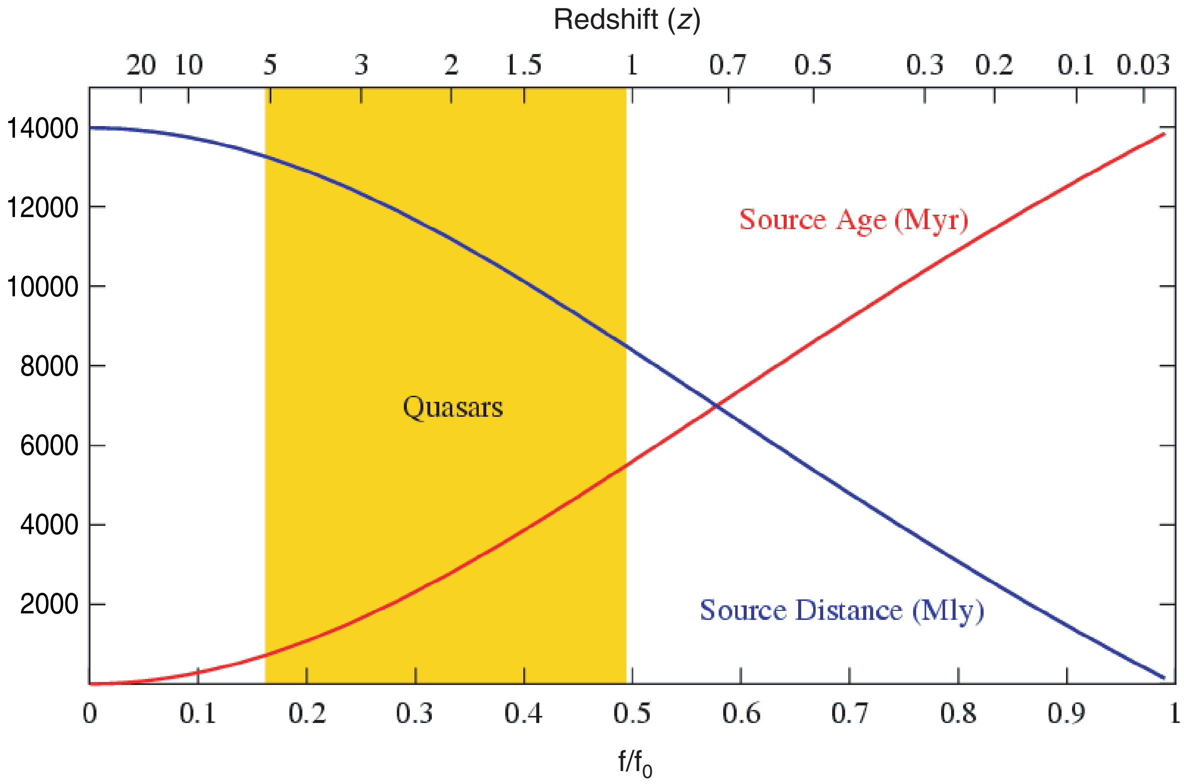

FIGURE 2.4 The distance and age of radio sources as a function of Doppler shift due to the expansion of the universe (logarithmic scales). The parameter z is known as the redshift. Myr, million years; Mly, million light-years.

hydrogen (HI) at redshifts of $z = 6$ to 15 (88-200 MHz) will probe the EoR. Indeed, HI may be observable in absorption against the cosmic background radiation itself at a redshift of $z = 30$ (45 MHz).

The history of the clustering of galaxies in the universe can be studied by surveys/observations of the Sunyaev-Zel'dovich (SZ) effect. The ionized gas that collects in the central region of a cluster of galaxies scatters the cosmic background radiation, producing a depression in the intensity of the background radiation at the location of the cluster. The radio data can be combined with x-ray observations to yield the redshift of the cluster. Large SZ surveys will trace the history of clustering of galaxies from early epochs. These surveys are conducted at millimeter wavelengths.

A new class of objects, submillimeter galaxies, is thought to represent galaxies in the earliest stages of evolution. The discovery of these objects has been one of the key developments of recent years. The emission from submillimeter galaxies arises from dense gas and dust heated by newly formed stars in the system. Because this emission is intrinsically bright and because, for objects at great distances, it is redshifted from the far-infrared into the submillimeter/millimeter band, these objects can be detected to great distances. At this time, submillimeter galaxies have been detected out to a redshift greater than 6, and modern instruments under construction will be able to see them at even greater distances, out to redshifts of $z \sim 10$. By studying objects at different distances, then, it is possible to view the evolutionary history of the development of galaxies and the star formation that occurs within them. Supermassive

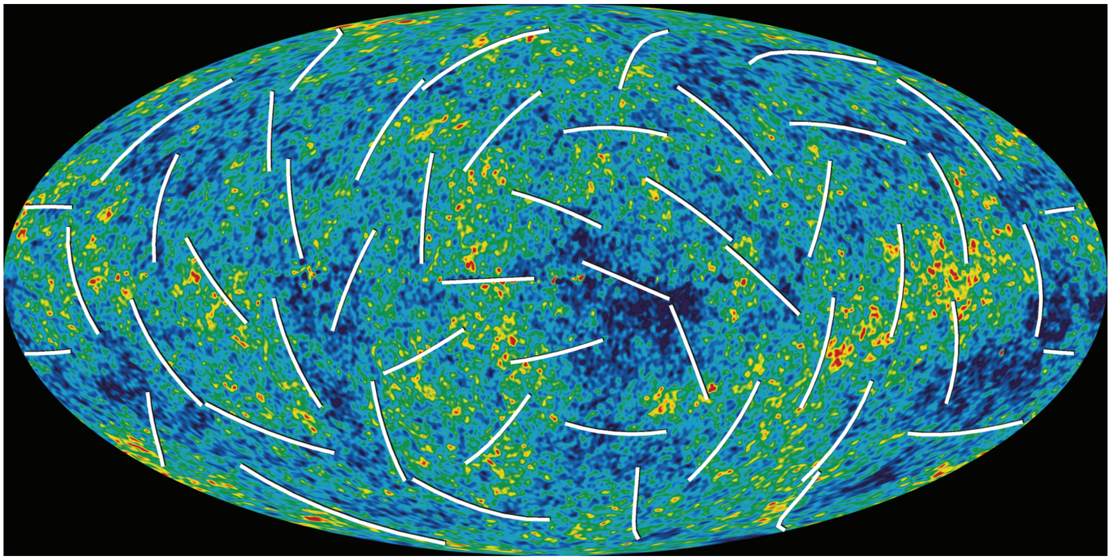

FIGURE 2.5 The microwave sky. The Wilkinson Microwave Anisotropy Probe (WMAP) has produced a new, more detailed picture of the infant universe. Colors indicate "warmer" (red) and "cooler" (blue) spots. The white bars show the "polarization" direction of the oldest light. This new information helps to pinpoint when the first stars formed and provides new clues about events that transpired in the first trillionth of a second of the universe. Courtesy of the NASA/WMAP Science Team.

The panel notes that the WMAP radiometers operated in five frequency bands, at 23, 33, 41, 61, and 94 GHz. Except for the highest band, these frequencies do not fall within Radio Astronomy Service bands; furthermore, the satellite was located at the L2 point (second Lagrange point) and had shielding to protect against radiation from the direction of the Sun and Earth.

nuclear black holes are believed to be ubiquitous in nearby, normal galaxies and a natural part of massive galaxy formation.

The most powerful radio sources known are quasars, which are distant, compact objects that emit radio energy at a prodigious rate. A quasar resides in the nucleus of its host galaxy, and the optical emission from the quasar exceeds the total starlight in the host galaxy. As a result, the host galaxy is difficult to observe at these wavelengths. The most distant quasars have been detected with z beyond 5 ($f/f_0 = 0.17$ to 0.2; see Figure 2.4). The study of quasars involves fundamental physics, in the continuing attempt to understand their sources of energy. 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 nucleus and can best be studied by radio methods. It is becoming increasingly evident that these galactic nuclei, including those of our own Galaxy, are powered by black holes.

Many distant galaxies are unusually strong continuum emitters of radio waves but are relatively faint when viewed with an optical telescope. These radio galaxies are the subject of many investigations attempting to discover the source of their radio energy and the circumstances of the explosive events that seem to have occurred in many of them.

Studies of galaxies depend heavily on observations of spectral lines at radio wavelengths. These observations provide information on the kinematics of the gas in the galaxies and on the nature of the star-forming interstellar medium within them. The 21 cm HI line and the millimeter-wave CO lines are typically used to trace the atomic and molecular phases of the interstellar medium in galaxies. The 21 cm

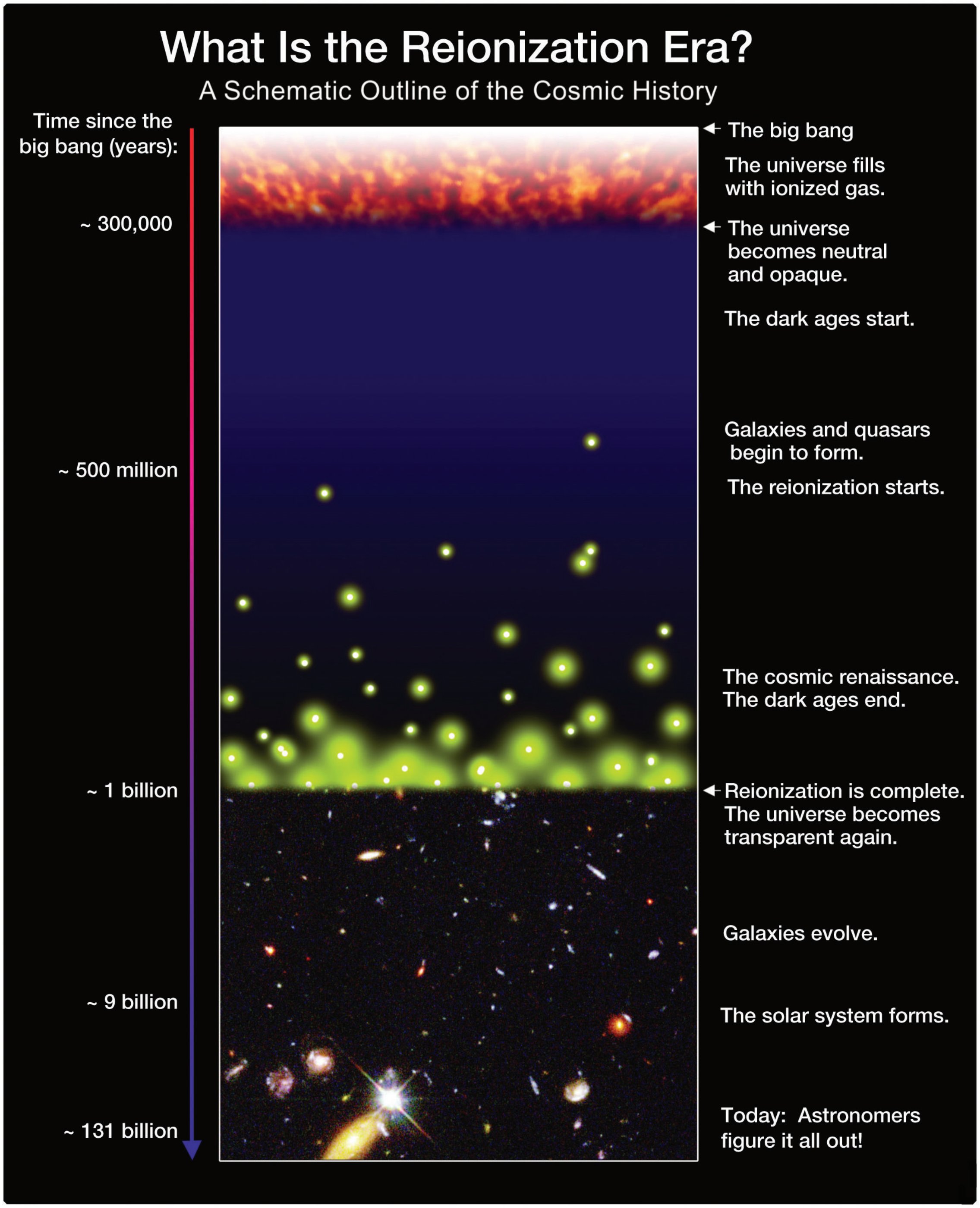

FIGURE 2.6 The history of the universe, the earliest epoch based in part on the Wilkinson Microwave Anisotropy Probe image of the cosmic background fluctuations that illustrate the "tiny density fluctuations." Courtesy of S.G. Djorgovski et al. and Digital Media Center, California Institute of Technology.

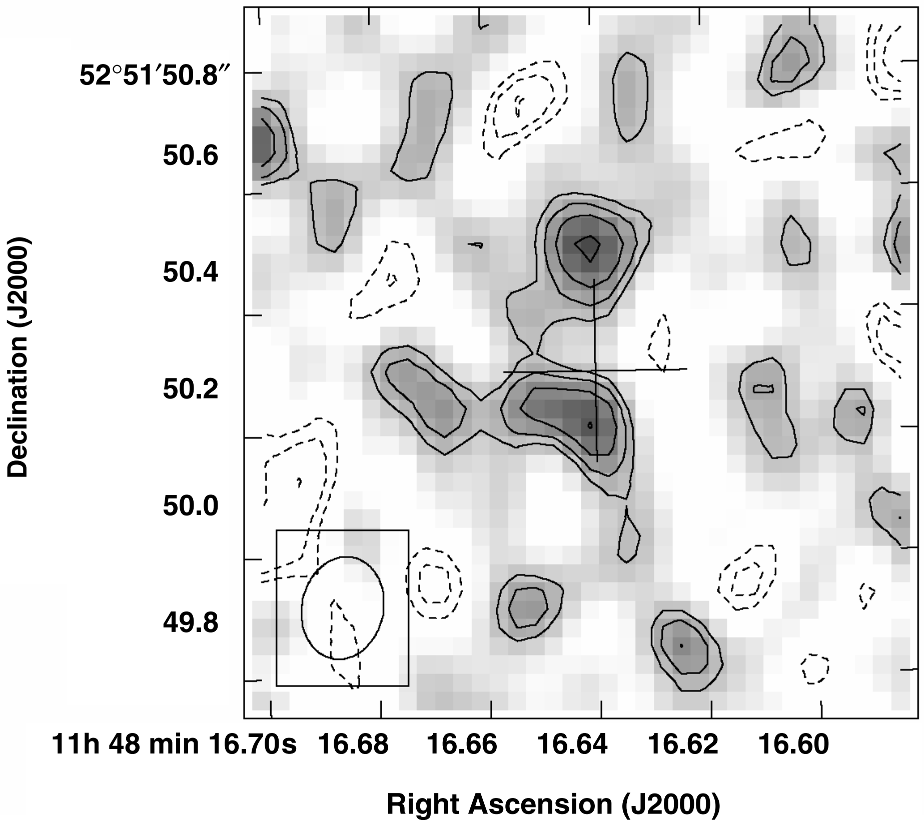

FIGURE 2.7 A Very Large Array image of CO (J = 3 – 2) emission in Sloan Digital Sky Survey (SDSS) J1148, showing the (possible) merger of two galaxies at a redshift of $z = 6.4$, in the epoch of reionization (see F. Walter, C. Carilli, F. Bertoldi, K. Menten, P. Cox, K.Y. Lo, X. Fan, and M.A. Strauss, "Resolved Molecular Gas in a Quasar Host Galaxy at Redshift $z = 6.42$," *The Astrophysical Journal,* Vol. 615, Pt. 2, pp. L17-L20, 2004; the rest frame emission frequency is 345 GHz, but the observations were made at 345/7.4 = 47 GHz). Courtesy of Chris Carilli, National Radio Astronomy Observatory, and Fabian Walter, Max Planck Institute for Astronomy.

HI line has also been extensively used to learn about the gravitational potential of the galaxies; this work led to the realization that a substantial fraction of the masses of galaxies is made up of material that is not visible. The "dark matter" that is implied by these observations and confirmed through other observational tests, such as the study of the cosmic microwave background, is one of the most important areas of research in modern astrophysics. For galaxies that are gas-rich and optically faint (or even optically "dark," i.e., containing too few stars to be seen), the measurement of the 21 cm HI line gives an accurate measure of the distance, thereby allowing a unique but important view of local large-scale structure (e.g., see Figure 2.8). HI also traces the debris remnants of tidal encounters among galaxies. Ongoing and future experiments will conduct these observations at lower frequencies and thus higher redshifts, allowing us to explore how the gas content of galaxies varies not only across space but also over cosmic time.

Our own Milky Way Galaxy is difficult to observe at optical wavelengths, since these wavelengths of light are blocked by clouds of interstellar dust. Radio waves, however, can penetrate these clouds and

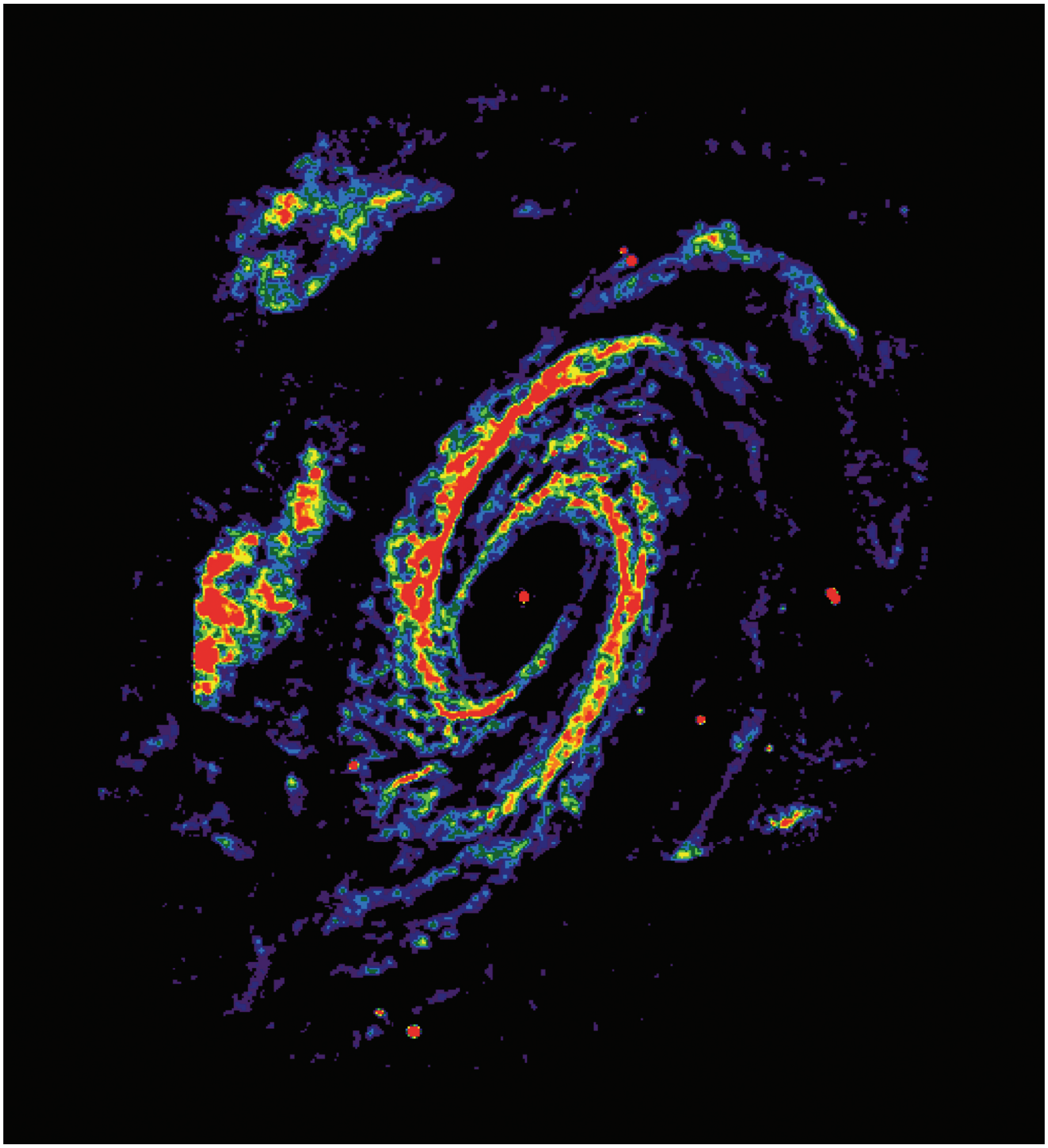

FIGURE 2.8 Very Large Array image of galaxy M81, a spiral galaxy about 11 million light-years from Earth and about 50,000 light-years across. The image was made using data taken over more than 60 hours of observing time. The spiral structure is clearly evident in this image, which shows the relative intensity of emission from neutral atomic hydrogen gas. In this pseudocolor image, red indicates strong radio emission and blue, weaker emission. Courtesy of National Radio Astronomy Observatory/Associated Universities, Inc.

allow astronomers to obtain a view of the entire Galaxy. Studies of the location and composition of interstellar clouds using radio observations provide fundamental information about the structure and evolution of the Galaxy that could not be obtained by other means.

Radio astronomy has also provided new information about the early and late stages of the lives of stars, stages that are important in the evolutionary process but that are not well understood. Strong and localized sources of radiation in spectral lines of the hydroxyl, water, and silicon monoxide 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. Recently, giant breeding grounds of massive new stars, and dark clouds where stars similar to the Sun are born, have been detected. Millimeter and submillimeter radio telescopes and interferometers are leading astronomers to a new era in the understanding of the star-formation process.

At the other end of the stellar life cycle, radio astronomers study the circumstellar envelopes of evolved, post-main-sequence stars, which shed material into the interstellar medium during the latter stages of their evolution. The most massive stars eject material in a supernova explosion at the end of their lives as stars. The supernova remnants that are left behind by this process may also be studied. Finally, radio astronomers have also discovered numerous very dense and compact neutron stars, which are the remnants of supernova explosions. A rapidly rotating neutron star often is observed as a pulsar, a periodic radio source, which emits a narrow beam of coherent radiation as the neutron star rotates. Pulsars have a period that ranges from on the order of a millisecond to many seconds. Therefore, they provide exquisite time resolution, are excellent clocks, and may prove to be the best time standards on some scales. Pulsars permit the study of the fundamental physics effects of general relativity.

In the solar system, the Sun has always been an important object for study by radio astronomers. Radio astronomy complements optical astronomy for study of the Sun. Observations of coronal mass ejections are of particular importance to "space weather" studies. The slowly varying component of solar radio emission has been found to provide one of the best indicators of the variation of solar activity over the Sun's 11-year cycle. In addition, the intense and rapid bursts of solar radio emission are providing greater understanding of what happens on the Sun during active periods and the way the Sun influences events in Earth's atmosphere, near-Earth space, and other portions of the solar system.

Comets are objects in the solar system that are thought to contain the most pristine material remaining from the origin of the solar system. As comets pass near the Sun, the volatile ices in the comet are sublimated; the gas that is produced flows out from the nucleus to form the comet's coma. Radio observations of this material provide the best way to measure the detailed molecular composition of the cometary ices and allow new insights into the composition of the protosolar cloud that formed the Sun and planets.

Finally, radio observations of the planets provide new information that cannot be achieved by other techniques. For example, the planet Jupiter produces frequent bursts of radio waves; their study by radio astronomers first determined the rotation period of the planet's core and showed the coupling between Jupiter's magnetosphere and the satellite Io. This has been confirmed and extended by measurements in the vicinity of Jupiter from the Pioneer and Voyager spacecraft. Radio measurements of the deep atmospheres of Venus and the outer planets provide the only means to probe these regions remotely and inform models of planetary formation. Millimeter-wave spectroscopic measurements of the upper atmospheres of Venus, Mars, and Saturn's satellite Titan provide some of the best information on the atmospheric photochemistry and circulation that is available. As illustrated in Figure 2.9, ground-based radio observations complement optical observations in providing the long-term monitoring necessary to study the seasonal cycles on Titan.

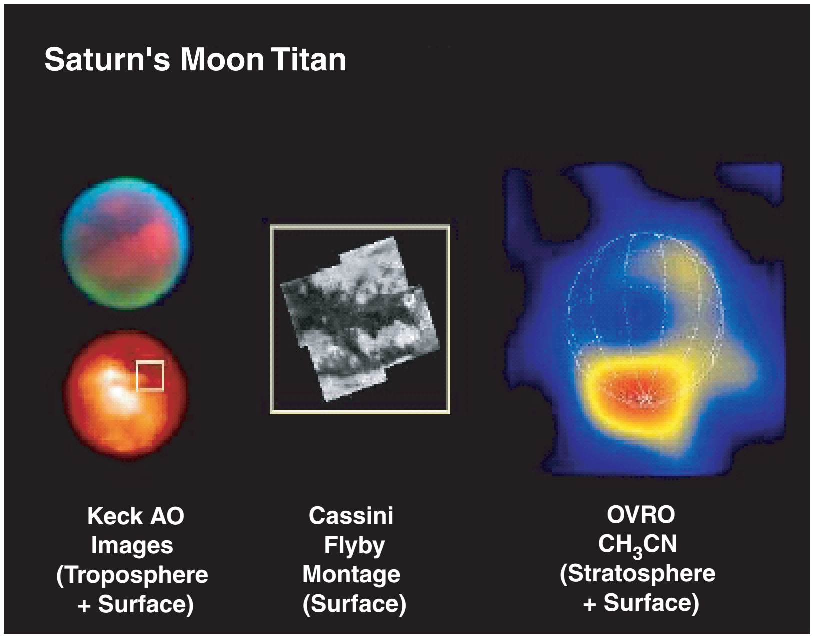

FIGURE 2.9 *Left:* Ground-based K-band Keck Observatory adaptive optics (AO) images of the leading and trailing hemispheres of Saturn's moon Titan. The color stretch in the image at the top highlights troposphere haze (blue) and polar clouds (green). *Middle:* Cassini high-resolution montage of the Fensal-Aztlan region of Titan from the September 7, 2005, flyby. *Right:* Owens Valley Radio Observatory (OVRO) 0.9 arcsec image of the acetonitrile emission from the southern polar stratosphere and upper troposphere. Only long-term monitoring with ground-based radio, millimeter, and submillimeter observatories and optical and infrared facilities can provide the very long baselines needed to study the seasonal cycles of this moon. Courtesy of Antonin Bouchez, W.M. Keck Observatory (left); NASA/Jet Propulsion Laboratory-California Institute of Technology (middle); and Mark A. Gurwell, Harvard-Smithsonian Center for Astrophysics/Owens Valley Radio Observatory (right).

2.1.4 Radar Astronomy

While astronomy is largely a passive activity, there is one exception. Operating in the Radiolocation Service bands at 2380 MHz and 8560 MHz, powerful radars at the Arecibo Radio Observatory and the NASA Goldstone Deep Space Communications Complex, respectively, are used to study the surfaces of the Moon, Mars, Mercury, and Venus and the satellites of Jupiter and Saturn. The radars are also powerful instruments for studying asteroids and comets. For near-Earth asteroids, such as Toutatis and Geographos, detailed information has been obtained on the shape, surface composition, and kinematics.

Although the transmitters are powerful (about 500 kW), the returned signals are very weak. Thus, interference from other active services can have a deleterious effect on the scientific data.

2.1.5 Very Long Baseline Interferometry

The technique of very long baseline interferometry allows radio astronomers to link radio telescopes many thousands of kilometers apart. VLBI provides highly accurate measurements of the structure of distant radio sources and molecular emission regions in space.

The angular resolution achieved by VLBI depends not on the size of the individual telescopes but on the distance between them. Data from individual telescopes are recorded simultaneously on high-data-rate recording systems (using very stable oscillators synchronized by atomic clocks). The recorded medium is shipped to a central correlator facility, and the data are processed to produce an interferometer system with baselines spanning continents and oceans.

For this technique to be fully exploited, telescopes in different countries must observe together on exactly the same frequency. Thus, it is necessary that the same passive frequency bands be protected in all of the regions of the world. The United States has built a dedicated system of VLBI telescopes, from Hawaii across the continent to the Virgin Islands, called the Very Long Baseline Array (VLBA; see footnote US311 in Box 4.1).

Originally developed as a radio astronomical technique for the high-resolution imaging of astronomical objects, VLBI has found many applications in Earth-based science, a notable example being the sensitive monitoring of crustal motions on Earth. The positional accuracy provided by the Global Positioning System (GPS) depends on the precise knowledge of irregularities of Earth's rotation provided by VLBI measurements of distant quasars. Using large numbers of time-difference measurements from many distant quasars observed with a global network of antennas, VLBI determines with unequaled precision the terrestrial reference frame (antenna locations on Earth), the celestial reference frame (quasar positions in the sky), and Earth's orientation in space. VLBI observations are now doing precision astrometry, measuring the motions of galaxies in the Local Group, the distance to the galactic center of the Milky Way with extreme precision, and observing the motions of stars in orbit around black holes in external galaxies. This capability is unique, and no other wavelength regime can compete for this kind of resolution. These time-difference measurements are precise to a few picoseconds. This high precision is made possible by simultaneous continuum observations in several discrete channels spanning over 100 MHz around 2300 MHz and spanning 500 MHz or more around 8600 MHz.

Although it is not possible to make such precise measurements using only bands allocated to the passive services, these measurements are possible because some interference can be tolerated at some of the antennas part of the time. However, the recent activation of broadcast satellites in the 2300 MHz band is making these measurements more difficult. The broadcast satellites and other sources of interference may make it necessary to move geodetic observations to the 31 GHz band, where 500 MHz is protected for radio astronomy and other passive services.

The need for global protection of the continuum bands used by VLBI became more urgent with the successful deployment in 1997 of the first orbiting VLBI antenna. Space antennas can greatly increase the angular resolution achievable with VLBI techniques. Because of the limited aperture size of orbiting antennas, the success of such projects depends crucially on being able to observe with many large ground-based antennas around the world.

2.1.6 Exploration of the Universe: Three Examples of Major Research Themes and Their Need for Protected Spectrum

2.1.6.1 The Origin and Evolution of Galaxies

Radio astronomy offers the means to study the evolution of galaxies from the very earliest times in the universe. At low frequencies, future facilities will have the sensitivity to detect the signatures left by the re-ionization of the universe induced by the first generation of galaxies and their constituent stars. The first supermassive black holes, formed in the cores of these galaxies, will also be detectable by these low-frequency facilities.

Submillimeter galaxies are detected with the use of ultrawideband continuum detectors and bolometers, which make use of most of the available frequency space within the millimeter and submillimeter atmospheric windows. The sensitivity of the measurements is greatly enhanced by the use of wide bandwidths, which places a premium on continuous, interference-free allocations for radio astronomy. Moreover, for follow-up work, it is important to measure the redshift of these objects via molecular-line observations. The redshifts of new objects are not known a priori, and these lines may be redshifted to any lower frequency. The ability to determine a redshift is directly related to the ability to cover the widest possible bandwidth in a search; therefore, it is important to preserve portions of the spectrum to allow this fundamental information to be measured. To study early galaxies as well as other objects, astronomers use radio astronomy data synergistically with the optical data from the Hubble Space Telescope, infrared data from the Spitzer Space Telescope, and x-ray data from the Chandra X-ray Observatory.

2.1.6.2 Prebiotic Chemical Evolution

The role of interstellar prebiotic chemistry in the origin of life will be better understood when there is a more complete inventory of complex organic molecules. These will be extraordinarily difficult to detect because they are probably much less abundant as compared with simple molecules and because their emission is spread over a much larger number of spectral lines. Such molecules will likely be detected via intensive searches across many wavelength bands, where numerous transitions can be measured in a self-consistent, physically connected data set. Preliminary modeling for such molecules suggests that at temperatures corresponding to warm molecular clouds, these species peak in emission in the millimeter windows.

2.1.6.3 The Search for Extraterrestrial Intelligence

One of the most exciting possible discoveries would be the detection of artificial radiation of nonhuman origin. In 1959, Cocconi and Morrison published a paper suggesting that the technology of radio astronomy had progressed to the point that interstellar communication between ourselves and a very distant civilization might be possible.[4] They suggested the 1420 MHz line of neutral hydrogen as an obvious universal communication channel. Independently, Frank Drake made the first radio search for extraterrestrial intelligence (SETI) using the Tatel Telescope of the National Radio Astronomy Observatory (NRAO) equipped with a single-channel, narrowband spectrometer and a receiver tuned to 1420 MHz. Project Ozma, as this search was called, was conducted in the spring of 1960. It examined two nearby solar-type stars for a few hundred hours. It was the first of nearly 60 searches that have been made over the past three decades, most of them at radio frequencies.

Footnote 722 (renumbered by the World Radiocommunication Conference [WRC] of 1995 as 5.341) was added to the radio regulations during the 1979 World Administrative Radio Conference (predecessor of the WRC). It recognizes the interest of the radio science community in this passive search technique. Since 1960, improvements in receiver technology and digital signal processing equipment, intended primarily for use in radio astronomy, have enabled far more sensitive and sophisticated

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[4] G. Cocconi and P. Morrison, "Searching for Interstellar Communications," *Nature,* Vol. 184, No. 4690, pp. 844-846, September 19, 1959.

searches for extraterrestrial technologies to be conducted. Making use of receiver instrumentation developed for radio astronomy, these searches have remained clustered about the frequencies of natural atomic and molecular emission lines and within the protected radio astronomy bands. Plausible arguments can be made for searching at these "magic frequencies," but most of the microwave window has remained unexplored. We can of course only speculate on the likelihood of civilizations with matching technology.

The SETI Institute has initiated a systematic search for signals throughout the 1 to 10 GHz frequency range that represents the clearest microwave window through the terrestrial atmosphere. This search is based on state-of-the-art signal processing equipment and wideband, low-noise receivers and feeds developed specifically for the effort. The search is being conducted with two complementary strategies, a targeted search of the nearest one thousand solar-type stars employing the Allen Telescope Array and an all-sky survey. Although this search will be much more comprehensive than any other ever undertaken, it is still a limited search.

Because of the technical challenges alone, SETI is an important scientific endeavor. SETI experiments require advanced methods of signal processing as an attempt is made to recognize and interpret weak signals of unknown intensity, frequency, and temporal characteristics amidst a background din of terrestrial and cosmic noise. As with more traditional astronomical studies of weak cosmic radio emission, terrestrial interference poses the greatest challenge to this microwave search.

2.2 REMOTE SENSING OF EARTH

2.2.1 Overview

The spectrum services and systems (see Table 1.1 in Chapter 1) that support the Earth sciences include the Earth Exploration-Satellite Service (EESS), the Radio Astronomy Service (RAS), the Space Research Service (SRS), the International Global Navigation Satellite System (GNSS) (IGS), the Meteorological Aids Service (MetAids), the Meteorological Satellite Service (MetSat), and the Space Operations Service (SOS). The EESS is dedicated to the measurement of all phenomena that can affect Earth's habitat and its environmental quality, including measurements for both research and operational purposes (Box 2.2). Accurate weather forecasts and timely warnings of severe weather save lives. The lives of people everywhere on Earth are affected by environmental conditions of the land, the oceans, and the atmosphere. Data collected by active and passive sensors are distributed worldwide and are used to benefit developing and developed countries alike. Spaceborne sensors are the only tools that can provide environmental data repetitively on a global scale. Use of active and passive microwave sensors removes the need for sunlight and permits penetration of clouds, thus providing nighttime as well as all-weather coverage. In addition to using spectrum for active and passive sensing from space, the Earth science services use spectrum for command, tracking, data acquisition, and communications and for ground-based radiometry of the atmosphere.[5] Ground-based passive and active microwave sensors

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[5] For background information from technical papers regarding the technical capabilities of the Earth Exploration-Satellite Service, see the following: P.W. Gaiser, K.M. St. Germain, E.M. Twarog, G.A. Poe, W. Purdy, D. Richardson, W. Grossman, W.L. Jones, D. Spencer, G. Golba, J. Cleveland, L. Choy, R.M. Bevilacqua, and P.S. Chang, "The WindSat Spaceborne Polarimetric Microwave Radiometer: Sensor Description and Early Orbit Performance," *IEEE Transactions on Geoscience and Remote Sensing,* Vol. 42, No. 11, pp. 2347-2361, November 2004; and E.G. Njoku, T.J. Jackson, V. Lakshmi, T.K. Chan, and S.V. Nghiem, "Soil Moisture Retrieval from Amsr-E," *IEEE Transactions on Geoscience and Remote Sensing,* Vol. 41, No. 2, pp. 215-229, 2003.

BOX 2.2
The 1995 Australia Prize

The Australia Prize, renamed the Prime Minister's Prize for Science in 2000, is awarded annually by the Australian government to an individual "for an outstanding specific achievement in a selected area of science and technology promoting human welfare."

In 1995, the Australia Prize was awarded to Dr. Richard Moore, Professor Emeritus of Computer and Electrical Engineering at the University of Kansas, for his work in pioneering "the field of microwave-based remote sensing that helped revolutionize mapping and monitoring of the Earth's surface." Dr. Moore was recognized for his invention of the scatterometer and the promotion of space-borne synthetic aperture radar (SAR), both of which use a microwave beam to map the natural environmental characteristics of Earth.

Utilizing Dr. Moore's techniques on a space platform, scientists were for the first time able to conduct large-scale measurements of environmental parameters such as soil moisture, plant respiration, and wind vectors in remote oceanic regions. In fact, it was these experiments that led to the discovery of ancient river beds beneath the Sahara Desert and deserts of northwestern Australia.

Today, remote-sensing instruments designed, developed, and promoted by Dr. Moore are used worldwide for monitoring forests, monitoring oceanic parameters such as sea-surface temperature and wind speed, identifying and tracking hurricanes and other extreme weather phenomena, and generally collecting data on global weather and climate trends.

SOURCE: Australian Department of Education, Science and Training, "1995 Australia Prize," available at https://sciencegrants.dest.gov.au/scienceprize/Pages/Doc.aspx?name=previous_winners/Aust1995Moore.htm, accessed February 7, 2007.

utilize many of the same bands used by satellites to provide additional complementary measurements of the atmosphere.

Microwave sensors can detect variations in Earth parameters not readily detected at optical wavelengths. They can measure temperature, humidity, cloud, and trace gas profiles; surface soil moisture; ocean and estuarian salinity; sea-surface temperature; land-surface roughness and biomass; ocean-surface wave height and sea state; and the moisture content and melt character of ice and snow. Snow- and ice-covered areas and bodies of water can be mapped under all weather conditions and with penetration depths not possible at optical or infrared wavelengths.

Observations of Earth's atmosphere, land areas, and oceans in the radio part of the electromagnetic spectrum have become increasingly important in understanding Earth as a system. Currently operational satellite instruments, including the Advanced Microwave Sounding Unit (AMSU) and instruments on the Defense Meteorological Satellite Program's passive microwave weather satellites (the Special Sensor Microwave/Imager [SSM/I] and Special Sensor Microwave/Temperature [SSM/T]), provide key meteorological data sets. Remote sensing satellite missions such as NASA's Earth Observing System (EOS) and the Tropical Rainfall Measurement Mission (TRMM) are providing information about water on a global basis and about rainfall amounts and patterns in the tropics. Current and future missions are expected to improve measurements of atmospheric temperature, water vapor and precipitation, soil moisture, concentrations of ozone and other trace gases, and sea-surface temperature and salinity. These multiyear, multi-billion-dollar missions are international in scope, reflecting the interests of many countries in obtaining accurate meteorological, hydrological, and oceanographic data and measurements of land-surface features and trace gases in the atmosphere.

The outcome of such remote sensing missions are improvements in weather forecasting; severe-storm monitoring; water resource, land, and biota management; and global climate and atmospheric chemistry models. The long-term economic impact of the information from remote sensing satellites is substantial, in both the production of food and other agricultural products and the operation of businesses and industries that are dependent on both local weather and long-term climate stability. Each year many thousands of lives are saved through advanced warning of dangerously inclement weather, for example, hurricanes, tornadoes, severe thunderstorms, and flash floods. Remotely sensed information from passive and active microwave sensors is also used increasingly to provide scientifically based guidelines for environmental policy.

2.2.2 Passive Sensing

2.2.2.1 Techniques

All matter emits, absorbs, and scatters electromagnetic energy to varying degrees. Water in its various phases (gas, liquid, and solid) exhibits particularly strong characteristic absorption, emission, and scattering features in the microwave portion of the electromagnetic spectrum. Passive sensors measure the electromagnetic energy emitted and scattered by Earth and constituents in the atmosphere.

Atmospheric gases emit and absorb microwave energy at discrete resonant frequency bands described by the laws of quantum mechanics. Atmospheric molecules of H_2O, for example, have resonances at 22.235 and 183.10 GHz; frequencies near these resonances are needed for the measurement of water vapor by passive spaceborne sensors. Other atmospheric constituents with resonant frequency bands in the microwave spectrum include O_2, O_3, CO, NO_x, and ClO. Measurements taken near the resonances of these gases can be used to determine the amount of the particular gas in the atmosphere and to obtain atmospheric temperature profiles. The frequency allocations needed for these measurements are rigidly determined by the location of the resonant frequency bands.

The energy emitted from any surface is a function of the frequency, surface roughness and dielectric properties, polarization, angle of incidence and aspect, and subsurface microstructure. Measurements of oceanic roughness are used in the study of ocean structure and winds over sea surfaces. Measurements of O_2 absorption are used to determine surface pressure over oceans, and measurement of surface roughness and dielectric constant variations are used in studies of ice, snow, and land parameters. Increasingly, these measurements are being used in operational environmental models for weather- and climate-forecasting purposes. Hydrological prediction services are beginning to use these data for river forecasting and flood control, fire-danger forecasting, and drought assessment and prediction.

The choice of frequency for surface measurements by passive sensors is not as tightly constrained as that for atmospheric gas measurements, since surface characteristics of land (Figure 2.10) and water (Figure 2.11) such as soil moisture and wind speed affect microwave emissions over a broader range of frequencies. However, the sensing of many surface phenomena requires simultaneous measurements at several frequencies in order to measure any single phenomenon because the energy emitted at any given frequency is determined by several overlapping phenomena. Sensing bands spaced at intervals of about an octave of the radio-frequency spectrum are needed within the frequency range from approximately 1 to 200 GHz. The selection of specific allocations can be based on the feasibility of sharing frequencies with other allocated radio services. Below 20 GHz, constraints on the parameters of active radio services may be needed to make sharing feasible.

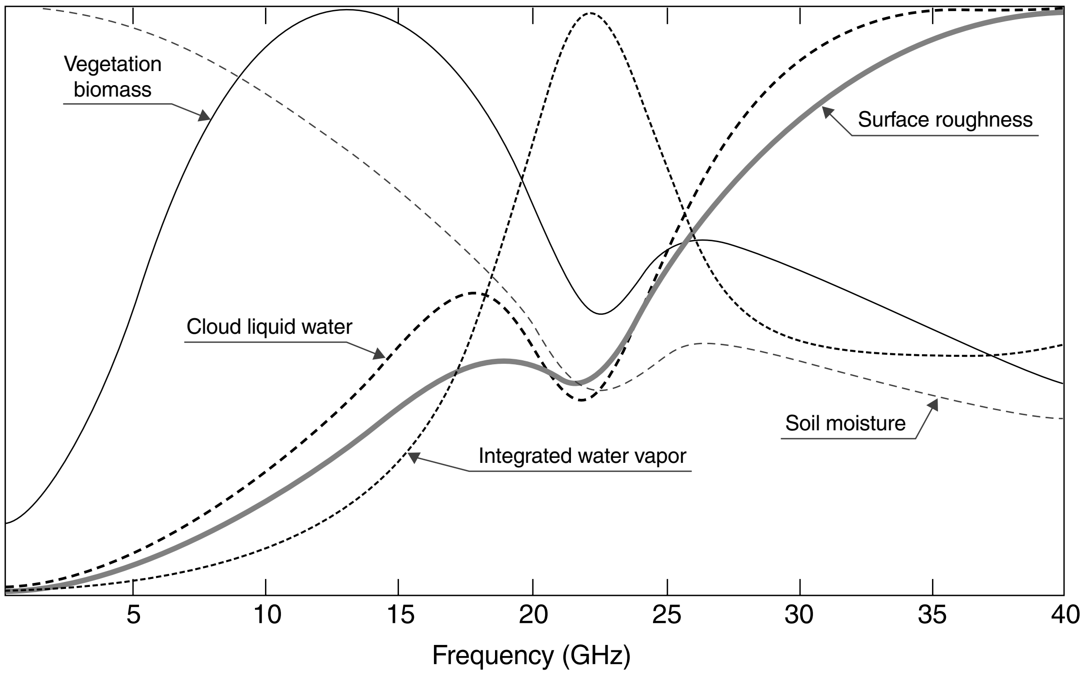

FIGURE 2.10 Relative sensitivity of brightness temperature to geophysical parameters as a function of frequency (over land surfaces).

Extensive studies have been carried out in the International Telecommunication Union's Radiocommunication Sector (ITU-R) to quantify the frequencies needed for passive sensor measurements. The results are documented in Recommendation ITU-R RS.515.

2.2.2.2 *Passive Sensors*

A major component of Earth remote sensing systems consists of spaceborne passive microwave radiometers. These sensors are similar in their basic design to radio astronomy receivers. Their use for remote sensing, however, differs in important ways from their application in radio astronomy. A fundamental difference in potential interference sources results because spaceborne sensors point toward Earth from space, in contrast to radio telescopes which point to space from Earth. Radio sources on Earth, particularly those transmitting toward space and which may be benign to radio astronomers, are typically incompatible with spaceborne EESS sensors. Another difference arises owing to the rapid motion of satellite-based sensors through space, which limits the integration time available for sensor measurements to seconds, compared with the longer integration times used by stationary radio telescopes. Thus, EESS remote sensor sensitivities are different from those achieved by radio telescope receivers. However, the maximum antenna gain must be considered in interference calculations, since Earth-viewing sensors are not able to avoid pointing at interference sources as they orbit Earth.

The instrument sensitivity needed to determine physical properties depends on the required observational accuracy. For example, users determining open-ocean salinity over a 30 to 36 parts per thousand range need accuracies of as low as 0.05 parts per thousand for use in numerical ocean models. In the

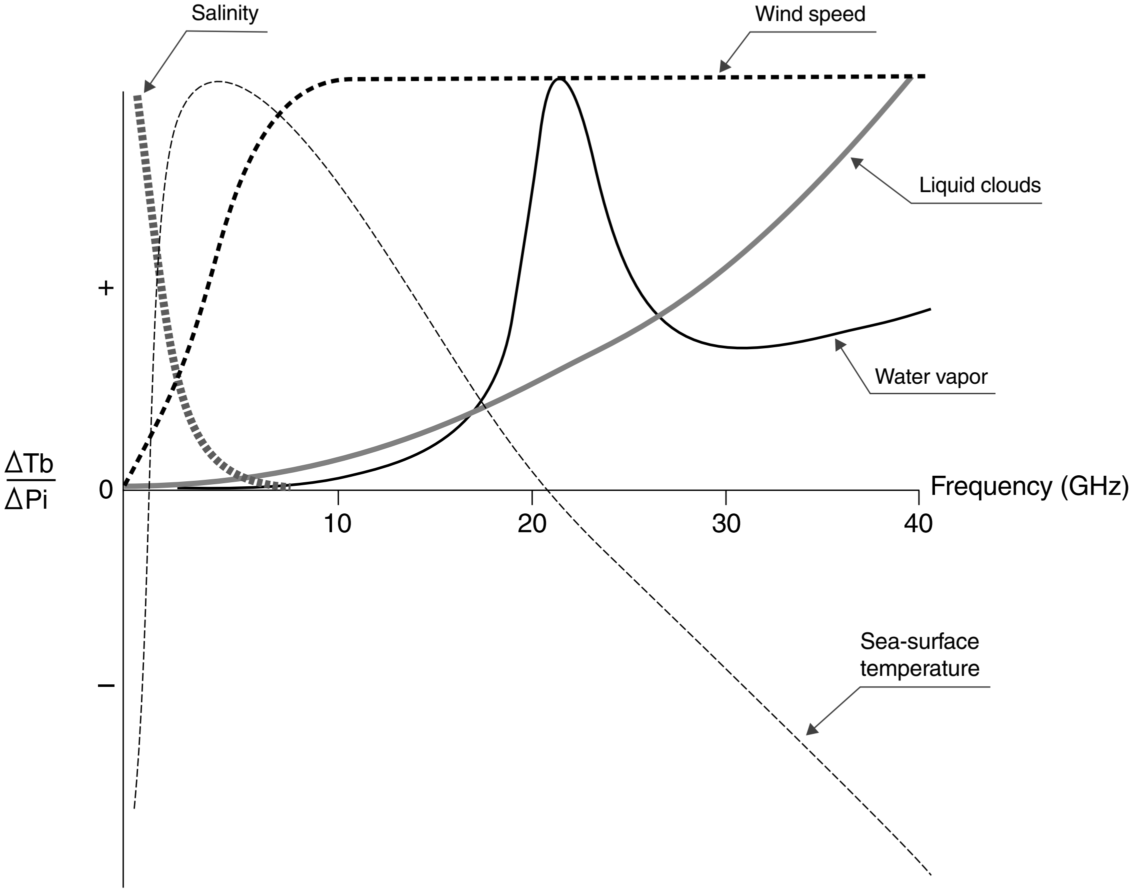

FIGURE 2.11 Relative sensitivity of brightness temperature to geophysical parameters as a function of frequency (over ocean surface).

1-2 GHz range, a measurement sensitivity of ~0.03 K would yield the requisite accuracy. Frequencies above 3 GHz are not sensitive to salinity variations and could not be used as a substitute for the 1-2 GHz range.

Performance criteria for spaceborne passive remote sensors have been studied in the ITU-R. Necessary bandwidths and sensitivities defined in terms of ΔT_e for various measurements are found in Recommendation ITU-R RS.1028. The ITU-R recommends that in shared frequency bands (except absorption bands), the availability of passive sensor data shall exceed 95 percent from all locations in the sensor service area in the case where the loss occurs randomly, and that it shall exceed 99 percent from all locations in the case where the loss occurs systematically at the same locations. For three-dimensional measurements of atmospheric temperature or gas concentration, the availability of data shall exceed 99.99 percent. Interference criteria have also been defined by the ITU-R. Permissible interference levels in dBW and interference reference bandwidths are contained in Recommendation ITU-R RS.1029. In bands that are allocated to the EESS on an exclusive basis, it has been determined by the ITU that "all emissions shall be prohibited."

2.2.3 Active Sensing

2.2.3.1 Techniques

Active sensors, such as terrestrial, airborne, or spaceborne radars, receive signals that they have transmitted after these signals have been reflected by land or ocean surfaces or by atmospheric hydrometeors. Major types of active sensors include the radar scatterometer, radar altimeter, image-forming radar, precipitation radar, and cloud-profiling radar.

Bandwidth requirements for active sensors vary with the type of sensor application. Scatterometers are typically narrowband, low-resolution devices requiring about 1 MHz of bandwidth. Synthetic aperture radars (SARs), precipitation radars, and cloud-profiling radars are medium-bandwidth devices; they can be designed to satisfy measurement resolution requirements in less than 100 MHz of bandwidth. Altimeters, however, require wide bandwidth, typically up to 600 MHz or more, to achieve centimeter measurement accuracy. Ultrawideband radars for snow-depth profiling are now in experimental development and require several gigahertz of bandwidth but operate over a limited spatial extent.

Because the reflected signal received by an active sensor depends on the dielectric properties of the surface and its roughness, the necessary frequencies for active sensing are determined by the phenomena to be measured. Generally speaking, bands spaced about an octave apart are needed, as in the case of passive sensor surface measurements and radio astronomy continuum measurements. The frequency bands to accommodate active sensor measurements range from below 1 GHz for surface measurements up to 150 GHz for cloud measurements. Within a set of approximately octave-spaced bands, the precise frequencies to be used are not critical. Thus, other factors such as sharing potential with other radio services need to be considered. Sharing between active spaceborne sensors and terrestrial radars (the radiolocation service, in ITU parlance) has been shown to be feasible with certain design constraints; the bands allocated for active sensing are all also allocated to the radiolocation service.

Active sensor frequency and bandwidth requirements have also been studied in the ITU-R. They can be found in Recommendation ITU-R RS.577.

2.2.3.2 Active Sensors

Current and planned Earth remote sensing systems include active spaceborne sensors, such as scatterometers, image-forming radars such as synthetic aperture radars, radar altimeters, precipitation radars, and cloud-profiling radars. Applications of active sensors include the measurement of soil moisture, snow, ice, rain, clouds, atmospheric pressure, and ocean wave parameters, and the mapping of geologic and geodetic features and vegetation.

Multispectral images obtained by SARs operating at 1215-1300 MHz, 5250-5350 MHz, and 9500-9800 MHz are used to study Earth’s ecosystems, climate, and geological processes, the hydrologic cycle, and ocean circulation. Altimeter measurements in the 5250-5350 MHz, 13.4-14 GHz, and 35-36 GHz bands provide data to study ocean-surface height and wave dynamics and their effects on climatology and meteorology. Spaceborne scatterometer measurements of ocean-surface wind speeds and direction in the 5250-5350 MHz, 9500-9800 MHz, and 13.25-14 GHz bands play a key role in understanding and predicting complex global weather patterns and climate systems. The TRMM uses a precipitation radar in the 13.4-14 GHz band to provide data on rainfall in the important intertropical convergence zone. The Global Precipitation Mission is a follow-on to the TRMM mission due to be launched toward the end of this decade and will incorporate radar bands at 35-36 GHz. The Cloudsat mission, launched in May 2006, measures clouds using the recently allocated band at 94-94.1 GHz.

Performance and interference criteria for active spaceborne sensors have been extensively studied. Performance criteria for active sensors have been defined in terms of the precision of measurement of physical parameters and the availability of measurements free from harmful interference. Interference criteria are stated in terms of the interfering signal power not to be exceeded in a reference bandwidth for more than a given percentage of time. The processing of SAR signals discriminates against interference depending on the modulation characteristics of the interfering signal and can materially improve the potential for sharing frequency bands.

Performance and interference criteria for active spaceborne sensors can be found in Recommendation ITU-R RS.1166.

2.3 THE ECONOMIC VALUE OF THE SCIENCE SERVICES

2.3.1 Investments in Infrastructure

As explained above, radio astronomy and Earth science require the operation of many facilities with different instruments and locations, including the vantage of space. Countries around the world that have made major investments in the development of radio astronomy and Earth science include Argentina, Australia, Brazil, Canada, China, Germany, France, India, Italy, Japan, The Netherlands, Russia, the United Kingdom, and the United States. As a return on those investments, radio astronomy and Earth remote sensing have, over the past half century, made fundamental new discoveries and have brought us closer to understanding both the nature of the universe and our immediate environment. The rapid rate of important discoveries in radio astronomy and Earth science will surely continue if the radio-frequency bands for the passive services are protected.

The United States alone plans to invest over $7 billion in the National Polar-orbiting Operational Environmental Satellite System (NPOESS) over the lifetime of the program to fulfill its identified operational and climate-monitoring needs. NPOESS is considered critical to the ability of the United States to maintain the continuity of data required for weather forecasting and global climate monitoring. NPOESS passive microwave sensors utilize frequencies ranging from 6 GHz to above 190 GHz to obtain more than 22 separate remotely sensed environmental parameters.

2.3.2 Technologies and Techniques

Because scientific discoveries are usually made at the limits of instrumental sensitivity, radio astronomy and remote sensing have contributed significantly to the development of new technology for medical, commercial, industrial, and defense purposes. Radio astronomy has been a copious source of transferable technology, algorithms, and trained individuals interested in applying remote sensing and receiver expertise in a variety of sectors, and especially in telecommunications.[6] Some examples are listed below:

- Originally developed as a radio astronomical technique for the high-resolution imaging of astronomical objects, very long baseline interferometry was used for applications in Earth science—for example, the determination of geophysical parameters used in studying plate tectonics, polar wandering,

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[6] National Research Council, *Working Papers: Astronomy and Astrophysics Panel Reports,* National Academy Press, Washington, D.C., 1991, p. 307.

latitude measurements, and variations in Earth's rotation, and the identification of potential earthquake zones through the precise measurement of fault motion. VLBI has since been replaced by the Global Positioning System.

- The VLBI reference frame of celestial coordinates, based on extremely distant radio sources, is basic to the periodic calibration of the GPS reference clocks.
- Pulsar observations, VLBI, and applications of Einstein's general theory of relativity play a major role in precision navigation and geodesy—including that of spacecraft—and timekeeping.
- VLBI instrumentation is the source of the technology used to locate interference to commercial satellite uplinks.
- Using radio astronomy and laboratory experiments, Sir Harold Kroto made the surprising discovery that long linear carbon chain molecules existed in interstellar space and also in stars. During laboratory attempts to understand how these species can to be so abundant, fullerene molecules were discovered.[7] Kroto shared the Nobel Prize in chemistry in 1996 with Richard Smalley and Robert Curl.
- Astronomers played a significant role in refining the hydrogen maser clock, which is now an important frequency standard in applications requiring high-precision ($1:10^{15}$) frequency stability over periods of ~1000 seconds.
- Computerized x-ray tomography employs software and methods originally developed for mapping radio sources. The data-intensive computing and storage systems that are developed for signal processing in areas such as pulsar searches have wide applications elsewhere.
- Extremely sensitive, low-noise receiver technology developed for radio astronomy has been used in implementing the Enhanced 911 emergency service.

Radio astronomers have adapted their methods of measuring microwave temperature for the noninvasive detection of tumors and other regions of vascular insufficiency. Microwaves have poorer angular resolution than infrared has but are more sensitive to deep-tissue temperatures. The combination of microwave and infrared thermographic data provides a true-positive detection rate of 96 percent, better than either alone, for breast cancer.[8] Astronomers were the first to employ conical (circularly polarized) feed horns, which later became popular on satellite transmitters because both polarizations could be transmitted by the same feed horn, linear polarizations requiring spatially separated crossed rectangular feeds.

2.3.3 The Value of Satellite Remote Sensing

Satellite remote sensing is one of the cornerstones of meteorology, oceanography, and environmental science, supporting analysis and research that provide assessments, predictions, and warnings to the public. Weather- and climate-sensitive industries account for about a quarter of the U.S. gross domestic product. Droughts, severe storms, and floods alone account for more than $20 billion in damage annually in the United States. The impact of El Niño events on the U.S. economy is estimated at $25 billion.[9] Without satellite remote sensing, the ability of the atmospheric and oceanic science community to monitor, analyze, and predict environmental conditions would be drastically diminished. Satellites

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[7] The Royal Society Web site, http://www.royalsoc.ac.uk/page.asp?id=1527; accessed April 21, 2006.

[8] National Research Council, *Working Papers: Astronomy and Astrophysics Panel Reports,* National Academy Press, Washington, D.C., 1991, p. 307.

[9] Stanley A. Changnon, Gerald D. Bell, David Changnon, Vernon E. Kousky, Roger A. Pielke, Jr., and Lee Wilkins, *El Niño, 1997-1998: The Climate Event of the Century,* Oxford University Press, New York, 2000.

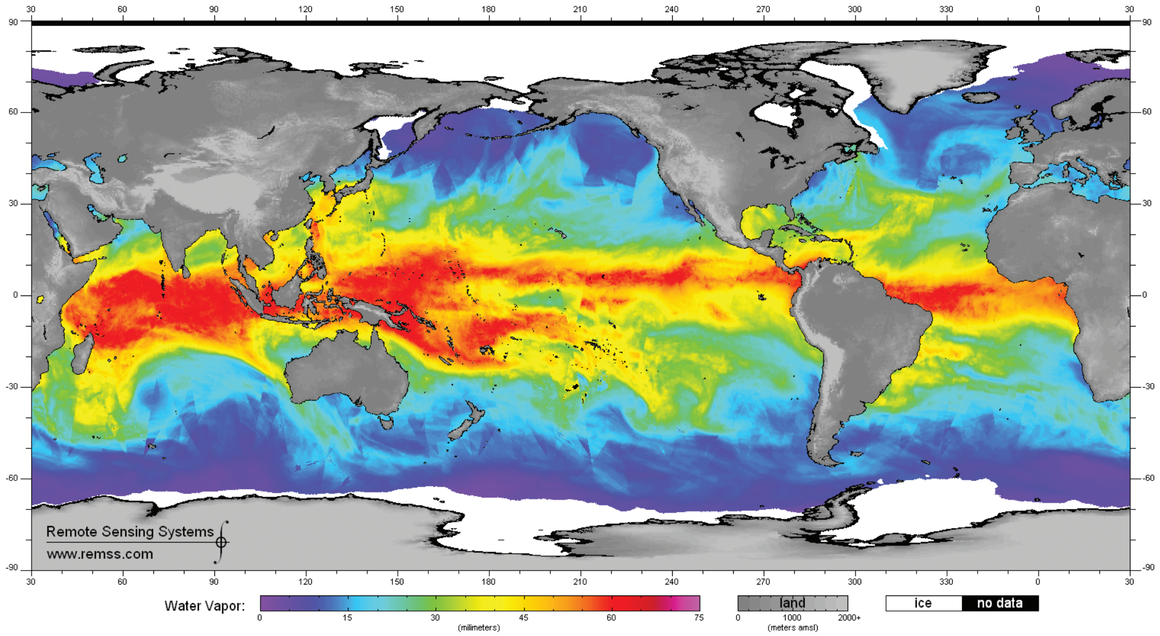

FIGURE 2.12 Global composites of water vapor for the 3-day period ending April 25, 2003, available at http://www.ssmi.com, accessed November 20, 2006. Courtesy of Remote Sensing Systems, Inc.

provide the only means of obtaining accurate assessments of land- and sea-surface and atmospheric conditions on a global scale.

Satellite remote sensing has long been used to estimate sea-surface temperature through passive radiometry. Sea-surface temperature impacts the atmosphere as a forcing field, coupling between the ocean and atmosphere through sensible and latent heat and freshwater fluxes. Until recently, cloud cover severely limited sea-surface temperature retrievals, but microwave techniques are now routinely used to see through clouds to provide accurate sea-surface temperature retrievals under almost all weather conditions. Figure 2.12 shows global fields of sea-surface temperature, surface wind speed, water vapor, cloud liquid water, and precipitation rate coverage in a 3-day composite. The availability of complete coverage with relatively fine temporal and spatial resolution is crucial to models of ocean and atmosphere coupling and variability. It has also provided new insights into the mechanism of transport of moisture over the globe, for example, the identification of intense trans-Pacific jets of moisture ("atmospheric rivers") that facilitate most of the meridional transport of water vapor from the tropics to the middle latitudes, along with the production of devastating winter storms along the western U.S. coast.

Satellite remote sensing contributes greatly to surface-oriented science. Examples include the Shuttle Radar Topology Mission, which provided a consistent, near-worldwide, digital elevation model for the first time and the breakthrough glacial observations made with Radarsat, which mapped the entirety of Antarctica. Radarsat, along with in situ GPS-based measurements, is providing the first large-scale measurement of glacial motions, critical for climate studies. Further, interferometric synthetic aperture radar (InSAR) and differential InSAR are providing new tools used to measure subtle movements in Earth's crust, for example, the subsidence areas exhibiting soil compaction or water table retreat or the buildup of surface strain along crustal fault lines.

Some examples of valuable microwave satellite remote sensing applications are listed below:

- The detection of forest fires through smoke by their microwave radiation;
- The measurement by passive remote sensing techniques of the temperature of Earth's atmosphere; surface properties including soil moisture, snow cover, and sea ice; the distribution of water vapor, cloud water, precipitation, and impurities such as carbon monoxide; and vegetation biomass properties;
- The monitoring of trace gases, such as ozone, important to atmospheric chemistry, air quality, and greenhouse warming;
- Early and accurate warnings of natural land-related disasters, and the mitigation of such events;
- Systematic environmental monitoring and the generation of information relevant to better management of natural resources, including forests, agricultural lands, wetlands, and freshwater;
- The mapping of conditions with potential for malaria outbreaks and other disease vectors;
- Studies of human impact on the environment—for example, urban development, deforestation, and diversion of natural waterways; and
- The measurement, via the newly allocated EESS secondary active band at 432-438 MHz (via footnote 5.279A), of Amazonian biomass (in conjunction with higher-frequency radar measurements of the top of the vegetation), as well as allowing measurements of soil, underlying brush cover, and soil prone to landslides in the western United States.

The potential loss of any critical band for the EESS could be expected to result in significant costs to society, resulting from reduced ability to forecast weather and the environment, manage resources, and predict disruptive climate changes.

As of this writing, the costs of severe weather events alone are often in the hundreds of millions of dollars per event. NOAA's National Weather Service forecasts, warnings, and the associated emergency responses result in a $3 billion savings in a typical hurricane season. Two-thirds of this savings, $2 billion, is attributed to the reduction in hurricane-related deaths, and one-third of this savings, $1 billion, is attributed to a reduction in property-related damage because of preparedness actions. Errors in temperature and precipitation forecasting for even benign meteorological events such as local or regional heat or cold waves can cost U.S. utilities approximately $1 million per degree Fahrenheit daily as a result of an impaired ability to match energy supplies with demand.[10] While it is difficult to ascribe forecast errors to interference occurring within any specific microwave band, it is noted that undetected interference in any passive microwave band can seed the growth of large errors in numerical weather-prediction models. (See also §3.7.1 and §3.9.1.) The costs of such forecasting errors are typically largest in areas of highest population density and thus of greatest spectral demand.

The prediction of climate changes on all timescales remains a nascent field, but it shows increasing promise as global modes of oscillation such as the El Niño-Southern Oscillation, Pacific Decadal Oscillation, and North Atlantic Oscillation; teleconnections of these modes to regional climate; and coupling of major large-scale climate subsystems are better understood. While the key predictors of climate events remain a subject of debate, measurements of global moisture, cloud, snow, ice, and thermal distribution remain key values that are unquestionably connected to regional weather patterns. As the ability to predict short-term climate improves, the utility of such measurements in making

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[10] National Oceanic and Atmospheric Administration, *Economic Statistics for NOAA,* 5th Ed., April 2006.

accurate climate predictions on both the short (monthly) and long (annual to decadal) timescales is anticipated to increase. Benefits to U.S. agriculture by altering planting decisions based on improved El Niño forecasts have been estimated at $265 million to $300 million annually, throughout El Niño, normal, and La Niña years. Costs associated with errors in predicting the onset of regional climate changes could thus easily amount to hundreds of millions of dollars per year.[11]

2.3.4 Education for Scientific Literacy

Astronomy is a compelling subject, as shown by public attendance at planetariums, the number of astronomy and space magazines, and the very large number of astronomy clubs and amateur astronomers. This interest serves as an effective basis for using astronomy in the curriculum for kindergarten through grade 12 to improve the scientific literacy of tomorrow's leaders and managers. Although at first glance they would seem too esoteric for such a purpose, radio telescopes have in fact proven very effective in education. For example, high school students across the United States are able to carry out research programs with the Goldstone Apple Valley Radio Telescope, based at NASA's tracking complex in California. Australia and Spain are instituting similar programs at their NASA tracking complexes.

The Massachusetts Institute of Technology's Haystack Observatory staff has developed a Small Radio Telescope (SRT) and high school lesson plans as a tool to introduce students to the basics of radio astronomy. The SRT is now available as a kit, and more than 85 SRTs are now in use around the world.

Earth remote sensing data are made publicly available at low cost or no cost via the Internet for use in schools. Landsat imagery and Shuttle Radar Topography Mission digital elevation models, as well as weather data and much data from the Earth Observing Satellite system, and in fact much of NASA's and NOAA's remote sensing data, are provided free of charge to U.S. researchers.[12] Within the framework of the Global Earth Observation System of Systems (GEOSS), Earth remote sensing data will become readily and rapidly distributed on a worldwide basis to support a wide range of activities by scores of countries within a number of societal benefit areas. The enhanced degree of awareness of Earth as a system stemming from such data use will provide a myriad of educational benefits to all students around the globe.

University radio observatories provide hands-on training for the next generation of engineers and instrument builders as well as astronomers. The Angel Ramos Foundation Visitor and Educational Facility at the National Astronomy and Ionosphere Center (NAIC) in Arecibo, Puerto Rico, receives 120,000 visitors per year and conducts a number of training programs for students and teachers alike. Likewise, the National Radio Astronomy Observatory has visitor centers at the Very Large Array headquarters in Socorro, New Mexico, and at the Robert C. Byrd Green Bank Telescope in Green Bank, West Virginia. The Green Bank NRAO facility hosts many educational programs. Research at NRAO and NAIC has provided data for many Ph.D.'s granted in the past 20 years, and both NRAO and NAIC run summer Research Experience for Undergraduates (REU) programs. The National Science Foundation also sponsors REU programs at Haystack Observatory and Cornell University.

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[11] National Oceanic and Atmospheric Administration, *Economic Statistics for NOAA,* 5th Ed., April 2006.

[12] National Research Council, *Utilization of Operational Environmental Satellite Data: Ensuring Readiness for 2010 and Beyond*, The National Academies Press, Washington, D.C., 2004; and National Research Council, *Satellite Observations of the Earth's Environment: Accelerating the Transition of Research to Operations,* The National Academies Press, Washington, D.C., 2003.

3

Science Service Allocations

3.1 GENERAL CONSIDERATIONS

This chapter lists and discusses the science service spectrum allocations in the United States[1] and their use. The Radio Regulations divides the world into three regions for spectrum allocation purposes. The United States is in Region 2 (see Figure 3.1).

3.1.1 Atmospheric Windows in the Radio Spectrum

The allocation of spectral bands for radio astronomy is based partly on the atmospheric windows available, as shown in Figure 3.2. Ground-based telescopes can observe only in the regions of the atmosphere that are not obscured. Below 50 GHz, there is a window between approximately 15 MHz and 50 GHz. Above 50 GHz, such radio windows occur at wavelengths around 3 mm (65-115 GHz), 2 mm (125-180 GHz), and 1.2 mm (200-300 GHz). At wavelengths shorter than 1 mm, the so-called submillimeter bands, the windows are less distinct, but clear ones exist at 0.8 mm (330-370 GHz), 0.6 mm (460-500 GHz), 0.4 mm (600-700 GHz), and 0.3 mm (800-900 GHz), as well as in other, smaller windows.

Furthermore, if Figure 3.2 showed absorption rather than transmission, the lines of particular importance to the Earth Exploration-Satellite Service (EESS) would be readily apparent: namely, the water lines at 22.235 and 183.1 GHz and the oxygen lines around 55-60 GHz and 118.75 GHz, as well as the available windows needed for comparison purposes, surface observations, and communications. Atmospheric absorption bands are used to measure atmospheric temperature and pressure profiles while using the windows to observe surface features, vegetation, and temperatures.

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[1] The U.S. and international spectrum allocation table and footnotes are available in the National Telecommunications and Information Administration's *Manual of Regulations and Procedures for Federal Radio Frequency Management (Redbook)* at http://www.ntia.doc.gov/osmhome/redbook/redbook.html and in the Frequency Allocation Table at http://www.fcc.gov/oet/spectrum/table/.

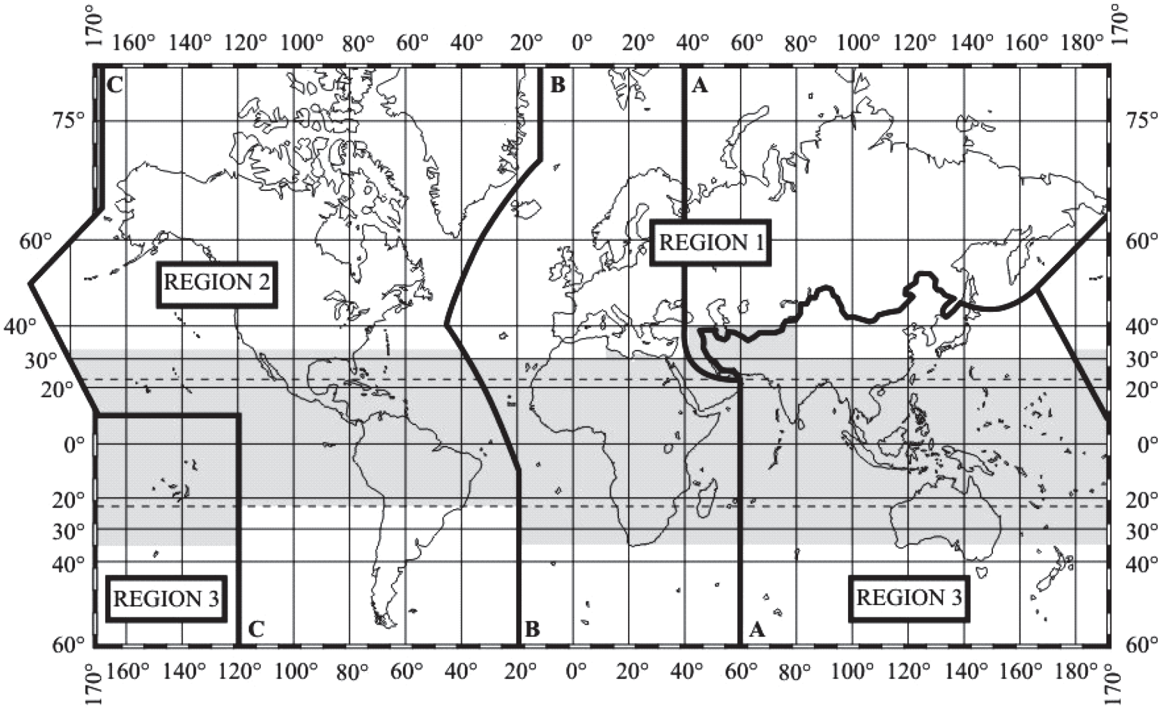

FIGURE 3.1 The regions as defined in Article 5 of the Radio Regulations. The shaded part represents the Tropical Zone. SOURCE: National Telecommunications and Information Administration, *Manual of Regulations and Procedures for Federal Radio Frequency Management (Redbook),* May 2003 edition, revised January 2006. See http://www.itu.int/ITU-R/ for more information.

3.1.2 Note to the Reader Regarding Frequency Allocation Tables

Because regulations, allocations, and footnotes can change, the reader is advised to consult the National Telecommunications and Information Administration's (NTIA's) *Manual of Regulations and Procedures for Federal Radio Frequency Management (Redbook)* or the Federal Communications Commission's (FCC's) *FCC Online Table of Frequency Allocations,* as well as the Radio Regulations, for the latest information. The Redbook can be found at http://www.ntia.doc.gov/osmhome/redbook/redbook.html, and the FCC's document can be found at http://www.fcc.gov/oet/spectrum/table/fcctable.pdf. The information given in this chapter is current as of January 2006.

Each of the following eight sections in this chapter begins with a table of allocations for a specified frequency range—allocations below 1 GHz (Table 3.1), between 1 and 3 GHz (Table 3.2), between 3 and 10 GHz (Table 3.3), between 10 and 25 GHz (Table 3.4), between 25 and 50 GHz (Table 3.5), between 50 and 71 GHz (Table 3.6), between 71 and 126 GHz (Table 3.7), and between 125 and 275 GHz (Table 3.8).

The first column of each table lists the band allocations, and the fourth column elaborates on the scientific use of each band. In the second column, primary allocations are shown in capital letters (e.g., "RAS"), and secondary allocations appear in lowercase letters (e.g., "ras"). Footnotes to the tables indicate where the allocations in other regions differ. Parentheses around a science service—for ex-

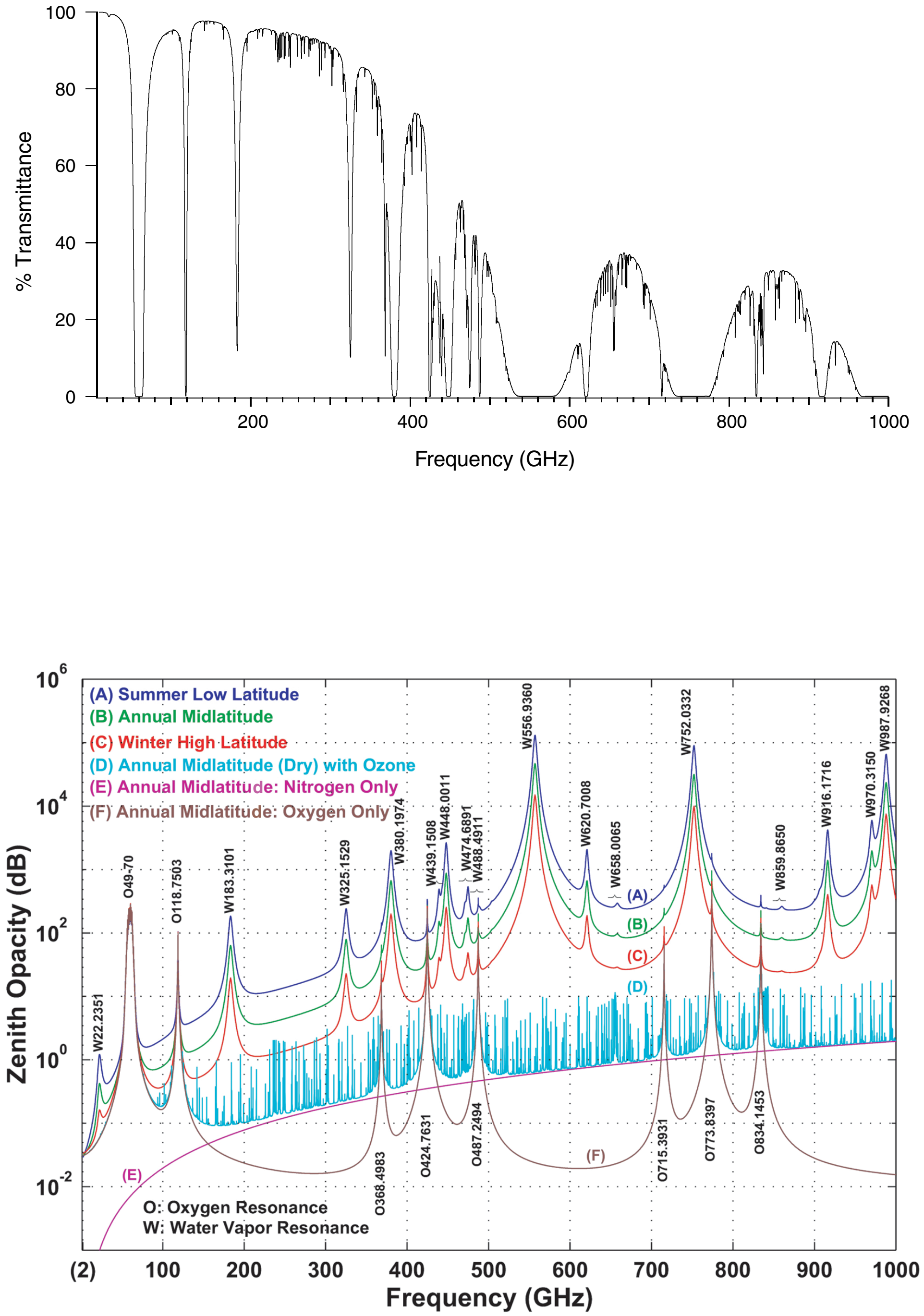

FIGURE 3.2 *Top:* Atmospheric windows in the radio spectrum commonly used in the Radio Astronomy Service community. The transmission is appropriate for a site of 400-m elevation and a precipitable water vapor content of 1 mm. Courtesy of Lucy Ziurys, University of Arizona. *Bottom:* Atmospheric zenith opacity in the radio spectrum commonly used in the Earth Exploration-Satellite Service community. From A.J. Gasiewski and M. Klein, "The Sensitivity of Millimeter and Sub-millimeter Frequencies to Atmospheric Temperature and Water Vapor Variations," *Journal of Geophysical Research-Atmospheres*, Vol. 13, pp. 17481-17511, July 16, 2000.

ample, "(ras)"—indicate that one or more footnotes in the ITU Radio Regulations and/or the U.S. Table of Frequency Allocations provide limited protection.

Footnotes in the ITU Radio Regulations and the U.S. Table of Frequency Allocations that modify the allocations are noted in the third column of each table. A brief synopsis of each of these footnotes is given when it is first referenced in a table. Readers are advised to check for footnotes such as 5.340 and US211 that cover several bands.

Appendix I spells out the acronyms used in Tables 3.1 through 3.8 and describes the ITU Radio Regulations and the U.S. Table of Frequency Allocations footnote designations (e.g., for 5.350, US211, G59, and NG101).

3.2 ALLOCATIONS BELOW 1 GHZ

The bands, services, footnotes, and scientific observations for each band in the allocations below 1 GHz are presented in Table 3.1.

3.2.1 Solar Radio Bursts

Radio observations made at frequencies below ~100 MHz also capture data on solar bursts. Occasionally, and frequently during sunspot maximum, dramatic radio bursts of several different characteristic types are generated in the Sun's atmosphere. Such bursts are sometimes associated with solar flares, which are sudden, violent explosions in the Sun's chromosphere. The radio bursts are observed from ~20 to ~400 MHz and are more intense at the lower frequencies. The high-energy particles ejected from the Sun during these bursts may interact with Earth's ionosphere and the stratosphere. Such interactions cause severe interruptions in radio communications and power systems and can also have dangerous effects on aircraft flights above 15 km. Studies of radio bursts aim to enable the prediction of failures in radio communications and the forecasting of other effects. Knowledge of the high-energy particle ejections from the Sun is essential for space exploration missions, both manned and unmanned. Continuous monitoring of the Sun's activity will remain a high priority for the foreseeable future.

3.2.2 Jupiter Radio Bursts

Also significant is the peculiar nonthermal burstlike radiation from the giant planet Jupiter; this radiation is best observed at frequencies from ~15 to ~40 MHz. Extensive observations are being made at low frequencies in order to study this unusual radiation. It was observed by the Voyager spacecraft, but further ground-based studies are essential.

3.2.3 Interstellar Medium

The low-frequency range below 1 GHz also has a great importance in the observations of both the thermal and nonthermal diffuse radiation in our own Milky Way Galaxy. Such galactic observations give information about the high-energy cosmic ray particles in our Galaxy and about their distribution, and also about the hot ionized plasma and star birth in the disk of our spiral Galaxy. In particular, the ionized interstellar clouds can be studied at low frequencies where the sources are opaque and their spectra approximate the Planck thermal radiation (blackbody) law. Such spectral observations can be used directly to measure the physical parameters of the radiating clouds, particularly their temperatures.

TABLE 3.1 Frequency Allocations Below 1 GHz: Bands, Services, Footnotes, and Scientific Observations

Band (MHz)	Services	Footnotes	Scientific Observations
13.36-13.41	RAS, FS[1]	5.149,[2] G115,[3] US342	Sun, Jupiter, interstellar medium, steep spectrum sources
25.55-25.67	RAS	5.149, US74,[4] US342	Sun, Jupiter, interstellar medium, steep spectrum sources
37.50-38.25	FS, MS, ras[5]	5.149, US81,[6] NG59,[7] NG124[8]	Sun, Jupiter, interstellar medium, steep spectrum sources
73.00-74.60	RAS, FS,[9] MS[10]	5.178,[11] US74	Sun, interstellar medium, steep spectrum sources
137-138	SO, MetSat, SRS, MS[12]	5.204, 5.205, 5.206, 5.207, 5.208, US319, US230	NOAA (EESS) communications bands
150.05-153.0	RAS,[13] FS, MS,[14] (ras)[15]	5.149, 5.208A[16]	Sun, interstellar medium, steep spectrum sources, pulsars, continuum (single-dish mode)
322.0-328.6	RAS, FS, MS	5.149, G27,[17] G100[18]	Deuterium, Sun, interstellar medium, steep spectrum sources, pulsars
400-406	MetAids (radiosonde), MetSat (S→E), MS (S→E), SRS (S→E), MS (S→E), EESS (E→S) See NTIA Redbook	5.263, 5.264, US70, US329, US320, US324	NOAA (EESS) communications bands
406.1-410	RAS, FS, MS	5.149, 5.208A, US74, G5,[19] G6,[20] US117,[21] US13[22]	Sun, interstellar medium, steep spectrum sources, pulsars
432-438	eess (active)	5.279A	Biomass and soil measurements
460-470	See NTIA Redbook		NOAA (EESS) communications bands
608-614	RAS,[23] mss[24]	5.149, 5.208A, US74, US246[25]	Sun, interstellar medium, steep spectrum sources, pulsars

Several hundred such galactic clouds appear approximately as blackbodies at frequencies below ~100 MHz.

The recombination lines that occur in this frequency range arise from very high energy levels, in which the electron orbits very far from the nucleus. In fact, these atoms are so large that the orbits of the outer electrons are affected by the electrons of other atoms in a measurable way, serving as a probe of the density of the gas. Recombination lines are further described in §3.3.8.

3.2.4 Deuterium

The frequency range 322-328.6 MHz contains the hyperfine-structure spectral line of deuterium at 327.384 MHz. The study of this line has impacts on problems related to the origin of the universe and the cosmological synthesis of the elements. The recent detection of deuterium emission in the outer region of our Galaxy required months of integration time, with careful attention to mitigation of radio-frequency interference. Continuing study of the deuterium abundance in other parts of our Galaxy can further refine our understanding of the early universe.

TABLE 3.1 Continued

NOTE: For definitions of acronyms and abbreviations, see Appendix I. For information about other features of this table, see §3.1.2, "Note to the Reader Regarding Frequency Allocation Tables."

[1] Not in the United States.
[2] ITU RR footnote 5.149 urges administrations to take all practical steps to protect the RAS from other services in this band.
[3] U.S. (federal government services) footnote G115 limits protection for national defense and emergency needs.
[4] U.S. (all services) footnote US74 limits protection from transmitters in other bands.
[5] Primary in the United States from 38.00-38.25 MHz.
[6] US81 authorizes limited military use in the 38.00-38.25 MHz band.
[7] NG59 authorizes use of the 37.60-37.85 MHz band by power service utilities.
[8] NG124 authorizes low-power police radio on a non-interference basis.
[9] In Regions 1 and 3.
[10] In Regions 1 and 3.
[11] Additional allocation in some Caribbean nations to the fixed and mobile services on a secondary basis.
[12] MS is secondary in 137.025-137.175 MHz and 137.825-138.0 MHz.
[13] In Region 1.
[14] Except aeronautical.
[15] In Region 2, by S5.149.
[16] 5.208A provides footnote protection from space transmitters outside the band.
[17] G27 limits the FS and MS to military use.
[18] See G100 in Appendix B.3.
[19] G5 authorizes FS and MS for government nonmilitary agencies only.
[20] G6 allows military operations subject to local coordination.
[21] US117 limits transmitter power.
[22] US13 authorizes hydrological and meteorological fixed stations at specific frequencies.
[23] Footnote protection only in Regions 1 and 3.
[24] Except aeronautical; Earth-to-space only.
[25] US246 prohibits transmissions.

3.2.5 Steep-Spectrum Continuum Sources

Most radio sources (such as radio galaxies, quasars, and supernova remnants) have characteristic nonthermal spectra produced by synchrotron emission from relativistic cosmic ray electrons moving in galactic-scale magnetic fields. As shown in Figures 2.1 and 2.2 in Chapter 2, these nonthermal sources typically have radio spectra with negative slopes of ~0.8 in a graph of log (flux density) versus log (frequency). Hence, such sources have higher radio flux densities at lower frequencies.

The steepness of the spectrum depends on the energy of the electrons. As synchrotron sources age, the most energetic electrons are lost and the spectra steepen with time.

At longer wavelengths, the spiraling electrons have increasingly higher cross sections for absorbing radiation, so that the emitted radiation is increasingly likely to be reabsorbed before escaping from the region. This causes turnovers in the spectra at low frequencies (see Figures 2.1 and 2.2), and the frequencies at which they occur are diagnostics of the emitting region.

The low-frequency part of the spectrum is also where one finds the emission from highly redshifted radio sources, those that exist in the most distant parts of the universe.

The Arecibo Telescope in Puerto Rico, The Green Bank Telescope in West Virginia, the Very Large Array in the state of New Mexico, and the Very Long Baseline Array (VLBA)—a system of 10 radio telescope antennas positioned from Hawaii to the U.S. Virgin Islands—operate in these bands, as well as the Giant Metrewave Radio Telescope (GMRT) in India and the Westerbork Array in the Netherlands.

High-resolution observations of radio galaxies and quasars have also been made with the GMRT using the method of lunar occultations, which uses the lunar disk to eclipse distant radio sources as they move across the sky. From such occultations, it has been possible to determine the shapes and positions of many extragalactic radio sources with very high accuracies, on the order of 1 arc second.

3.2.6 Pulsars

One of the most interesting and significant discoveries in radio astronomy has been the detection of pulsars, for which Antony Hewish was awarded the Nobel Prize in physics in 1974. The understanding of stellar evolution has been advanced by providing a method of studying these rapidly rotating, highly magnetized neutron stars. Pulsars' extreme magnetic, electric, and gravitational fields, impossible to reproduce in laboratories on Earth, allow observations of matter and radiation under such conditions. Pulsars now provide the most accurate timekeeping, surpassing the world's ensemble of atomic clocks for long-term time stability.

Pulsars are understood to be highly condensed neutron stars that rotate with a period as short as a millisecond. Such objects are produced by the collapse of the cores of massive stars during the catastrophic explosions known as supernova outbursts. The radio spectra of pulsars indicate a nonthermal mechanism, perhaps of synchrotron emission type. Observations have shown that the pulsars emit strongest at frequencies in the range from ~50 to 600 MHz. Hence, many observations are being performed at such frequencies. However, important observations and surveys are being conducted at frequencies up to 10 GHz.

The discovery and the study of pulsars during the past two decades have opened up a major new chapter in the physics of highly condensed matter. The study of neutron stars with densities on the order of 10^{14} g/cm^3 and with magnetic-field strengths of 10^{12} gauss has already contributed immensely to our understanding of the final stages of stellar evolution and has brought us closer to understanding black holes (which are thought to be the most highly condensed objects in the universe). Low-frequency bands 6-8 GHz are indeed important for pulsar observations, but exclusive bands in this range are not allocated.

The Nobel Prize in physics in 1993 was awarded to Russell A. Hulse and Joseph H. Taylor, Jr., "for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation."[2] Binary pulsars have provided the best experimental tests of predictions of the theory of general relativity and strong evidence for the existence of gravitational radiation.

Careful analysis of pulse timing residuals led to the startling discovery by radio astronomers Aleksander Wolszczan and Dale Frail in 1991, and confirmed in 1994, that pulsars can have planet-sized bodies in orbit around them—the first detection of extrasolar planets. Pulsars are also diagnostics of the interstellar medium's density and magnetic field. Continuum bands, particularly those at frequencies below 3 GHz, are most valuable for these studies.

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[2] Located at http://nobelprize.org/nobel_prizes/physics/laureates/1993/press.html, accessed September 14, 2006.

3.3 BANDS BETWEEN 1 AND 3 GHZ

In addition to the bands listed in Table 3.2, scientific use is also made of the 1675-1690 MHz Meteorological Aids Service (MetAids) band; the 1215-1300 MHz EESS active band, which is used for synthetic aperture radar (SAR) missions; and the Global Positioning System (GPS) bands at 960-1215 MHz, 1215-1300 MHz, and 1559-1610 MHz.

3.3.1 Neutral Atomic Hydrogen

One of the most important spectral lines at radio wavelengths is the 21 cm line (1420.406 MHz), corresponding to the $F = 1 \rightarrow 0$ hyperfine transition of neutral atomic hydrogen (HI). Radio observations of this line have been used since its discovery in 1951 to study the structure of our Galaxy and those of other galaxies. Because of Doppler shifts owing to the distance and motion of the hydrogen clouds that emit this radiation, the frequency for observing this line emission ranges from below 1 GHz to ~1430 MHz. Numerous and detailed studies are being made of the HI distribution in our Galaxy and in other galaxies. 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 of other galaxies; and the masses of other galaxies.

The HI emission is relatively strong and, with current receiver sensitivity, such emission is detectable from any direction in our Galaxy and from a very large percentage of the nearby galaxies. The 1330-1400 MHz band is important for observations of redshifted HI gas from distant external galaxies. Such observations of redshifted HI have been made in a quasi-continuous range of frequencies down to 1260 MHz. Below this frequency, detections have been made at individual, isolated frequencies. Observations of HI below 1330 MHz have been limited in the past by spectrometer bandwidths, dynamic range, and limitations of sampling (dump time). Studies of the evolution of the HI mass function with cosmic time will require observations below 1260 MHz and are being proposed for systematic and concerted studies. As radio telescopes become more powerful, it will be possible to detect more-distant, and therefore more-redshifted (and therefore younger) galaxies. This increase in capability will allow astronomers to study how galaxies evolve.

3.3.2 Lines of Hydroxyl

The study of hydroxyl (OH) is of great interest for investigating the physical phenomena associated with the formation of protostars and the initial stages of star formation.

3.3.2.1 Thermal Emission

The OH molecule has been observed widely in our Galaxy in the four hyperfine components of the ground-state lambda-doubling transitions at 1665, 1667, 1612, and 1720 MHz. OH has been detected in thermal emission and absorption in several hundred different molecular complexes in our Galaxy.

Thermal OH emission, which predominates in the low-density envelopes of molecular clouds, is the principal means for studying these envelopes. In addition, the two oppositely circularly polarized components become slightly separated in frequency in the presence of a magnetic field. This so-called Zeeman effect is the only way to measure the strength of the magnetic field in these regions. The magnetic field may play a major role in the dynamics of the gas.

TABLE 3.2 Frequency Allocations Between 1 and 3 GHz: Bands, Services, Footnotes, and Scientific Uses

Band (MHz)	Services	Footnotes	Scientific Use
1300-1350	AeRNS,[1] rls, (ras)	5.149,[2] 5.337,[3] G2[4]	Extragalactic HI,[5] recombination lines
1350-1400	FS,[6,7] MS,[8,9] LMS,[10] RLS, (ras), (srs),[11] (eess)[12]	5.149, 5.334,[13] 5.338,[14] 5.339,[15] US311,[16] US350,[17] US351,[18] G2, G27,[19] G114[20]	Extragalactic HI, recombination lines
1400-1427	RAS, EESS (passive), SRS (passive)	5.340,[21] 5.341,[22] US74, US246	Galactic and local extragalactic HI, recombination lines, radio source spectra, galactic continuum
1559-1610	AeRNS, RNSS (S→E) and (S→S)	5.341, 5.355,[23] 5.359,[24] G126[25]	Extragalactic OH masers
1610-1610.6	MSS (E→S), AeRNS, RDSS (E→S),[26] (ras)	5.341, 5.355, 5.359, 5.363,[27] 5.364,[28] 5.367,[29] 5.370,[30] 5.371,[31] 5.372,[32] US208,[33] US260,[34] US319[35]	Extragalactic OH
1610.6-1613.8	RAS, MSS (E→S), AeRNS, RDSS (E→S)[36]	5.149, 5.341, 5.355, 5.359, 5.363, 5.364, 5.367, 5.369, 5.370, 5.371, 5.372, US319	OH
1660-1660.5	MSS (E→S), RAS	5.149,[37] 5.341, 5.351,[38] 5.376A[39]	OH
1660.5-1668.4	RAS, SRS (passive), fs, ms (except aems)	5.149, 5.341, 5.379,[40] 5.379A,[41] US74,[42] US246	OH
1668.4-1670	RAS, MetAids,[43] FS,[44] MS (except Ae)[45]	5.149, 5.341, US74, US99[46]	OH
1670-1675[47]	MetAids,[48] FS,[49] MetSat (S→E), MS (except Ae)[50]	5.341, US211[51]	OH
1690-1700	MetAids,[52] MetSat (S→E),[53] MSS (E→S),[54] fs,[55] ms (except Ae),[56] (eess)	5.289,[57] 5.341, 5.382,[58] US211	
1700-1710	FS, MetSat (S→E), MS (except Ae),[59] MSS (E→S),[60] (eess)	5.289, 5.341, 5.384,[61] G118[62]	
1718.8- 1722.2[63]	FS, MS, ras	5.149, 5.341, 5.385,[64] US256[65]	OH
2025-2110	SpaceOps, EESS (S→E, S→S), FS,[66] MS,[67] SRS (S→E, S→S)	5.391,[68] 5.392,[69] US90,[70] US222,[71] US346,[72] US347[73]	
2110-2120[74]	FS, MS, SRS (deep S→E)	US252[75]	
2200-2290	SRS (deep S→E, S→S), EESS (S→E, S→S), FS,[76] MS,[77] SRS (S→E, S→S)	5.391,[78] 5.392,[79] US303[80]	Deep space downlinks, VLBI
2290-2300	FS, MS, SRS[81]		
2310-2360	ms, rls, fs, BS	US338[82]	Radar astronomy[83]
2640-2655	srs (passive), eess (passive), FS, MS, FSS, BSS	5.339[84]	Extragalactic radio sources, galactic continuum

TABLE 3.2 Continued

Band (MHz)	Services	Footnotes	Scientific Use
2655-2690	ras, srs (passive), eess (passive), FS, FSS,[85] MS, BSS, MSS	5.149, US205,[86] US269,[87] NG47,[88] NG101,[89] NG102[90]	
2690-2700	RAS, EESS (passive), SRS (passive)	5.340, 5.413,[91] US74, US246	

NOTE: For definitions of acronyms and abbreviations, see Appendix I. For information about other features of this table, see §3.1.2, "Note to the Reader Regarding Frequency Allocation Tables."

[1] In the United States only.
[2] 5.149 urges administrations to take all practical steps to protect the RAS from other services using the band 1330-1400 MHz.
[3] 5.337 limits ANS to ground-based radars and airborne transponders activated by these radars.
[4] Government radiolocation is limited to the military services.
[5] HI, neutral atomic hydrogen.
[6] In Region 1 only.
[7] Secondary from 1390 to 1395 MHz and no allocation from 1395 to 1400 MHz in the United States.
[8] In Region 1 only.
[9] Secondary from 1390 to 1395 MHz and no allocation from 1395 to 1400 MHz in the United States.
[10] In the United States only from 1395 to 1400 MHz.
[11] 1370-1400 MHz only.
[12] 1370-1400 MHz only.
[13] 5.334, in Canada and the United States, adds the Aeronautical Radionavigation Service on a primary basis between 1350 and 1370 MHz.
[14] 5.338 allows existing installations of the radionavigation service in certain countries in eastern Europe to continue to operate in the band 1350-1400 MHz.
[15] 5.339 authorizes passive EESS and SRS in the 1370-1400 MHz band.
[16] US311 provides partial geographic protection only from 1350 to 1400 MHz.
[17] US350: LMS is limited to medical telemetry and telecommand operations.
[18] US351: Government operations are on a noninterference basis with nongovernment operations.
[19] G27 limits the FS and MS to military use.
[20] G114 authorizes space-to-Earth relay of nuclear burst data by the FSS and MSS in the 1369.05-1381.05 MHz band.
[21] 5.340 prohibits all emissions in this band.
[22] 5.341 makes note of SETI.
[23] 5.355 adds FS on a secondary basis in certain countries.
[24] 5.359 adds FS on a primary basis in certain counties but urges administrations to make no additional allocations.
[25] G126 allows addition of differential GPS on a primary basis.
[26] Primary in Region 2, secondary in Region 3, not in Region 1.
[27] 5.363 adds AeRNS on a primary basis in Sweden.
[28] 5.364 limits transmitter power and requires coordination.
[29] 5.367 adds AeMS(route) on a primary basis.
[30] 5.370: RDSS is secondary in Venezuela.
[31] 5.371 adds RDSS on a secondary basis in Region 1.
[32] 5.372 protects the RAS in the band 1610.6-1613.8 MHz from the RDSS and MSS.
[33] US208 states that sharing criteria and techniques need to be developed.
[34] US260 authorizes AeMS when it is an integral part of the ARS.
[35] US319 limits federal government use.
[36] 5.364 limits transmitter power and requires coordination.
[37] 5.149 urges protection of RAS when making assignments to other services in the band 1660-1670 MHz.
[38] 5.351 forbids feeder links.
[39] 5.376A protects the RAS from the MSS Earth stations.
[40] 5.379 provides additional secondary allocation to MetAids in certain countries.
[41] 5.379A urges further protection to the RAS in the 1660.5-1668.4 MHz band.
[42] US74 limits the protection to the RAS.

continued

TABLE 3.2 Continued

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[43] In the United States for radiosondes.
[44] Except in the United States.
[45] In the United States for radiosondes.
[46] US99 requires the advance notification of use of radiosondes in the 1668.4-1670 MHz band.
[47] Became mixed-use spectrum in the United States in January 1999.
[48] In the United States for radiosondes.
[49] Except in the United States.
[50] Except in the United States.
[51] US211 urges protection of adjacent RAS bands.
[52] US99 requires the advance notification of use of radiosondes in the 1668.4-1670 MHz band.
[53] US99 requires the advance notification of use of radiosondes in the 1668.4-1670 MHz band.
[54] In Region 2, except in the United States.
[55] US99 requires the advance notification of use of radiosondes in the 1668.4-1670 MHz band.
[56] US99 requires the advance notification of use of radiosondes in the 1668.4-1670 MHz band.
[57] 5.289 allows EESS (S→E) transmissions subject to not causing harmful interference to other services in this band.
[58] 5.382 adds other primary services in certain countries.
[59] US99 requires the advance notification of use of radiosondes in the 1668.4-1670 MHz band.
[60] In Region 2, except in the United States.
[61] 5.384 adds SRS (S→E) on a primary basis in India, Indonesia, and Japan.
[62] G118 limits government use of FS in this band.
[63] Within the larger band of 1710-1930 MHz by S4.149.
[64] 5.385 provides a secondary allocation to the RAS.
[65] US256 urges consideration of the RAS by other services in specific geographic areas.
[66] In the United States, nongovernment only.
[67] In the United States, nongovernment only.
[68] 5.391 excludes high-density mobile systems.
[69] 5.392 limits (S→S) in the SpaceOps, EESS, and SRS.
[70] US90 limits the pfd at the surface of Earth from SpaceOps, EESS, and SRS.
[71] US222 authorizes GOES (S→S) transmissions from Wallops Island, Virginia; Seattle, Washington; and Honolulu, Hawaii, in the band 2025-2035 MHz.
[72] US346 establishes rules for coexistence of government SpaceOps, EESS, and SRS with new broadcasting and TV services.
[73] US347 permits EESS and SRS (E→S) and (S→S) transmissions on a case-by-case noninterference basis.
[74] To be auctioned by September 30, 2002.
[75] US252 also allocates this band to SRS deep space (E→S) transmissions from Goldstone, California.
[76] In the United States, line of sight only.
[77] In the United States, line of sight only including aeronautical telemetry, but excluding flight testing of manned aircraft.
[78] 5.391 excludes high-density fixed service.
[79] 5.392 urges all practical steps to avoid interference from (S→S) operations in SpaceOps, SRS, and EESS.
[80] US303 authorizes the SRS, SpaceOps, and EESS to transmit to the TDRSS in the band 2285-2290 MHz on a case-by-case basis, subject to pfd limitations.
[81] Deep space, space to Earth.
[82] US338 requires coordination of all Wireless Communications Services in the band 2305-2320 MHz within 50 km of Goldstone, California.
[83] The Goldstone Solar System Radar operates at 2320 MHz.
[84] 5.339 adds the EESS and SRS in this band on a secondary basis.
[85] Except in Region 1.
[86] US205 prohibits troposcatter radar.
[87] US269 urges consideration of radio astronomy in the 2690-2700 MHz band.
[88] NG47 authorizes other special allocations.
[89] NG101 limits BSS.
[90] NG102 limits FSS.
[91] 5.413 mirrors US269.

Emission lines from ^{18}OH and ^{17}OH have been detected in some molecular regions of our Galaxy. The data from these lines allow the study of the abundances of the oxygen isotopes involved. Such studies are a crucial part of understanding the network of chemical reactions involved in the formation of atoms and molecules. The data can help astronomers to understand the physics of stellar interiors, the chemistry of the interstellar medium, and the physics of the early universe.

3.3.2.2 Maser Emission

Extremely narrow and intense emission lines of OH have been seen in certain galactic regions. This emission is due to maser action and can be associated with star-forming regions and with more-evolved stars. Observations of OH maser sources using the powerful technique of very long baseline interferometry (VLBI) have shown that the masing regions have apparent angular sizes on the order of 0.01 arc second or less. Such apparent sizes translate to linear sizes on the order of a few times the mean distance between Earth and the Sun (150 million km) and occur at the heart of regions with active star formation.

The 1612 MHz transition is an extremely important hyperfine line of OH. This line emission occurs in many types of objects in the Galaxy, and high-angular-resolution observations of these objects in this line measure their distances and can be used collectively to measure the distance to the center of the Galaxy.

3.3.2.3 Extragalactic Megamasers

OH can be seen in other galaxies by absorption against radio sources in galactic nuclei and by maser emission. The OH megamaser emission from galactic nuclei can be more than a million times more luminous than that from galactic masers and can be seen to great distances. The present redshift limit for extragalactic masers is 50,000 km/s ($z = 0.17$), which causes the OH line to be observed at 1428 MHz. These powerful megamasers arise within the cores of galaxies; this action results in amplification (rather than absorption) of the nuclear radio continuum. Use of the OH line to study these very peculiar and active galaxies allows radio astronomers to diagnose the temperature and density of the molecular gas in the centers of these galaxies.

3.3.3 Extragalactic Radio Source Spectra

The study of the continuum emission of radio sources requires observations throughout a very wide frequency range. The 1-3 GHz bands (at 1400-1427 MHz, 2200-2300 MHz, and 2655-2700 MHz) are important for continuum observations to determine the physical parameters in a wide variety of radio sources (Figures 2.1 and 2.2 in Chapter 2). Many extragalactic radio sources show a “break” in their nonthermal spectrum in the region between 1 and 3 GHz; continuum measurements in the range of 2 to 3 GHz are essential to define such a spectral characteristic accurately. The spectral break at relatively high frequencies from synchrotron sources is closely related to the lifetime of relativistic particles in radio galaxies and quasars. Such information is crucial to our understanding of the physical processes taking place in radio sources.

3.3.4 Galactic Continuum

The frequency bands in the range from 1 to 3 GHz are also important for galactic studies of ionized hydrogen clouds and the general diffuse radiation of the Galaxy. Since, at such frequencies, available radio telescopes have adequate angular resolution (narrow beams, of the order of 10 arc minutes [arcmin] for large telescopes), many useful surveys of the galactic plane have been performed, including the regions of the galactic center, which is invisible at optical wavelengths because of the interstellar absorption by dust particles.

The Arecibo Observatory's telescope, with a beam of 3.3 arcmin, will soon begin surveying the galactic continuum (at a resolution of better than 10 arcmin) to study the galactic magnetic field. The most serious hindrance to full exploitation of existing cosmic microwave background (CMB) data sets, including those from the Wilkinson Microwave Anisotropy Probe (WMAP) and future data sets from the Planck mission and other future missions, is the understanding of the galactic foreground, especially at the frequencies used for CMB experiments (20-100 GHz). It is thus imperative that detailed studies of the galactic continuum emission be undertaken.

3.3.5 Very Long Baseline Interferometry

Because of the sensitive, large antennas of the NASA Deep Space Network and other deep space stations, the 2290-2300 MHz band allocated to the Space Research Service (SRS) is also used for VLBI observations in radio astronomy. The 2200-2290 MHz band is widely used in conjunction with the SRS band just above it. In particular, major geodetic and astrometric programs are being carried out jointly in the 2200-2300 MHz frequency range.

The study of the nuclei of galaxies, including that 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 possibility 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 relevant and major astrophysical topics.

The center of our Galaxy is perhaps its most interesting region, but it can be observed only at infrared and radio wavelengths, since such long wavelengths are not affected by the dust particles in interstellar space. Because of this use by radio astronomers, many radio telescopes are equipped to use this band, which in turn allows radio telescopes to support important space missions.

Continuum observations in several discrete channels spanning over 100 MHz around 2300 MHz and spanning 500 MHz or more around 8600 MHz are used for high-precision position measurements, important for both radio astronomy and the Earth sciences. Although it is not possible to make such precise measurements using only bands allocated to the passive services, these measurements are possible because some interference can be tolerated at some of the antennas part of the time. However, the recent activation of broadcast satellites in the 2300 MHz band is making these measurements more difficult. The broadcast satellites and other sources of interference may make it necessary to move geodetic observations to the 31 GHz band, where 500 MHz is protected for radio astronomy and other passive services.

3.3.6 Astronomical Polarization Studies

An important study at radio wavelengths is the polarization of the radiation that is observed from radio sources. Radio sources are often found to be weakly linearly polarized, with a polarization angle that depends on frequency. This effect is due to the fact that the propagation medium in which the radio waves travel to reach us is composed of charged particles, electrons, and protons, in the presence of magnetic fields. The determination of the degree and angle of polarization gives us information on the magnetic fields and electron densities of the interstellar medium, and in certain cases on the nature of the emitting sources themselves. The degree of polarization of radio waves is higher at higher frequencies. The frequency bands near 2300, 2700, and 5000 MHz are important bands for polarization measurements.

3.3.7 Soil Moisture

A combination of active and/or passive microwave measurements can be used to remotely sense soil moisture under moderately vegetated areas (up to ~5 kg/m^2 of vegetation water content) with an uncertainty of approximately 4 percent volumetric soil moisture. Passive measures rely on the dependence of the microwave emissivity of soil to its water content, but passive measures are complicated by surface roughness. Lower microwave frequencies provide good soil penetration depth, permitting measurements of soil moisture down to ~10 cm depth at 1.4 GHz, and less so at higher frequencies. Active measurements rely on the dependence of soil backscatter on water content and are complicated by surface roughness and scattering by vegetation cover. While passive techniques have a strong two-decade development heritage, active measurements can, however, provide finer spatial resolution than is possible with passive techniques. Thus, a combination of active and passive measurements can be used to separate the effects of surface roughness and vegetation scattering from the soil-moisture signature while providing the desired spatial resolution.

Soil moisture is a key component of the land-surface hydrospheric state. It is essential to estimating latent heat and carbon fluxes at the land-atmosphere boundary. These quantities are vital to weather and climate prediction and research.

3.3.8 Recombination Lines

After an atom is ionized, the nucleus eventually recaptures an electron, which then cascades down through a series of energy levels, emitting narrow spectral line radiation. Such lines occur throughout the spectrum and serve as probes of the temperature and density of nebulae surrounding newly formed stars and the extended envelopes of certain late-type stars.

The physics of the ionized hot gaseous clouds between the stars has been studied by observations of radio lines of excited hydrogen, helium, and carbon. Some of these studies have been made at frequencies of 1399 and 1424 MHz. Detailed observations of radio recombination lines in many interstellar clouds have made possible the derivation of physical parameters such as temperature, density, and velocity distributions. Radio studies have been particularly helpful for observations of these clouds, which are partially or totally obscured at optical wavelengths by interstellar dust.

3.3.9 Radar Astronomy

The Arecibo Observatory in Puerto Rico and the NASA Goldstone 70 m antenna in California have powerful radar transmitters that are used to study objects in the solar system as far away as Saturn. Mercury, Venus, the Moon, Mars, and the satellites of Jupiter and Saturn (including the rings of Saturn) are all objects of study. Comets and asteroids, particularly those that pass near to Earth, are routine targets of these radars.

Although the transmitters are very powerful, about 500 kW, the returned signals are extremely weak and vulnerable to interference. The radar frequency 2320 MHz is close to powerful broadcast satellite transmissions near 2330 MHz, which is a great concern. This panel also notes the importance of bistatic radar and radar interferometry for the study of the most-distant bodies but also of near-Earth asteroids, including potentially dangerous ones. Another important use of radio astronomy telescopes is for ground-based telemetry for space missions (e.g., the Cassini mission used Very Long Baseline Array during the descent of the Huygens probe at Titan, and the Green Bank Telescope acquired signals from the probe).

3.3.10 Sea-Surface Salinity

The emissivity of seawater below 3 GHz is affected by its near-surface salinity. Monthly averaged global maps of salinity with 0.1-0.2 part-per-thousand sensitivity are theoretically possible at 1.4 GHz. The emissivity, however, is also affected by the sea-surface roughness. Thus, active microwave measurements near 1.3 GHz utilizing a radar scatterometer are needed in combination with passive measurements to correct the radiometer brightness temperatures and thus estimate surface salinity at sensitivities approaching the theoretical precision.

Monthly global maps of sea-surface salinity (SSS) would complement sparsely sampled in situ measurements of SSS from ships and ocean buoys. When combined with available global sea-surface temperature data, the improved SSS measurements would greatly improve models of density-driven ocean circulation and could be used to develop a significantly better understanding of heat flux at the sea surface for coupled ocean-atmosphere climate models. Ocean circulation is largely responsible for oceanic heat transport, which in turn strongly influences climate and is suspected of influencing the intensity and frequency of hurricanes. Coupled ocean-atmosphere models are used for the study of natural climate variability and for understanding and predicting climate changes. Remotely sensed salinity measurements are also valuable for understanding sea-ice melting and freezing processes; improved discrimination between meltponds, sea-ice leads, and polynia; and littoral and estuarine biological blooms and their impact on primary production and the health of fisheries.

3.4 BANDS BETWEEN 3 AND 10 GHZ

In addition to the bands listed in Table 3.3, the following bands are used for scientific research: the EESS active (secondary) band at 3.1-3.3 GHz, the Meteorological Satellite Service (MetSat) radar EESS active (secondary) band at 9.975-10.025 GHz, the EESS active bands at 17.20-17.30 GHz and (secondary) 24.05-24.25 GHz, and the EESS passive (secondary) band at 4.200-4.400 GHz.

An EESS passive (secondary) band runs from 4.90 to 5.00 GHz. The SRS Earth-to-space communication band is 7.145-7.235 GHz. Additional (MetSat) communication bands are 7.450-7.55 GHz (geostationary) and 7.55-7.85 GHz (low-Earth orbiters). Note that some of these allocations may be difficult to find in the regulatory footnotes.

3.4.1 Formaldehyde

Formaldehyde (H_2CO) is detected in interstellar clouds via its K-doubling transition ($J_{K-1,K+1} = 1_{10}\text{-}1_{11}$) at 4829.66 MHz. This line is a useful tracer of the more diffuse interstellar medium because it can be detected in absorption against strong background radio sources. The distribution of H_2CO clouds can give independent evidence of the distribution of the interstellar material and can help in understanding the structure of our Galaxy. H_2CO lines from the carbon-13 isotope and oxygen-18 isotope have been detected, and studies of the isotopic abundances of these elements are being carried out.

TABLE 3.3 Frequency Allocations Between 3 and 10 GHz: Bands, Services, Footnotes, and Scientific Uses

Band (MHz)	Services	Footnotes	Scientific Use
3260-3267	RLS, (ras)	5.149,[1] US110,[2] G59[3]	CH
3332-3339	RLS, (ras), aems,[4] fs,[5] ms[6]	5.149, G31[7]	
3345.8-3352.5	RLS, (ras), aems,[8] fs,[9] ms[10]	5.149, G31	
4800-4990	FS, MS, ras, eess (passive), srs (passive)	5.149, 5.339,[11] 5.442,[12] 5.443,[13] US203,[14] US257[15]	Formaldehyde, continuum
4990-5000	RAS, FS, MS,[16] srs (passive)	5.149, 5.402,[17] US74,[18] US211,[19] US246[20]	Continuum, VLBI
5250-5255	EESS (active), RLS, SRS (active)	5.448A[21]	
5255-5350	EESS (active), AeRNS, rls	5.448B,[22] 5.449[23]	
5350-5460	EESS (active), AeRNS	5.449	
5660-5725	RLS, aems, srs (deep space)	5.454[24]	
6425-6650	FS, FSS, MS, (eess passive), (srs passive)	5.458[25]	Passive remote sensing
6650-6675.2	FS, FSS (E→S), MS, (eess passive), (srs passive), (ras)	5.149,[26] 5.458	Methanol, passive remote sensing
6675.2-6700	FS, FSS (E→S), MS, (eess passive), (srs passive)	5.458	Passive remote sensing
6700-7075	FS, FSS, MS, (eess passive), (srs passive)		
7075-7125	FS, MS, (eess passive), (srs passive)		
7125-7190	FS, MS,[27] (eess passive), (srs passive)		
7190-7235	FS, MS,[28] SRS (E→S), (eess passive), (srs passive)	5.458	Deep space uplinks, passive remote sensing
7235-7250	FS, MS,[29] (eess passive), (srs passive)	5.458	Passive remote sensing
8025-8175	EESS (S→E), FS, FSS (E→S), MS,[30] mss[31] (E→S)	5.462A,[32] 5.463[33]	
8175-8215	EESS (S→E), FS, FSS (S→E), MetSat (E→S), MS	5.462A, 5.463	
8215-8400	EESS (S→E), FS, FSS (E→S), MS	5.462A, 5.463	
8400-8450	FS, MS,[34,35] SRS (deep S→E)	5.465,[36] 5.466[37]	Deep space downlinks, continuum, VLBI
8450-8500	SRS (S→E)	5.466	Continuum, VLBI
8500-8550	RLS	5.468,[38] 5.469[39]	Radar astronomy
8550-8650	EESS (active), RLS, SRS (active)	5.468, 5.469, 5.469A[40]	
9500-9800	EESS (active), RLS, RNS, SRS (active)		

NOTE: For definitions of acronyms and abbreviations, see Appendix I. For information about other features of this table, see §3.1.2, "Note to the Reader Regarding Frequency Allocation Tables."

continued

TABLE 3.3 Continued

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[1] 5.149 urges administrations to take all practical steps to protect radio astronomy in this band.
[2] US110 limits nongovernment operation.
[3] G59 gives priority to military operation.
[4] Except Region 1.
[5] Region 2 only.
[6] Region 2 only.
[7] G31 limits operation to military.
[8] Except Region 1.
[9] Region 2 only.
[10] Region 2 only.
[11] 5.339 adds passive EESS and SRS as secondary in the band 4950-4 990 MHz.
[12] 5.442 prohibits AeMS in the bands 4825-4835 MHz and 4950-4990 MHz.
[13] 5.443: RAS is primary in Argentina, Australia, and Canada in the 4825-4835 MHz and 4950-4990 MHz bands.
[14] US203 identifies observatories using the 4825-4835 MHz band to observe formaldehyde.
[15] US257 identifies observatories using the 4950-4990 MHz continuum band.
[16] Except aeronautical.
[17] 5.402 urges protection from second harmonic radiation.
[18] US74 limits the protection to the RAS.
[19] US211 urges protection from aeronautical and space stations in adjacent bands.
[20] US246 prohibits transmissions.
[21] 5.448A: EESS and SRS shall not constrain the RLS.
[22] 5.448B: The EESS shall not interfere with the AeRNS.
[23] 5.449 limits AeRNS to airborne radars and associated beacons.
[24] 5.454 upgrades SRS to primary in many states of the former Soviet Union.
[25] 5.458 urges administrations to take into account passive EESS and SRS measurements made in the bands 6425-7075 MHz (oceans only) and 7075-7250 MHz in future planning.
[26] 5.149 urges protection for the RAS in this band within 5925-6700 MHz.
[27] Except in the United States.
[28] Except in the United States.
[29] Except in the United States.
[30] Not in the United States.
[31] United States only, but no aircraft.
[32] 5.462A limits pfd of geostationary EESS transmitters in Regions 1 and 3.
[33] 5.463 prohibits aircraft stations.
[34] Except in the United States.
[35] Except aeronautical.
[36] 5.465: Deep space only.
[37] 5.466: SRS is secondary in certain countries.
[38] 5.468: Additional allocation in certain countries.
[39] 5.469: Additional allocation in certain countries.
[40] 5.469A: EESS and SRS may not cause harmful interference to RLS.

The combination of the 4830 MHz and 14.5 GHz formaldehyde lines is a sensitive and useful diagnostic of the density in the emitting gas.

Extragalactic formaldehyde megamaser emission and absorption are found in a growing number of galaxies. Since formaldehyde is a good tracer of intermediate- to high-density gas, this line is very important for the study of the molecular structure of other galaxies.

3.4.2 Continuum and Very Long Baseline Interferometry

The spectral band around 5 GHz has been one of the most widely used frequency ranges in radio astronomy during the past 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 ionized 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.

Heavy use has been made of the radio astronomy band at 5 GHz for VLBI observations. Angular resolutions of 0.3 milliarc seconds have been achieved with intercontinental baselines, and many countries (Australia, Canada, Germany, Great Britain, The Netherlands, Russia, South Africa, Spain, and Sweden) have collaborated in this effort. From such studies, astronomers are finding that quasars are composed of intricate structures with many strong localized sources of radio emission.

The 8400-8500 MHz band is widely used for VLBI studies in conjunction with and in support of geodetics and space research (space-to-Earth) experiments.

3.4.3 Soil Moisture

Passive microwave measurements in the C-band region, typically near 6.8 GHz, can be used to infer soil moisture in the surface layer (typically 0-1 cm) under bare soil and lightly vegetated areas (up to ~2 kg/m^2) to approximately 10 percent volumetric accuracy. Applications are discussed in §3.3.7.

3.4.4 Sea-Surface Temperature

The brightness temperature of the sea surface is dependent on the thermometric sea-surface temperature (SST), the salinity, and surface roughness and foam. Observation at frequencies above ~5 GHz ensures minimal dependency on sea-surface salinity, and observation below ~10 GHz reduces the effect of roughness, ocean foam, and clouds while maintaining sensitivity to SST, especially in colder regions. An optimal spectral region to determine SST using microwave radiometry is thus near ~6 GHz, although no EESS allocation currently exists near this frequency.

Sea-surface temperature measurements of ~0.3ºC precision or better are possible from spaceborne radiometers operating near ~6.8 GHz with 100-400 MHz bandwidth. Estimates of SST based on microwave radiometric measurements over the ocean at this frequency are largely immune to cloud cover, which strongly inhibits thermal infrared (IR) measurements. Microwave SST measurements are also complementary to IR measurements in providing SST data more representative of the bulk water temperature rather than of the thin infrared skin-depth layer. When combined, IR and microwave SST measurements can potentially provide measurements of the heat flux from the ocean surface.

SST data are used to support studies of a broad range of sea-surface phenomenology, climate studies, and weather forecasting. For example, the strengthening of hurricanes and cyclones strongly depends on oceanic heat content, which is directly related to SST. In general, climate studies require only relatively coarse spatial resolution (~25 km) but measurements under all cloud conditions. Accurate microwave measurements thus play a significant role in providing input SST data for numerical climate models.

3.4.5 Microwave Radiometric Imagery

See §3.5.13 for applications of microwave radiometric imagery.

3.5 BANDS BETWEEN 10 AND 25 GHZ

The bands, services, footnotes, and scientific observations for each band in the allocations between 10 and 25 GHz are presented in Table 3.4.

3.5.1 Very Long Baseline Interferometry

Many of the nonthermal synchrotron sources are only detectable at higher frequencies, and the frequency range of 10-25 GHz gives us such observational information. This frequency range is also important for monitoring the intensity variability of the quasars. These objects, which could be the most-distant celestial objects that astronomers can detect and which produce surprisingly large amounts of energy, have been found to vary in intensity over periods of weeks and months. Such observations lead researchers to estimate 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 higher frequencies; observations at these frequencies facilitate the discovery and the monitoring of these events. The energy emitted during any one such burst from a quasar is equivalent to the complete destruction of a few hundred million stars in a period of a few weeks or months. Astronomers do not yet understand the fundamental physics that can produce such events. Observations of the size and variability of these sources are the primary means that can be used to determine their nature. These observations are now best performed in the frequency range from 10 to 15 GHz.

The small sizes of the quasars are revealed from the VLBI observations mentioned above. Such observations are also being made in the frequency band at 10.6-10.7 GHz, and observations at 15.40 GHz have been successful. The higher frequencies provide better angular resolutions and enable more accurate determination of the sizes and structures of quasars.

3.5.2 Precipitation Measurements

Precipitation measurements using microwave remote sensing may utilize both active and passive sensing. Rain mapping using radar reveals the three-dimensional structure of precipitation, which can be used to develop statistical cloud and raincell models and to provide improved calibration of rainfall measurements derived using passive radiometry alone. Microwave radiometric measurements within

TABLE 3.4 Frequency Allocations Between 10 and 25 GHz: Bands, Services, Footnotes, and Scientific Uses

Band (GHz)	Services	Footnotes	Scientific Use
10.6-10.68	EESS (passive), FS, RAS, SRS (passive), MS[1] (except AeMS), rls	5.149,[2] 5.482,[3] US265,[4] US277[5]	Precipitation, continuum, VLBI
10.68-10.70	EESS (passive), RAS, SRS (passive)	5.340,[6] 5.483,[7] US74,[8] US246[9]	Precipitation, continuum, VLBI
12.75-13.25	FS, FSS (E→S), AeRNS, MS, sr[10] (E→deep S)	5.441,[11] US251[12]	Deep space mission links
13.25-13.4	EESS (active), AeRNS, SRS[13] (active)	5.498A,[14] 5.499[15]	
13.4-13.75	EESS (active), RLS, SRS, sftss	5.499, 5.500,[16] 5.501,[17] 5.501A,[18] 5.501B[19]	

TABLE 3.4 Continued

Band (GHz)	Services	Footnotes	Scientific Use
13.75-14	FSS (E→S), RLS,[20] sftss (E→S), srs[21]	5.484A,[22] 5.499, 5.500, 5.501, 5.502,[23] 5.503[24]	
14-14.25	FSS (E→S), RNS,[25] mss[26] (E→S), srs	5.484A, 5.505,[27] US292[28]	
14.25-14.3	FSS (E→S), RNS,[29] sr[30]	5.484A, 5.505, 5.508,[31] 5.509[32]	
14.4-14.47	FS, FSS (E→S), MS (except AeMS), sr (S→E)	5.484A	
14.47-14.5	FS,[33] FSS (E→S), MS (except AeMS), mss[34] (E→S), ras[35]	5.149,[36] US203[37]	Formaldehyde
14.5-14.7145	FS, FSS[38] (E→S), MS,[39] srs		
14.7145-14.8	FS,[40] FSS,[41] MS, srs	US310[42]	
14.8-15.1365	FS,[43] MS, srs	US310	
15.1365-15.2	FS, MS,[44] srs		
15.2-15.35	FS, MS,[45] srs, eess (passive)	5.339,[46] US211[47]	
15.35-15.40	EESS (passive), SRS (passive), RAS	5.340,[48] 5.511,[49] US74, US246	Continuum
16.6-17.1	RLS, srs (deep space, E→S)	5.512,[50] 5.513[51]	
17.2-17.3	RLS, EESS (active), SRS (active)	5.512, 5.513, 5.513A[52]	
18.6-18.8	SRS (passive),[53] EESS (passive),[54] FS, FSS (S→E), MS (except AeMS)	5.522,[55] 5.523,[56] US254,[57] US255,[58] US334[59]	Precipitation
21.2-21.4	EESS (passive), SRS (passive), FS, MS	US263[60]	
22-22.21	FS, MS, (ras)	5.149	Extragalactic water masers
22.21-22.5	RAS, EESS (passive), SRS (passive), FS, MS (except AeMS)	5.149, 5.532,[61] US263	Water masers, atmospheric water vapor
22.5-22.55	FS, MS	US211[62]	Water masers
22.55-23.55	FS, ISS, MS, (ras)	5.149	Water masers
23.6-24	EESS (passive), RAS, SRS (passive)	5,340, US74, US246[63]	Continuum, ammonia
24.05-24.25	RLS, eess (active)	5.150[64]	

NOTE: For definitions of acronyms and abbreviations, see Appendix I. For information about other features of this table, see §3.1.2, "Note to the Reader Regarding Frequency Allocation Tables."

[1] Except in the United States.
[2] 5.149 urges protection of RAS from other services and particular airborne and space stations.
[3] 5.482 limits the power of FS and MS stations.
[4] US265 limits the power of FS transmissions.
[5] US277 adds RAS as primary in the United States but without protection from licensed FS stations in the 100 most populated urban areas.
[6] 5.340 forbids emissions except as noted in 5.483.
[7] 5.483 adds FS and MS (except AeMS) in certain countries.

continued

TABLE 3.4 Continued

[8] US74 limits protection from services in other bands.
[9] US246 forbids transmissions in this band.
[10] Except in the United States.
[11] 5.441 limits geostationary FSS.
[12] US251 adds SRS (deep space to Goldstone, California).
[13] Secondary in the United States only for Earth to deep space.
[14] 5.498A: EESS and SRS will not cause harmful interference to the AeRNS.
[15] 5.499 adds FS in Bangladesh, India, and Pakistan.
[16] 5.500 adds FS and MS in certain countries.
[17] 5.501 adds RNS in certain countries.
[18] 5.501A limits primary SRS allocation to active spaceborne sensors; other uses are on a secondary basis.
[19] 5.501B: EESS and SRS shall not cause harmful interference to RLS.
[20] Except in the United States.
[21] United States only.
[22] 5.484A limits FSS.
[23] 5.502 limits FSS.
[24] 5.503 retains primary status for older SRS stations.
[25] Secondary in the United States.
[26] Except aeronautical.
[27] 5.505 adds FS in certain countries.
[28] US292 makes RNS secondary to FSS.
[29] Except in the United States.
[30] Except in the United States.
[31] 5.508 adds FS in certain countries.
[32] 5.509 adds MS in certain countries.
[33] Secondary in the United States.
[34] Land MSS in the United States only.
[35] Except in the United States.
[36] 5.149 urges all practical steps to protect RAS.
[37] US203 notes observatories making formaldehyde observations.
[38] Except in the United States.
[39] Secondary in the United States.
[40] Secondary in the United States.
[41] Except in the United States.
[42] US310 authorizes SRS transmissions to the Tracking and Data Relay Satellite System.
[43] Secondary in the United States.
[44] Secondary in the United States.
[45] Secondary in the United States.
[46] 5.339 adds SRS (passive) and EESS (passive) on a secondary basis.
[47] US211 urges protection of nearby radio astronomy band.
[48] 5.340 prohibits all emissions.
[49] 5.511 adds FS and MS on a secondary basis in certain countries.
[50] 5.512 adds FS and MS on a primary basis in certain countries.
[51] 5.513 adds FS and MS on a limited primary basis in certain countries.
[52] 5.513A: Spaceborne active sensors shall not cause harmful interference to other services.
[53] Secondary in Regions 1 and 3.
[54] Secondary in Regions 1 and 3.
[55] 5.522 urges protection of passive sensors in EESS and SRS.
[56] 5.523 urges limiting the power of FSS space-to-Earth stations.
[57] US254 limits the power of FS and MS stations.
[58] US255 limits the power of FSS stations at Earth's surface.
[59] US334 specifies restrictions on FSS.
[60] US263 limits protection of EESS and SRS from FS and MS.
[61] 5.532: EESS and SRS shall not impose constraints on FS and MS.
[62] US211 urges additional protection to the RAS from adjacent bands.
[63] US246 prohibits all transmissions.
[64] 5.150 adds industrial, scientific, and medical (ISM) applications to this band.

the bands at 6, 10, 18, 23, 37, and 89 GHz are of primary interest for precipitation measurement. Active measurements of precipitation are carried out near 13.6, 35.5, and 94 GHz.

The accurate measurement of the spatial and temporal variation of rainfall around the globe, particularly over the vast undersampled oceanic and tropical areas, is one of the most difficult and important problems of meteorology. Satellite-based microwave remote sensing of precipitation can provide the best-available means of obtaining data detailing four-dimensional distribution of rainfall and latent heating on a global basis. The availability of these data significantly improves ongoing efforts to predict climate change. As an example, they enable the mapping of larger time and space variations of rainfall in quasi-periodic circulation anomalies, such as the Madden-Julian oscillation in the western Pacific and the El Niño-Southern Oscillation over the broader Pacific basin. The availability of these data sets also allows more thorough study of the critical onset of large annual circulation regimes, such as the Asian summer monsoon. These phenomena all have far-reaching economic and societal impacts on affected regions.

3.5.3 Water Masers

The discovery in 1968 of the H_2O molecule in interstellar space presented many new and interesting puzzles. These lines are extremely intense. They are occasionally the most intense radio sources in the sky at 22.2 GHz. It was soon discovered that the intensities of these lines are highly variable, that the sizes of the H_2O sources are extremely small (a few astronomical units), and that the lines are highly polarized. Interstellar H_2O maser action is necessary to explain such observations. Such sources seem to be similar to the OH sources discussed above. H_2O sources have been observed to show multiple components, each one with a slightly different velocity in the line of sight (Figure 3.3). Astronomers believe that such molecular clouds are related to the formation of protostars. VLBI observations at 22.2 GHz provide valuable information on the sizes and structure of the H_2O maser sources.

3.5.4 Ammonia

The discovery of NH_3 (ammonia) in interstellar space presented an example of a molecule radiating thermally. The distribution of NH_3 clouds in the Galaxy and their relation to the other molecules that have been discovered are of great interest. Radio lines of ammonia arise from the inversion of nitrogen through the plane of the hydrogen atoms. The molecule inverts in many of its rotational levels. Hence, there are numerous inversion lines of ammonia that can be studied, which makes this molecule an excellent indicator of gas temperature.

3.5.5 Integrated Precipitable Water

Integrated precipitable water from the surface to 30 mb (roughly the tropopause) can be estimated to an uncertainty of <2 mm or ~ 10 percent (millimeters of condensed water) using space-based radiometric measurements in the K-band region. These measurements are of major use for meteorological research and forecasting and for astronomical and military applications. Radio wave propagation delays due to atmospheric water vapor can also be derived from radiometric measurements in the spectral region near 22 GHz.

For an estimate of the total columnar water, the optimum frequency is one for which the water-vapor-density weighting function has a constant profile with height. Weighting functions in the region

FIGURE 3.3 Combined radio and optical images of M33 (Triangulum Galaxy) by T. Rector, National Radio Astronomy Observatory, and M. Hanna, National Optical Astronomy Observatory. The locations and expected motions of two sites of H_2O masers from massive star-forming regions are indicated. Very Long Baseline Array observations over a period of 3 years have yielded the relative motions of these masers; thus one can "see" the Galaxy rotate. Combining this measurement with the rotation speed and inclination (from HI data) of the Galaxy gives a direct measurement of its distance. Courtesy of National Radio Astronomy Observatory/Associated Universities, Inc., and National Optical Astronomy Observatory/Association of Universities for Research in Astronomy/National Science Foundation.

of the 22.235 GHz weak water-vapor absorption line display these characteristics and are widely used as the primary radiometric channel for estimates of integrated precipitable water vapor and path delay.

The atmospheric index of refraction, *N*, governs the propagation velocity. In the propagation medium (e.g., the atmosphere), the magnitude of *N* is in turn governed by temperature, pressure, and water-vapor density. For a radio wave propagating between the surface and a point outside the atmosphere, the electrical radio wave path length is longer than the physical path length. The difference is called the excess electrical path length. This value is a function of the integrated profile of *N* along the path. The ability to measure *N* accurately is important in many applications, including radar altimetry of ocean-surface height (the error for state-of-the-art systems is <2 cm) and radio astronomical observations using very long baseline interferometry. Radar mapping of the height of the ocean surface is critical to the understanding of ocean circulation, including the identification of gyres and stream boundaries that channel significant amounts of heat throughout the ocean.

It is noted that the same bands that are used to measure water vapor from space are also used on ground- and ship-based radiometers to measure integrated precipitable water vapor from the surface of Earth. These ground-based sensors are becoming widely used around the globe to help initialize numerical weather-prediction models and for the calibration of remote sensing satellites. Although they do not provide global measurements, they are particularly accurate over both land and water, since they view water vapor against a strong contrasting background caused by the cold cosmic emission temperature of 2.73 K.

3.5.6 Cloud Liquid Water

For nonprecipitating clouds, microwave radiometric brightness temperatures near 10, 18, and 37 GHz can be used to estimate the integrated amount of cloud liquid water to within ~0.05 mm or 10 percent total columnar water precision. Within the next 5 to 10 years, inclusion of cloud microphysics in climate models is expected. Measurements of cloud liquid water will be needed to diagnose and validate these cloud models, which in principle have the ability to greatly improve understanding of climate, rainfall variability, and the atmospheric radiation budget. The inclusion of cloud water into numerical weather-prediction models will also provide an important means of accurately modeling the influences of short- and long-wave radiation on the evolution of severe weather. Accurate measurements of cloud water amounts also play an important role in global climate models and in understanding the impact of anthropogenic and natural aerosols on clouds, rainfall, and climate.

As with water vapor, the same bands that are used to measure cloud liquid water from space are also used on ground- and ship-based radiometers to measure cloud liquid water from Earth’s surface, but with greater accuracy because of the cold cosmic background. Widespread global deployment of these sensors is occurring.

3.5.7 Soil Moisture

See §3.3.7 for applications of soil moisture.

3.5.8 Snow Cover

Snow cover and snow water equivalent are derived from microwave radiometric imagery primarily at 18, 23, and 37 GHz, with atmospheric sounding data to remove the atmospherically induced noise in the retrieval. Snow-cover information under clear or cloudy conditions is achievable using microwave radiometers in LEO at a spatial resolution of ~20 km. Microwave measurements provide important continuity of snow-cover measurements under cloudy conditions when visible and/or IR measurements cannot view Earth's surface.

Forecasts of river stages, avalanche danger, spring flooding, air rescue conditions, freshwater resources, and soil trafficability all heavily depend on snow-cover information, especially in data-sparse and/or data denied areas where dependence on remotely sensed data is high. Snow-cover and -depth retrievals using microwave radiometric window bands (e.g., 18, 37, and 89 GHz) provide input to numerical land-surface and hydrological forecast models.

Snow cover also plays an important role in the understanding of climate change. For example, continental-scale annual average snow cover, which is easily detectable from satellites (using microwave data to ensure that cloudy conditions do not affect the average), may be a sensitive early indicator of atmospheric warming or cooling. Snow-cover changes also produce strong feedback to the atmospheric energy budget because of the large changes in surface albedo caused by the presence or absence of snow. This feedback is important on both short-term, seasonal-to-interannual, and longer-term (annual to decadal) timescales. Snow-cover measurements over sea ice also provide important information on the flux of heat from the ocean to the atmosphere as modulated by the insulating properties of overlying snow layers.

3.5.9 Sea-Surface Wind Speed and Direction

Sea-surface wind speed is derived very accurately from brightness temperature data collected from LEO at 18 and 23 GHz. Measurements at 37 GHz and near 10 GHz also support these retrievals by helping correct for clouds and water vapor. Wind-speed retrieval accuracy better than 1 m/s uncertainty has been demonstrated with current on-orbit radiometric systems. Further improvements are expected with simultaneously retrieved wind-direction information.

Wind-speed data with <2 m/s uncertainty are needed as inputs to prepare tropical cyclone warnings, initialize numerical weather-prediction models, derive sea state, and for use in ship and aircraft routing, flight safety, and other operations such as data buoy dispersions.

The sea-surface wind vector (both speed and direction) has been retrieved using radar scatterometry on spaceborne and airborne experimental systems operating near 13 GHz (NASA Scatterometer [NSCAT]). Spaceborne scatterometer wind retrieval performance is on the order of ~1 m/s and ±20º directional uncertainty. Sea-surface wind direction may also be derived using highly sensitive passive polarimetric measurements at 10, 18, 23, and 37 GHz. This technique has been demonstrated with several airborne campaigns and the WindSat spaceborne passive microwave sensor. Sea-surface wind vector can be retrieved using polarimetry at levels of uncertainty similar to those that have been demonstrated with radar scatterometry, but with less saturation in speed at high winds than is possible with scatterometers.

A U.S. Navy study concluded that skill in sea-surface wave forecasting depends heavily on the skill of predicting sea-surface winds. At 20 km horizontal resolution, sea-surface winds from a polar-orbiting weather satellite with a measurement accuracy of ±2 m/s or ±10 percent (whichever is greater) will yield open-ocean wave heights within errors of 10 to 20 percent and wave energy within 20 to 50 percent. Such systems provide accurate wind and wave data to support both ocean-based defense operations and commercial shipping. Sea-surface wind-speed and -direction data also support numerical weather-forecasting models of the National Center for Environmental Prediction.

3.5.10 Sea Ice

Measurement of sea-ice characteristics, including ice age, ice type, and ice coverage and motion, is derived from microwave radiometric imagery at 18, 23, and 37 GHz. Ice-surface temperature can be estimated from the microwave imagery; the retrieved values are much less dependent on clouds and atmospheric variability than are measurements obtained from IR brightness temperatures. Sea-ice type is determinable as first-year ice and multiyear ice with a greater than 70 percent confidence level. The state of ice in early formation, such as new ice and young ice, as well as the state of "old" ice (ice age between first year and multiyear) is also detectable, albeit with somewhat less confidence. Ice motion is generally detectable using microwave radiometric imagery to ~1 km per day motion, depending on the atmospheric and surface state.

Arctic and Antarctic operations, maritime commerce, and oceanographic and climate research are extremely dependent on sea-ice-cover, ice-age, and ice-motion data derived from satellite imagery. When sea ice obtains a specific age and/or thickness, icebreaker support is mandatory to prevent vessel damage. Old ice achieves significant tensile strength as it becomes compacted over time and as salinity is lowered. Similarly, submarine surfacing operations are highly dependent on sea-ice concentration and ice-cover thickness. Ridging of old ice can result in ice keels penetrating to tens of meters below the sea surface, posing a significant hazard to submarine navigation. The marginal ice zone (the zone of sea ice between open sea and inner ice pack) is subject to significant variability in response to oceanographic and atmospheric forcing. Vessels that are not ice-strengthened risk damage if sea ice is advected into their operating area due to such forcings.

For climate studies, changes in polar ice cover are primary indicators of global climate change. Reductions in Arctic sea-ice cover are anticipated to significantly affect the global balance of solar heating and atmospheric temperature, moisture, and cloud cover. Changes in polar ice cover will also alter the ecological balance in the Arctic and Antarctic regions.

3.5.11 Sea-Surface Altimetry

Radar altimetry from low-Earth-orbiting platforms is performed using single- and dual-frequency radar altimeters operating at ~13.6 GHz and 5.3 GHz to derive sea-surface height and ocean topology data. Future systems may also utilize 35.5 GHz. The typical precision of these measurements is 3-4 cm over a range of ~200 meters and 4-5 cm overall after orbital variations are accounted for. To achieve this accuracy, precise estimates of the excess path delay derived from radiometric measurements near 22.235 GHz are also required. (See §3.5.6.)

For operational oceanography and forecasting, sea-surface height/topography observations from polar-orbiting weather satellites provide the only means of acquiring the high-quality global data needed to analyze transient ocean current features (i.e., eddies) to the resolution and accuracy required for emerging coupled ocean-atmospheric models.

For climate monitoring and assessment, sea-surface altimetry and sea-level data are applicable to many areas of study. In the tropical oceans, sea level provides estimates of the upper-level heat content, which is important for numerical ocean-forecast models. State-of-the-art altimeters are sufficient to determine the general circulation and its variability accurately enough to allow a quantitative assessment of the ocean's role in Earth's climate, hydrological, and biochemical systems. In addition, ocean altimetry systems allow the observation of changes to shorefast continental ice.

3.5.12 Ice-Surface Temperature

The temperature of the ice surfaces on either land or water to ~1 K measurement uncertainty is required from the next-generation operational microwave radiometers operating in LEO. The data may be derived using radiometric brightness temperatures at 10, 18, 23, and 37 GHz, with additional support with atmospheric characterization from sounding in the 50-56 GHz and 183 GHz spectral regions.

Surface temperatures are not available in data-sparse regions throughout the Arctic and Antarctic, making estimations of ice thickness difficult and potentially inaccurate. Remotely sensed ice-surface temperature maps produced on a daily basis will be invaluable for estimating sea-ice growth and decay. The temperature uncertainty must be accurate to within 1°C to ensure an accurate calculation of frost degree-day information.

3.5.13 Microwave Radiometric Imagery

Many meteorological and surface environmental data products are produced using multivariable algorithms to retrieve a set of geophysical parameters simultaneously from calibrated multichannel microwave radiometric imagery. For example, sea-surface temperature, wind speed, water vapor, and cloud water are simultaneously estimated using multichannel imagery from NASA's Tropical Rainfall Measurement Mission (TRMM) Microwave Imager. If one or more bands were removed from the imagery set, the ability to perform the multivariable estimate would be inhibited. In general, radiometric measurements over the range from ~6 to >183 GHz using EESS-allocated frequencies—and in some cases additional bands not allocated to the EESS—are used for the generation of microwave-based imagery. In addition to the lists in the tables in this handbook, a list of useful microwave bands and radiometric imagery products can be found in ITU-R SA.515.

3.5.14 Sea-Surface Temperature

Sea-surface temperature is measured using passive microwave channels at 10.7 GHz. While not as sensitive as those measurements at 6.8 GHz, the higher frequency provides finer spatial resolution for the same-size antenna aperture. For applications of SST, see §3.4.4.

3.6 BANDS BETWEEN 25 AND 50 GHZ

The frequency region between 30 and 40 GHz is the first atmospheric window in the millimeter radio region where ground-based observations can be made. On either side of this frequency band, water and oxygen molecules in Earth's atmosphere attenuate the incoming radiation. The O_2 absorption beginning at ~50 GHz is sufficiently strong to render ground-based observations impossible. Conversely, the contrast between an opaque atmosphere at the edges of this band and a transparent atmosphere within the band provides the means for measuring various terrestrial parameters (see Table 3.5).

3.6.1 Atmospheric Effects on Earth-Surface Parameter Retrieval

Algorithms performing retrieval of Earth-surface parameters using passive microwave radiometry often use simultaneous measurements of emissions at 18 and 23 GHz. In general, thermal emissions originating from Earth's surface over this frequency range exhibit few or readily predictable variations

TABLE 3.5 Frequency Allocations Between 25 and 50 GHz: Bands, Services, Footnotes, and Scientific Uses

Band (GHz)	Services	Footnotes	Scientific Use
25.5-27	EESS (S→E), FS, ISS, MS, sftss (E→S)	5.536,[1] 5.536A,[2] 5.536B[3]	
27-27.5	FS, FSS[4] (E→S), ISS, MS, eess[5] (S→S)	5.536, 5.537[6]	
28.5-29.5	FS, FSS (E→S), MS, eess (E→S)	5.541[7]	
29.5-30	FSS (E→S), MSS[8] (E→S), eess[9] (E→S)	5.541, 5.542[10]	
31.0-31.3	FS, MS, sftss (S→E), srs, (ras)	5.149,[11] 5.544,[12] 5.545,[13] US211[14]	Atmospheric water vapor, precipitation
31.3-31.5	EESS (passive), RAS, SRS (passive)	5.340,[15] US74[16]	Continuum, complex organic molecules
31.5-31.8	EESS (passive), RAS, SRS (passive), fs,[17] ms[18] (excluding aems)	5.149,[19] 5.340, 5.546,[20] US74, US246	Cloud water, precipitation
31.8-32	FS,[21] RNS, SRS (deep S→E)	5.547B,[22] 5.548,[23] US69,[24] US211, US262[25]	DSN downlinks
32-32.3	FS,[26] ISS, RNS, SRS (deep S→E)	5.547C,[27] 5.548, US69, US262	DSN downlinks
34.2-34.7	RLS, SRS (E→deep S)	5.549[28]	
34.7-35.2	RLS, srs[29]	5.549	
35.5-36	MetAids, EESS (active), RLS, SRS (active)	5.549, 5.551A,[30] US252,[31] US360[32]	
36-37	EESS (passive), FS, MS, SRS (passive)	5.149,[33] US342,[34] US263[35]	Cloud water, precipitation, complex organic molecules
37-37.5	FS, MS, SRS (S→E)		
37.5-38	FS, FSS (S→E), MS, SRS (S→E), eess[36] (S→E)		
38-39.5	FS, FSS (S→E), MS (S→E), eess[37]		
39.5-40	FS, FSS (S→E), MS, MSS, eess[38] (S→E)		
40-40.5	EESS (E→S), eess (S→E), FS,[39] FSS (S→E), MS, MSS (S→E), SRS (E→S)		
42.5-43.5	FS, FSS (E→S), MS (excluding AeMS), RAS	5.149,[40] US342[41]	Continuum, VLBI, SiO masers
48.94-49.04	RAS, FS, FSS, MS	5.149,[42] 5.340,[43] 5.555,[44] US264,[45] US297,[46] US342	CS

NOTE: For definitions of acronyms and abbreviations, see Appendix I. For information about other features of this table, see §3.1.2, "Note to the Reader Regarding Frequency Allocation Tables."

[1] 5.536 limits ISS to SRS, EESS, and IMS applications.

[2] 5.536A: EESS Earth stations cannot claim protection from FS and MS stations in neighboring countries.

continued

TABLE 3.5 Continued

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[3] 5.536B: EESS Earth stations cannot claim protection from FS and MS stations in certain countries.
[4] Region 2 only, except in the United States.
[5] United States only.
[6] 5.537 expands use of nongeostationary satellites by space services using ISS.
[7] 5.541 limits EESS to the transfer of data between stations and not to operation of sensors.
[8] Secondary in Regions 1 and 3 up to 29.9 GHz and everywhere above 29.9 GHz.
[9] Except in the United States.
[10] 5.542 adds FS and MS on a secondary basis in certain countries.
[11] 5.149 urges protection of RAS in the 31.2-31.3 GHz band.
[12] 5.544 limits the flux density for the SRS.
[13] 5.545 raises SRS to primary in certain countries.
[14] US211 urges applicants for space and airborne assignments to protect RAS in the adjacent band.
[15] 5.340 forbids all emissions.
[16] US74 provides protections from extraband radiation.
[17] Regions 1 and 3 only.
[18] Regions 1 and 3 only.
[19] 5.149 urges protection of RAS in the 31.5-31.8 GHz band in Regions 1 and 3, particularly from space and airborne stations.
[20] 5.546 allocates this band to FS and MS on a primary basis in certain countries.
[21] Except in the United States.
[22] 5.547B deletes FS in the United States.
[23] 5.548 urges administrations to prevent harmful interference between the services in this band.
[24] US69 forbids ground-based radionavigation aids except when operated in cooperation with airborne or shipborne radionavigation devices.
[25] US262 limits use of this band to Goldstone, California.
[26] Except in the United States.
[27] 5.547C deletes FS in the United States.
[28] 5.549 adds FS and MS in certain countries.
[29] 5.547C deletes FS in the United States.
[30] 5.551A: EESS and SRS shall not cause interference to or claim protection from other primary services.
[31] US252 limits SRS to downlinks to Goldstone, California.
[32] US360 adds government FSS (S→E) on a primary basis.
[33] 5.149 urges protection of spectral line observations of the RAS between 36.43 and 36.5 GHz.
[34] US342 urges protection of spectral line observations of the RAS between 36.43 and 36.5 GHz.
[35] US263 disallows protection of SRS and EESS from the FS and MS.
[36] Except in the United States.
[37] Except in the United States.
[38] Except in the United States.
[39] Except in the United States.
[40] 5.149 urges protection of RAS in the bands 42.77-42.87 GHz, 43.07-43.17 GHz, and 43.37-43.47 GHz, especially from space and airborne stations.
[41] US342 urges protection of spectral line observations in this band.
[42] 5.149 urges protection of RAS in this band, especially from space and airborne stations.
[43] 5.340 prohibits all emissions.
[44] 5.555 adds RAS as a primary service for this band within the larger 47.2-50.2 GHz band.
[45] US264 forbids airborne stations.
[46] US297 allows feeder links for the BS.

across this range. Atmospheric attenuation under clear conditions is a function of water vapor and cloud amount for the 18 and 37 GHz bands, with measurements near 22.235 GHz showing higher attenuation than those of either window region owing to water vapor. Therefore, under clear conditions, algorithms benefit from noise reduction due to multiple independent measurements of the surface emission. Also, because the ~22.235 GHz measurements exhibit an additional dependence on integrated water vapor, the effects of atmospheric water vapor can be corrected in part, resulting in less residual systematic error due to the atmosphere.

An additional value of measurements in the region of ~37 GHz and/or ~31 GHz is the factor of ~2 improvement in horizontal spatial resolution (HSR) from diffraction-limited antennas compared with the HSR available at 18 GHz. The HSR requirements are often a key attribute for the retrieval of surface parameters, particularly over land, where data utility improves, in principle, for retrievals of homogenous pixels. However, under increasingly cloudy conditions, extinction due to Mie scattering and absorption more rapidly affects 37 GHz measurements, lowering their sensitivity to surface emission. Therefore, in principle, a mechanism exists for estimating cloud amounts and/or for removing some of the effect of clouds, preventing biasing of surface-parameter retrievals.

Many retrievals of surface and atmospheric environmental parameters in microwave remote sensing are carried out using a core combination of ~18, ~23, and ~37 GHz emission measurements. A partial list of these environmental parameters includes precipitation (§3.5.2), precipitable water (§3.5.5), cloud liquid water (§3.5.6), soil moisture (§3.5.7), snow cover (§3.5.8), sea-surface winds (§3.5.9), sea ice (§3.5.10), and ice surface temperature (§3.5.12). If atmospheric temperature and/or moisture sounding channels are available, they can also be included to provide additional aid in removing the effects of atmospheric variability.

3.6.2 SiO Masers

The 42.5-43.5 GHz band contains the lowest rotational transitions ($J = 1 \rightarrow 0$) of vibrational states of SiO. These transitions have been detected as strong maser emission from the envelopes of evolved stars and in young star-forming regions. VLBI measurements of these masers are providing probes of instellar envelopes, yielding information on temperature, density, stellar wind velocities, and envelope geometry.

3.6.3 Carbon Monosulphide

The 48.94-49.04 GHz band contains the lowest rotational transitions of CS and its isotopes such as $C^{33}S$ and $C^{34}S$. They serve primarily as a tracer of dense cold molecular clouds. Since CS is a relatively high density tracer, whereas CO is a low-density tracer, this species can also be an important diagnostic of the molecular material in other galaxies, and in particular the active nuclei and starburst galaxies.

3.6.4 Organic Acetylenic Chains

The spectral region from 30 to 50 GHz contains the strongest lines of HC_3N, a molecule that is a signpost of pre-protostellar conditions and a good temperature probe for extremely cold gas. It represents the shortest of a series of long-chain molecules of the form HC_xN ($x = 1, 3, 5, 7, 9, 11, \ldots$).

3.6.5 Continuum and Very Long Baseline Interferometry

The region is important for defining the high-frequency continuum spectra of galactic and extragalactic objects. For example, at these frequencies, one can observe emission from dust in extremely dense cores, which are opaque at higher frequencies.

3.6.6 Microwave Radiometric Imagery

See §3.5.13 for applications of microwave radiometric imagery.

3.7 BANDS BETWEEN 50 AND 71 GHZ

The bands, services, footnotes, and scientific observations for each band in the allocations between 50 GHz and 71 GHz are presented in Table 3.6.

3.7.1 Atmospheric Temperature Profiling

Retrieval of the atmospheric temperature profile using passive sounding in the ~50-62 GHz region uses the multitude of spin-rotational O_2 transitions in this region. Atmospheric attenuation varies from ~1 dB near ~50 GHz for clear atmospheric conditions to >200 dB at nadir for selected frequencies within ~58 to ~62 GHz. This characteristic provides the ability to estimate the atmospheric temperature within a specific altitude region by a careful selection and control of channel frequency. Atmospheric temperature profiles can be measured with an uncertainty of ~1 K with ~1-1.5 km altitude resolution to support a large variety of operational and scientific applications. The same oxygen resonance frequency that enables these measurements also leads to the strong absorption of terrestrial anthropogenic emissions, so that in many (albeit not all) cases the spectrum from ~58 to ~62 GHz can be shared with terrestrial active systems without interference.

Atmospheric profiles of temperature from polar-orbiting satellites are required to initialize the current and emerging global ocean-atmosphere models. These models provide essential global meteorological and oceanographic predictions for many civil and military applications. High profile-measurement accuracies are essential for proper operation and input for prediction models. For example, it has been shown that for temperature profile inputs not meeting 1 K to 3 K (depending on altitude) uncertainty, the profile data corrupt the model rather than increase its capability to forecast. Observational errors, usually on smaller scales, amplify the model error and, through nonlinear interactions, gradually spread to longer scales, eventually destroying forecast skill. In previous studies, numerical models using data with a standard deviation of 0.5°C at all levels had an exponential error growth with a doubling time of about 2.5 days. Similar results were found for other data types (i.e., winds, moisture, and so on), with forecast errors as high as 20 to 30 percent.

Atmospheric circulation is the main driver of regional changes in near-surface wind, temperature, precipitation, soil moisture, and other surface variables. These variables constrain the ability to make use of Earth’s resources and sustain humanity’s existence. Variations in these variables are strongly related through large-scale features of the atmospheric circulation as well as through interactions involving land and ocean surfaces. Atmospheric circulation is in turn dependent on the variables that define its structure and on dynamics such as wind speed and direction, temperature, humidity, and geopotential height. Two well-known examples of large-scale features are the El Niño-Southern Oscillation and the North Atlantic Oscillation, both of which are a product of global-scale climate fluctuations. Evidence from satellites globally observing associated changes in atmospheric variables may enhance the understanding of the specific relationships between surface and atmospheric variables and provide a better basis for validation of those relationships.

Currently, atmospheric temperature profiles are measured using LEO satellite microwave sounders. A number of present-day technological developments are enabling the future deployment of a geostationary orbiting microwave temperature sounder.

3.7.2 Mesospheric Temperature Profile

Within the ~50 to 62 GHz O_2 complex, spectrum near the strongest oxygen transitions (e.g., 9+ and 7+) is used to measure temperature profiles in the upper atmosphere from ~40 to ~90 km in altitude. The

TABLE 3.6 Frequency Allocations Between 50 and 71 GHz: Bands, Services, Footnotes, and Scientific Uses

Band (GHz)	Services	Footnotes	Scientific Use
50.2-50.4	EESS (passive), FS,[1] MS,[2] SRS (passive)	5.340,[3] 5.555A,[4] US263[5]	Temperature profiling
51.4-52.6	FS,[6] MS,[7] EESS[8] (passive), SRS[9] (passive), RAS[10]	5.556[11]	
1-3 52.6-54.25	EESS (passive), SRS (passive)	5.340, 5.556, US246[12]	Temperature profiling, interstellar O_2
54.25-55.78	EESS (passive), ISS, SRS (passive)	5.556B,[13] 909,[14] US263[15]	
54.25-56.9	EESS (passive), FS, ISS, MS, SRS (passive)	5.556A,[16] 5.557,[17] 5.558,[18] US263[19]	
56.9-57	EESS (passive), FS, ISS, MS, SRS (passive)	5.557, US263[20]	
57-58.2	EESS (passive), FS, ISS, MS, SRS (passive)	5.556A, 557, US263[21]	
58.2-59	EESS (passive), FS,[22] MS,[23] SRS (passive), RAS[24]	5.547, 5.556, US246	Interstellar O_2
59.0-59.3	EESS (passive), FS, ISS, MS, RLS, SRS (passive)	5.556A, 5.558, 5.559, US353	

NOTE: For definitions of acronyms and abbreviations, see Appendix I. For information about other features of this table, see §3.1.2, "Note to the Reader Regarding Frequency Allocation Tables."

[1] In the United States only.
[2] In the United States only.
[3] 5.340 prohibits all emissions.
[4] 5.555A allowed FS and MS as primary until July 1, 2000.
[5] US263 cancels protection of EESS and SRS from FS and MS.
[6] Except in the United States.
[7] Except in the United States.
[8] Only in the United States.
[9] Only in the United States.
[10] Only in the United States.
[11] 5.556 notes that radio astronomy observations may be carried out under national arrangements.
[12] US246 forbids all emissions.
[13] 5.556B adds MS on a low-density basis in Japan.
[14] Old series international footnote 909 allows AeMS subject to not causing harmful interference to ISS.
[15] US263 cancels protection of EESS and SRS from FS and MS.
[16] 5.556A limits use of this band by ISS.
[17] 5.557 adds RLS on a primary basis in Japan.
[18] 5.558 allows AeMS subject to not causing interference to ISS.
[19] US263 cancels protection of EESS and SRS from FS and MS.
[20] US263 cancels protection of EESS and SRS from FS and MS.
[21] US263 cancels protection of EESS and SRS from FS and MS.
[22] Except in the United States.
[23] Except in the United States.
[24] In the United States only.

Defense Meteorological Satellite Program Special Sensor Microwave Imager Sounder will use frequencies between ~60.4 and 61.2 GHz and a separate channel near 63 GHz to obtain such mesospheric temperature profiles. Splitting of the strong O_2 transitions by Earth's magnetic field provides vertical response (or, weighting) functions that depend on the polarization of the received signal.

3.8 BANDS BETWEEN 71 AND 126 GHZ

In addition to the bands listed in Table 3.7, the 78.00-79.00 GHz EESS active band is to be used for cloud monitoring and should be specifically listed rather than being relegated to a footnote, since it is a primary allocation. The spectrum within 102 and 126 GHz is not entirely allocated to EESS passive, but rather is broken into 102-105 GHz, 105-109.5 GHz, 109.5-111.8 GHz, 114.25-116 GHz, 116-119.98 GHz, and 119.98-122.25 GHz segments with different sharing services. EESS passive service is allocated only in the 109.5-111.8 GHz and 114.25-122.25 GHz bands. Per NTIA's Redbook, even the Radio Astronomy Service allocation is fragmented: primary between 76 and 77.5 GHz, secondary from 77.5 to 78 GHz, primary between 78 and 116 GHz. The fragmentation of the 71-106 GHz spectral region is unfortunate and should be addressed at future World Radiocommunication Conferences.

3.8.1 Interstellar Molecular Lines

Since there is relatively little absorption from atmospheric O_2 and H_2O, the 3 mm band between 65 and 115 GHz is perhaps one of the best high-frequency regions for both continuum and line observations of celestial objects. In particular, this band contains the fundamental ($J = 1 \rightarrow 0$), or lowest-energy, transition of most common interstellar molecules, including CO, HCO^+, HCN, CCH, CN, HNC, HCO, HNO, H_2CO, and N_2H^+. More than 100 molecules have been detected in this frequency range, as have 25 different isotopic species. These also include favorable transitions of such simple molecules as SO, SO_2, SiO, SiS, and MgNC and such complex molecules as CH_3CH_2OH, CH_3CH_2CN, and CH_3OCH_3. Two vibrational states of the transitions of SiO fall in this range; SiO is one of the few molecules

TABLE 3.7 Frequency Allocations Between 71 and 126 GHz: Bands, Services, Footnotes, and Scientific Uses

Band (GHz)	Services	Footnotes	Scientific Use
72.77-72.91	FS, FSS (E→S), MS, MSS (E→S), RAS[1]	5.149,[2] 5.556,[3] US270[4]	HC_3N (important lines at 72.039 GHz for DCO^+ and 72.415 GHz for DCN)
74-75.5	FS, FSS (S→E), MS, srs[5] (S→E)	US297[6]	$HCNH^+$, N_2O, H_2CO
75.5-76	AeMS, AeMSS, srs[7] (S→E)		
76-81	RAS (except secondary between 77.5-78), RLS, aems,[8] aemss,[9,10] srs[11] (S→E)	5.560[12]	HDO
81-84	RAS, FS, FSS (S→E), MS, MSS (S→E), srs[13] (S→E)		C_3H_2, HC_3N
84-86	RAS, FS, MS, BS, BSS, (ras)	US211[14]	NH_2D, CH_3CCH
86-92	EESS (passive), RAS, SRS (passive)	5.340,[15] US74,[16] US246[17]	SiO, $H^{13}CO^+$, HCO^+, HCN, CCH, HNC, CH_3CN, $HC^{15}N$, $H^{13}CN$, $HN^{13}C$, HCO

TABLE 3.7 Continued

Band (GHz)	Services	Footnotes	Scientific Use
92-94	FS, FSS (S→E), MS, RLS, RAS	5.149, 5.556	^{13}CS, N_2H^+, AlNC
94-94.1	EESS (active), RLS, SRS (active), RAS	5.562[18]	Cloud radar
95-100	MS, MSS, RNS, RNSS, RAS[19]	5.149, 5.555[20]	CS, SO, $C^{34}S$, MgNC
100-102	RAS, EESS (passive), FS,[21] MS,[22] SRS (passive)	5.341,[23] US246	Extragalactic CO, HC_3N
102-105	FS, FSS (S→E), MS,[24] RAS[25]	5.341, US211	CH_3CCH
105-116	EESS (passive), RAS, SRS (passive)	5.340, 5.341, US74, US246	SO, CN, CO, ^{13}CO, $C^{18}O$, $C^{17}O$, ^{13}CN
116-119.98	EESS (passive), FS, ISS, MS, SRS (passive)	5.341, 5.558, US211, US263	
119.98-120.02	EESS (passive), FS, ISS, MS, SRS (passive), aems	5.341, US211, US263	
120.02-126	EESS (passive), FS, ISS, MS, SRS (passive)	5.138,[26] US211, US263[27]	Temperature profiling

NOTE: For definitions of acronyms and abbreviations, see Appendix I. For information about other features of this table, see §3.1.2, "Note to the Reader Regarding Frequency Allocation Tables."

[1] In the United States only.
[2] 5.149 urges protection of RAS in this band.
[3] 5.556 allows RAS under national arrangements.
[4] US270 adds RAS to this band within the larger 71-74 GHz band.
[5] Except in the United States.
[6] US297 allows feeder links for BS.
[7] Except in the United States.
[8] Primary in the United States between 77.5 and 78 GHz.
[9] Primary in the United States between 77.5 and 78 GHz.
[10] In the United States only above 77 GHz.
[11] Primary in the United States between 77.5 and 78 GHz.
[12] 5.560 allows radars on space stations to be operated between 78 and 79 GHz on a primary basis for EESS and SRS.
[13] Except in the United States.
[14] US211 urges additional protection to RAS from adjacent bands.
[15] 5.340 prohibits all emissions.
[16] US74 limits protection of RAS from extraband radiation.
[17] US246 prohibits all emissions.
[18] 5.562 limits EESS and SRS to spaceborne cloud radars.
[19] 5.555 adds RAS as primary between 97.88 and 98.08 GHz.
[20] 5.555 adds RAS as primary between 97.88 and 98.08 GHz.
[21] Except in the United States.
[22] Except in the United States.
[23] 5.341 draws attention to SETI research in this band.
[24] Except in the United States.
[25] In the United States.
[26] 5.138 allows ISM applications subject to special agreements.
[27] US263 specifies that EESS and SRS will not be protected from FS and MS.

showing maser emission and the only one showing strong maser emission in an excited vibrational state. N_2H^+, HCS^+, $HCNH^+$, and HCO^+ are vitally necessary participants in the ion-molecule reactions believed to be key 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 can be studied. As an example, the basic molecule HCN has the isotopic species $H^{12}C^{14}N$, $H_3C^{14}N$, and $H^{12}C^{15}N$ in the 86-92 GHz range, and all have been observed in the interstellar gas. It is clear that this region of the millimeter spectrum will remain one of the most-used for radio astronomy.

3.8.2 Carbon Monoxide

The discovery of interstellar CO at 115.271 GHz has been of fundamental significance 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. Studies have yielded new information on the distribution of gas in spiral galaxies. Allowance for Doppler shifts characteristic of nearby and even distant galaxies is essential for adequate protection of radio spectral lines.

Because the CO molecule is so ubiquitous and therefore present under nearly all physical and chemical conditions, its emission is the principal tool available to astronomers today for the study of the star-forming gas in the Milky Way Galaxy, and even in quite distant galaxies. CO studies give information about disks around forming stars and, in the future, with the expansion of millimeter-wave interferometer instruments, they may tell of the conditions for planet formation. Furthermore, CO emission studies reveal the presence of bursts of star formation activity in nearby and, in some cases, distant galaxies. These bursts have recently been related to collisions between galaxies and possibly to the formation of massive black holes and quasars. CO lines are also used to measure the mass loss rates from late-type stars.

The 100-102 GHz band is used for radio astronomy observations of redshifted CO in distant galaxies.

The 200-300 GHz band contains the second available rotational line of carbon monoxide ($^{12}C^{16}O$), together with its isotopic variants $^{13}C^{16}O$ and $^{12}C^{18}O$. These are very strong and important lines both within our Galaxy and in distant galaxies. In combination with the first lines in the 106-116 GHz band, they permit the determination of the physical characteristics of the gas within the galaxies. The coverage for $^{12}C^{16}O$ extends to galaxies at velocities of 2000 km/s, but it should be much greater in order to give protection to the work of learning about the structure and evolution of much more distant galaxies in the future.

3.8.3 Isotope Ratios

One important use of molecular lines is the study of isotope ratios, in particular, the $^{12}C/^{13}C$, $^{16}O/^{18}O$, and $^{32}S/^{34}S$ ratios. These ratios give important insight into theories of nucleosynthesis in stars and models of star-formation rates and the relative masses involved, that is, galactic chemical evolution. The important molecules in this context are ^{12}CO, ^{13}CO, and ^{18}CO; ^{12}CN and ^{13}CN; and ^{12}CS, ^{13}CS, and $C^{34}S$. The fundamental transitions of CO and CN and their isotopomers are in the 3 mm band, as well as favorable lines of CS. All of these species are important isotopic tracers.

Molecules can also be used to investigate deuterium/hydrogen ratios. Because of chemical fractionation, very high deuterium/hydrogen ratios are found in certain interstellar molecules as a result of ion-molecule chemistry. DCN and DCO^+ are important tracers in this context. Their lowest-energy spectral transitions lie near 72 GHz.

3.8.4 Interstellar and Circumstellar Chemistry

The 3 mm band, along with the 2 mm window, is particularly relevant to studies of interstellar chemistry, as these bands contain favorable transitions of most known molecules. As mentioned, species of interest include molecular ions such as HCO^+ and $HCNH^+$, the free radicals CN and CCH, and a large number of organic molecules, including C_3H_2, CH_3OH, CH_3CH_2CN, CH_3COCH_3, and CH_3OCHO. Also, the spectral lines originating from long-chain carbon species such as C_3H, C_3N, C_4H, C_7H, C_8H, and so on are prominent in these bands, as well as those of silicon-, magnesium-, and aluminum-bearing molecules (SiS, SiC_2, SiC_3, MgCN, AlCl, AlNC, and so on). The long-chain molecules and the refractory species play significant roles in the chemistry of circumstellar envelopes of late-type stars.

3.8.5 Astrobiology

Some theories posit that interstellar chemistry may have supplied the prebiotic compounds essential for terrestrial life. Consequently, establishing the inventory of organic molecules in interstellar gas is of interest to the study of the origin of life. Because organic molecules have many favorable transitions at millimeter wavelengths, this spectral region is crucial for the identification of such species. The 2 and 3 mm spectral regions have been the prime wavelength regions for the detection of organic molecules. Many possible new organic compounds may be identified in interstellar gas. It is important to recognize that new frequencies are regularly becoming available for possible new molecules, and hence broadband protection of the 2 and 3 mm windows is desirable.

3.8.6 Atmospheric Temperature Profile

The atmospheric temperature profile can be derived using passive radiometric measurements on and near the 118.75 GHz O_2 transition. Temperature profiles derived from this band complement those derived using the 50-60 GHz complex by providing independent measurements, albeit with reduced sensitivity at higher altitudes and less penetrability of clouds and precipitation. However, diffraction-limited apertures of fixed size will yield temperature profiles with better horizontal spatial resolution with 118 GHz measurements compared with data from 50-60 GHz. As a result, channels near 118 GHz are being considered for use in sonding and imaging from a geostationary microwave sensor. Moreover, the difference in response between similar clear-air channels at 50-60 GHz and ~118 GHz will provide additional information on cloud and precipitation amounts.

3.8.7 Precipitation

Passive microwave measurements near 89 GHz play an important role in the retrieval of precipitation data, particularly over land. Owing to the combination of high emissivity and cloud thickness and temperature over land, signatures of convective precipitation cells are often strongest at 89 GHz. At this frequency there is high sensitivity to clouds over land, causing the upwelling brightness temperatures to be cooler rather than warmer, as observed over a relatively cold ocean background. Clouds over land exhibit much less contrast at lower microwave window frequencies (e.g., 10, 18, and 37 GHz) causing 8 GHz observations to play an important role in determining rain rate over land. See also §3.5.2.

3.8.8 Cloud Base Height and Cloud Parameters

A spaceborne 94 GHz cloud-profiling radar (CloudSat) was successfully launched in May 2006, with an objective of measuring the altitude and properties of clouds with 500 m vertical resolution, 1.2 km cross-track resolution, and with a sensitivity of –30 to –36 dBZ (decibels of *Z*, where *Z* is the energy reflected back to the radar, or reflectivity). This advanced W-band radar will gather information on the vertical structure of highly dynamic cloud systems to provide global measurements of cloud properties. These measurements will help scientists compile a database of cloud properties to improve the representation of clouds in global climate and numerical weather-prediction models.

Cloud base information for a range of cloud types, particle distributions (microphysics), and liquid water content is desired to support both operational and scientific objectives. Ceiling height data are vital to identify regions of potential aircraft icing and for determining the most effective altitudes for commercial flight operations. For climate measurements, cloud base height is critical for determining the long-wave energy budget at Earth's surface, and for understanding the impacts of anthropogenic aerosols on cloud formation, precipitation, and short- and long-wave energy fluxes.

3.8.9 Microwave Radiometric Imagery

See §3.5.13 for applications of microwave radiometric imagery.

3.9 BANDS BETWEEN 126 AND 400 GHZ

In addition to the bands listed in Table 3.8, the 130-134 GHz and 237.9-238 GHz (cloud radars only) are EESS active bands. The 155.5-158.5 GHz EESS passive band expires January 1, 2018.

3.9.1 Molecular Lines

The atmospheric windows at 1 mm (200-300 GHz) and 0.8 mm (325-375 GHz) contain a wide range of interstellar molecules. The $J = 3 \rightarrow 2$ and $J = 4 \rightarrow 3$ transitions of such species as HCO^+ and HCN are important tracers of high-density gas in the molecular clouds. The $J = 2 \rightarrow 1$ and $J = 3 \rightarrow 2$ lines of CO, as well as its isotopic variants, lie in these bands. Multiple transition studies of CO enable the density and temperature profiles of molecular clouds to be determined and are used as tracers of the total amount of molecular gas. Also in these wavelength regions, diatomic hydride and polyatomic hydride species have some of their lowest-energy rotational transitions, such as MgH, KH, H_2O, and H_3O^+. In fact, only at frequencies above 200 GHz can these hydride molecules be studied in the interstellar medium. Because they contain hydrogen atoms bonded to one heavier atom, they rotate very quickly. Therefore, their rotational transitions lie at higher frequencies than those of other interstellar molecules. Investigating simple hydride species is crucial for interstellar chemistry. Because of the high abundance of hydrogen, such species are prevalent in molecular clouds and are the initial species produced by interstellar chemistry.

Passive measurements near the 183.31 GHz water-vapor line, aided by measurements in the adjacent transmission window at the EESS-allocated bands of 150-151 GHz or 164-168 GHz, are critical for the global measurement of atmospheric water-vapor profiles. Measurements from spaceborne sensors in LEO are carried out to obtain atmospheric water-vapor profiles from Earth's surface to 100 mb with a measurement uncertainty of ~20 percent and ~35 percent for clear and cloudy conditions, respectively. These measurements are used to support meteorological forecasting and climatological modeling. Mois-

TABLE 3.8 Frequency Allocations Between 126 and 400 GHz: Bands, Services, Footnotes, and Scientific Uses

Band (GHz)	Services	Footnotes	Scientific Use
140.69-140.98	MS, MSS, RAS, RNS, RNS, rls	5.149,[1] 5.340,[2] 5.555[3]	H_2CO
144.68-147.12	RLS, aems, aemss, RAS[4]	5.149, 5.555	H_2CO, DCN (Note: DCO^+ at 144.07 GHz)
148.5-151.0	EESS (passive), RAS, SRS (passive)	US246	
150-151	EESS (passive), FS, FSS (S→E), MS, SRS (passive), ras	5.149, 5.385,[5] US263[6]	NO, H_2CO
151-156	FS, FSS (S→E), MS	US211[7]	CS, CH_3CN, CH_3CCH
156-158	EESS[8] (passive), FS, FSS (S→E), MS		
158-164	FS, FSS (S→E), MS	US211	
164-167	EESS (passive), RAS, SRS (passive)	US246	(H_2S at 168.7 GHz)
170-174.5	FS, ISS, MS, ras[9]	5.149, 5.385	
174.8-182.0	EESS (passive), FS, ISS, MS, SRS (passive), ras[10]	5.149, 5.385, US263	
176.5-182	FS, ISS, MS, ras[11]	5.149, 5.385, US211	
182-185	EESS (passive), RAS, SRS (passive)	5.340,[12] 5.563,[13] US246[14]	
185-190	FS, ISS, MS, EESS (passive), ras[15]	5.149, 5.385, US211	
190.0-191.8	EESS (passive), SRS (passive)	5.340, US246	
200-209	EESS (passive), RAS, SRS (passive)	5.341,[16] 5.563A, US74, US246	
209-217	FS, FSS (E→S), MS, RAS	5.341, 5.342	
217-226	FS, FSS (E→S), MS, RAS, SRS (passive)	5.562B, 5.341, 5.342	
226-231.5	EESS (passive), RAS, SRS (passive)	US246	
231.5-235	FS, FSS (S→E), MS, rls	US211	^{12}CO
235-238	EESS (passive), FS, FSS (S→E), MS, SRS (passive)	US263	
250-252	EESS (passive), SRS (passive), RAS[17]	5.149, 5.555[18]	NO
261-265	MS, MSS, RAS,[19] RNS, RNSS	5.149, 5.385,[20] 5.554, 5.555, 5.564[21]	HCN, CCH
265-275	FS, FSS, MS, RAS	5.149	HCO^+
275-300	FS,[22] MS,[23] (ras), (eess), (srs)	5.565[24]	N_2H^+

continued

TABLE 3.8 Continued

Band (GHz)	Services	Footnotes	Scientific Use
300-400	(ras), (eess), (srs)	5.565	CO, CS, CN, HCO^+, HCN, MgH, H_3O^+, SiO

NOTE: For definitions of acronyms and abbreviations, see Appendix I. For information about other features of this table, see §3.1.2, "Note to the Reader Regarding Frequency Allocation Tables."

[1] 5.149 urges protection of RAS.
[2] 5.340 forbids emissions from airborne stations and from space stations toward Earth between 140.69 and 140.98 GHz.
[3] 5.555 adds RAS as primary in the bands 140.69-140.98 GHz, 144.68-144.98 GHz, 145.45-145.75 GHz, and 146.82-147.12 GHz.
[4] 5.555 adds RAS as primary in the bands 140.69-140.98 GHz, 144.68-144.98 GHz, 145.45-145.75 GHz, and 146.82-147.12 GHz.
[5] 5.385 adds RAS as secondary in the bands 150-151 GHz, 174.42-175.02 GHz, 177-177.4 GHz, 178.2-178.6 GHz, 181-181.46 GHz, 186.2-186.6 GHz, and 257.5-258 GHz.
[6] US263 specifies that EESS and SRS will not be protected from FS and MS.
[7] US211 urges additional protection to RAS from adjacent bands.
[8] Except in the United States.
[9] In the sub-band 174.42-175.02 GHz.
[10] In the sub-band 174.42-175.02 GHz.
[11] In the sub-bands 177-177.4 GHz, 178.2-178.6 GHz, and 181-181.46 GHz.
[12] 5.340 forbids all emissions, but see 5.563.
[13] 5.563 adds FS and MS in the United Kingdom.
[14] US246 forbids all emissions.
[15] In the sub-band 186.12-186.6 GHz.
[16] 5.341 makes note of SETI observations in this band.
[17] In the sub-band 250-251 GHz.
[18] 5.555 adds RAS as primary for 250-251 GHz and 262.24-262.76 GHz.
[19] In the sub-band 262.24-262.76 GHz.
[20] 5.385 adds RAS as secondary for 257.5-258 GHz.
[21] 5.564 makes RAS primary within the larger band 252-265 GHz in Germany, Argentina, Spain, Finland, France, India, Italy, and The Netherlands.
[22] In the United States.
[23] In the United States.
[24] 5.565 urges that administrations take all practicable steps to protect the passive services from harmful interference in certain designated bands, and other bands yet to be identified, until the next competent World Radiocommunication Conference.

ture profiles can also be used to support path delay and attenuation estimates for active remote sensing systems (e.g., radar altimetry) and satellite radio-frequency links. Accurate measurements of upper tropospheric water vapor are also obtained by viewing Earth's limb from LEO to support scientific studies of the upper atmosphere and atmospheric chemistry. In general, measurements near 183 GHz are widely used. Observation from geostationary orbit is planned in the future.

3.9.2 Atmospheric Water-Vapor Profile

The hydrologic cycle is critical to the dynamical and thermodynamical functioning of the global climate system and to its impacts on human society. The distributions of water vapor, cloud liquid water, and cloud ice in the atmosphere and the evolution of these distributions with time determine to a great extent the radiation characteristics of clouds, with consequent large impacts on the radiation balance of the atmosphere. Water vapor is an important greenhouse gas, greatly influencing the surface radiation budget even in the absence of clouds. Condensation and evaporation of water in the atmosphere affect large transfers of energy and have enormous influence on large-scale circulation in the troposphere.

Atmospheric profiles of moisture measured from polar-orbiting LEO satellites are required to initialize high-resolution global ocean-atmosphere models that provide the global meteorological and oceanographic predictions necessary for civil and military operations. Much of the atmospheric moisture is concentrated close to Earth's surface in the lowest ~1.5-2.5 km of the atmosphere. Comparisons of model simulations indicate that if the measurement accuracies of moisture profiles are less than threshold values (generally those values listed above), the remotely sensed profile data that are used as input corrupt the model rather than increases its capability to forecast. Observational errors, usually on the smaller scales, amplify and, through nonlinear interactions, gradually spread to the longer scales, eventually destroying forecast skill. In previous studies, numerical models using data with a standard deviation of 0.5°C at all levels exhibited an exponential error growth with a doubling time of about 2.5 days. Similar results were found for other data types (i.e., winds, moisture, and so on) with forecast errors as high as 20 to 30 percent.

Passive measurements near the strong 183.31 GHz water-vapor line, aided by measurements in the adjacent transmission window at the EESS-allocated bands of 150-151 GHz or 164-168 GHz, are critical for the global measurement of atmospheric water vapor profiles. Measurements from spaceborne sensors in LEO are carried out to obtain atmospheric water-vapor profiles from Earth's surface to 100 mb with a measurement uncertainty of ~20 percent and ~35 percent for clear and cloudy conditions, respectively. These measurements are used to support meteorological forecasting and climatological modeling. Moisture profiles can also be used to support path delay and attenuation estimates for active remote sensing systems (e.g., radar altimeters) and satellite radio-frequency links. Accurate measurements of upper tropospheric water vapor are also obtained by viewing Earth's limb from LEO to support scientific studies of the upper atmosphere and associated atmospheric chemistry. In general, water-vapor measurements near 183 GHz are widely used.

3.9.3 Precipitation

Passive microwave remote sensing from satellites and aircraft at frequencies above 90 GHz are used to estimate hydrometeor properties of cirrus clouds and the higher altitude (frozen particle regimes) of convective and anvil clouds. Specific frequencies in use on various systems include 150 GHz, 166 GHz, 183.31±1 GHz, 183.31±3 GHz, 183.31±7 GHz, 183.31±10 GHz, 220 GHz, 325 GHz, 340 GHz, 380 GHz, 424 GHz, ~500 GHz, and 640 GHz. These channels are particularly sensitive to the frozen particles, and several have been used to estimate snowfall rate over land surfaces. Furthermore, since these channels tend to become opaque to the land surface in the presence of clouds, they may be useful in estimating light rain over land surfaces. Precipitation observation may be possible with high spatial resolution using a geostationary microwave sounder and frequencies at ~183, 340, 380, and 424 GHz.

It is important to have knowledge of cirrus clouds and the frozen particles in convective and anvil clouds for several reasons: (1) in order to enhance cloud-resolving models, (2) to better understand the relationships between the frozen and melting particles, (3) to clarify relationships between the passive observations and frozen particles, (4) to improve latent heating and global change models that are particularly sensitive to cirrus ice clouds and to the ice in convective and anvil clouds, and (5) to provide indirect information on surface rain rate below the cirrus anvil. Finally, real-time estimates of snowfall rate would be extremely useful for urban management.

3.9.4 Cloud Ice Water Path

Retrieval of Cloud Ice Water Path (CIWP) data is supported by passive microwave measurements at 89 GHz and above (e.g., 150, 166, 183, ~220, and ~340 GHz). Retrieval of CIWP data depends strongly on knowledge of the cloud particle size distributions. Therefore, retrievals are improved using multiple high-frequency brightness temperature measurements. Measurement uncertainties of ~10 percent for the range of ~0.5-2.6 kg/m^2 of CIWP are anticipated.

The inclusion of cloud microphysics into cloud and climate models within the decade is anticipated by many numerical weather modelers. Accordingly, measurements of cloud ice water will be needed to diagnose and validate these cloud models, which, in principle, have the ability to greatly improve the understanding of climate, rainfall, and precipitation variability and the atmospheric radiation budget.

3.9.5 Atmospheric Chemistry

The first Microwave Limb Sounder (MLS) on NASA's Upper Atmosphere Research Satellite used channels near 63, 183, and 205 GHz to measure emissions of chlorine monoxide, water vapor, ozone, and sulfur dioxide. Chlorine monoxide is a key reactant in the chlorine chemical cycle that destroys ozone. A new MLS instrument is on NASA's AURA spacecraft (launched in July 2004); it uses channels near 118 GHz for temperature and pressure profiling, 190 and 183 GHz for HNO_3 and water-vapor measurements, 240 GHz for O_3, and 640 GHz and 2.5 THz to support detailed studies of the stratosphere and the chemistry associated with ozone depletion.

3.9.6 Cosmic Background Radiation

The frequency band at 217-231 GHz provides a continuum window near the peak of the 2.7 K cosmic background radiation. This radiation, emitted when the universe was only about 100,000 years old, is one of the most significant discoveries in the study of cosmology. Further detailed studies of its properties will yield unique information about the early universe. Observations of the cosmic background from the ground are severely limited by the high, variable intensity of atmospheric emission. Observations near this frequency are important for such fundamental measurement as the velocity of the Galaxy with respect to the background radiation field and the rotation and symmetry of the universe. Because of the low intensity of the background radiation, accurate measurement of its distribution must be made from high-altitude aircraft, balloons, and spacecraft in an environment free from interference.

4

Technical Aspects of Protection for the Scientific Use of the Radio Spectrum

As long ago as 1960, the vulnerability of radio astronomy to interference was being documented by the International Radio Consultative Committee (CCIR) of the International Telecommunication Union (ITU).[1] The threshold levels of interference to radio astronomy bands are published in Recommendation ITU-R RA.769, "Protection Criteria for Radioastronomical Measurements."[2] With the increasing commercial use of the spectrum, it is ever more important to implement ways to protect radio astronomy and other services from adjacent and neighboring band interference resulting from air-to-ground and space-to-ground transmissions.

4.1 INTERFERENCE DETRIMENTAL TO RADIO ASTRONOMY

4.1.1 Radio Astronomy Signals

The threshold levels of interference detrimental to radio astronomy[3] given in Recommendation ITU-R RA.769 are specified in both power flux density (pfd) and spectral power flux density (spfd) at the radio telescope site. They are based on a consideration of the effect of interference on measurements of the total power received in a single antenna. Several criteria are basic to this analysis:

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[1] The CCIR has now been replaced by the ITU Radiocommunication Sector (ITU-R).

[2] These thresholds were originally published in CCIR Report 224: *Documents of the Xth Plenary Assembly,* Geneva, 1963, Vol. IV, p. 331.

[3] For background information from technical papers regarding the detection of radio frequency interference, see the following: E.G. Njoku, P. Ashcroft, T.K. Chan, and L. Li, "Global Survey and Statistics of Radio-Frequency Interference in AMSR-E Land Observations," *IEEE Transactions on Geoscience and Remote Sensing,* Vol. 43, No. 5, pp. 938-946, 2005; S.W. Ellingson and J.T. Johnson, "A Polarimetric Survey of Radio Frequency Interference in C- and X-Bands in the Continental United States Using WindSat Radiometry," *IEEE Transactions on Geoscience and Remote Sensing,* Vol. 44, No. 3, pp. 540-548, March 2006; and J.T. Johnson, A.J. Gasiewski, B. Güner, G.A. Hampson, S.W. Ellingson, R. Krishnamachari, N. Niamsuwan, E. McIntyre, M. Klein, and V.Y. Leuski, "Airborne Radio Frequency Interference Studies at C-band Using a Digital Receiver," *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 44, No. 7, Pt. 2, pp. 1974-1985, 2006.

- *The maximum level of interference that can be tolerated is that which increases the output power of the receiver by 10 percent of the root mean square (rms) noise level at the output after averaging for 2000 seconds.* Because of the low level of cosmic signals, radio astronomers almost always work at levels close to the limits set by the system noise. This criterion can be thought of as allowing uncertainties in the data to be increased by 10 percent.
- *Interference that is being considered is received in the antenna sidelobes*. It is not realistic to set thresholds for interference received in the main beam of a large radio telescope; such interference occurs only transiently and is dealt with by an editing of the data. A value for the sidelobe gain of 0 dBi (i.e., equal to that of an isotropic radiator) is used in the calculations.[4] The corresponding collecting area is $\lambda^2/4\pi$, where λ is the wavelength. The choice of the 0 dBi level is discussed in Chapter 4 of the *ITU Handbook on Radio Astronomy* (2003 edition),[5] with respect to the models of sidelobe gain for large antennas that are given in Recommendations ITU-R SA.509, S.580, and S.1428.
- *The signal-to-noise ratio at the output of the receiver is measured after the data values have been averaged for a period of 2000 seconds*. This value was typical of a long integration period in the 1960s when these calculations were first made; it continues to be used as a generally representative value. More recently there are observations, such as searches for prebiotic interstellar molecules, that push sensitivity to the limits of what is possible, with integration times on the order of days and even months.

For an interfering signal with pfd F_H, the interference-to-noise ratio can be calculated using the values of bandwidth, antenna noise temperature, and receiver noise temperature appropriate for each band. By equating the interference-to-noise ratio to 0.1, the threshold value F_H is obtained. The corresponding value of the threshold as spfd across the band is $S_H = F_H/\Delta f$, where Δf is the bandwidth. In Tables 1 and 2 of Recommendation ITU-R RA.769, values of F_H and S_H are given for representative radio astronomy bands across the spectrum for both continuum and spectral line observations. For continuum observations, the bandwidth used is the width of the allocated radio astronomy band; for spectral line (multichannel) observations, a value for the channel bandwidth appropriate for observations within the particular band is used. These values apply to observations that measure the total power received in a single antenna. Threshold values for interferometers and synthesis arrays are somewhat less stringent and are considered in §4.3.5. However, such instruments are not suitable for observations

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[4] The ability of an antenna/receiver system to detect a signal (or equivalently, the susceptibility of being adversely affected by signals) is dependent on the inherent sensitivity of the receiver, as well as on the direction that the antenna happens to be pointing relative to the transmitter. However, even though the antenna may not be pointing directly toward the transmitter, it nonetheless has some ability to receive signals from essentially all directions, which is roughly equivalent to the reception achieved by a small wire antenna. Such a wire antenna is approximately able to receive signals equally from all directions and is therefore called an isotropic antenna (although a true isotropic antenna is not realizable in practice). Since the reception is approximately the same, the off-axis performance is generally assumed to be equivalent on average. A ratio of 1 converts to 0 dBi, where the "i" refers to the fact that the comparison is being made to an isotropic antenna (see Appendix H for a full discussion of the 0 dBi sidelobe gain).

The use of 0 dBi means that the transmitter engineer need not consider the potential impact on a large variety of different radio telescope designs, the calculations are much simplified when gain and pointing direction are removed as variables, and the onus is on the radio astronomy design engineers and observers for dealing with regions of the radio astronomy antenna pattern near the main beam that are above isotropic. In some specific cases, for example, nongeosynchronous satellites, the 0 dBi model may not be adequate.

[5] International Telecommunication Union, *ITU Handbook on Radio Astronomy,* 2nd Ed., Geneva, Switzerland, 2003.

of extended objects, for which total-power observations are essential. Thus, the values in Tables 1 and 2 of Recommendation ITU-R RA.769 are the basic protection criteria for radio astronomy.

4.1.2 Remote Sensing

Environmental remote sensing measurements are extremely vulnerable to interference because there is no established way to detect and reject data that are contaminated with low-level interference—that is, interference that cannot be differentiated from signals originating from background thermal emission. The propagation of undetected contaminated data into numerical weather- and climate-prediction models may have a significant destructive impact on the reliability and/or quality of weather forecasting in some cases. In other cases observations may be partially obscured or denied completely owing to strong out-of-band or weak in-band emissions affecting regional or broad-area measurements.

Criteria for threshold levels of interference for passive remote sensing are defined by limiting the maximum permissible interference power within a reference bandwidth. This interference level is determined by fixing the unwanted signal level below 20 percent of $\Delta P = k\Delta T_e B$, where ΔT_e is the sensitivity of passive radiometric sensors, k is Boltzmann's constant, and B is the receiver bandwidth. Recommendation ITU-R SA.1028 provides the performance criteria for satellite passive remote sensing, and ITU-R SA.1029.1 provides the interference criteria that are compatible with those performance objectives by defining the maximum permissible interference level within a reference bandwidth which is not necessarily the same as any particular sensor's bandwidth.

The ITU further recommends that in shared frequency bands (except absorption bands), the availability of passive Earth Exploration-Satellite Service (EESS) sensor data shall exceed 95 percent from all locations in the sensor service area in the case where the loss occurs randomly, and that it shall exceed 99 percent from all locations in the case where the loss occurs systematically at the same locations. For three-dimensional measurements of atmospheric temperature of gas concentration or of water-vapor measurements, the availability of data shall exceed 99.99 percent. In bands that are allocated to the EESS and other passive services on an exclusive basis, the Radio Regulations state that "all emissions shall be prohibited (RR 5.340)." See §2.2.2.2, "Passive Sensors," in this handbook for more information.

For active microwave remote sensing, frequency and bandwidth requirements have also been studied in the ITU-R and can be found in Recommendation ITU-R SA.577.4. Performance criteria for active microwave remote sensors have been extensively studied and have been defined in terms of interfering power within a reference bandwidth. These recommendations can be found in ITU-R SA.1166.1.

4.1.3 Out-of-Band and Spurious Signals

When considering the regulation of signals that may spill into science service bands, account should be taken of how such signals will appear to the scientific instruments in question. Radio astronomy observations of transient phenomena generally are vulnerable. Ultrahigh-energy cosmic rays can be observed in the very high frequency (VHF) radio band, which can be interfered with by human-made sources such as ocean-wave radars. Giant pulses from pulsars share a similar time-frequency signature with chirp radar.[6] Nontransient observations can be interfered with by intermodulation and harmonic

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[6] See S.W. Ellingson and G.A. Hampson, "Mitigation of Radar Interference in L-Band Radio Astronomy," *Astrophysical Journal Supplement Series,* Vol. 147, No. 1, pp. 167-176, July 2003.

products from VHF broadcast signals (those generated from both the transmitting and the receiving end). These interfering signals are routinely detected throughout the L band and appear somewhat like spectral lines. They are not difficult to discriminate against, but their removal is time-consuming and often frustrating. In other words, interference that can be recognized as such can be excised, resulting only in a reduction in efficiency. But most unwanted signals that are not easily recognizable can masquerade as valid scientific data.

Because it is not possible for radio astronomy to operate in frequency bands for which there are transmitting antennas within the line of sight, the sharing of primary radio astronomy bands with services using satellite downlink transmissions or aeronautical transmissions is avoided. The most serious cases of interference to radio astronomy during recent years have resulted from transmitters on satellites producing unwanted emissions that fall within radio astronomy bands.

An example of interference from a geostationary orbit (GEO) satellite in a band adjacent to a radio astronomy band is provided by a European television broadcast satellite transmitting in the Fixed Satellite Service band 10.7-10.95 GHz. A measured spectrum showed that at 10.7 GHz, the upper edge of a primary radio astronomy band, the spfd from the satellite was approximately 39 dB greater than the corresponding threshold value for continuum observations in Table 1 of Recommendation ITU-R RA.769. The resulting radiation into the 10.6-10.7 GHz radio band makes that band completely unusable for observations by the 100 m radio telescope at Effelsberg, Germany: for further details see Chapter 6 in the *ITU Handbook on Radio Astronomy* (2003 edition).

The Russian Global Navigation Satellite System (GLONASS) radiodetermination system provides an example of interference from non-geostationary orbit satellites (non-GSO), shown in Figure 4.1. The

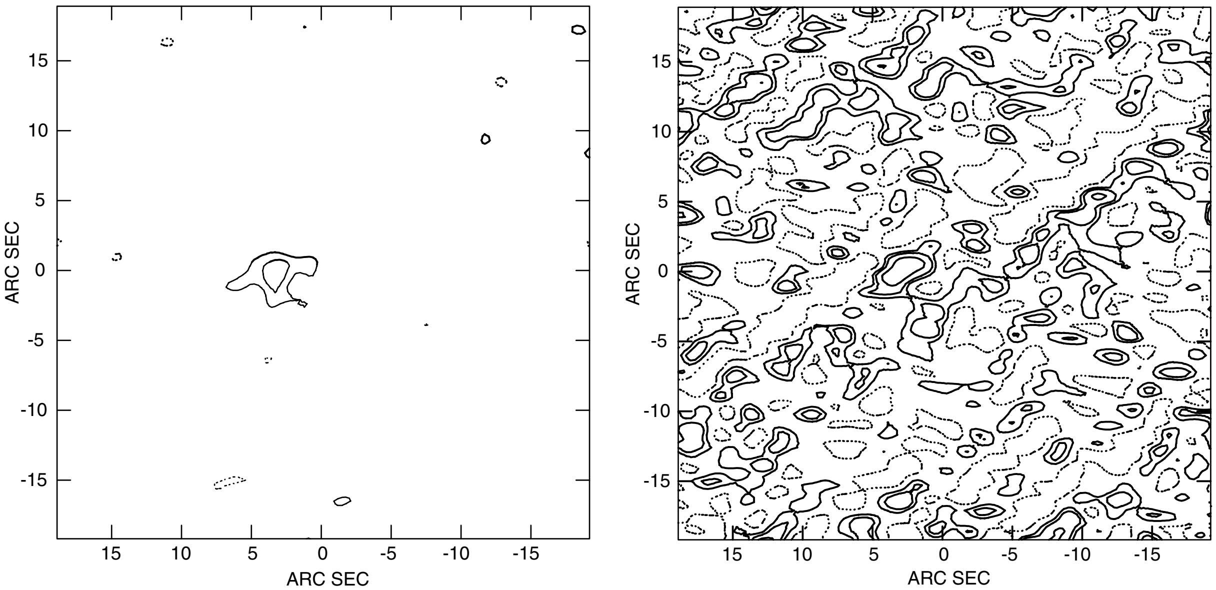

FIGURE 4.1 The effect of radio-frequency interference from an Iridium satellite on a radio astronomical observation, as shown by a comparison of two VLA images of the same OH/IR star at 1612 MHz. In the image on the left, no satellite is present. In the image on the right, an Iridium satellite is approximately 22 degrees from the star. Courtesy of Gregory B. Taylor, University of New Mexico.

modulation scheme used by these satellites (digital phase-shift keying) results in a power spectrum of the form $[\sin(\pi x)/\pi x]^2$, where x is a measure of the frequency relative to the center frequency of the transmitter. This type of spectrum has extensive sidelobes, which fall off with frequency by only 6 dB per octave of x. For many years these sidelobes have caused serious interference to observations in the 1610.6-1613.8 MHz and 1660-1670 MHz radio astronomy bands. Note that the receivers of GLONASS and similar systems that use this type of modulation have bandwidths that accept only the central maximum of the transmitted spectrum, and the extended sidebands serve no useful purpose.

Interference from satellites in GEO presents a special problem, because a constellation of interfering satellites distributed along the orbit could preclude the observation within a band of sky centered on the orbit. The apparent declination of the orbit varies by approximately 10° as seen from observatories at intermediate latitudes in the Northern and Southern Hemispheres of Earth (see Figure 1 in Annex 1 of Recommendation ITU-R RA.517, or see ITU-R RA.612). Thus, the whole sky can be observed if observations can be made to within 5° of the orbit from observatories in both hemispheres. In the sidelobe model in Recommendation ITU-R SA.509, the sidelobe gain at 5° from the main-beam axis is 15 dBi, so values of the detrimental thresholds for such observations are 15 dB lower than those based on a sidelobe gain of 0 dBi, as in the tables in Recommendation ITU-R RA.769. It is desirable that these lower detrimental thresholds be applicable to unwanted emissions from GEO satellites. For further discussion, see ITU-R RA.769 or Chapter 4 of the *ITU Handbook on Radio Astronomy* (2003 edition).

4.1.4 Occasional Unavoidable Interference

Recognizing that interference to radio astronomy is difficult to avoid, the ITU recommends that the fraction of time during which transmissions from any one service into a radio astronomy band exceed the corresponding threshold level (ITU-R RA.769) should not exceed 2 percent. The corresponding fraction of time for the aggregate emission from all services within the radio astronomy band should not exceed 5 percent. These limits are specified in Recommendation ITU-R RA.1513, Annex 1 of which contains a discussion of the basis and application of the limits.

4.2 SEPARATION OF INCOMPATIBLE SERVICES

4.2.1 Geographical Separation

The signal levels received by radio astronomers from cosmic objects are generally many tens of decibels weaker than the signal levels usually required for communications, broadcasting, radar, and other transmitting services. An important degree of protection from ground-based transmitters can be obtained by choosing observatory sites in locations of low population density and taking advantage of shielding by mountains or other terrain features. However, at frequencies above about 60 GHz, atmospheric absorption becomes important, and observatories must be located at high elevations. In these cases sites with effective terrain shielding are hard to find. Transmitters on aircraft, spacecraft, balloons, and high-altitude platform stations can remain within the line of sight over long distances. Choice of the site for an observatory is of little help in providing protection against them.

It is useful to establish a coordination zone around an observatory for protection against terrestrial transmissions of a particular service. For example, coordination zones are used for cases in which the radio astronomy band is shared with the terrestrial mobile service (see Box 4.1). Such a zone can be defined by the requirement that, at the observatory, the sum total of all transmissions from outside the zone should not exceed a detrimental threshold for the frequency band concerned. Coordination zones

BOX 4.1
Footnote US311

US311 Radio astronomy observations may be made in the bands 1350-1400 MHz, 1718.8-1722.2 MHz, and 4950-4990 MHz on an unprotected basis at the following radio astronomy observatories:

Allen Telescope Array, Hat Creek, California: Rectangle between latitudes 40° 00′ N and 42° 00′ N and between longitudes 120° 15′ W and 122° 15′ W
NASA Goldstone Deep Space Communications Complex, Goldstone, California: 80 kilometers (50 mile) radius centered on latitude 35° 18′ N, longitude 116° 54′ W
National Astronomy and Ionosphere Center, Arecibo, Puerto Rico: Rectangle between latitudes 17° 30′ N and 19° 00′ N and between longitudes 65° 10′ W and 68° 00′ W
National Radio Astronomy Observatory, Socorro, New Mexico: Rectangle between latitudes 32° 30′ N and 35° 30′ N between longitudes 106° 00′ W and 109° 00′ W
National Radio Astronomy Observatory, Green Bank, West Virginia: Rectangle between latitudes 37° 30′ N and 39° 15′ N and between longitudes 78° 30′ W and 80° 30′ W
National Radio Astronomy Observatory Very Long Baseline Array Stations: 80 kilometers (50 mile radius centered on:

	Latitude (North)	Longitude (West)
Pie Town, NM	34° 18′	108° 07′
Kitt Peak, AZ	31° 57′	111° 37′
Los Alamos, NM	35° 47′	106° 15′
Fort Davis, TX	30° 38′	103° 57′
North Liberty, IA	41° 46′	91° 34′
Brewster, WA	48° 08′	119° 41′
Owens Valley, CA	37° 14′	118° 17′
Saint Croix, VI	17° 46′	64° 35′
Mauna Kea, HI	19° 48′	155° 27′
Hancock, NH	42° 56′	71° 59′

Owens Valley Radio Observatory, Big Pine, California: Two contiguous rectangles, one between latitudes 36° 00′ N and 37° 00′ N and between longitudes 117° 40′ W and 118° 30′ W and the second between latitudes 37° 00′ N and 38° 00′ N and between longitudes 118° 00′ W and 118° 50′ W.

"In the bands 1350-1400 MHz and 4950-4990 MHz, every practicable effort will be made to avoid the assignment of frequencies to stations in the fixed and mobile services that could interfere with radio astronomy observations within the geographic areas given above. In addition, every practicable effort will be made to avoid assignment of frequencies in these bands to stations in the aeronautical mobile service which operate outside of those geographic areas, but which may cause harmful interference to the listed observatories. Should such assignments result in harmful interference to these observatories, the situation will be remedied to the extent practicable."

SOURCE: Reprinted from FCC, Online Table of Frequency Allocations, 47 C.F.R. § 2.106, revised on November 29, 2006, accessed on December 14, 2006.

can also be effective for protection in cases in which the potentially interfering transmissions are from a service with an allocation close to a radio astronomy band edge.

Defining the boundaries of a zone requires knowledge of the radiated powers in the direction of the observatory and a determination of the transmission loss in various directions with respect to the observatory. The transmission loss for propagation over terrain is calculable from terrain profiles. Major observatories usually have gridded elevation data for their surrounding area and software for the calculation of propagation loss. In the case of terrestrial mobile transmitters, it is often useful to use the Monte Carlo method to determine how the flux density at the observatory varies with the size of the coordination zone, using the criteria in Recommendation ITU-R RA.1513 for the percentages of time for which flux density in excess of the detrimental thresholds can be allowed. If it is necessary that a transmitter be sited within the coordination zone, then coordination between the transmitting service and the observatory is required. Protection of the observatory may be possible by various means, such as placing a null in the pattern of the transmitter in the direction of the observatory or, if the allocated transmitter frequency is outside the radio astronomy band, by additional filtering at the transmitter.

The calculation of separation distances for services in shared bands and the use of coordination zones are discussed in Annex 1 of Recommendation ITU-R RA.1031 and, for observations above 60 GHz, in ITU-R RA.1272.

4.2.2 Spectral Separation

A second strategy for mitigating the detrimental effect of an emission on a passive service is that of spectral separation. In this strategy, the center frequencies of the active-service emissions are moved sufficiently far from the band of interest to the active service so as to reduce detrimental effects to an acceptable level.

The required separation depends on the strength and spectrum of the emission as seen by the receiver, as well as on the design of the receiver. All emissions naturally have spectra that extend above and below the carrier frequency. Regardless of how this emission is filtered before transmission, some fraction of this power remains. The total power that is subsequently delivered to a band used by passive services then depends on the transmitting power and the characteristics of the transmitter's filter.

This design of the receiver determines the vulnerability of the receiver to out-of-band emissions through a separate mechanism: compression. Just as in the design of communications receivers, receivers for passive services represent a trade-off between sensitivity and linearity. The extremely weak nature of the signals of interest to scientific users constrains sensitivity requirements, with the result that a low-noise figure is essential. This consideration subsequently limits the type of filtering that can be done at the receiver. For example, any filter preceding the first amplifier must have sufficiently low insertion loss so as not to dominate the noise figure.

This constraint on the filter's insertion loss limits the order of the filter design, which in turn limits the rate of attenuation with increasing frequency separation. Thus, the need for high sensitivity in the passive scientific services limits the amount of suppression that can be achieved for out-of-band signals. Just as in a communications receiver, out-of-band signals stronger than a threshold determined by this suppression cause the receiver to enter a nonlinear mode of operation—that is, compression. At this point, received signals become distorted.

In summary, there are two technical considerations in determining the separation between active and passive services required to limit interference to acceptable levels: (1) the actual out-of-band power spectral density delivered to the receiver, and (2) the receiver's limited ability to maintain linearity in the presence of strong out-of-band emissions, owing to the need to achieve an extremely low noise figure.

There is no substitute for a situation-specific engineering analysis to determine the actual potential for detrimental interference due to these mechanisms; nonetheless, the situation is clearly helped by preferentially avoiding the assignment of bands used by high-power transmitters near the band edges of passive services.

4.3 TECHNOLOGICAL SOLUTIONS

In considering interference from transmitters in other bands, definitions of the following terms, which can be found in Appendix A, are important: necessary bandwidth, out-of-band emission (OOBE), spurious emission, unwanted emissions.[7] In addition, OOBEs are usually defined as those that fall within ±250 percent of the necessary bandwidth from the band center. With a few exceptions, spurious emissions are those at frequencies that are separated from the band center by more than ±250 percent of the necessary bandwidth. Further discussion of these definitions can be found in Chapter 6 of the *ITU Handbook on Radio Astronomy* (2003 edition).

Interference from transmitters in other bands can be generated by several mechanisms:

- Modulation sidebands can fall within a neighboring radio astronomy band when the transmitted spectrum is not adequately filtered.
- Two or more strong signals in a system that has a nonlinear response can generate beat frequencies at sums and differences of the frequencies and their harmonics.
- Harmonics can be generated by nonlinear responses within the transmitter, and filtering of the output to remove such unwanted responses may be absent or inadequate.

Limits on spurious emissions are given in Appendix 3 of the ITU Radio Regulations, and also in Recommendation ITU-R SM.329 (spectrum-management series). However, these limits generally fall short of being able to protect radio astronomy to the required levels (Recommendation ITU-R RA.769) by several tens of decibels. Further discussion is given in Chapter 6 of the *ITU Handbook on Radio Astronomy* (2003 edition), including calculations based on these limits as applied to non-GSO and GEO satellites.

4.3.1 Advanced Modulation

The extensive unwanted sidebands generated by types of digital phase-shift keying are mentioned in §4.1.2. One method of control of the sidebands of these and similar types of digital modulation is through the use of modulation techniques that control the rate of change of amplitude or phase at the transitions and thereby greatly reduce the level of unwanted frequency components that cause the sidebands. Several practical modulation systems of this type have been developed—for example,

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[7] For background information from technical papers regarding the mitigation of radio-frequency interference, see the following: American Geophysical Union, "Mitigation of Radio Frequency Interference in Radio Astronomy," *Radio Science,* Vol. 40, No. 5, 2005, available at http://www.agu.org/journals/ss/RADFREQ1/, accessed November 15, 2006; F.H. Briggs and J. Kocz, "Overview of Technical Approaches to Radio Frequency Interference Mitigation," *Radio Science,* Vol. 40, No. 5, pp. RS5S02.1-RS5S02.11, 2005; S.W. Ellingson, "RFI Mitigation and the SKA," *Experimental Astronomy,* Vol. 17, Nos. 1-3, pp. 261-267, June 2004, reprinted in *The Square Kilometre Array: An Engineering Perspective,* P.J. Hall (ed.), Springer, Dordrecht, The Netherlands, 2005; and A.J. Boonstra, "Radio Frequency Interference Mitigation in Radio Astronomy," Netherlands Foundation for Research in Astronomy, Delft, The Netherlands, June 16, 2005.

Gaussian-filtered minimum shift keying. These are capable of reducing the power level in the sidebands by many tens of decibels.

4.3.2 Filtering in Radio Astronomy Receivers

As explained in §4.2.2, the ability of passive services to employ filtering of sufficiently high order to mitigate the deleterious effects of emissions outside the radio astronomy band is severely limited by the need to achieve an extremely low noise figure. The requirements for a filter designed to mitigate out-of-band emission effectively must take into account (1) the strength of the interfering signal at the receiver, (2) the total received power level at which the receiver enters a state of compression, and (3) the potential for the generation of harmonic and intermodulation products due to any power remaining after filtering. It is not possible—or reasonable—to assign a single requirement for out-of-band suppression achieved by a filter for this application; situation-specific engineering analysis is required.

It should be noted that in certain cases it is possible to do better by employing alternative filtering technologies. For example, it may be more effective to notch specific interferers than to develop filters with broad band-stop characteristics. Also, it is now possible to design filters using cooled or superconducting materials that allow greater out-of-band suppression to be achieved without compromising insertion loss (sensitivity), albeit at greatly increased cost. As stated above, a proper situation-specific engineering analysis is required to determine whether these alternative techniques can provide the necessary attenuation.

4.3.3 Filtering in Transmitters

Band-pass filtering in transmitters to confine the transmitted power to the allocated band of the transmitting service can be an effective technique in reducing band-edge interference. In certain cases it introduces technical difficulties. For example, in very high power transmitters, as used in some terrestrial television stations, the power dissipated in an output filter is a serious consideration. In some satellite transmitters, such as those of the Iridium system, the transmitting antenna is a phased array in which each radiating element is driven by a separate power amplifier. Power limitations on satellites necessitate the use of power amplifiers in which linearity is sacrificed to some degree to obtain high efficiency. Since harmonics and intermodulation products can be generated by nonlinearity in the output stages, effective filtering requires a separate filter for each amplifier. The additional weight of such filters can make their implementation impractical. Filtering is more practical in satellites which use, for example, a parabolic reflector antenna in which the filtering is required in only one (or a small number) of signals going to the feed system.

4.3.4 Transmitter Beamshaping

In the case of transmitters in fixed terrestrial locations, it is often possible to place a null in the radiation pattern in the direction of a radio astronomy observatory. This technique has been used on numerous occasions to protect radio telescopes at Green Bank, West Virginia, within the National Radio Quiet Zone. In the case of a simple antenna such as a vertical dipole, generating the null basically requires using two such dipoles, fed through a power divider, and phased so that the two signals cancel for propagation in the direction of the observatory.

4.3.5 Interferometric Excision

For a radio telescope that consists of a combination of individual antennas, the response to interference is generally reduced relative to that of a system that measures the total power received in a single antenna. The simplest combination is a two-element interferometer: that is, a system with two spaced antennas connected to a receiving system that produces an output proportional to the voltage product of the two received signals. Synthesis arrays consist of arrays of antennas connected in pairs as interferometers.

Two effects reduce the response to interference in interferometric systems. These are related to the fringe oscillations that occur as the relative phase of the signal from the two antennas varies, and, for wideband systems, to the decorrelation that results from the difference in the time delays of the interfering signals in reaching the two antennas.

The treatment of interference in these cases is more complicated than for a single antenna. Results for two synthesis arrays and for very long baseline interferometry (VLBI) are plotted as a function of frequency in Recommendation ITU-R RA.769 and in the *ITU Handbook on Radio Astronomy* (2003 edition, Figure 4.2). These results are expressed in terms of the detrimental threshold levels for interference. The period of the fringe oscillations increases as the baseline (spacing) of the antennas, measured in wavelengths, is increased. The reduction in the interference response becomes effective when the fringe period is similar to or less than the time for which each data point is averaged. The reduction increases with frequency, since the fringe periods decrease. As the interference response is decreased, the corresponding detrimental threshold is increased.

For example, for the Very Large Array (VLA) in its longest-spacing configuration, the detrimental threshold at meter wavelengths is approximately 12 dB higher than that for a single antenna, and at 43 GHz it is 35 dB higher. For VLBI, in which the antenna spacings are typically 100 km or more, the reduction of the fringe responses is effectively complete, but other effects of the interference result in detrimental thresholds no more than 40 to 50 dB higher than the corresponding single-antenna values.

It is important to note that observations using interferometric techniques are applicable to measurements of discrete sources, and VLBI is only applicable to exceedingly small, bright objects. Total-power measurements using single antennas remain essential for measurements of extended sources and do not enjoy this advantage. Also, the ability of interferometric arrays to discriminate against interference decreases as the antennas become more closely spaced, as required for measurements of extended sources.

4.4 MITIGATION TECHNIQUES FOR PASSIVE REMOTE SENSING

Increased occurrences of radio-frequency interference (RFI) have been noted by passive remote sensing in regions of the spectrum that are heavily used by other services. For example, airborne radiometers operating within the EESS-allocated 1400-1427 MHz band have incurred interference from radiolocation services operating adjacent to the band.

In the C-band region (5-7 GHz), NASA's Earth Observing System Advanced Microwave Scanning Radiometer on Aqua is the first spaceborne radiometer with channels near 6.8 GHz since the Nimbus 7 Scanning Multi-channel Microwave Radiometer that stopped operating in September 1987. There is no EESS allocation near 6.8 GHz, and subsequent use of this spectral region, primarily by the fixed service, mobiles service, and fixed-satellite service, in accordance with the national and international allocations, has caused the band to be unusable for passive microwave measurements over land in much of the world's developed regions without the application of RFI mitigation.

RFI mitigation techniques are being explored for passive radiometric observations in RFI-affected areas. In general, these techniques require costly and extensive modifications to the sensor and retrieval algorithms.

4.4.1 Sub-banding

The technique of sub-banding requires the sensor's receiver passband to be split into multiple sub-bands. Calibrated brightness temperatures are derived for each sub-band and are intercompared to identify any sub-bands that may have brightness temperatures exceeding a predetermined variance from the group. A logic tree is followed based on the level of agreement in brightness temperatures among the sub-bands. In cases where one sub-band is determined to be an outlier, it can be thrown out and the others averaged to provide an estimate of brightness temperature with only degradation in noise performance (sensitivity).

4.4.2 Digitization and Signal Excision

The digitization and signal-excision technique requires the signal passband to be digitally sampled. Initially this procedure was developed to be effective against RFI from pulsed emitters. After digital sampling, the time sequence of samples is checked for large deviations that are characteristic of coherent RFI. If the pulse repetition rate and pulse duration of the interferer are known, the input can be effectively blanked during the pulse period with little impact to the radiometric sensitivity and accuracy.

4.5 GOALS FOR ADDITIONAL PROTECTION

4.5.1 Bandwidths

In general, a 1 to 2 percent bandwidth is the minimum practical allocation; a 5 percent bandwidth would be desirable for the continuum bands. This practice is strongly reinforced by the new and rapidly increasing requirements for bandwidth allocation at all frequencies, and it addresses the concerns for both EESS and radio astronomy applications. For example, this requirement can be met by the use of the same fractional bandwidth allocations for spectral lines (such as for complex molecular line studies in the Galaxy and for redshifted lines of distant galaxies) as well as for continuum astronomy, so long as the allocated bands occur reasonably frequently throughout the full spectrum.

4.5.2 Unwanted Emissions

The EESS and Radio Astronomy Service communities share mutual concerns regarding unwanted emissions. In particular, passive EESS observations are prone to the same problems that face the radio astronomy community, although the two communities are usually looking in opposite directions (one looking to, the other from, Earth). Strong efforts must be made to protect radio astronomy bands from interference due to air- or space-to-ground transmissions in other bands.[8] Passive services are particu-

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[8] See Appendix A for ITU definitions relating to interference.

larly sensitive to spurious, out-of-band, and harmonic emissions from other services. A major effort to modernize and upgrade engineering standards for active services is desirable, especially with regard to out-of-band emissions. Modernization of these standards would be useful to other services as well as to radio astronomy. This is particularly the case with airborne and satellite transmitters because of the potential clear line of sight to the radio telescope and devices that do not require licensing.

4.5.3 New Frequencies of Interest

In the past 30 years, radio astronomy 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 amino acids. It is anticipated that in the future, still-more-complex molecules, and possibly amino acids, will be found. The identification of complex molecules can be made only by detecting of a number of radio lines. Consequently, observations may be necessary either in or adjacent to bands allocated to other services. If unwanted emissions are minimized, observations adjacent to the bands of other services may be possible.

Appendixes

Appendix A

Definitions of Terms

The following National Telecommunications and Information Administration definitions are reprinted from the ITU Radio Regulations,[1] as indicated by the parenthetical "RR."

Accepted Interference:[2] Interference at a higher level than that defined as permissible interference and which has been agreed upon between two or more administrations without prejudice to other administrations. (RR)

Allocation (of a frequency band): Entry in the Table of Frequency Allocations of a given frequency band for the purpose of its use by one or more (terrestrial or space) radiocommunication services or the radio astronomy service under specified conditions. This term shall also be applied to the frequency band concerned. (RR)

Carrier Power (of a radio transmitter): The average power supplied to the antenna transmission line by a transmitter during one radio-frequency cycle taken under the condition of no modulation. (RR)

Class of Emission: The set of characteristics of an emission, designated by standard symbols, e.g., type of modulation of the main carrier, modulating signal, type of information to be transmitted, and also if appropriate, any additional signal characteristics. (RR)

Effective Radiated Power (e.r.p.) (in a given direction): The product of the power supplied to the antenna and its gain relative to a half-wave dipole in a given direction. (RR)

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[1] National Telecommunications and Information Administration, *Manual of Regulations and Procedures for Federal Radio Frequency Management (Redbook)* (2003 edition), available at http://www.ntia.doc.gov/osmhome/redbook/6.pdf, accessed August 16, 2006.

[2] The terms "accepted interference" and "permissible interference" are used in the coordination of frequency assignments between administrations.

Equivalent Isotropically Radiated Power (e.i.r.p.): The product of the power supplied to the antenna and the antenna gain in a given direction relative to an isotropic antenna (absolute or isotropic gain). (RR)

Gain of an Antenna: The ratio, usually expressed in decibels, of the power required at the input of a loss free reference antenna to the power supplied to the input of the given antenna to produce, in a given direction, the same field strength or the same power flux density at the same distance. When not specified otherwise, the gain refers to the direction of maximum radiation. The gain may be considered for a specified polarization. Depending on the choice of the reference antenna a distinction is made between:

- absolute or isotropic gain (Gi), when the reference antenna is an isotropic antenna isolated in space;
- gain relative to a half-wave dipole (Gd), when the reference antenna is a half-wave dipole isolated in space whose equatorial plane contains the given direction;
- gain relative to a short vertical antenna (Gv), when the reference antenna is a linear conductor, much shorter than one quarter of the wavelength, normal to the surface of a perfectly conducting plane which contains the given direction. (RR)

Harmful Interference: Interference which endangers the functioning of a radio navigation service or of other safety services or seriously degrades, obstructs, or repeatedly interrupts a radio communication service operating in accordance with these Regulations. (RR)

Interference: The effect of unwanted energy due to one or a combination of emissions, radiations, or inductions upon reception in a radio communication system, manifested by any performance degradation, misinterpretation, or loss of information which could be extracted in the absence of such unwanted energy. (RR)

Mean Power (of a radio transmitter): The average power supplied to the antenna transmission line by a transmitter during an interval of time sufficiently long compared with the lowest frequency encountered in the modulation taken under normal operating conditions. (RR)

Necessary Bandwidth: For a given class of emission, the width of the frequency band which is just sufficient to ensure the transmission of information at the rate and with the quality required under specified conditions. (RR) (See Annex J for formulas used to calculate necessary bandwidth.)

Occupied Bandwidth: The width of a frequency band such that, below the lower and above the upper frequency limits, the mean powers emitted are each equal to a specified percentage B/2 of the total mean power of a given emission. Unless otherwise specified by the ITU-R for the appropriate class of emission, the value of B/2 should be taken as 0.5%. (RR)

Out-of-band Emission: Emission on a frequency or frequencies immediately outside the necessary bandwidth which results from the modulation process, but excluding spurious emission. (RR)

Peak Envelope Power (of a radio transmitter): The average power supplied to the antenna transmission line by a transmitter during one radio-frequency cycle at the crest of the modulation envelope taken under normal operating conditions. (RR)

Permissible Interference:[3] Observed or predicted interference which complies with quantitative interference and sharing criteria contained in these Regulations or in ITU-R Recommendations or in special agreements as provided for in these Regulations. (RR)

Power: Whenever the power of a radio transmitter etc. is referred to it shall be expressed in one of the following forms, according to the class of emission, using the arbitrary symbols indicated:

- peak envelope power (PX or pX);
- mean power (PY or pY); and
- carrier power (PZ or pZ).

For different classes of emission, the relationships between peak envelope power, mean power, and carrier power, under the conditions of normal operation and of no modulation, are contained in ITU-R Recommendations which may be used as a guide. For use in formulae, the symbol p denotes power expressed in watts and the symbol P denotes power expressed in decibels relative to a reference level. (RR)

Spurious Emission: Emission on a frequency or frequencies which are outside the necessary bandwidth and the level of which may be reduced without affecting the corresponding transmission of information. Spurious emissions include harmonic emissions, parasitic emissions, intermodulation products, and frequency conversion products, but exclude out-of-band emissions. (RR)

Unwanted Emissions: Consist of spurious emissions and out-of-band emissions. (RR)

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[3] The terms “accepted interference” and “permissible interference” are used in the coordination of frequency assignments between administrations.

Appendix B

Information on Footnotes to Science Services Allocations

Radio regulations are adopted by adhering Administrations and have treaty status. Footnotes to these regulations often contain critical information that provides protection to particular services on a primary or secondary basis. These footnotes change frequently. For the most current list of footnotes see http://www.fcc.gov/oet/spectrum/table/fcctable.pdf. Box B.1 gives an example of several different types of footnotes to demonstrate the nature of footnotes and their role in spectrum policy.

BOX B.1
Sample Footnotes

International Footnotes

Example:

5.372 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. 29.13 applies).

General U.S. Footnotes

Example:

US81 The band 38-38.25 MHz is used by both Government and non-Government radio astronomy observatories. No new fixed or mobile assignments are to be made and Government stations in the band 38-38.25 MHz will be moved to other bands on a case-by-case basis, as required, to protect radio astronomy observations from harmful interference. As an exception however, low powered military transportable and mobile stations used for tactical and training purposes will continue to use the band. To the extent practicable, the latter operations will be adjusted to relieve such interference as may be caused to radio astronomy observations. In the event of harmful interference from such local operations, radio astronomy observatories may contact local military commands directly, with a view to effecting relief. A list of military commands, areas of coordination, and points of contact for purposes of relieving interference may be obtained upon request from the Office of the Chief Scientist, Federal Communications Commission, Washington, D.C. 20554.

Government (U.S.) Footnotes

Example:

G6 Military tactical fixed and mobile operations may be conducted nationally on a secondary basis; (1) to the meteorological aids service in the band 403-406 MHz; and (2) to the radio astronomy service in the band 406.1-410 MHz. Such fixed and mobile operations are subject to local coordination to ensure that harmful interference will not be caused to the services to which the bands are allocated.

Nonfederal Government (U.S.) Footnotes

Example:

NG124 In the Public Safety Radio Service allocation within the bands 30-50 MHz, 150-174 MHz and 450-470 MHz, Police Radio Service licensees are authorized to operate low powered radio transmitters on a secondary non-interference basis in accordance with the provisions of Section 2.803 and 90.19 (f) (5) of the Rules.

Appendix C

International Astronomical Union Spectral Lines of Most Importance Below 300 GHz

At each triennial meeting of the General Assembly, the International Astronomical Union (IAU) carefully reviews the list of astrophysically most important spectral lines that it maintains. The IAU expresses the need to protect these frequency bands from in-band, band-edge, and harmonic emissions, especially from spaceborne transmitters.

In preparation for World Radiocommunication Conference 2000, which revised the allocations above 71 GHz, a millimeter-wavelength working group of the Scientific Committee on Frequency Allocations for Radio Astronomy and Space Science examined all then-known transitions in the millimeter and submillimeter wavebands. The working group selected a limited number of the astrophysically most important spectral lines to supplement the earlier lists, such as those produced by the IAU, to be used in allocating frequency bands to the Radio Astronomy Service. Spectral lines below 300 GHz are listed in Table C.1. (Unless otherwise noted, the band limits are Doppler-shifted frequencies corresponding to radial velocities of ±300 km/s, consistent with line radiation occurring in the Galaxy. These data and further information can be found on the Web site of the European Science Foundation's Committee on Radio Astronomy Frequencies at http://www.astron.nl/craf/iaulist.htm.)

TABLE C.1 The Most Important Spectral Lines Below 275 GHz

Substance	Formula	Frequency (GHz)	Suggested Minimum Band (GHz)	Band Allocation Status[1]
Deuterium	D I	0.327384	0.327-0.3277	P
Hydrogen	HI	1.420406[2,3]	1.370-1.427	S 1.33-1.40 P 1.40-1.427
Hydroxyl radical	OH	1.6122314[4,5]	1.6068-1.6138	P 1.6106-1.6138
		1.6654026[6]	1.6598-1.6671	P 1.66-1.67
		1.6673596[6]	1.6618-1.6690	
Hydroxyl radical	OH	1.7205303[3,6]	1.7148-1.7222	S 1.7188-1.7222
Methyladyne	CH	3.2637943[3,6]	3.2424-3.2671	S 3.260-3.267
		3.3354813[3,6]	3.3244-3.3388	S 3.332-3.339
		3.3491933[3,6]	3.3380-3.3525	S 3.3458-3.3525
Formaldehyde	H_2CO	4.8296603[3,6]	4.8136-4.8345	S 4.8-4.9
Methanol	CH_3OH	6.6685183[3,7]	6.6618-6.6752	S 6.650-6.6752
Helium	$^3He^+$	8.665650	8.6570-8.6743	
Methanol	CH_3OH	12.178[3,8]	12.17-12.19	
Formaldehyde	H_2CO	14.488[3,6]	14.44-14.50	S 14.47-14.50
Cyclopropenylidene	C_3H_2	18.343[3,6,8]	18.28-18.36	
Water vapor	H_2O	22.235[3,6]	22.16-22.26	F 22.01-22.21 P 22.21-22.50
Dicarbon monosulphide	CCS	22.344	22.32-22.37	
Ammonia	NH_3	23.694[6]	23.61-23.89	P 23.60-24.00
		23.723[6]		
		23.870[6]		
Sulphur monoxide	SiO	30.002	29.97-30.03	
Methanol	CH_3OH	36.169	36.13-36.21	P[9] 36-37
Silicon monoxide	SiO	42.519	42.47-42.57	
		42.821	42.78-42.86	F 42.77-42.87
		43.122	43.08-43.17	F 43.07-43.17
		43.424	43.38-43.47	F 43.37-43.37
Dicarbon monosulphide	CCS	45.379	45.33-45.42	
Carbon monosulphide	CS	48.991	48.94-49.04	P 48.94-49.04
Oxygen	O_2	61.1	56.21-63.06	P[10] 58.2-59.0
Deuterated water	HDO	80.578	80.50-80.66	
Cyclopropenylidene	C_3H_2	85.339	85.05-85.42	
Silicon monoxide	SiO	86.243	86.16-86.33	P
Formylium	$H^{13}CO^+$	86.754	86.67-86.84	P
Silicon monoxide	SiO	86.847	86.76-86.93	P
Ethynyl radical	C_2H	87.300[11]	87.21-87.39	P

continued

TABLE C.1 Continued

Substance	Formula	Frequency (GHz)	Suggested Minimum Band (GHz)	Band Allocation Status[1]
Hydrogen cyanide	HCN	88.632[6]	88.34-88.72	P
Formylium	HCO^{++}	89.189[6]	88.89-89.28	P
Hydrogen isocyanide	HNC	90.664	90.57-90.75	P
Diazenylium	N_2H^+	93.174	93.08-93.27	
Carbon monosulphide	CS	97.981[6]	97.65-98.08	
Sulfur monoxide	SO	99.300	99.20-99.40	
Methyl acetylene	CH_3CCH	102.5	102.39-102.60	
Methanol	CH_3OH	107.014	106.91-107.12	
Carbon monoxide	$C^{18}O$	109.782	109.67-109.89	P
Carbon monoxide	^{13}CO	110.201[6]	110.83-110.31	P
Carbon monoxide	$C^{17}O$	112.359[8]	112.25-112.47	P
Cyano radical	CN	113.500	113.39-113.61	P
Carbon monoxide	CO	115.271[6]	114.88-115.39	P
Oxygen	O_2	118.750	118.63-118.87	P[6] 116-126
Formaldehyde	$H_2{}^{13}CO$	137.450[3,8]	137.31-137.59	
Formaldehyde	H_2CO	140.840	140.69-140.98	P
Carbon monosulphide	CS	146.969	146.48-147.12	P 146.82-147.12
Nitric oxide	NO	150.4	149.95-150.85	S 150-151
Methanol	CH_3OH	156.602	156.45-156.76	
Water vapor	H_2O	183.310	183.13-183.49	
Carbon monoxide	$C^{18}O$	219.560	219.34-219.78	P
Carbon monoxide	^{13}CO	220.399[6]	219.67-220.62	P
Cyano radical	CN	226.600	226.37-226.83	P
Cyano radical	CN	226.800	226.57-227.03	P
Carbon monoxide	CO	230.538[6]	229.77-230.77	P
Carbon monosulphide	CS	244.953[8]	244.14-245.20	
Nitric oxide	NO	250.6	250.35-250.85	P
Ethynyl radical	C_2H	262.000	261.74-262.26	
Hydrogen cyanide	HCN	265.886	265.00-266.15	
Formylium	HCO^{++}	267.557	266.66-267.82	
Hydrogen isocyanide	HNC	271.981	271.71-272.25	
Carbon monosulphide	^{13}CS	277.455	277.18-277.73	
Diazenylium	N_2H^+	279.511	279.23-279.79	
Carbon monosulphide	$C^{34}S$	289.209	288.92-289.50	
Sodium hydride	NaH	289.860	289.57-290.15	
Carbon monosulphide	CS	293.912	292.93-294.21	

TABLE C.1 Continued

NOTE: Definitions of abbreviations for the various services referred to in the footnotes to this table are provided in Appendix I.

[1] P: primary allocation, S: secondary allocation, F: protection by footnote.

[2] An extension to lower frequencies of the allocation of 1400-1427 MHz is required to allow for the Doppler shifts for HI observed in distant galaxies.

[3] For passive EESS and SRS, along with FS and MS.

[4] The current international allocation is not primary and/or does not meet bandwidth requirements. See the ITU-R Radio Regulations for more detailed information.

[5] Because these line frequencies are also being used for observing other galaxies, the listed bandwidths include Doppler shifts corresponding to radial velocities of up to 1000 km/s. It should be noted that HI has been observed at frequencies redshifted to 500 MHz, while some lines of the most abundant molecules have been detected in galaxies with velocities up to 50,000 km/s, corresponding to a frequency reduction of up to 17%.

[6] For passive EESS and SRS, along with FS and MS.

[7] This line is not mentioned in Article 8 of the ITU-R Radio Regulations.

[8] For passive EESS and SRS, along with FS and MS.

[9] For passive EESS and SRS, with secondary allocations to FS and MS.

[10] United States only.

[11] There are six closely spaced lines associated with this molecule at this frequency. The listed band is wide enough to permit observations of all six lines.

SOURCE: Data and further information can be found at the Web site of the European Science Foundation's Committee on Radio Astronomy Frequencies at http://www.astron.nl/craf/iaulist.htm, accessed October 26, 2005.

Appendix D

International Astronomical Union Spectral Lines of Most Importance Above 300 GHz

At each triennial meeting of the General Assembly, the International Astronomical Union (IAU) carefully reviews the list of astrophysically most important spectral lines that it maintains. The IAU expresses the need to protect these frequency bands from in-band, band-edge, and harmonic emissions, especially from spaceborne transmitters.

In preparation for World Radiocommunication Conference 2000, which revised the allocations above 71 GHz, a millimeter-wavelength working group of the Scientific Committee on Frequency Allocations for Radio Astronomy and Space Science examined all then-known transitions in the millimeter and submillimeter wavebands. The working group selected a limited number of the astrophysically most important spectral lines to supplement the earlier lists, such as those produced by the IAU, to be used in allocating frequency bands to the Radio Astronomy Service. Spectral lines above 300 GHz are listed in Table D.1. (These data and further information can be found on the Web site of the European Science Foundation's Committee on Radio Astronomy Frequencies at http://www.astron.nl/craf/iaulist.htm.)

TABLE D.1 The Most Important Spectral Lines Between 275 and 1000 GHz

Substance	Formula	Frequency (GHz)	Suggested Minimum Band (GHz)
Diazenylium	N_2H^+	279.511	279.23-279.79
Carbon monosulphide	CS	293.912	292.93-294.21
Hydronium	H_3O^+	307.192	306.88-307.50
Deuterated water	HDO	313.750	313.44-314.06
Carbon monoxide	$C^{18}O$	329.330	329.00-329.66
Carbon monoxide	^{13}CO	330.587	329.49-330.92
Carbon monosulphide	CS	342.883	341.74-343.23
Carbon Monoxide	CO	345.796	345.45-346.14
Hydrogen cyanide	HCN	354.484	353.30-354.84
Formylium	HCO^+	356.734	355.54-357.09
Oxygen	O_2	368.498	368.13-368.87
Diazenylium	N_2H^+	372.672	372.30-373.04
Water vapor	H_2O	380.197	379.82-380.58
Hydronium	H_3O^+	388.459	388.07-388.85
Carbon monosulphide	CS	391.847	390.54-392.24
Oxygen	O_2	424.763	424.34-425.19
Carbon monoxide	$C^{18}O$	439.088	438.65-439.53
Carbon monoxide	^{13}CO	440.765	439.30-441.21
Carbon monoxide	CO	461.041	459.50-461.50
Heavy water	HDO	464.925	464.46-465.39
Carbon	CI	492.162	490.52-492.65
Hydrogen cyanide	HCN	531.716	529.94-532.25
Carbon monosulphide	CS	538.689	536.89-539.23
Water vapor	$H_2{}^{18}O$	547.676	547.13-548.22
Carbon monoxide	^{13}CO	550.926	549.09-551.48
Water vapor	H_2O	556.936	556.38-557.49
Ammonia	$^{15}NH_3$	572.113	571.54-572.69
Ammonia	NH_3	572.498	571.93-573.07
Carbon monoxide	CO	576.268	574.35-576.84
Carbon monosulphide	CS	587.616	587.03-588.20
Deuterated water	HDO	599.927	599.33-600.53
Water vapor	H_2O	620.700	620.08-621.32
Hydrogen chloride	HCl	625.040	624.41-625.67
Hydrogen chloride	HCl	625.980	625.35-626.61
Carbon monosulphide	CS	636.532	634.41-637.17
Carbon monoxide	^{13}CO	661.067	658.86-661.73
Carbon monoxide	CO	691.473	689.17-692.16
Oxygen	O_2	715.393	714.68-716.11
Carbon monosulphide	CS	734.324	733.59-735.06
Water vapor	H_2O	752.033	751.28-752.79
Oxygen	O_2	773.840	773.07-774.61
Hydrogen cyanide	HCN	797.433	794.77-798.23
Formylium	HCO^+	802.653	799.98-803.46
Carbon monoxide	CO	806.652	803.96-807.46
Carbon	C I	809.350	806.65-810.16
Carbon monosulphide	CS	832.057	829.28-832.89
Oxygen	O_2	834.146	833.31-834.98
Carbon monosulphide	CS	880.899	877.96-881.78
Water vapor	H_2O	916.172	915.26-917.09
Carbon monoxide	CO	921.800	918.72-922.72
Carbon monosulphide	CS	929.723	926.62-930.65
Water vapor	H_2O	970.315	969.34-971.29
Carbon monosulphide	CS	978.529	977.55-979.51
Water vapor	H_2O	987.927	986.94-988.92

SOURCE: Data and further information can be found at the Web site of the European Science Foundation's Committee on Radio Astronomy Frequencies at http://www.astron.nl/craf/iaulist.htm, accessed October 26, 2005.

Appendix E

Selected Rules and Regulations of the Federal Communications Commission

The rules and regulations of the Federal Communications Commission (FCC) are codified in Title 47 of the *Code of Federal Regulations* (CFR). They are initially published in the *Federal Register*. Links to the CFR are maintained by the FCC at wireless.fcc.gov/rules.html. Table E.1 presents a selected list of FCC rules particularly relevant to the Radio Astronomy Service and the Earth Exploration-Satellite Service.

TABLE E.1 Selected Rules and Regulations of the Federal Communications Commission

Rule or Part No.	Subject of Part in CFR, Title 47
1.924	Practice and Procedure (Public Mobile, Wireless Communications, Maritime, Aviation, Private Land Mobile, Personal Radio, Fixed Microwave)
15	Radio Frequency Devices
18	Industrial, Scientific, and Medical Equipment
21.113(a)	Domestic Public Fixed Radio Services
23.20(b)	International Fixed Public Radiocommunication Services
24.213(a)(1)	Personal Communications Services
25.202(f), 25.203(f), 25.216(a)	Satellite Communications
73.1030(a)	Radio Broadcast Services
74.12, 74.24(i)	Experimental Radio, Auxiliary, Special Broadcast and Other Program Distributional Services
78.19(c)	Cable Television Relay Service
97.203(e), 97.205(f)	Amateur Radio Service (Repeaters, Beacons)

Appendix F

Titles of ITU Recommendations for Radio Astronomy and for Space Applications and Meteorology

F.1 ITU RECOMMENDATIONS RELEVANT TO RADIO ASTRONOMY

The following International Telecommunication Union Radiocommunication Sector (ITU-R) recommendations,[1] shown below by recommendation number and title, apply to the protection of the Radio Astronomy Service. The recommendations are alphanumerically ordered. For the most recent recommendations refer to *ITU-R Recommendations.*

F.1612	Interference evaluation of the fixed service using high altitude platform stations to protect the radio astronomy service from uplink transmission in high altitude platform station systems in the 31.3-31.8 GHz band
F.1766	Methodology to determine the probability of a radio astronomy observatory receiving interference based on calculated exclusion zones to protect against interference from point-to-multipoint high-density applications in the fixed service operating in bands around 43 GHz
M.829	Frequency sharing in the 1660-1660.5 MHz band between the mobile-satellite service and the radioastronomy service
M.1316	Principles and a methodology for frequency sharing in the 1610.6-1613.8 and 1660-1660.5 MHz bands between the mobile-satellite service (Earth-to-space) and the radio astronomy service
M.1583	Interference calculations between non-geostationary mobile-satellite service or radionavigation-satellite service systems and radio astronomy telescope sites

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[1] Reprinted from International Telecommunication Union, *ITU-R Recommendations*, Geneva, Switzerland, 2006, available at http://www.itu.int/opb/, accessed December 12, 2006.

M.1748	Protection of the radio astronomy service in the band 1400-1427 MHz from unwanted emissions of MSS feeder links that may operate in the bands 1390-1392 MHz (Earth-to-space) and 1430-1432 MHz (space-to-Earth)
RA.314	Preferred frequency bands for radioastronomical measurements
RA.479	Protection of frequencies for radioastronomical measurements in the shielded zone of the Moon
RA.517	Protection of the radio astronomy services from transmitters operating in adjacent bands
RA.611	Protection of the radio astronomy service from spurious emissions
RA.769	Protection criteria used for radioastronomical measurements
RA.1031	Protection of the radioastronomy service in frequency bands shared with other services
RA.1237	Protection of the radio astronomy service from unwanted emissions resulting from applications of wideband digital modulation
RA.1272	Protection of radio astronomy measurements above 60 GHz from ground based interference
RA.1417	A radio-quiet zone in the vicinity of the L2 Sun-Earth Lagrange point
RA.1513	Levels of data loss to radio astronomy observations and percentage-of-time criteria resulting from degradation by interference for frequency bands allocated to the radio astronomy on a primary basis
RA.1630	Technical and operational characteristics of ground-based astronomy systems for use in sharing studies with active services between 10 THz and 1000 THz
RA.1631	Reference radio astronomy antenna pattern to be used for compatibility analyses between non-GSO systems and radio astronomy service stations based on the [equivalent power flux density] concept
RA.1750	Mutual planning between the Earth exploration-satellite service (active) and the radio astronomy service in the 94 GHz and 130 GHz bands
S.1341	Sharing between feeder links for the mobile-satellite service and the aeronautical radionavigation service in the space-to-Earth direction in the band 15.4-15.7 GHz and the protection of the radio astronomy service in the band 15.35-15.4 GHz
S.1586	Calculation of unwanted emission levels produced by a non-geostationary fixed-satellite service system at radio astronomy sites
SA.509	Space research earth station and radio astronomy reference antenna radiation pattern for use in interference calculations, including coordination procedures
SA.1345	Methods for predicting radiation patterns of large antennas used for space research and radio astronomy

F.2 ITU RECOMMENDATIONS FOR REMOTE SENSING

The following reprinted ITU-R recommendations, shown by recommendation number and title, apply to the protection of the Earth Exploration-Satellite Service, Space Research Service, and Meteorological Aids Service active and passive sensors. The recommendations are alphanumerically ordered. For the most recent recommendations refer to *ITU-R Recommendations.*

F.1613	Operational and deployment requirements for fixed wireless access systems in the fixed service in Region 3 to ensure the protection of systems in the Earth exploration-satellite service (active) and the space research service (active) in the band 5250-5350 MHz
M.1653	Operational and deployment requirements for wireless access systems including radio local area networks in the mobile service to facilitate sharing between these systems and systems in the Earth exploration-satellite service (active) and the space research service (active) in the band 5470-5570 MHz within the 5460-5725 MHz range
M.1747	Protection of the Earth exploration-satellite service (passive) in the band 1400 1427 MHz from unwanted emissions of mobile satellite service feeder links that may operate in the bands 1390-1392 MHz (Earth-to-space) and 1430-1432 MHz (space-to-Earth)
RS.515	Frequency bands and bandwidths used for satellite passive sensing
RS.516	Feasibility of sharing between active sensors used on Earth exploration and meteorological satellites and the radiolocation service
RS.577	Preferred frequencies and necessary bandwidths for spaceborne active remote sensors
RS.1028	Performance criteria for satellite passive remote sensing
RS.1029	Interference criteria for satellite passive remote sensing
RS.1165	Technical characteristics and performance criteria for radiosonde systems in the meteorological aids service
RS.1166	Performance and interference criteria for active spaceborne sensors
RS.1259	Feasibility of sharing between spaceborne passive sensors and the fixed service from 50 to 60 GHz
RS.1260	Draft revision to Recommendation ITU-R RS.1260—Feasibility of sharing between active spaceborne sensors and other services in the range 420-470 MHz
RS.1261	Feasibility of sharing between spaceborne cloud radars and other services in the range 92-95 GHz
RS.1262	Sharing and coordination criteria for meteorological aids in the 400.15-406 MHz and 1668.4-1700 MHz bands
RS.1263	Interference criteria for meteorological aids operated in the 400.15-406 MHz and 1668.4-1700 MHz bands
RS.1264	Feasibility of frequency sharing between the meteorological aids service and the mobile-satellite service (Earth-to-space) in the 1668.4-1700 MHz band
RS.1279	Spectrum sharing between spaceborne passive sensors and inter-satellite links in the range 50.2-59.3 GHz

RS.1280	Selection of active spaceborne sensor emission characteristics to mitigate the potential for interference to terrestrial radars operating in frequency bands 1-10 GHz
RS.1281	Protection of stations in the radiolocation service from emissions from active spaceborne sensors in the band 13.4-13.75 GHz
RS.1282	Feasibility of sharing between wind profiler radars and active spaceborne sensors in the vicinity of 1260 MHz
RS.1346	Sharing between the meteorological aids service and medical implant communication systems (MICS) operating in the mobile service in the frequency band 401-406 MHz
RS.1347	Feasibility of sharing between radionavigation-satellite service receivers and the Earth exploration-satellite (active) and space research (active) services in the 1215-1260 MHz band
RS.1416	Sharing between spaceborne passive sensors and the inter-satellite service operating near 118 and 183 GHz
RS.1449	Feasibility of sharing between the fixed-satellite service (FSS) (space-to-Earth) and the Earth exploration-satellite (passive) and space research (passive) services in the band 18.6-18.8 GHz
RS.1624	Sharing between the Earth Exploration-Satellite (passive) and airborne altimeters in the aeronautical radionavigation service in the band 4200-4400 MHz
RS.1628	Draft new Recommendation ITU-R RS.[DOC. 7/60] - Sharing in the band 35.5-36 GHz between the Earth exploration-satellite service (active) and space research service (active), and other services allocated in this band
RS.1632	Draft new Recommendation ITU-R RS.[Doc. 7/46] - Sharing in the band 5250-5350 MHz between the Earth exploration-satellite service (active) and wireless access systems (including radio local area networks) in the mobile service
RS.1744	Technical and operational characteristics of ground-based meteorological aids systems operating in the frequency range 272-750 THz
RS.1745	Use of the band 1668.4-1710 MHz by the meteorological aids service and meteorological-satellite service (space-to-Earth)
RS.1749	Mitigation technique to facilitate the use of the 1215-1300 MHz band by the Earth exploration-satellite service (active) and the space research service (active)
S.1339	Sharing between spaceborne passive sensors of the Earth exploration-satellite service and inter-satellite links of geostationary-satellite networks in the range 54.25 to 59.3 GHz

Appendix G

Earth Science Passive Sensor Needs Above 71 GHz

Tables G.1 and G.2 present the panel's summary of Earth science passive sensor needs and current allocations above 71 GHz.

TABLE G.1 Passive Sensor Needs and Current Allocations Between 75 and 275 GHz

Allocated Band (GHz)		Earth Observing System Instruments	Current Allocation	Other Primary Services	Notes
Lower	Upper				
86	92	AMSR, AMSR2, AMSU-A, -B, CMHS, CMSU, MIMR, MTZA, MVZA, MZOAS, SSM/IS, TMI	Primary (exclusive passive)	Radio Astronomy, Space Research (passive)	Clouds, oil spills, ice, snow
100	102	IKAR	Primary	Fixed, Mobile, Space Research (passive)	NO line at 100.49 GHz, limb
105	116	ODIN	Primary (exclusive passive)	Radio Astronomy, Space Research (passive)	O_3 line at 110.8 GHz, limb; CO line at 115.221 GHz, limb; CO line at 115.27 GHz
116	126	Radiometer (ODIN), AMAS, AMSR2, MILES, MLS, ODIN, SMILES, GEM	Primary	Fixed, ISS, Mobile, Space Research (passive)	Need 115.25-122.25 GHz; O_2 line for temperature at 118.8 GHz; NO line at 125.61 GHz, limb. Parameters sensed are wind velocity, temperature, oxygen, and magnetic field
150	151	AMSU-B, MHS	Primary	Fixed, Fixed-Satellite (S-E), Mobile, Space Research (passive)	Want 2 GHz, prefer between 140-150 GHz; surface, water vapor, and cloud parameters for water vapor sounding; NO line at 150.74 GHz, limb
156	158	AMSR2, MHS, MVZA	Primary	Fixed, Fixed-Satellite (S-E), Mobile	Want 155.5-158.5 GHz; surface, water vapor, cloud parameters for water vapor sounding
164	168	AMSR2, CMHS, IMAS, GEM, GeoSTAR	Primary (exclusive passive)	Radio Astronomy, Space Research (passive)	Cloud water, rain, ice; ClO line at 164.38 GHz; ClO line at 167.2 GHz
174.5	176.5	AMAS, AMSR2, AMSU-B, CMHS, HSB, MHS, MILES, MLS, MVZA, SMILES, SSM/IS, GEM, GeoSTAR	Primary	Fixed, ISS, Mobile, Space Research (passive)	Want 174.5-191.6 GHz to improve sounding; three-dimensional sounding for water vapor, both LEO and GEO; NO line at 175.86 GHz for limb sounding
176.5	182	GEM, GeoSTAR	None	Fixed, ISS, Mobile	Needed to improve sounding; three-dimensional sounding for water vapor, both LEO and GEO
182	185	AMSU-B, MHS, MLS, GEM, GeoSTAR	Primary (exclusive passive)	Radio Astronomy, Space Research (passive)	Water vapor line at 183.31 GHz; O_3 line at 184.75 GHz; want 174.5-191.6 GHz to improve sounding; three-dimensional sounding for water vapor, both LEO and GEO

TABLE G.1 Continued

Allocated Band (GHz)					
Lower	Upper	Earth Observing System Instruments	Current Allocation	Other Primary Services	Notes
185	190		None	Fixed, ISS, Mobile	Needed to improve sounding; three-dimensional sounding for water vapor, both LEO and GEO; radio astronomy has secondary allocation by footnote from 186.2-186.6 GHz
190	191.6		None	Mobile, Mobile Satellite, Radionavigation, Radionavigation-Satellite	Needed to improve sounding; three-dimensional sounding for water vapor, both LEO and GEO; S5.554 also allocates a form of FSS service in conjunction with MSS and RDNSS from 190-200 GHz
199	200	AMAS, MLS, MASTER	None	Mobile, Mobile Satellite, Radionavigation, Radionavigation-Satellite	Want 199-207 GHz; S5.554 also allocates a form of FSS service in conjunction with MSS and RDNSS from 190-200 GHz
200	202	AMAS, MLS, MASTER	Primary	Fixed, Mobile, Space Research (passive)	Want 199-207 GHz; NO line at 200.98 GHz, limb
202	207	AMAS, MLS, MASTER	None	Fixed, Fixed Satellite (E-S), Mobile	Want 199-207 GHz; ClO; O_3 line, limb; N_2O; H_2; and H_2O_2
217	231	MLS, MASTER	Primary (exclusive passive)	Radio Astronomy, Space Research (passive)	4 GHz needed, best 217-225 GHz; NO line at 226.09 GHz, limb; O_3 line at 230 GHz, limb; CO line at 230.54 GHz, limb
235	238		Primary	Fixed, FSS (S-E), Mobile, Space Research (passive)	O_3 line at 235.71 GHz, limb; O_3 line at 237.15 GHz, limb
250	252		Primary (exclusive passive)	Space Research (passive)	NO line at 251.21 GHz, limb

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TABLE G.2 Passive Sensor Needs and Current Allocations Above 275 GHz

Allocated Band (GHz)		Earth Observing System Instruments	Current Allocation	Other Primary Services	Notes
Lower	Upper				
275	277		5.565		NO line at 276.33 GHz, limb
296	300	MLS, MASTER	None		Want 296-306 GHz; window, line wings
300	302	MLS, MASTER	5.565		Want 296-306 GHz; NO line at 301.44 GHz; O_3 line, limb; N_2O line; O_2 line
302	306		None		Want 296-306 GHz
316	324		None		Want ±9.0 or 9.5 GHz around 325 GHz
324	326	MASTER	5.565		Want ±9.0 or 9.5 GHz, nadir water vapor from GEO, limb from LEO; H_2O, water vapor sounding at 325.1 GHz
326	334		None		Want ±9.0 or 9.5 GHz around 325 GHz
336	344	GEM	None		Need 339-348 GHz for water vapor sounding, precipitation cell imaging, and Cloud Ice Water Path measurement
345	347	MASTER	5.565		Want 339-348 GHz; CO line at 345.8 GHz, limb; HNO_3 line at 346 GHz
347	348		None		Want 339-348 GHz
363	365		5.565		O_3 line at 364.32 GHz, limb
371.5	379		None		Water vapor line at 380.2 GHz; need 17 GHz for close to nadir sounding from GEO
379	381	GEM	5.565		Water vapor line at 380.2 GHz; need 17 GHz for close to nadir sounding from GEO
381	388.5		None		Water vapor line at 380.2 GHz; need 17 GHz for close to nadir sounding from GEO
409	411	GEM	None		Temperature sounding, centered at 410 GHz
416	433	GEM	None		Temperature sounding centered at 424.7 or 2 bands above
485	487	ODIN	None		O_2 line at 486 GHz, limb
498	505	SOPRANO, MASTER	None		BrO line at 498.1 GHz, limb; O_3 line at 498.2 GHz, limb; N_2O line at 498.3 GHz, limb; H_2O line at 498.4 GHz, limb; ClO line at 498.5 GHz, limb; CH_3Cl line at 498.6 GHz, limb; Water vapor sounding, near nadir GEO at 498-502 GHz

TABLE G.2 Continued

Allocated Band (GHz)					
Lower	Upper	Earth Observing System Instruments	Current Allocation	Other Primary Services	Notes
523	527		None		Water vapor sounding, near nadir GEO
538	542		None		Water vapor sounding, near nadir GEO
541	558		None		Lines of HNO_3 and O_3, limb
547	584	ODIN	None		Mesospheric H_2O
552	562		None		Water vapor sounding, near nadir GEO
563	580.4	ODIN	None		Lines of ClO and O_3
624	629	SMILES, SOPRANO	None		ClO_2 line at 624.271 GHz, limb; SO_2 line at 624.344 GHz, limb; BrO line at 624.77 GHz, limb; O_3 line at 625.656 GHz, limb; HCl line at 625.9 GHz, limb; CH_3Cl line at 627.177 GHz, limb; O_2 line at 627.773 GHz, limb; HOCl line at 628.46 GHz, limb
640	653	MLS (new); SMILES	None		Lines: CH_2CL, ClO, BrO, HCl, HOCl, SO_2; H_2O line at 647.198 GHz, limb; ClO line at 649.45 GHz, limb; HO_2 line at 649.701 GHz, limb; HNO_3 line at 650.279 GHz, limb; O_3 line at 650.733 GHz, limb; NO line at 651.771 GHz, limb; N_2O line at 652.834 GHz, limb
951	956	SOPRANO	None		O_2 line at 952 GHz, limb; NO line at 953 GHz, limb
1228	1230	MLS (new)	None		HF line at 1228.95 GHz, limb
2520	2525	MLS (new)	None		OH line at 2522.78 GHz, limb

Appendix H

Use of 0 dBi for Sidelobe Gain in Calculations of Interference in Radio Astronomy Bands

The use of 0 dBi for the gain of the sidelobes of a radio astronomy antenna, in the computation of levels of detrimental interference, originated in the analysis in International Radio Consultative Committee (CCIR) Report 224.[1] Report 224 evolved into Recommendation ITU-R RA.769 when the CCIR was replaced by the International Telecommunication Union's Radiocommunication Sector (ITU-R). As stated in Report 224: "To estimate typical values of the harmful interference level, we may approximate our real antenna by an isotropic antenna, except in the direction of the main lobe and near side lobes."

The isotropic model represents the average gain of any low-loss antenna, independent of the details of its design. In practice, it is less than the gain of the main beam and near sidelobes of a radio astronomy antenna and a little higher than the gain of the sidelobes that are more than about 20º from the boresight (the center of the main beam). The use of a single reference value for the gain of the radio astronomy antenna in calculations of detrimental thresholds of interference is intended to provide approximate numbers that are independent of the detailed type of antenna and its pointing direction. This single reference value facilitates the assessment of any interference situation. It frees the transmitter engineer from a consideration of the detailed radio telescope design and pointing angles. Also, the calculations are much simplified when gain and pointing direction are removed as variables.

In some specific cases, however, this simple gain model is not adequate—in particular, in the case of interference from non-geosynchronous satellites. A more detailed antenna pattern and coordination algorithm are then used, as described in Recommendations ITU-R S.1586 and M.1583. The resulting analysis sets a value of the detrimental threshold such that the fraction of time that the interference level exceeds the threshold is equal to the maximum tolerable value of 2 percent for any one network, as specified in Recommendation ITU-R RA.1513. Generally, however, it is found that this threshold is within a very few decibels of that derived using the simpler isotropic-sidelobe model.

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[1] See, for example, *CCIR Report 224: Documents of the Xth Plenary Assembly*, Vol. IV, p. 331, Geneva, Switzerland, 1963.

TABLE H.1 Characteristics of Antenna Sidelobe Models

ITU-R Recommendation	Φ_0 (G = 0 dBi)	$\Omega/2\pi$
SA.509 (32-25 log Φ)	19.05°	5.5%
S.580 (29-25 log Φ)	14.45°	3.2%
RA.1631 and S.1428 (34-30 log Φ)	13.59°	2.85%

An examination of the choice of 0 dBi, rather than some other constant gain figure, can be made with the aid of the more detailed reference models of sidelobe levels that have subsequently been developed. An early reference model for a large antenna is found in Recommendation ITU-R RS.509. The sidelobe gain as a function of boresight angle Φ is equal to (32-25 log Φ) dBi for $1^{\circ}<\Phi<48^{\circ}$, and is a constant value of –10 dBi for $\Phi > 48^{\circ}$. With this model the 0 dBi sidelobe level occurs at a boresight angle of $\Phi_0 = 19^{\circ}$. However, radio astronomy antennas are commonly used over a range of elevation angles down to ~10° when tracking a source under study across the sky. As a result, sidelobes of a level several decibels greater that 0 dBi are sometimes presented toward the horizon, which is the direction of incidence for signals from terrestrial transmitters. Hence, for sidelobes represented by Recommendation ITU-R RS.509, the 0 dBi figure does not guarantee freedom from interference.

The average percentage of data loss when the detrimental threshold is determined using the 0 dBi figure can be estimated using the models for antenna sidelobe levels, as follows. Included here are more recent models based on improved antenna design, which are found in Recommendations ITU-R S.580, S.1248, and RA.1631. For each of the models, the boresight angle Φ_0 for which the gain is 0 dBi is given in column 2 of Table H.1. The solid angle of the antenna response for which the gain exceeds 0 dBi is $\Omega = 2\pi\ (1\text{-}\cos\Phi_0)$ steradian. This is given for each model in column 3 of the table, expressed as a fraction of the hemisphere (from the horizon to the zenith) from which interference can arrive. Thus, if it is assumed that the angles of pointing of the radio astronomy antenna are uniformly distributed over the sky (which is only approximately the case) and that one interfering transmitter is active, the values in column 3 provide an estimate of the fraction of time that the interference received exceeds the detrimental level.[2] For the more recent sidelobe models in the table these values are ~3 percent, and to reduce this result to 2 percent (the maximum tolerable value, as noted above), one would need to use a detrimental threshold based on a sidelobe gain slightly higher than 0 dBi. However, the 0 dBi value has the advantage of simplicity, and within the uncertainties of the pointing distribution, it results in detrimental thresholds in reasonable accord with the acceptable loss of observing time.

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[2] When the elevation angle of the main beam of the radio astronomy antenna is less than Φ_0, some of the sidelobes with a gain higher than 0 dBi are pointing toward the ground and thus are not susceptible to interference. In practice, this effect is reduced by the fact that radio astronomy antennas rarely point below ~7°, and it is neglected in the present approximate analysis.

Appendix I

Selected Acronyms/Abbreviations and Footnote Designations

For the reader's convenience, following is an alphabetical list of selected acronyms and abbreviations used in this handbook. Designations for footnotes to science service allocations are then listed.

ACRONYMS AND ABBREVIATIONS

Ae	aeronautical
AeMS	Aeronautical Mobile Service (MS with aircraft)
AeMSS	Aeronautical Mobile Satellite Service (MSS with aircraft)
AeRLS	Aeronautical Radiolocation Service
AeRNS	Aeronautical Radionavigation Service
AMatSat	Amateur Satellite Service
AmS	Amateur Service
AMSU	Advanced Microwave Sounding Unit
ANS	Air Navigation Service
Bn	necessary bandwidth
BS	Broadcasting Service
BSS	Broadcasting Satellite Service
CCIR	International Radio Consultative Committee (antecedent of the ITU-R)
E→S	Earth to space
EESS	Earth Exploration-Satellite Service
EOS	Earth Observing System

FS	Fixed Service (point-to-point transmissions, such as radio relay towers)
FSS	Fixed Satellite Service (between satellites and fixed ground stations, such as telephone, television, data links)
GEO	geostationary orbit (satellite)
GNSS	Global Navigation Satellite System
GOES	Geostationary Operational Environmental Satellites
GPS	Global Positioning System
IAU	International Astronomical Union
IGS	International Global Navigation Satellite System (GNSS)
ISM	industrial, scientific, and medical (bands in which radio-frequency-noisy systems can be operated); interstellar medium (consisting of the gas, dust, atomic particles, and magnetic fields between the stars)
ISS	Inter-Satellite Service
ITU	International Telecommunication Union
ITU-R	Radiocommunication Sector of the ITU
ITU-RR	ITU Radio Regulations
IUCAF	Scientific Committee on Frequency Allocations for Radio Astronomy and Space Science
LEO	low Earth orbit
LMS	Land Mobile Service
LMSS	Land Mobile Satellite Service
MetAids	Meteorological Aids Service (radiosondes, etc.)
MetSat	Meteorological Satellite Service
MMSS	Maritime Mobile Satellite Service
MS	Mobile Service
MSS	Mobile Satellite Service (telecommunications between mobile stations and satellites)
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NTIA	National Telecommunications and Information Administration
OOBE	out-of-band emission
pfd	power flux density (usually measured in Wm^{-2})
RAS	Radio Astronomy Service
RDSS	Radiodetermination Satellite Service
RFI	radio-frequency interference
RLS	Radiolocation Service (radars)
RNS	Radionavigation Service
RNSS	Radionavigation Satellite Service (for example, GPS)
RR	Radio Regulations (the international treaty governing spectrum use)

S→E	space to Earth
S→S	space to space
SAR	synthetic aperture radar
SETI	search for extraterrestrial intelligence
SFS	Standard Frequency and Time Signal Service (such as WWV)
SFTSS	Standard Frequency and Time Signal-Satellite Service
SOS	Space Operations Service
SpaceOps	Space Operations Service (satellite command and control)
spfd	spectral power flux density (measured in $Wm^{-2}\ Hz^{-1}$)
SRS	Space Research Service
SSM/I	Special Sensor Microwave/Imager (of the Defense Meteorological Satellite Program)
SSM/T	Special Sensor Microwave/Temperature (of the Defense Meteorological Satellite Program)
TDRSS	Tracking and Data Relay Satellite System
TRMM	Tropical Rainfall Measurement Mission
VLA	Very Large Array
VLBA	Very Long Baseline Array
VLBI	very long baseline interferometry
WARC	World Administrative Radio Conference (antecedent of WRC)
WRC	World Radiocommunication Conference

FOOTNOTE DESIGNATIONS

- 5: Footnotes designated “5” (e.g., 5.364) come from the ITU Radio Regulations (see Appendix B.1).
- US: Footnotes consisting of the letters “US” followed by one or more digits (e.g., US13) denote stipulations applicable to both government and nongovernment services (see Appendix B.2).
- G: Footnotes consisting of the letter “G” followed by one or more digits (e.g., G59) denote stipulations applicable only to U.S. federal government services (see Appendix B.3).
- NG: Footnotes consisting of the letters “NG” followed by one or more digits (e.g., NG101) denote stipulations applicable only to U.S. nonfederal government services (see Appendix B.4).