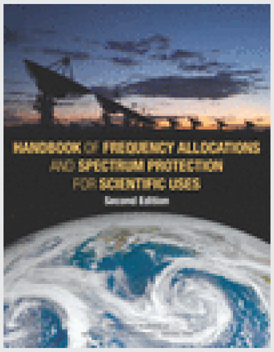

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HANDBOOK OF FREQUENCY ALLOCATIONS AND SPECTRUM PROTECTION FOR SCIENTIFIC USES

Second Edition

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

The National Academies of
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PANEL ON FREQUENCY ALLOCATIONS AND SPECTRUM PROTECTION FOR SCIENTIFIC USES: SECOND EDITION

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Preface

This handbook was developed by the National Academies of Sciences, Engineering, and Medicine'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 committee was given the following task:

> An ad hoc committee under the auspices of the National Research Council will prepare the second edition of the 2007 NRC report, "Handbook of Frequency Allocations and Spectrum Protection for Scientific Uses." The report will describe the radio frequency bands used by the scientific services, primarily the passive radio astronomy and Earth remote-sensing services. The report will include relevant regulatory information and a discussion of the scientific use of frequency bands. It will serve as a reference or handbook, guiding spectrum managers and spectrum regulatory bodies on science issues, serving as a resource to scientists on spectrum regulation for research, and providing information to other spectrum users on the concerns of the scientific users of the spectrum. It will not contain any recommendations.

The volume sets forth the principles 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: the *Handbook on Radio Astronomy* by the International Telecommunication Union (ITU);[1] the "Redbook" of the National

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[1] International Telecommunication Union, *Handbook on Radio Astronomy,* 3rd edition, Geneva, Switzerland, 2013.

Telecommunications and Information Administration[2] (NTIA) (please note that the NTIA Redbook is a dynamic document; it is suggested that readers check the NTIA Web site, listed below, for the latest allocations and regulations); the *Table of Frequency Allocations* published by the Federal Communications Commission (FCC)[3]; *Spectrum Management for Science in the 21st Century*[4]; and the handbooks for radio astronomy and frequency management from the European Science Foundation's Committee on Radio Astronomy Frequencies (CRAF). Because radio-frequency regulations, regulatory footnotes, and frequency allocations are subject to change, readers are advised to check the ITU, NTIA, and FCC websites, listed below, for the latest information.

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

- Committee on Radio Frequencies (CORF) of the National Academies of Sciences, Engineering, and Medicine: http://sites.nationalacademies.org/bpa/bpa_048819;
- International Telecommunication Union: http://www.itu.int;
- Scientific Committee on Frequency Allocations for Radio Astronomy and Space Science (IUCAF) of the International Council for Science: http://www.iucaf.org;
- Federal Communications Commission: http://www.fcc.gov;
- National Telecommunications and Information Administration: http://www.ntia.doc.gov/osmhome/redbook/redbook.html;
- National Radio Astronomy Observatory Spectrum Management: http://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: http://www.craf.eu; and
- National Science Foundation Electromagnetic Spectrum Management (ESM): http://nsf.gov/funding/pgm_summ.jsp?pims_id=5654.

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[2] National Telecommunications and Information Administration, *Manual of Regulations and Procedures for Federal Radio Frequency Management* (Redbook), May 2013 edition, revised May 2014, available at http://www.ntia.doc.gov/osmhome/redbook/redbook.html.

[3] Federal Communications Commission, *Table of Frequency Allocations,* May 15, 2015, available at https://www.fcc.gov/oet/spectrum/table/fcctable.pdf.

[4] National Research Council, *Spectrum Management for Science in the 21st Century*, The National Academies Press, Washington, D.C., 2010.

Acknowledgments

This handbook grew out of materials presented and ideas expressed in the first edition of this report, *Handbook of Frequency Allocations and Spectrum Protection for Scientific Uses*.[1]

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 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:

Tomas E. Gergely, National Science Foundation,
Michael Marcus, Marcus Spectrum,
James M. Moran, Harvard-Smithsonian Center for Astrophysics,
Jeffrey Piepmeier, NASA Goddard Space Flight Center, and
Charles Wende, NASA Headquarters (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 Martha P. Haynes, Cornell University, who 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.

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[1] National Research Council, *Handbook of Frequency Allocations and Spectrum Protection for Scientific Uses*, The National Academies Press, Washington, D.C., 2007.

The panel thanks the past members of the Committee on Radio Frequencies and the authors of and contributors to the previous edition for their contributions to this effort. The panel also thanks Mangala Sharma, Sandra Cruz-Pol, and Glen Langston of the National Science Foundation; Thomas von Deak and John Zuzek of the National Aeronautics and Space Administration; and Tomas Gergely, whose knowledge and support were essential resources. In addition, the panel thanks the following members of the larger scientific community for their contributions to the handbook: J. Labelle, Dartmouth College; S. A. Cummer, Duke University; A. Weatherwax, Merrimack College; P.J. Erickson, F.D. Lind, and J. Vierinen, MIT Haystack Observatory; A. Komjathy and R. Jarnot, NASA Jet Propulsion Laboratory; P. Bernhardt, Naval Research Laboratory; M. Durand, Ohio State University; J. Mathews, Pennsylvania State University; S. Close, Stanford University; S. Palo, University of Colorado, Boulder; T. Pavelsky, University of North Carolina; and J. Sahr, University of Washington.

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Summary

The electromagnetic spectrum is a vital part of our environment. Measures of radio frequency emissions from natural phenomena enable both practical applications, such as weather predictions and studies of the changing of Earth's climate here at home, and reveal the physical properties of cosmic sources. For example, 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 spectrum 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. To explore these natural phenomena, the passive scientific services push the limits of receiver technology in order to detect extremely weak signals from both near and distant sources. However, because the passive scientific services aim to detect radio emission produced by nature, they do not have the option of increasing the signal strength from the source.[1] Rather, the signal-to-noise ratio is limited only by the sensitivity of the receiving instruments and the noise in the environment. If the instruments are to achieve their theoretical limit, then 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. Chapters 2 and 3 discuss the relevant scientific background necessary to understand the issues with spectrum management for radio astronomy and Earth remote sensing applications, respectively. Chapter 4 discusses issues related to spectrum protection. Chapter 5 lists the science service spectrum allocations in the United States and their uses.

In addition, the report has a number of appendixes. Appendix A offers National Telecommunications and Information Administration definitions concerning interference. Appendix B lists the Institute of Electrical and Electronics Engineers letter designations for radar frequency bands. Appendix C lists important International Astronomical Union (IAU) spectral lines below 300 GHz. Appendix D lists important IAU spectral lines between 300 to 1000 GHz. Appendix E lists important IAU spectral lines above 1 THz. Appendix F examines the use of 0 dBi for sidelobe gain in calculations of interference in radio astronomy. Appendix G presents selected Federal Communications Commission rules and regulations. Appendix H 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 for the Scientific Services

1.1 FREQUENCY PROTECTION GOALS FOR THE SCIENTIFIC SERVICES

Preservation and promotion of frequency allocations for scientific services have a significant societal impact. For example, the international frequency allocations for the Earth Exploration Satellite Service (EESS) enable scientific studies of the entire Earth's biosphere, including global measures of soil and water content. These EESS studies provide critical information on issues impacting the global economy, including essential economic sectors such as food, transportation, and energy. The international frequency allocations for Radio Astronomy Service (RAS) enable a wide range of scientific studies, including exploration of the origin of our solar system and the detection of radio emission originating from the edge of the observable universe. The results of RAS studies provide context for our place in the universe and inspire the next generation of scientists. Preserving interference free access to the radio spectrum for scientific use is thus crucial both to provide information on the conditions of our planet Earth that have global consequences and to enable discoveries that will lead to a better understanding of the natural world.

Scientific research that uses the radio spectrum benefits from U.S. radio-frequency managers who work with national and international regulatory bodies to improve spectrum access for the scientific services throughout the world. This includes working with radio-frequency managers of other Administrations[1] at World Radiocommunication Conferences (WRCs) to preserve and promote both federal and international allocations for scientific uses. For example, it is important to protect bands allocated to the science services from emissions spilling over from adjacent bands in order to ensure the efficacy of scientific research. Of the several scientific services (see Table 1.1), the passive-use allocations to the RAS and the EESS are particularly vulnerable to interference because noise levels must be extremely low in order to detect the faint signals generated by natural phenomena and processes. In this context, it is important that regulatory actions do not change the radio regulations in ways that would be deleterious to RAS and EESS, even when these services are not considered explicitly.

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[1] An "administration" is any governmental department or service responsible for international telecommunications regulation.

TABLE 1.1 Scientifically Relevant 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

NOTE: Chapters 2, 3, and Section 1.5 describe how these services contribute to scientific endeavors.

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. However, in practice, most spectral allocations are shared with active services and, with the introduction of higher-powered space transmitters and the use of spread spectrum modulation techniques, both EESS and RAS are increasingly vulnerable to interference, even in their protected bands. Thus, while spectral sharing of the passive service allocations with compatible active service allocations are possible in some circumstances, special care must be taken to provide protection for scientifically critical spectral windows and for geographic regions where radio telescopes are located. Of particular concern are those radio emissions that exist very close to the atomic and molecular spectral line frequencies reserved for the scientific services. For example, for many years, RAS allocations for observations of hydroxyl (OH) between 1610.6 and 1613.8 MHz have been impacted negatively by interference from the sidebands of spaceborne transmitters, even though their central transmitting frequencies lie outside the radio astronomy bands. It is particularly difficult to avoid interference from airborne and spaceborne transmitters, because radio telescopes are directed upward and terrain shielding (the use of geographical features to block radio signals) cannot be utilized to block transmission originating from high altitude. Novel approaches for effective spectral sharing need to be developed to enable efficient use of the radio spectrum for scientific and other applications.

1.2 REGULATORY STRUCTURES

Radio regulations are formulated at several levels and involve a plethora of acronyms (see Appendix H). At the international level, regulations for use of the radio spectrum that will become treaty obligations of members of the International Telecommunication Union (ITU) are formulated at World Radiocommunication Conferences. The ITU Radiocommunications Sector (ITU-R) prepares material for these conferences and drafts recommendations that may be incorporated into regulations or, at the very least, are influential documents for telecommunications regulators and spectrum users around the world.

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 WP7A, time and frequency standards, and WP7B, space research and EESS (mostly communications). In the past, the communications aspects of the EESS had been assigned to WP7C rather than WP7B. However, WP7B is now concerned with communications between spacecraft as well as from the spacecraft to the ground. Indeed, without the communications protected by WP7B, it would be almost impossible to conduct science from space.

Additional input from the scientific community comes from the Scientific Committee on Frequency Allocations for Radio Astronomy and Space Science (IUCAF), which operates under the auspices of the International Council of Scientific Unions (ICSU) that operates under the aegis of the United Nations Educational, Scientific, and Cultural Organization (UNESCO). 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.

ITU Study Groups (SGs) can elaborate on Recommendations that may be approved between WRCs or at a Radiocommunication Assembly, which is held just before a WRC. WRCs are large, diplomatic meetings that now take place approximately every 3 to 5 years. Even though Recommendations are not mandatory, most administrations abide by them. WRCs revise the Radio Regulations, and once accepted by administrations, the Radio Regulations become part of a treaty and thereby become mandatory. The SGs contribute to a WRC through their input to the draft Conference Preparatory Meeting (CPM) Report.

The relationship among national and international radio regulatory and advisory bodies with respect to RAS and EESS 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 Inter-department 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. In practice, NTIA and IRAC see every pending FCC frequency allocation that could impact federal government allocations—including the scientific services. NTIA, with advice from IRAC, then interacts with the FCC to determine the final outcomes.

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. WP7C, part of U.S. Study Group 7,

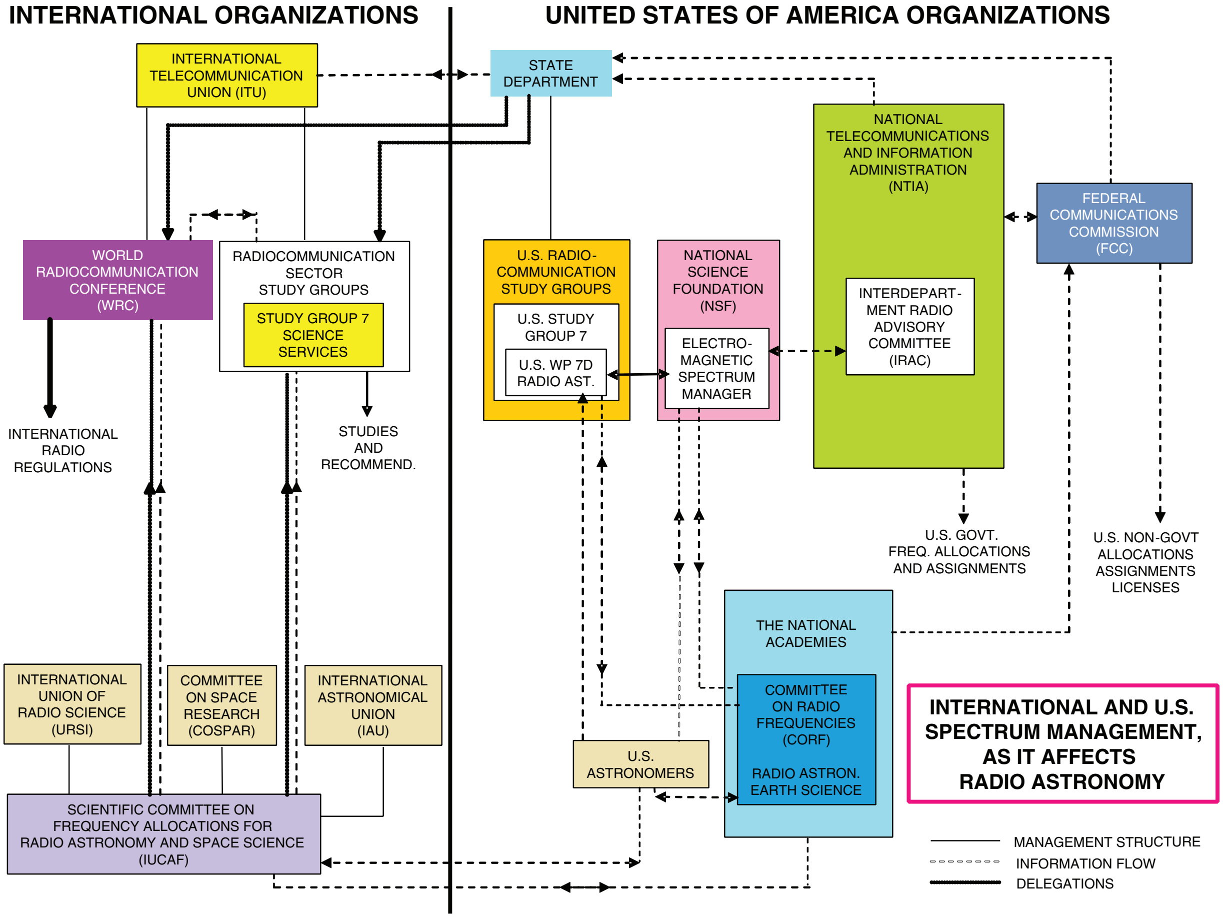

FIGURE 1.1 This Radio Astronomy Service (RAS) diagram depicts the complex relationship among the national and international radio regulatory bodies for RAS. The color coding is designed to highlight similar agencies and connections between the international and domestic (U.S.) organizations. For example, yellow and orange colors indicate ITU- and U.S.-based study groups. U.S. federal agencies are highlighted in shades of blue, green, and red, while international and domestic science committees and communities are denoted in beige.

develops U.S. positions and draft documents concerning remote sensing (U.S. WP7D does so for RAS, and U.S. WP7B does so for the Space Operations Service [SOS] and Space Research Service [SRS]). These documents are reviewed by the U.S. 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, remote sensing scientists, and others who use the passive and active bands for scientific research can interact with the system of spectrum management through the Committee on Radio Frequencies[2] (CORF) of the National Academies of Sciences, Engineering,

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[2] CORF is a standing committee of the National Academies of Sciences, Engineering, and Medicine operating under the auspices of the Board on Physics and Astronomy. For more information on CORF, see its website at http://sites.nationalacademies.edu/bpa/bpa_048819.

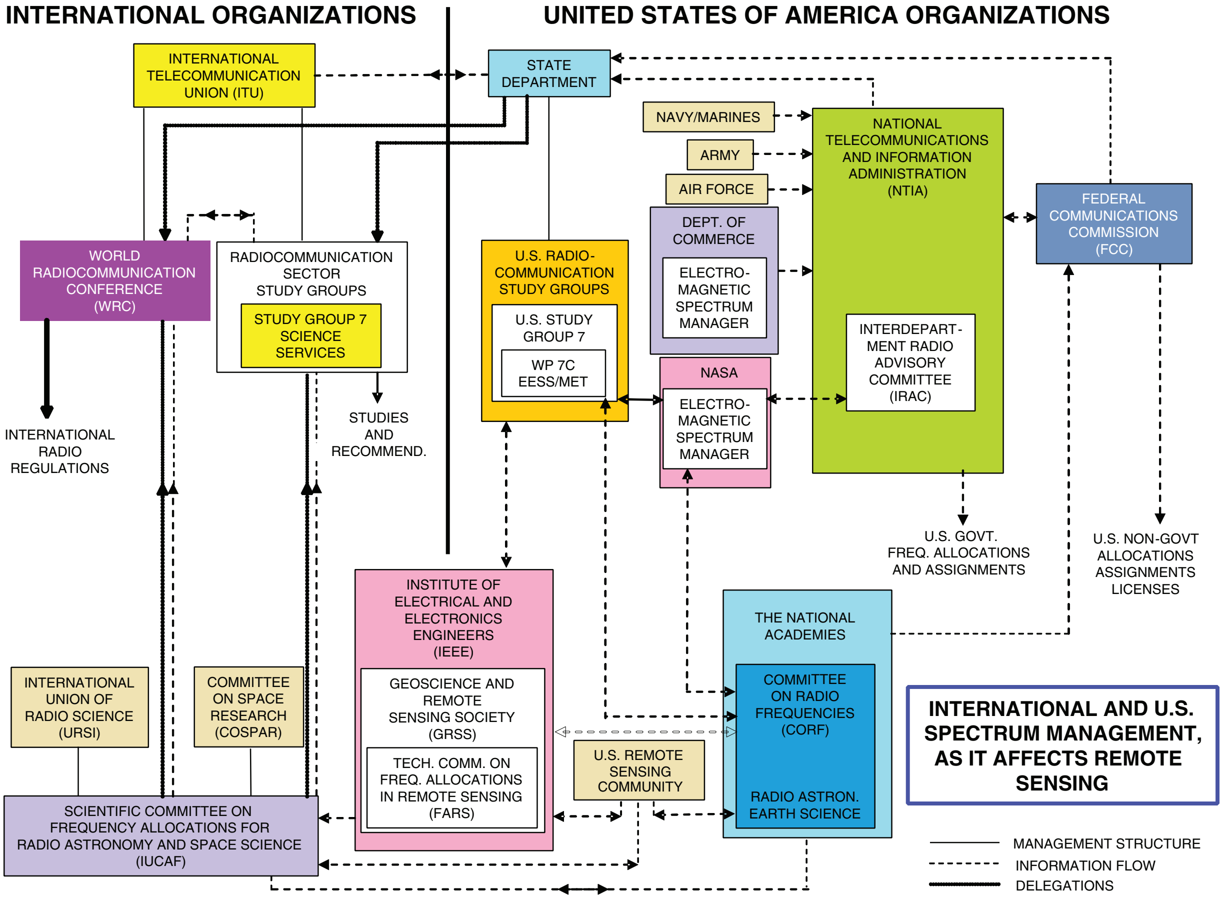

FIGURE 1.2 This Earth Exploration Satellite Service (EESS) diagram depicts the complex relationship among the national and international radio regulatory bodies for the EESS. The color coding is designed to highlight similar agencies and connections between the international and domestic (U.S.) organizations. For example, yellow and orange colors indicate ITU and U.S.-based study groups. U.S. federal agencies are highlighted in shades of blue, green, and red, while international and domestic science committees and communities are denoted in beige.

and Medicine, and U.S. WP7A, WP7B, 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 https://www.fcc.gov/exparte) and NTIA, and with members of IUCAF.

As indicated above, CORF is a committee of the Academies, which are private, nonprofit institutions that provide expert advice on some of the most pressing challenges facing the nation and the world. 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 FCC.

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,
- 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 (1.400-1.427 GHz) and to the predicted deuterium (D) line (0.322-0.3286 GHz).

By the end of WARC-59, considerable action had been taken to meet these needs. 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 WRC in 2000 (WRC-2000), the spectrum allocations above 71 GHz were revised, and a number of new allocations to RAS were made. Following WRC-2007, additional protections of the 1.400-1.427 GHz passive band were implemented to reduce unwanted emissions from the neighboring Amateur Service (AMT), Fixed Service (FS), and Mobile Service (MS). In addition, Resolution 739 (Rev. WRC-07) set unwanted emission thresholds for emission from satellite services in adjacent and nearby RAS allocated bands. WRC-2012 increased the upper end of the frequency range under consideration for allocations by the ITU from 1 to 3 THz and identified spectral windows where active service applications should take all practicable steps to protect the passive services from harmful interference, but did not impose mandatory protection criteria for passive services within the 275-1000 GHz frequency range.

An extensive discussion of the science enabled by RAS allocations is presented in Chapter 2 and the frequency bands allocated to RAS are listed in Chapter 5.

1.4 EARTH EXPLORATION SATELLITE SERVICE

Since many scientific programs require mapping of the entire Earth, regardless of geo-political boundaries, international cooperation is a critical requirement for EESS. Indeed, EESS is by its nature a global endeavor that relies on mutual cooperation among nations and their compliance with agreed-upon rules for access to the radio-frequency spectrum. Portions of the radio spectrum must be set aside to achieve the science goals of Earth-observing satellites, and their allocation must be respected globally. Thus, in sharp contrast to RAS, where protection of a few specific geographic locations may be sufficient, EESS requires global enforcement of the radio regulations.

EESS 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 utilizes passive sensors operating in the visible part of the electromagnetic spectrum. EESS includes both active and passive uses and must use radio frequencies to send its data to Earth. Frequencies were first allocated to EESS and 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 MHz 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. Following WRC-2007, additional protections of the 1.400-1.427 GHz passive band were implemented to reduce unwanted emissions from neighboring AMT, FS, and MS services. In addition, mandatory unwanted emissions limits were adopted for FS in bands neighboring the EESS allocations at 10.6-10.68, 31.3-31.5, 50.2-50.4, and 52.6-54.25 GHz. WRC-2012 adopted additional protections for the 86-92 GHz band.

An extensive discussion of the science enabled by EESS allocations is presented in Chapter 3, and the frequency bands allocated to EESS are listed in Chapter 5.

1.5 OTHER SCIENTIFIC SERVICES

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

1.5.1 The Meteorological Satellite Service and Meteorological Aids Service

Earth science studies of climate and weather often rely on information gathered from weather satellites and weather balloons. The Meteorological Satellite Service (MetSat) and the Meteorological Aids Service (MetAids) provide communication to weather satellites and weather balloons, respectively. Thus, while not used to collect or generate scientific data directly, the more than 1900 radiosonde stations located worldwide, which support nearly 1 million launches of weather balloons per year, provide measures of pressure, temperature, humidity, and vertically sampled wind profiles that are critical to the interpretation and analysis of EESS scientific research, and thus are included in the broad list of scientific services.

1.5.2 The Space Research and Space Operations Services

SRS and SOS need to be protected and managed in order to enable the scientific community to operate spacecraft and to retrieve data taken by them. Without these bands, spaceborne science cannot be carried out.

SRS covers the communications services necessary for spacecraft launch and for data communications with spacecraft. The major network supporting space exploration 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 some Earth-orbiting missions.

The majority of Earth-orbiting missions are supported by Earth stations located throughout the globe. At present, more than 100 Earth stations have the capability of receiving high rate (more than 100 Mb/s) stored data from low Earth-orbiting EESS satellites using the 8025-8400 MHz EESS communications band. An additional 130 Earth stations can receive medium rate (20 Mb/s) real-time data directly from some EESS satellites when such data are needed for immediate use. The EESS tracking telemetry, and command functions, generally use S-band (around 2 GHz) and a subset of the EESS Earth stations.

EESS Earth stations may be dedicated to individual missions (e.g., NOAA's meteorological satellite ground stations and the International Ground Station Network operated by the U.S. Geological Survey to support Landsat). Other Earth stations may work in concert to service many missions (e.g., NASA's Near Earth Network). Earth stations located at very high latitudes are particularly effective at servicing polar, or near-polar, orbiting satellites because only two Earth stations (e.g., Fairbanks, Alaska, and Svalbard, Spitzbergen, Norway) are needed to contact the satellite and collect data at least once each orbit. At one time, NASA operated a "picket fence" of 12 Earth stations, spread from North to South to obtain one contact per orbit with equatorial-orbiting spacecraft.

Another communications path is via a data relay satellite, such as NASA's Tracking and Data Relay Satellite System (TDRSS). The data relay satellite then forwards the data from another satellite to the ground via a K-band link, and forwards commands in the reverse direction to the satellite. The TDRSS uniquely provides 24-hour uninterrupted communications when mission operations require it (e.g., the inhabited International Space Station).

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

1.5.3 Frequency, Time, and Position Systems

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

These systems provide timing measurements 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 (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 Global Navigation Satellite Systems (GNSSs)—GPS and the Russian Global Navigation Satellite System (GLONASS)—and intends to incorporate future GNSSs, such as Europe's Galileo system. While the IGS is primarily used by the EESS for spacecraft position and timing information in support of remote sensing, occultation of IGS transmissions through the limb of the atmosphere provide high-quality data used for temperature and humidity profile with exceptional vertical resolution. These data are assimilated into numerical weather forecast models. There are also experimental scientific uses of IGS for radio science and bistatic radar. NASA has funded the Cyclone GNSS (CyGNSS) mission to study tropical cyclone winds using the reflected IGS from ocean waves. This technique has the potential to observe oceanic winds in all conditions.

1.6 THE ECONOMIC VALUE OF THE SCIENCE SERVICES

1.6.1 Investments in Infrastructure

Radio astronomy and Earth science require the operation of many facilities with different instruments and locations, including the vantage point 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, Sweden, the United Kingdom, and the United States. As a return on those investments, radio astronomy and Earth remote sensing have, over the past decades, 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.

1.6.2 Technologies and Techniques Developed from Radio Astronomy

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.[3] Some examples are listed below:

- Originally developed as a radio astronomical technique for the high-resolution imaging of astronomical objects, very long baseline interferometry (VLBI) is used for applications in Earth science—for example, the determination of geophysical parameters used in studying plate tectonics, polar wandering, latitude measurements, and variations in Earth's rotation, and the identification of potential earthquake zones through the precise measurement of fault motion.
- The VLBI reference frame of celestial coordinates, based on extremely distant radio sources, is basic to the periodic calibration of the GPS reference clocks.

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[3] National Research Council, *Spectrum Management for Science in the 21st Century,* The National Academies Press, Washington, D.C., 2010, p. 130; International Telecommunication Union, *ITU Handbook on Radio Astronomy,* 2nd ed., Geneva, Switzerland, 2013, p. 4.

- Pulsar and VLBI observations are used to examine and test Einstein's general theory of relativity; timekeeping, precision navigation, and geodesy—including that of spacecraft—require consideration of general relativistic effects.
- VLBI instrumentation is the source of the technology used to locate interference to commercial satellite uplinks.
- John O'Sullivan and collaborators at the Commonwealth Scientific and Industrial Research Organisation were working on improving the quality of radio images made using interferometry and patented a related technique for reducing multipath interference in network radio transmissions, a critical component of wireless networks (WiFi).
- 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 came to be so abundant, fullerene molecules were discovered. 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 part in 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.
- Amplifiers developed for millimeter-wave and THz local oscillators are finding their way into point-to-point wireless systems.

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. Astronomers were also 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 require spatially separated crossed rectangular feeds.

1.6.3 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.[4] Weather- and climate-sensitive industries account for about one-quarter of the U.S. gross domestic product. Droughts, severe storms, and floods 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.[5] 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 provide the only means of providing accurate assessments of land- and sea-surface and atmospheric conditions on a global scale and are a critical component for better understanding and predicting the trajectory of Earth's

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[4] ITU-R Report RS.2178 (10/2010).

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

climate. Remotely sensed information from passive and active microwave sensors is increasingly being used to provide guidelines for environmental policy decisions.

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. 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 geographic delineation of forest fire extent 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, using 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 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.

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.[6] Although 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. The costs of such forecasting errors are typically largest in areas of highest population density and thus of greatest spectral demand.

Although 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 connected to regional weather patterns. Furthermore, the prediction of climate changes on all timescales shows increasing promise as global modes of oscillation, such as the El Niño-Southern Oscillation, Pacific Decadal Oscillation, and North Atlantic Oscillation, the teleconnections of these modes to regional climate, and the coupling of major large-scale climate subsystems are better understood. Indeed, as the ability to predict short-term climate improves, the utility of such measurements in making 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.[7]

1.6.4 Education for Scientific Literacy

Both RAS and EESS science programs provide training and educational opportunities for students of all ages. 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 and involvement 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. Indeed, 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, the Massachusetts Institute of Technology's Haystack Observatory staff developed a Small Radio Telescope (SRT) and high school lesson plans as a tool to introduce students to the basics of radio astronomy. More than 100 SRTs were built from the original kits; as of 2012, the SRT has been re-designed so that it can be assembled from commercially available equipment, providing further educational opportunities as students build the telescope themselves.

The Angel Ramos Foundation Visitor and Educational Facility at the National Astronomy and Ionosphere Center (NAIC) in Arecibo, Puerto Rico, receives 100,000 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 the National Radio Astronomy Observatory (NRAO) and NAIC has provided data for many Ph.D.s granted in the past 50 years, and both NRAO and NAIC run

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

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

summer Research Experience for Undergraduates programs. University radio observatories also provide hands-on training for the next generation of engineers and instrument builders as well as astronomers.

Earth remote sensing data are made publicly available at low cost or no cost via the Internet for use in schools. Landsat imagery, weather data, and most data from NASA and NOAA's Earth Observing Satellite system are provided free of charge to U.S. researchers.[8] For instance, digital elevation models from NASA's February 11-22, 2000, Shuttle Radar Topography Mission that operated at 5.3 GHz is the most downloaded NASA data set of all time. Within the framework of the Global Earth Observation System of Systems, Earth remote sensing data are 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 provides a myriad of educational benefits to all students around the globe.

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[8] 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.

2

Scientific Background: Radio Astronomy Service

2.1 INTRODUCTION AND OVERVIEW

The comprehensive study of cosmic objects at radio frequencies began following the serendipitous discovery of celestial radio emission in 1932 by Karl Jansky of the Bell Telephone Laboratories, as a by-product of studies of system and thermal noise in radio-telephone 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 over the years, becoming a major tool of modern astronomy and astrophysics.[1] Due to the extreme physical conditions associated with some celestial objects, radio observations permit the study of a wide range of physical environments, including extremes in density, temperature, pressure, and unusual chemical compositions that cannot be reproduced on Earth.

Radio emission from celestial objects arises under conditions that are different from those processes that produce visible radiation. The light waves studied by optical astronomers originate from objects such as stars and circumstellar nebulae. Celestial radio waves, however, come from diverse environments that are not always accessible at other wavelengths (see, for example, Figure 2.1). Indeed, studies at radio wavelengths often reveal new classes of objects. Moreover, study by radio astronomers of the same celestial objects that optical astronomers study provides independent insight into the physical processes that are not probed at other wavelengths.

Study of the radio emission from celestial sources provides unique insight into the formation, evolution, and physical characteristics of a wide range of astronomical objects and phenomena. Of particular importance for research into the formation and evolution of celestial objects is the fact that some astronomical sources of radio waves are at the farthest limits of the known universe. Observations of these distant sources provide information about the condition of the universe a very long time ago because the radio waves from these sources have been traveling for many billions of years (see Figure 2.2). On the

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[1] For background information from technical papers regarding the technical capabilities of the Radio Astronomy Services, see the following: T.L. Wilson, K. Rohlfs, and S. Huettemeister, *Tools of Radio Astronomy*, 6th ed., December 2013; 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 that traces 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.

other hand, other sources of radio waves are in our backyard: the Sun and Jupiter both exhibit bursts of radio emission. Specific examples of the scientific use of the radio spectrum for astronomical research are highlighted in the following sections.

2.1.1 Types of Radio Emission: 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 Figure 2.3). Individual measurements are made with broadband detectors that span up to 8 GHz and are therefore sensitive to interference over a large range of frequencies, from meter to millimeter wavelengths (several MHz to hundreds of GHz). The radio continuum arises from three main processes, all of which have major application in the study of astronomical objects:

- Thermal (blackbody) radiation following the Planck law, that is emitted by objects according to their physical temperature,
- Free-free emission, which is produced in an ionized gas of freely colliding electrons and protons with an intensity proportional to the temperature of the electrons, and
- Non-thermal emission, mostly produced by incoherent *synchrotron radiation*, in which very high energy electrons spiral around magnetic-field lines, and also by a variety of coherent processes, such as plasma and cyclotron radiation.

An additional effect arises from the Inverse Compton effect, in which relativistic electrons in foreground galaxies shift the photons emitted by the microwave background to higher energies, thus producing an apparent absorption in the radio band. This is also known as the Sunyaev-Zel’dovich (SZ) effect.

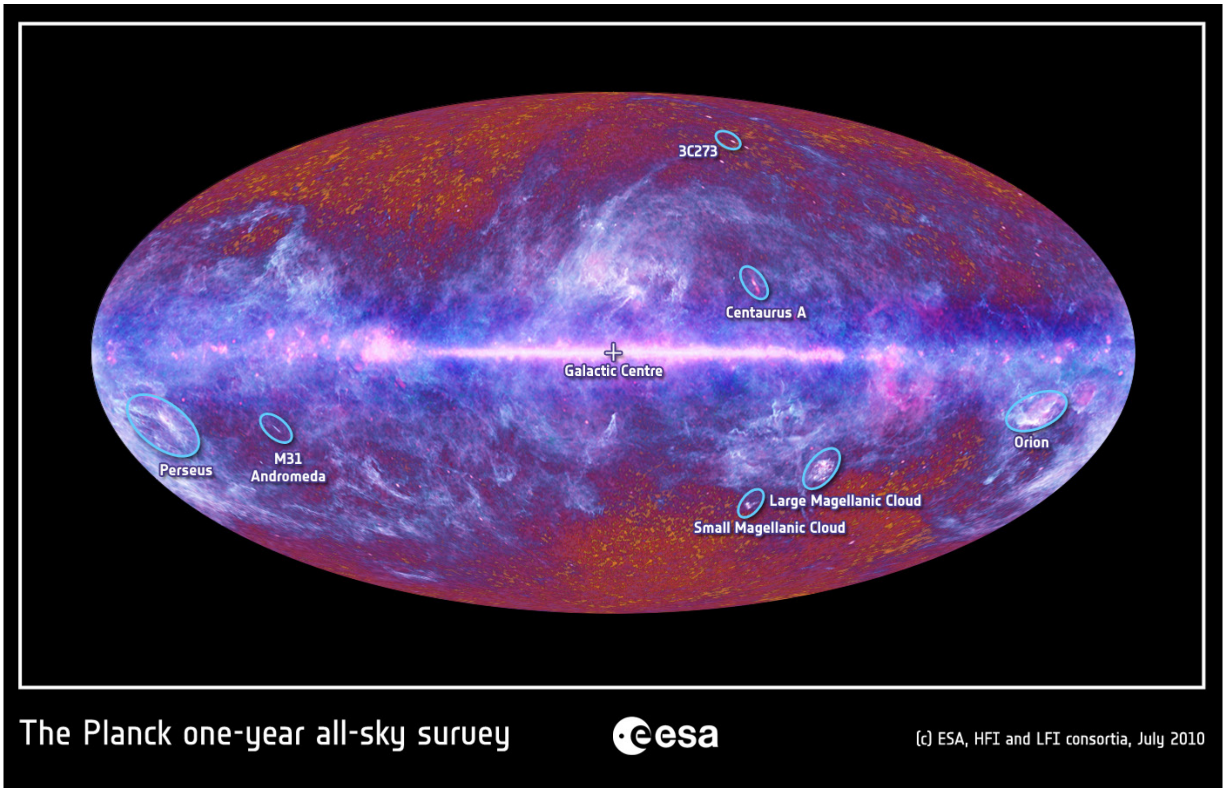

FIGURE 2.1 Multi-frequency all-sky image of the microwave sky composed using data from the European Space Agency (ESA)/NASA Planck satellite covering the electromagnetic spectrum from 30-857 GHz. The mottled structure of the cosmic microwave background radiation (CMB), with its tiny temperature fluctuations reflecting the primordial density variations that are the origin of today's cosmic structure, is clearly visible in the high-latitude regions of the map. The central band is the plane of our galaxy. A large portion of the image is dominated by the diffuse emission from its gas and dust. The great spiral galaxy in Andromeda, 2.2 million light years from Earth, appears as a sliver of microwave light, released by the coldest dust in its giant body. Other, more distant, galaxies with supermassive black holes appear as single points of microwaves dotting the image. The image was derived from data collected by Planck during its first all-sky survey, and comes from about 12 months of observations. SOURCE: ESA, "The Microwave Sky as Seen by Plank," July 2010, http://www.esa.int/spaceinimages/Images/2010/07/The_microwave_sky_as_seen_by_Planck. Copyright ESA/HFI and LFI consortia.

Observations of continuum intensities at a number of frequencies are used to 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. Using a wide signal bandwidth allows higher sensitivity to be obtained because the Gaussian noise is reduced by a factor proportional to the square root of the bandwidth. At high frequencies, bandwidths of up to 8 GHz are commonly used for single antennas such as the Green Bank Telescope (GBT), as well as arrays such as the Very Large Array (VLA). The radio bands, particularly those at frequencies below 3 GHz, are especially valuable for the study of quasars, radio galaxies, pulsars, radio transients, the Sun, and planets in our solar system and beyond. At the high frequency end, continuum observations at frequencies above 20 GHz are used for the study of the angular distribution, polarization, and fine structure of the 2.7 K cosmic microwave background (see Figure 2.1), a remnant of the Big Bang.

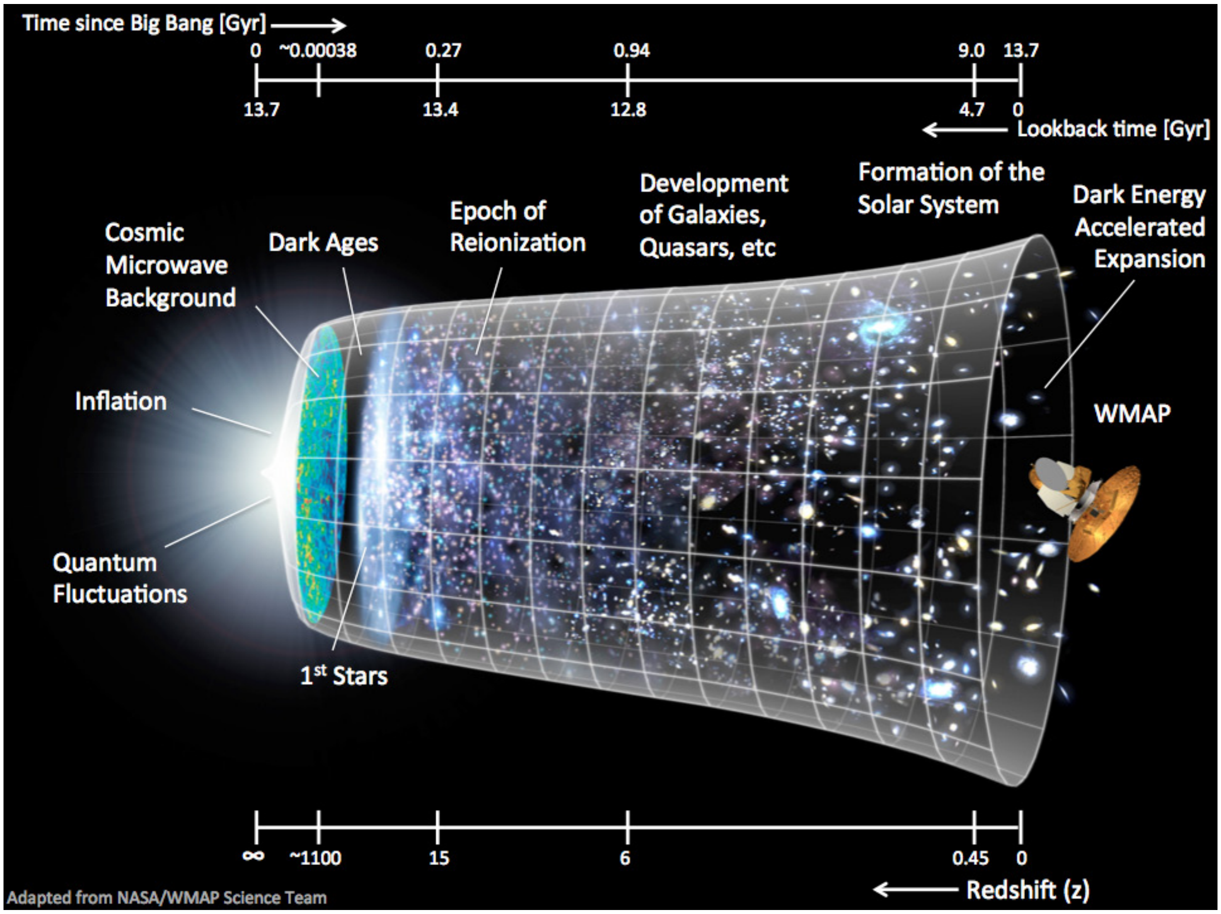

FIGURE 2.2 Schematic of the development of the universe, with time on the upper horizontal axis and redshift (see Box 2.2) on the lower horizontal axis. The development started with the Big Bang, 13.7 Gigayears in the past. Immediately after the Big Bang, matter was hot and ionized. With expansion, the ionized material cooled, with matter and radiation decoupling. The remnant of the Big Bang that is detected as the cosmic microwave background formed at a redshift, z, of about 1100. After redshift 1100, the matter became neutral, until stars formed. Between redshifts of 15 to 6, the first generations of stars, galaxies, and quasars re-ionized matter, resulting in the so-called Epoch of Reionization (EoR). After the EoR, galaxies continued to form and evolve; within the Milky Way Galaxy, our solar system formed only 4.7 Gyr ago. At the present time, the expansion rate of the universe appears to be accelerating, which is attributed to Dark Energy. SOURCE: Adapted from NASA/WMAP Science Team, "Timeline of the Universe," page updated December 21, 2012, http://map.gsfc.nasa.gov/media/060915/index.html.

2.1.2 Types of Radio Emission: Spectral Lines

Spectral line radiation is emitted when an atom or molecule undergoes a radiative transition between energy levels. This radiation is emitted at a well-defined frequency and thus results in a line in the radio spectrum (Figure 2.4). For molecules, many of the rotational and vibrational transitions occur in the centimeter and millimeter wavebands, so many spectral line studies, including the discovery in outer space of new molecular species, can only be carried out in the radio part of the spectrum. In addition,

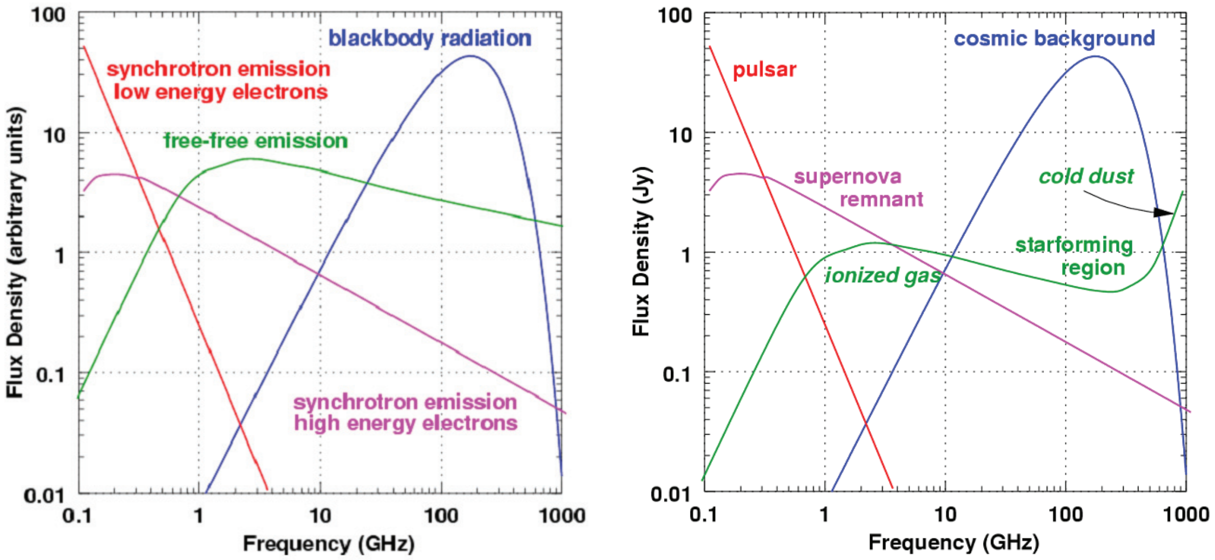

FIGURE 2.3 *Left:* Continuum spectra produced by various emission mechanisms. *Right:* Types of astronomical sources that produce the corresponding radio continuum emission. The flux levels shown correspond to the strongest known sources. A Jansky (Jy) is 10^{-26} W m^{-2} Hz^{-1}.

radio techniques allow spectral lines to be observed with very high frequency resolution that cannot be attained by techniques commonly employed at other wavelengths.

Each atomic and molecular species 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, which arises from neutral 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 rotational energy of the molecule. Studies of the different transitions of the abundant carbon monoxide (CO) molecule at 115, 230, 345 GHz, and beyond (Figure 2.5) provide fundamental information about the nature and distribution of the densest forms of the interstellar medium.

Observations of spectral lines allow astronomers to measure the Doppler shift arising from the relative motion of the source and the observer. The observed frequency of the spectral line, often reported as the redshift (Box 2.2), is a combination of the systemic motion of the celestial object and local kinematic motions of the emitting or absorbing medium. Study of the source location, kinematics, and angular sizes of the regions provide important information about the physical conditions in and near the source and about motions within the source.

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. This rapid expansion of our knowledge has led to the development of a new and exciting branch of astronomy: astrochemistry, which 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. Because planets form as a by-product of star formation, knowledge of interstellar chemistry and the origins of molecular species are vital to an understanding of the early planetary chemistry and the origin of life. Spectral lines from more than 155 different molecular species have now been detected in interstellar

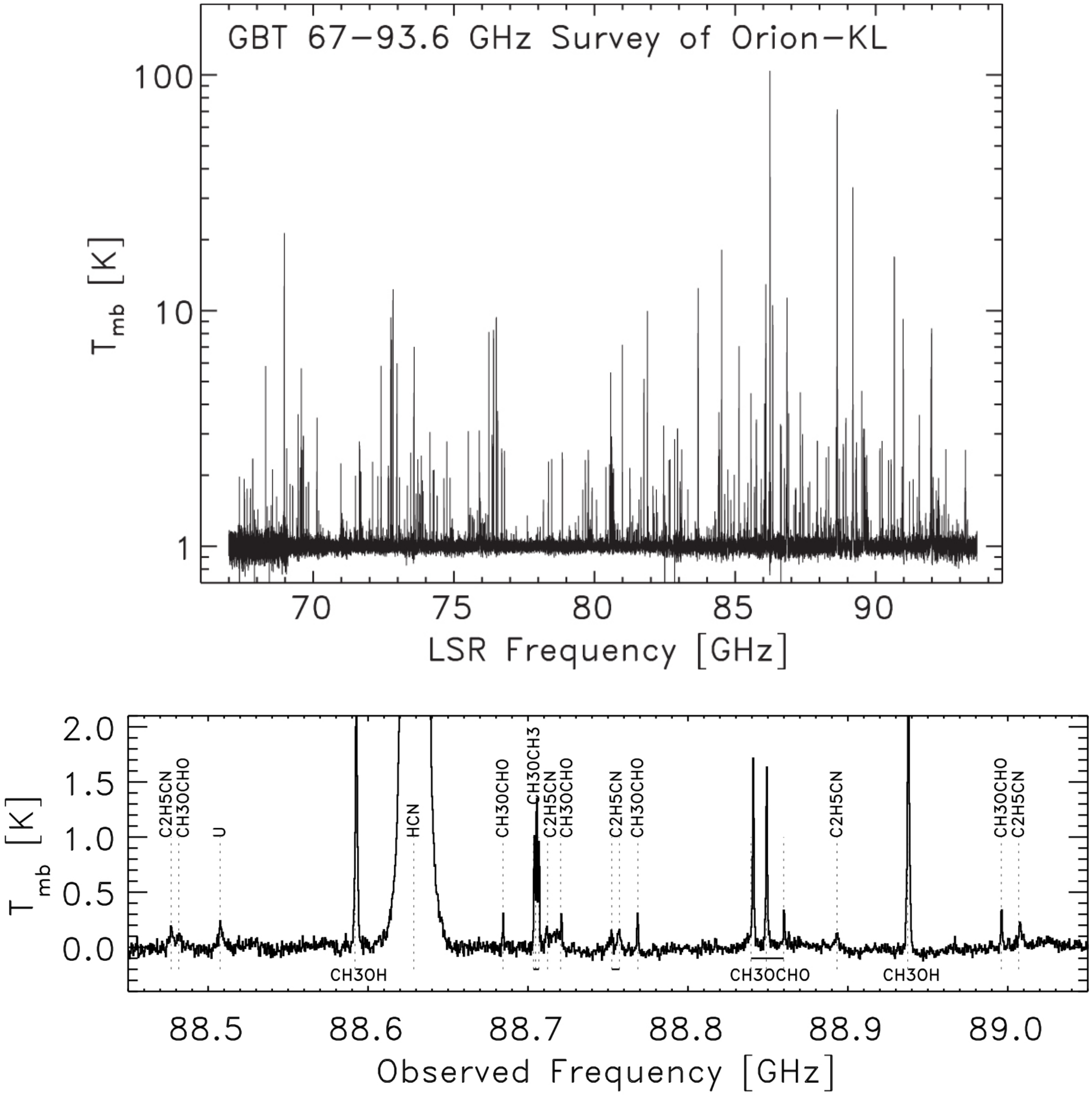

FIGURE 2.4 Orion-KL Spectrum. *Top:* 67 to 93.6 GHz spectrum of the high-mass star forming region in the Orion-KL nebula. The observations were made with the Green Bank Telescope with a spectral resolution of 390 kHz. At least 727 individual spectral features of dozens of different molecular species are seen. *Bottom:* Expanded view in frequency and sensitivity of a frequency range. Spectral features are marked by the dotted lines and labeled by species. For clarity, the dotted lines of neighboring transitions from the same species are connected by a solid line below the spectrum. The feature labeled with a "U" is unidentified. SOURCE: D.T. Frayer, R.J. Maddalena, M. Meijer, L. Hough, S. White, R. Norrod, et al., The GBT 67-93.6 GHz Spectral Line Survey of Orion-KL, *Astronomical Journal* 149:162-166, 2015; courtesy of NRAO/AUI.

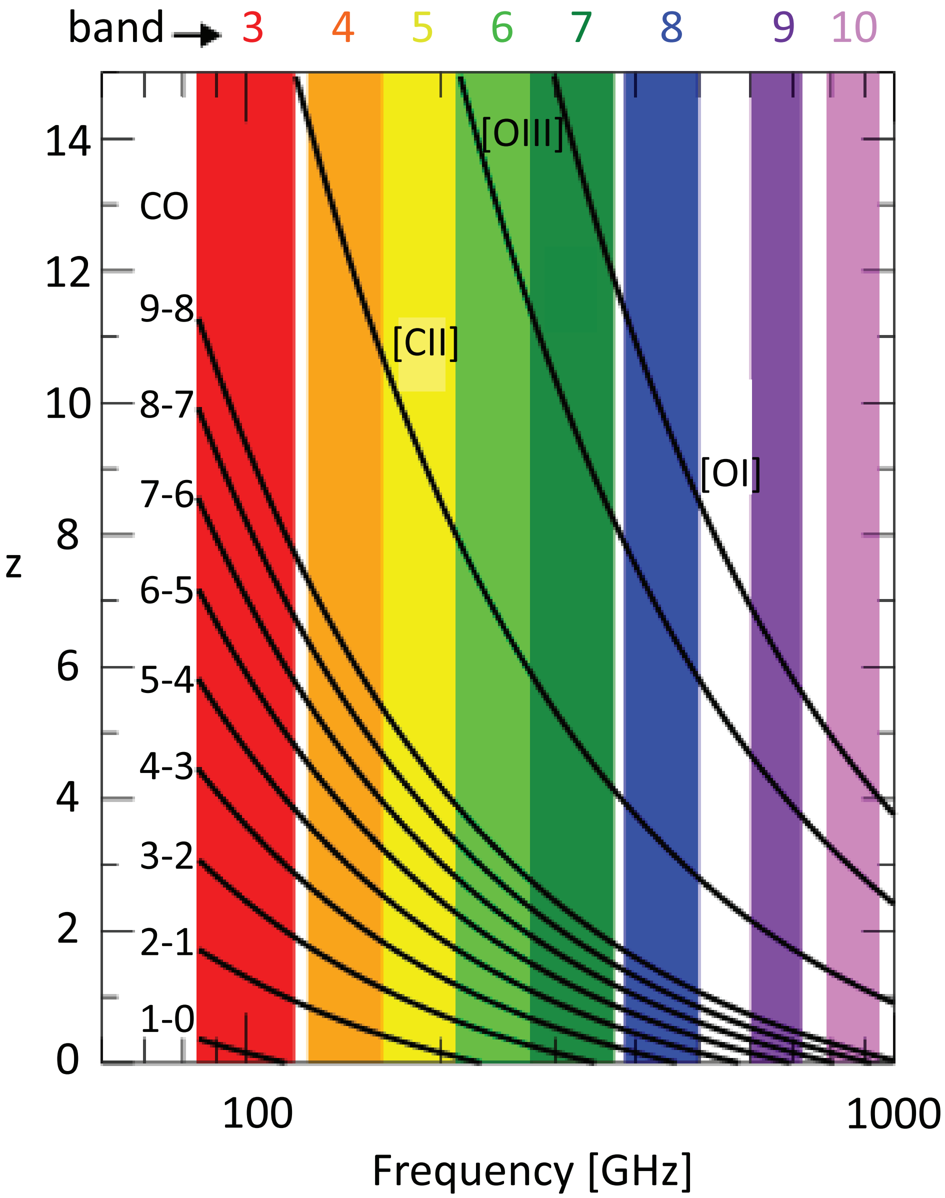

FIGURE 2.5 The expansion of the universe results in an apparent Doppler shift of spectral lines for distant sources. The parameter z [$(f_{\text{emit}} - f_{\text{obs}})/f_{\text{obs}}$] is known as the redshift. Illustrated here are the redshifted frequencies for selected CO rotational transitions and the [CII] 158 micron, [OIII] 88 micron, and [OI] 63 micron fine structure lines. The color-shaded vertical regions indicate the frequency range of the Atacama Large Millimeter Array receivers (bands). Observations of multiple CO lines from the same source enable the study of the physical conditions (temperature and density) associated with molecular clouds and star forming regions in both nearby and extremely distant objects. SOURCE: Adapted from R. Maiolino, Prospects for AGN studies with ALMA, *New Astronomy Reviews* 52(6):339-357, copyright 2008, with permission from Elsevier.

BOX 2.2
Redshifts and the Early Universe

The expansion of the universe stretches electromagnetic waves such that they are received on Earth at a frequency lower than the frequency at which they were emitted. This effect is known as a redshift, *z*, because light is shifted toward the red end of the spectrum because of this expansion. In addition, because the velocity of light is finite, light from distant galaxies was emitted at earlier times and has been stretched more than light emitted from nearby objects, resulting in a direct correspondence between the observed redshift and the distance to an extragalactic source. However, while measurement of an object's redshift is relatively straightforward and precise, usually based on the observed frequencies of known spectral lines, determination of an accurate distance for a celestial object is much more difficult. Thus, astronomers often refer to the redshift of a source rather than its distance. Further, by taking advantage of the finite travel time for light, astronomers can "look back in time" by observing high redshift (distant) galaxies to see the universe at earlier epochs. The correspondence between redshift and lookback time is illustrated in Figure 2.2.

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, D, and E in this handbook list the spectral lines considered by the International Astronomical Union (IAU) to be the ones most important to astronomy (as of 2015) 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, because 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 the pollution of the spectrum with unnecessary emissions.

2.1.3 Atmospheric Windows and Frequency Bands for Radio Astronomy

The allocation of spectral bands for radio astronomy science applications is based partly on the atmospheric windows available, as shown in Figure 2.6. Ground-based radio 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 0.9 mm (325-375 GHz), 0.7 mm (375-500 GHz), 0.45 mm (600-720 GHz), and 0.35 mm (780-900 GHz), as well as in other, smaller, windows.

Within these atmospheric windows, many scientifically important parts of the spectrum have been protected for astronomical research (see Chapter 5). Radio astronomers regularly use frequencies

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

Di-atomic	Tri-atomic	4 Atoms	5 Atoms	6 Atoms	7 Atoms
H_2	C_3	*c*-C_3H	C_5	C_5H	C_6H
AlF	C_2H	*l*-C_3H	C_4H	*l*-H_2C_4	CH_2CHCN
AlCl	C_2O	C_3N	C_4Si	C_2H_4	CH_3C_2H
C_2	C_2S	C_3O	*l*-C_3H_2	CH_3CN	HC_5N
CH	CH_2	C_3S	*c*-C_3H_2	CH_3NC	CH_3CHO
CH^+	HCN	C_2H_2	H_2CCN	CH_3OH	CH_3NH_2
CN	HCO	NH_3	CH_4	CH_3SH	*c*-C_2H_4O
CO	HCO^+	HCCN	HC_3N	HC_3NH^+	H_2CCHOH
CO^+	HCS^+	$HCNH^+$	HC_2NC	HC_2CHO	C_6H^-
CP	HOC^+	HNCO	HCOOH	NH_2CHO	CH_3NCO
SiC	H_2O	HNCS	H_2CNH	C_5N	
HCl	H_2S	$HOCO^+$	H_2C_2O	*l*-HC_4H	
KCl	HNC	H_2CO	H_2NCN	*l*-HC_4N	
NH	HNO	H_2CN	HNC_3	*c*-H_2C_3O	
NO	MgCN	H_2CS	SiH_4	H_2CCNH (?)	
NS	MgNC	H_3O^+	H_2COH^+	C_5N^-	
NaCl	N_2H^+	*c*-SiC_3	C_4H^-	HNCHCN	
OH	N_2O	CH_3	HC(O)CN		
PN	NaCN	C_3N^-	HNCNH		
SO	OCS	PH_3	CH_3O		
SO^+	SO_2	HCNO	NH_4^+		
SiN	*c*-SiC_2	HOCN	H_2NCO^+ (?)		
SiO	CO_2	HSCN	$NCCNH^+$		
SiS	NH_2	H_2O_2			
CS	H_3^+	C_3H^+			
HF	SiCN	HMgNC			
HD	AlNC	HCCO			
FeO ?	SiNC				
O_2	HCP				
CF^+	CCP				
SiH ?	AlOH				
PO	H_2O^+				
AlO	H_2Cl^+				
OH^+	KCN				
CN^-	FeCN				
SH^+	HO_2				
SH	TiO_2				
HCl^+	C_2N				
TiO	Si_2C				
ArH^+					
NO^+ ?					

NOTE: Tentative detections, which have a reasonable chance to be correct, are indicated by “?”. Some detections that have been reported as secure ones are indicated by “(?)” because (partial) overlap of lines cannot be ruled out at the moment or because the line list is somewhat small.

8 Atoms	9 Atoms	10 Atoms	11 Atoms	12 Atoms	>12 Atoms
CH_3C_3N	CH_3C_4H	CH_3C_5N	HC_9N	*c*-C_6H_6	$HC_{11}N$
$HC(O)OCH_3$	CH_3CH_2CN	$(CH_3)_2CO$	CH_3C_6H	*n*-C_3H_7CN	C_{60}
CH_3COOH	$(CH_3)_2O$	$(CH_2OH)_2$	C_2H_5OCHO	*i*-C_3H_7CN 2014	C_{70}
C_7H	CH_3CH_2OH	CH_3CH_2CHO	$CH_3OC(O)CH_3$	$C_2H_5OCH_3$?	C_{60}^+
C_6H_2	HC_7N				
CH_2OHCHO	C_8H				
l-HC_6H	$CH_3C(O)NH_2$				
CH_2CHCHO (?)	C_8H^-				
CH_2CCHCN	C_3H_6				
H_2NCH_2CN	CH_3CH_2SH (?)				
CH_3CHNH					

SOURCE: Universität zu Köln, Physikalisches Institut, “Molecules in Space,” October 2015, http://www.astro.uni-koeln.de/cdms/molecules.

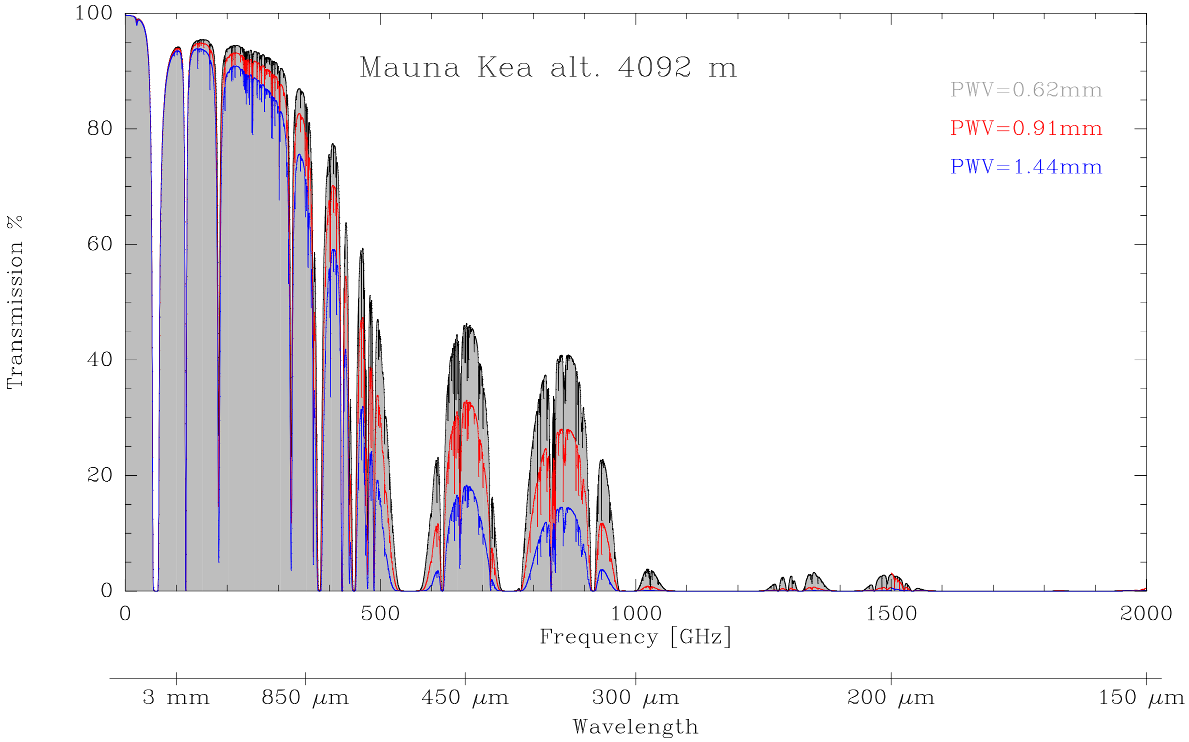

FIGURE 2.6 Atmospheric windows in the radio spectrum commonly used in the Radio Astronomy Service correspond to regions with high atmospheric transmission. Radio observatories with high-frequency receivers are usually located at high elevations, and at historically dry sites, to minimize atmospheric attenuation of cosmic signals. The atmospheric transmission at the top of Mauna Kea, Hawaii, is shown for three values of precipitable water vapor (0.62 mm, 0.91 mm, and 1.44 mm) corresponding to the best 10% (black), 25% (red), and 50% (blue) conditions at the site. SOURCE: P. Tremblin, N. Schneider, V. Minier, G.Al. Durand, and J. Urban, Worldwide site comparison for submillimetre astronomy, *Astronomy and Astrophysics* 548:A65, 2012; see also N. Schneider, J. Urban, and P. Baron, Potential of radiotelescopes for atmospheric line observations: Observation principles and transmissioncurves for selected sites, *Planetary and Space Science* 57(12):1419-1433, copyright 2009, with permission from Elsevier.

from the lowest allocated radio astronomy band at 13.36-13.41 MHz to frequencies above 1000 GHz. However, with the discovery of new astronomical objects and the development of better equipment and techniques, much needs to be done to protect the current allocations and to meet the needs of modern research. The following areas are 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 measurements, which depend on averaging for noise reduction.[2] The Doppler shift of spectral lines due to the expan-

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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.

sion of the universe or local motions of astronomical objects 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 be 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 airborne and spaceborne transmitters, because their modulation techniques are often inefficient and terrain around observatories does not provide shielding for transmitters at high elevation.
- *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.

Despite the above concerns, the shared use of the radio spectrum by both active services and the receive-only Radio Astronomy Service (RAS) is possible in certain circumstances, such as active use of low power or shielded transmitters. For example, the RAS allocation at 608-614 MHz (TV Channel 37) has been shared successfully with medical telemetry devices with no conflict for years. At high frequencies, similar sharing between passive and active use may be possible because of the severe attenuation of the propagating signal and to the geographic isolation of millimeter-wave radio telescopes (which are located on high, arid mountaintops to minimize atmospheric attenuation of already weak signals). However, as a practical matter, commercial applications that choose to use the opaque bands, between the atmospheric windows, will not only avoid conflict with the radio astronomy service, but also minimize conflicts between other active services. In all cases, however, reducing interference from active users of the radio spectrum will increase the efficacy of both the receive-only science applications delineated below and other users of the radio spectrum.

2.2 THE SOLAR SYSTEM AND EXTRASOLAR PLANETS

Radio observations of our solar system span the range of dynamic, but well studied, sources such as our Sun, to observations of stable, but transient, sources such as near-Earth asteroids. The discovery of planets around other stars has led to the burgeoning study of extrasolar planets (exoplanets), the evolution of planetary systems, and a renewed interest in the possibility of other forms of life in the universe.

2.2.1 The Sun

In the solar system, radio observations of the Sun complement optical observations (see Figure 2.7). For example, observations of coronal mass ejections are of particular importance in the study of space weather. 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 22-year cycle. In addition, the intense and rapid bursts of solar radio emission provide 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. Solar monitoring programs at 2.8 GHz have shown that the solar emissions at these radio wavelengths are tightly correlated with ultraviolet and x-ray emissions. In addition, as the longest running indicator of solar activity, solar monitoring at 2.8 GHz can be conducted in any weather conditions and at much less expense than space-based observations. Overall, solar monitoring

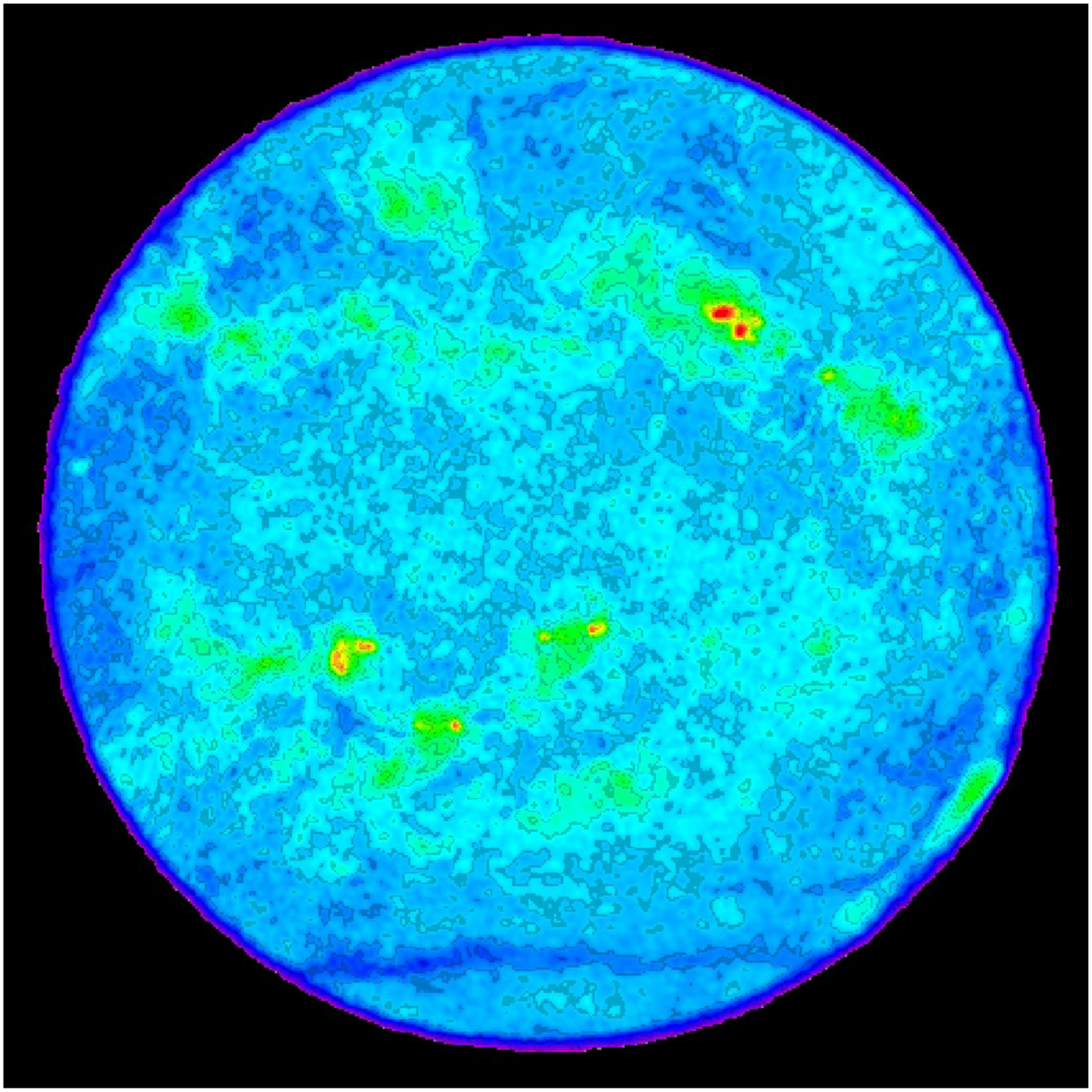

FIGURE 2.7 A 4.9 GHz image of the Sun obtained with the Very Large Array. Several active regions associated with sunspots are seen as well as a line of absorption due to an Hα filament crossing the southern part of the image. SOURCE: “The Radio Sun,” image, April 11, 1999, http://images.nrao.edu/506; courtesy of NRAO/AUI and Stephen White, University of Maryland.

programs with frequency coverage from 1 to 18 GHz provide insight into the nature and evolution of coronal magnetic fields and the temperature and density of nonthermal electrons in active regions.

Radio observations of the Sun made at frequencies below ~100 MHz provide essential data on solar bursts. Occasionally, and more 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. Radio bursts and coronal mass ejections 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 cause damage to orbiting satellites, and 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 passengers on 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.

2.2.2 Geodesy

Originally developed as a radio astronomical technique for the high-resolution imaging of astronomical objects, Very Long Baseline Interferometry (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. 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. 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 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.

Although it is not possible to make such precise measurements using only bands allocated to the passive services, use of broader bandwidths are possible because the interferometric technique provides some mitigation against radio frequency interference that is present in only one of the antennas. 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.

2.2.3 Comets and Asteroids

Comets likely preserve 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. "Parent" species are those directly sublimated from the nucleus, while "daughter" species are formed through photo-destruction within the coma. Many parent molecules are only detectable via radio spectroscopy, so radio observations provide the best way to measure the detailed molecular composition of the cometary ices, which then relate to the volatile composition of the protosolar cloud that formed the Sun and planets. High-resolution radio spectroscopy enables analysis of the dynamics of gas production, the excitation mechanisms affecting coma molecules, and what fraction of the nucleus is actively outgassing. In addition, quasi-thermal broadband emission from cometary dust can be detected in the millimeter and submillimeter wavelength ranges, enabling assessment of the structure, porosity, mass, and density of dust that was aggregated from the protosolar nebula.

Asteroid thermal emission, which typically peaks in the mid-infrared bands, can still be detected at radio wavelengths for some bodies. For larger or closer objects, the Atacama Large Millimeter Array (ALMA) can provide high enough resolution to make thermal maps of asteroid surfaces at submillimeter (>300 GHz) wavelengths. Such observations place important constraints on thermal inertia, which relates to the density and porosity of the object, which is an important element in assessing impact hazards, and complements radar observations.

2.2.4 Radar Astronomy

While radio astronomy is largely a receive-only activity, there is one exception. Operating in the Radiolocation Service bands at 2380 MHz and 8560 MHz, powerful radars at the Arecibo Observatory and the NASA Goldstone Deep Space Communications Complex, respectively, are used to study the surfaces of the Moon, Mars, Mercury, Venus, comets, asteroids, and the satellites and rings of Jupiter and Saturn. Additional transmitters at 7200 MHz are also used by other Deep Space Network antennas, as well as X-band (8560 MHz) transmitters at various private and international facilities. Though many radar signal returns are received by the transmitting station, in some cases it is advantageous to receive at a different station in *bistatic* mode. Bistatic observations are used when the radar target (the moon or a near-Earth object) is too close to Earth to switch transmit/receive modes in time to capture the echo. In addition, bistatic operations permit the optimal combination of transmitter resolution and receiving station sensitivity, such as transmission at Goldstone and receipt at Arecibo. Furthermore, by receiving radar echoes with an interferometer array, such as the VLA or the Very Long Baseline Array (VLBA), the technique of radar speckle tracking provides a high-resolution option for both planetary and asteroidal targets.

Observations with planetary radar systems have made unique and critical contributions to our knowledge of the Moon, terrestrial planets, satellites, asteroids, and comets. Radar astrometry can improve orbit characterization and predictions, which assist with planning and executing spacecraft rendezvous, analysis of non-gravitational effects on the orbits, testing General Relativity predictions, measuring solar oblateness, and assessing impact hazards. Radar imaging at high resolution, often rivaling that of spacecraft encounters, enables determination of object shapes, estimation of spin pole positions, discovery of satellites or contact binaries, and characterization of surface and near-surface processes and properties (see Figure 2.8). Radar characterizations of binary/multiple systems can constrain masses, densities, and material properties critical for hazard assessment. In addition, radar astrometry places strong constraints on Yarkovsky drift, which results from asymmetrical thermal emissions and can alter the orbits of small objects. Yarkovsky effects are important to the assessment of impact hazards, but also offer another means of estimating masses because the effect is proportional to object size.

Although the transmitters are very powerful, the returned signals decrease with the fourth power of the distance to the target and, therefore, are extremely weak and vulnerable to interference. In particular, the Arecibo S-band radar frequency 2380 MHz is close to powerful broadcast satellite transmissions near 2330 MHz, which is of great concern for the reliable detection of the weak return signals. Bistatic operations require coordinated protection of frequency bands at two or more stations, and often a rapid response time for scheduling and coordination when newly discovered targets are being observed.

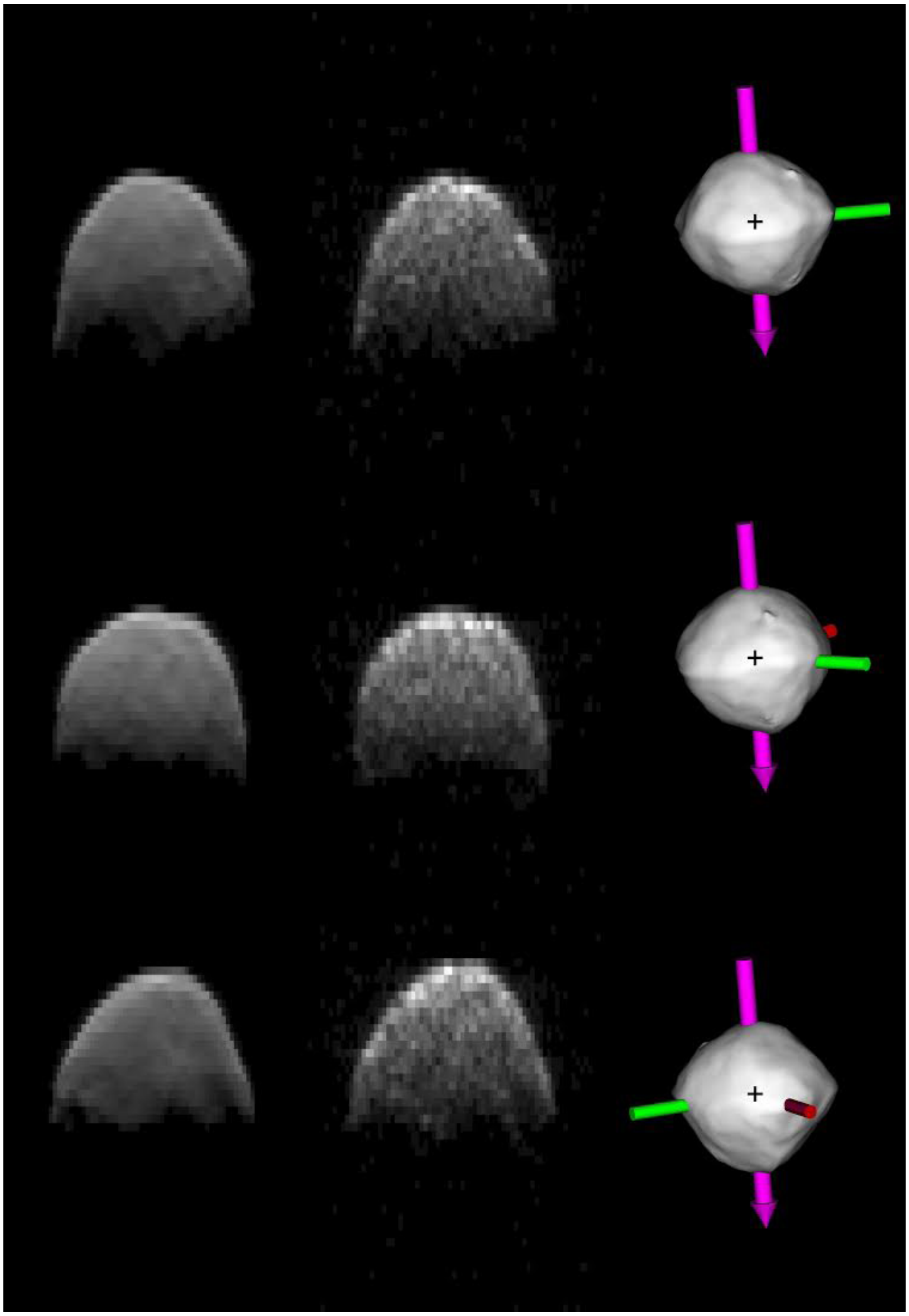

FIGURE 2.8 A radar investigation and model of asteroid 101955 Bennu, a target for the OSIRIS-REX sample-return mission. A simulation of the data based on the model is shown at the left for three different times on September 23, 1999. In the center are the delay-Doppler images from the S-band Arecibo Planetary Radar observations, where the width of the image is proportional to the asteroid's rotation speed, and the height of the image shows the radar range, related to the object's physical size. At right is how Bennu would appear on the sky viewed from Earth at the time the data were taken (the cross indicates the sub-radar point on the model). SOURCE: Courtesy of Michael C. Nolan, Arecibo Observatory.

2.2.5 Our Solar System

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 from ~15 to ~35 MHz; 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. Furthermore, these bursts are an example of a coherent emission mechanism that is not completely understood. This has been confirmed and extended by measurements in the vicinity of Jupiter from flyby and orbital 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. Low frequency observations have also detected electric discharges in the atmospheres of Saturn, Uranus, and Neptune. 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. Ground-based radio observations complement optical observations in providing the long-term monitoring necessary to study the seasonal cycles on Titan, viewing Saturn's rings at different geometries, and monitoring Venus radar returns for evidence of volcanic activity.

In addition, another important use of radio astronomy telescopes is for ground-based telemetry for space missions, including, for example, use of the VLBA in support of the Cassini mission during the descent of the Huygens probe at Titan, and use of the Green Bank Telescope to acquire signals from the probe during its descent to measure wind speeds on Titan. As large, sensitive receivers with large collecting areas, Green Bank and Arecibo can be used to confirm a spacecraft landing or recover homing signals from spacecraft for which anomalies have occurred. Frequencies used in these experiments are necessarily limited to those available on spacecraft transmitters, which are generally in X-band (8-12 GHz), but vary depending on the Doppler shift due to motion of the spacecraft or its target object in the solar system.

2.2.6 Extrasolar Planets

Given the dramatic strength of Jovian Bursts at low frequencies, considerable effort is currently being directed into searches for emission from extrasolar planets (exo-planets) below 80 MHz with new instruments such as the Long Wavelength Array (LWA). These observations enable a search for stellar bursts coupled with planetary orbits in these systems and provide evidence for evaporation of extrasolar planetary atmospheres. Such observations have the potential to reveal extrasolar planetary magnetic field strengths, the exoplanet's composition, and how bursts may influence habitability for extremely small planetary orbits. In particular, magnetic fields are critical to the establishment of life as they deflect high-energy charged particles and help to confine planetary atmospheres. The presence and strength of magnetic fields also provide insight into the internal structure of planets. As extrasolar planet detections increase, new fields of research are emerging, enabled by radio astronomy, including studies of composition, atmospheres, and habitability.

Searches for protoplanetary bodies are undertaken in the infrared, submillimeter, and millimeter as dusty debris disks are thermal emitters within these wavelength regimes. One spectacular example of a protoplanetary disk imaged with the ALMA interferometer is the HL-Tau system (Figure 2.9). The multiple rings and gaps are indicative of protoplanetary bodies that have collapsed and swept their orbits clear of debris while, at the same time, they shepherd the remaining dust and gas into tighter, more confined, zones. Similar high spatial resolution imaging of other young stellar systems has the potential to provide unique insight into the formation of planets and solar systems like our own.

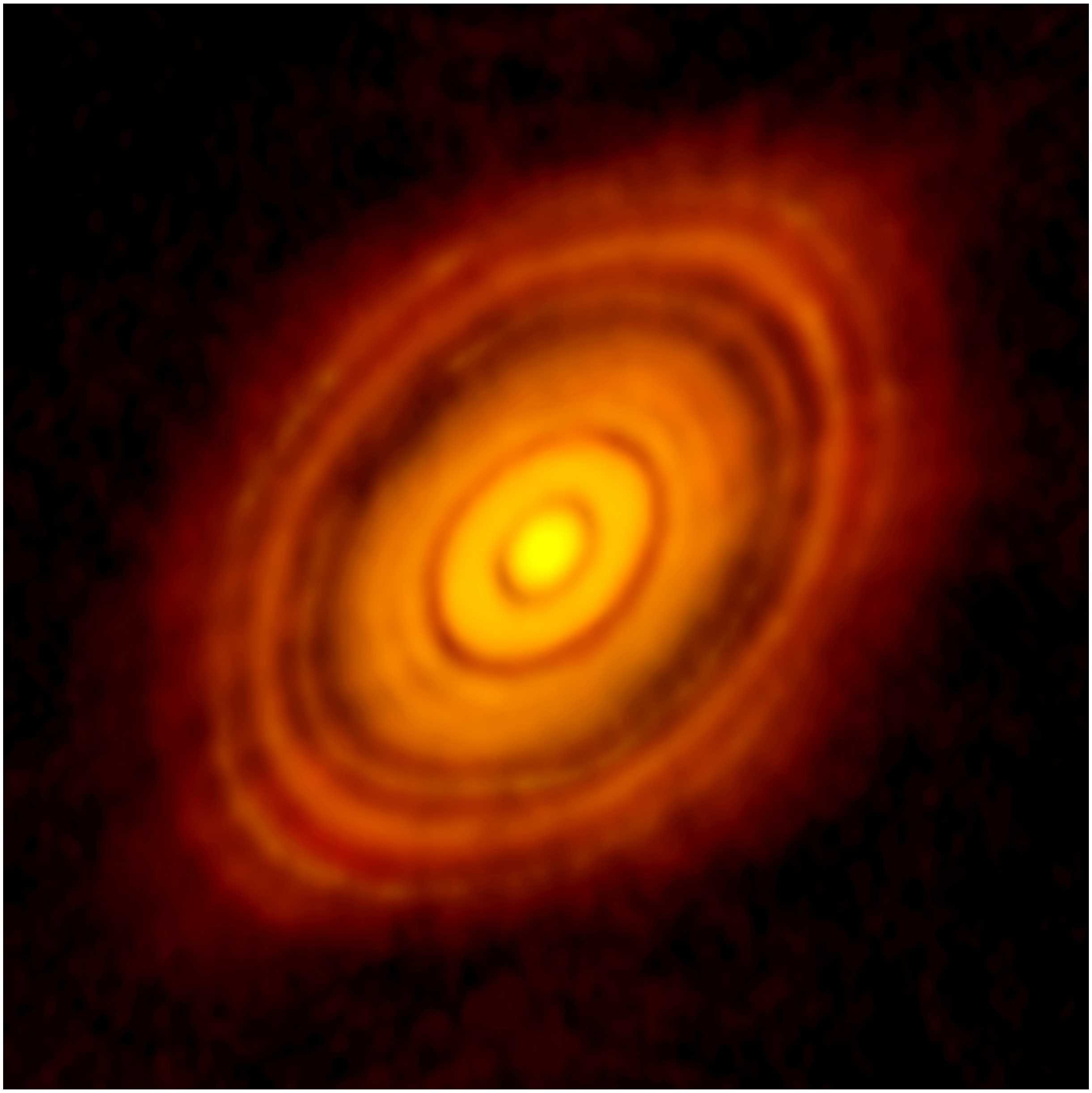

FIGURE 2.9 A 300 GHz Atacama Large Millimeter Array image of the young star HL Tau and its protoplanetary disk that shows multiple rings and gaps characteristic of emerging planets as they sweep their orbits clear of dust and gas. SOURCE: Courtesy of ALMA (NRAO/ESO/NAOJ); C. Brogan, B. Saxton (NRAO/AUI/NSF); see NRAO, "Birth of Planets Revealed in Astonishing Detail in ALMA's 'Best Image Ever,'" press release, November 6, 2014, https://public.nrao.edu/news/pressreleases/planet-formation-alma.

2.2.7 Prebiotic Chemical Evolution

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 65-115 GHz (3 mm) and 125-180 GHz (2 mm) spectral regions (see Figure 2.6) have been the prime frequency 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, enhanced by the addition of more sensitive laboratory spectroscopy in support of millimeter-wave observations with ALMA. Because temperature environments in our solar system and in extrasolar planetary systems cover a wide range, higher energy transitions at 1 mm and shorter can yield important insights into the distribution of those molecules, hence, broadband protection of millimeter-wave windows is desirable, as well as for observations above 300 GHz.

2.2.8 The Search for Extraterrestrial Intelligence

Making use of receiver instrumentation developed for radio astronomy, radio searches for extraterrestrial intelligence (SETI) are largely clustered about the frequencies of natural and molecular emission lines and within the protected radio astronomy bands. For example, in 1959, Frank Drake made the first radio search for extraterrestrial intelligence using the Howard E. Tatel Telescope of the National Radio Astronomy Observatory (NRAO) equipped with a single-channel narrowband spectrometer and a receiver tuned around 1420 MHz. In recognition of the interest of the radio science community in these passive search techniques, 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 (WARC, the predecessor of the WRC). Recent improvements in receiver technology and digital signal processing equipment, intended primarily for use in radio astronomy, have enabled far more sensitive and sophisticated searches for extraterrestrial technologies to be conducted.

One 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. Plausible arguments can also be made for searching at “magic frequencies,” but most of the microwave window has remained unexplored.

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 direction, 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 such searches.

2.3 THE MILKY WAY AND OTHER GALAXIES

Radio observations of our galaxy and others reveal complex structures from individual stellar systems to extensive stellar nurseries, all of which are situated within a dusty interstellar medium. Spectral line observations trace the kinematics and distribution of atomic and molecular gas in cold, warm, and hot phases of the interstellar medium. Meanwhile, continuum observations reveal dust and magnetic fields throughout the galaxy. Observations of pulsars test theories of general relativity and also trace the distribution of ionized plasma throughout the Milky Way.

2.3.1 The Interstellar Medium: Neutral and Ionized Atomic Gas

The material between the stars in the Milky Way and other galaxies includes an inhomogeneous mix of ionized, neutral atomic, and molecular gas. Spectral lines from atomic transitions trace the diffuse component of this interstellar medium. 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 both 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. Within this range, the 1330-1420 MHz band is particularly important for observations of redshifted HI gas from distant external galaxies and quasars (see Box 2.2). However, studies of the evolution of the HI mass function over cosmic time will require observations at even lower frequencies; currently, surveys below 1200 MHz are being proposed for systematic study of the evolution of the atomic gas component in external galaxies. Such studies are 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 comparable hyperfine-structure transition of atomic deuterium occurs at 327.384 MHz. The study of this line is significant for questions related to the origin of the universe and the cosmological synthesis of the elements. However, because of its low abundance, 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.

Other important atomic transitions include the atomic recombination lines that occur after an ionized atom 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-stage stars. Radio studies have been particularly helpful for observations of these nebulae, which are partially or totally obscured at optical wavelengths by interstellar dust. The recombination lines that occur below 3 GHz arise from very high energy levels, in which the electron orbits very far from the atomic nucleus. In fact, these atoms are so large that the orbits of the outer electrons are affected by the free electrons in a measurable way, serving as a probe of the density of the ionized gas. 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.

2.3.2 The Interstellar Medium: Cold Molecular Gas

Molecular transitions provide unique information regarding the physical properties of the interstellar medium, measurement of relative chemical abundances, and the identification of regions that are favorable for star formation. A listing of many of the important molecular transitions for astronomical studies is provided in Appendices C, D, and E. To provide context for the general study of the molecular components of the Milky Way and other galaxies, several of the most commonly observed molecular lines are discussed in more detail here. For example, the discovery of interstellar carbon monoxide (CO) at 115.271 GHz has been of fundamental significance for the study of star-forming gas in the Milky Way

Galaxy and in distant galaxies. 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. CO studies give information about disks around forming stars and, in the future, they may tell of the conditions for planet formation. CO lines are also used to measure the mass loss rates from evolved stars. Furthermore, CO emission studies reveal the presence of bursts of star formation activity in nearby and distant galaxies. These bursts have recently been related to collisions between galaxies and possibly to the formation of massive black holes and quasars. Allowance for Doppler shifts characteristic of nearby and distant galaxies is essential for adequate protection of radio spectral lines for scientific research. For example, the 100-116 GHz band is used for radio astronomy observations of redshifted CO in distant galaxies and for isotopic transitions of ^{12}CO, ^{13}CO, and $C^{18}O$ in the Milky Way and nearby galaxies.

A wide range of interstellar molecules can be observed through the atmospheric windows (see Figure 2.6) at 3 mm (65-115 GHz), 2 mm (125-180 GHz), 1.2 mm (200-300 GHz), 0.9 mm (325-375 GHz), 0.7 mm (375-500 GHz), 0.45 mm (600-720 GHz), and 0.35 mm (780-950 GHz). The CO molecule is important because this is a good tracer of the abundance of molecular hydrogen in the interstellar medium. Rotational lines of CO have been detected to redshifts of more than 5 (see Figure 2.5 for a schematic of the visibility of various CO transitions in the atmospheric windows as a result of the Doppler shift due to the expansion of the universe). The 3 mm window 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. In addition, 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. The 1.2 mm and 0.9 mm bands include the $J = 2 \rightarrow 1$ and $J = 3 \rightarrow 2$ lines of CO, as well as its isotopic variants; the 0.7 mm band contains the $J = 4 \rightarrow 3$ line of CO, and the $^3P_1$-$^3P_0$ fine structure line of neutral carbon, while the 0.35 mm band contains the $J = 7 \rightarrow 6$ line of CO and the $^3P_2$-$^3P_1$ fine structure line of neutral carbon. 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. The rotational transitions of such species as HCO^+ and HCN lie in these bands as well and are important tracers of high-density gas in molecular clouds. 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^+. Only at frequencies above 200 GHz can these hydride molecules be studied in the interstellar medium. 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.

Isotope ratios, particularly the $^{12}C/^{13}C$, $^{16}O/^{18}O$, and $^{32}S/^{34}S$ ratios, give important insight into theories of nucleosynthesis in stars and models of star-formation rates and the relative masses involved. As an example, the basic molecule HCN has the isotopic species $H^{12}C^{14}N$, $H^{13}C^{14}N$, and $H^{12}C^{15}N$ in the 86-92 GHz range, and all have been observed in interstellar gas. Similarly, the 48.94-49.04 GHz band contains the lowest rotational transitions of CS and its isotopes such as $C^{33}S$ and $C^{34}S$. 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.

The discovery of ammonia (NH_3) in interstellar space presented an example of a molecule radiating thermally. The distribution of NH_3 clouds in our galaxy and their relation to the other molecules that have been discovered are of great interest. Radio lines of ammonia at 23 GHz 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.

At lower frequencies, formaldehyde (H_2CO) is detected in interstellar clouds via its K-doubling transition ($J_{K-1,K+1} = 1_{10}$-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. 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.

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. Emission lines from ^{18}OH and ^{17}OH have been detected in some molecular regions of our galaxy and other galaxies. 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. OH lines also appear as masers in both our galaxy and in extragalactic sources (see Section 2.3.4).

Finally, 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 ($x = 1, 3, 5, 7, 9, 11, \ldots$).

2.3.3 The Interstellar Medium: Dust

Cold dust, with grain temperatures of 10 K to 30 K, makes up much of the total mass of dust in our galaxy and in other galaxies. In fact, aside from planets, dust emission provides the most prominent source of broadband radiation at millimeter/submillimeter wavelengths. Observations indicate that the spectral energy distribution of dust emission is quasi-thermal. Specifically, in the millimeter/submillimeter wavelength range, the emission follows the modified Rayleigh-Jeans relation with intensity increasing proportional to frequency to the second power. However, at higher frequencies, the intensity is directly proportional to dust temperature and optical depth. The intensity is measured to vary as $I(\nu) \propto \nu^{\beta+2}$ power, where the value of+2 arises from the Rayleigh-Jeans factor and β has a value of 1 to 2, depending on the composition of the dust. Measurement of the quasi-thermal emission from dust grains is an important component in the determination of source mass and estimation of energy balance in the interstellar medium. For example, it is possible to estimate the column density of hydrogen in all forms (atomic, molecular, and ionized) from the dust emission by measuring the spectral energy distribution (SED) on both sides of the peak to derive a dust temperature and to infer properties of the dust grains.

Dust grains come in a wide range of sizes, with a typical size of 0.1 microns, and are mainly silicates or graphites with an icy surface. However, it is likely that the structure of dust grains is not spherical. Measurements of absorption (in the optical and near-infrared) and emission (in the millimeter/submillimeter) from dust grains show linear polarization, so grains are elongated and can be aligned by magnetic fields. Dust grains are important catalysts for complex astrochemistry reactions, as they provide surfaces on which molecules may form and then later be ejected into the interstellar medium.

Small grains are thought to be particularly important for astrochemistry, because they have a large surface area to volume ratio.

2.3.4 Masers

Extremely narrow and intense emission lines can arise if the physical conditions and geometric alignment are optimal for microwave amplification by stimulated emission of radiation (masers). Masers can be associated with star-forming regions and with more-evolved stars. Within the Milky Way, OH maser sources have apparent angular sizes on the order of 0.01 arcsecond 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 our 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 our galaxy. OH masers in other galaxies can be more than a million times as luminous as galactic masers. These so-called megamasers arise within the cores of galaxies; this action results in amplification (rather than absorption) of the nuclear radio continuum. Because they are so bright, these powerful OH megamasers can be seen to great distances, currently up to 80,000 km/s ($z = 0.27$). Use of the OH 1667 MHz 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. Similarly, extragalactic formaldehyde megamaser emission and absorption are found in a growing number of galaxies. Because 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.

The discovery in 1968 of extremely intense lines at 22.2 GHz from the H_2O molecule in interstellar space has also resulted in many new and interesting puzzles. 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. Additionally, H_2O masers often show multiple components, each one with a slightly different velocity in the line of sight. Tracing the kinematic motions of H_2O masers in external galaxies has led to the first geometric distance measurements in extragalactic sources (see Section 2.3.9).

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. In addition, two vibrational states of the transitions of SiO fall in the 3 mm spectral window. SiO is the only molecule that shows strong maser emission in an excited vibrational state.

2.3.5 Magnetic Fields

Magnetic fields may play a major role in the dynamics of the interstellar gas in galaxies. The strength of the magnetic field along a line of sight can be inferred from its effects on the propagation of radio waves. For example, the OH molecule has four hyperfine components of the ground state lambda-doubling transitions at 1665, 1667, 1612, and 1720 MHz. The two oppositely circularly polarized components become slightly separated in frequency in the presence of a magnetic field. This so-called Zeeman effect is an effective method to measure the strength of the magnetic field in our galaxy and in other galaxies with OH megamaser emission.

Alternative techniques to measure the magnetic field strength along the line of sight include observations of continuum emission from pulsars (Section 2.3.7). The frequency dependence of pulse arrival times is proportional to the electron density along the line of sight. At the same time, the observed

Faraday rotation is proportional to the magnetic field strength and the electron density. Thus, ratios of the rotation measure to the dispersion measure for pulsars located throughout our galaxy trace the strength of the galactic magnetic field along many lines of sight. Continuum bands, particularly those at frequencies below 3 GHz, are most valuable for these studies.

2.3.6 Stars and Stellar Processes

While stars range widely in mass, the most common types are at the lowest masses: M, L, and T dwarfs. These stars have extremely long formation times and lifetimes. Radio observations of these stars can detect stellar flares, star-spots or other magnetic activity. Flares can be synchronized with the orbit of a close-orbiting planet, making radio pulse timing another good option for detecting extrasolar planets (comparable to the investigation of pulsars, Section 2.3.7), constraining orbital timescales, and assessing habitability. Stellar flares are of particular interest because of their potential influence on planetary habitability. Because of their abundance in our galaxy, coupled with their strong magnetic fields and associated activity, low-mass stars are ideal for radio observations and inform the study of all types of stars and planetary systems.

Brown dwarfs, sub-stellar objects that are not massive enough to sustain core hydrogen fusion, are also interesting objects for radio astronomy observations. In particular, as star-planet transition objects, they offer us insight into both stars and planets. Brown dwarfs alone are brighter and easier to detect than planets, and brown dwarfs with extrasolar planets provide an interesting contrast to planetary systems with more massive host stars.

At the end-stages of their stellar life cycle, stars shed material into the interstellar medium. The physical conditions of circumstellar envelopes of late-stage stars are favorable for the formation of complex long-chain carbon species such as C_3H, C_3N, C_4H, C_7H, C_8H, as well as those of silicon-, magnesium-, and aluminum-bearing molecules (SiS, SiC_2, SiC_3, MgCN, AlCl, AlNC). Observations of these spectral lines in the 3 mm and 2 mm windows (see Figure 2.6) provide insight into the chemistry of circumstellar envelopes of late-stage stars. In addition, observations of SiO maser transitions at 42.5-43.5 GHz provide probes of the stellar envelopes, yielding information on temperature, density, stellar wind velocities, and envelope geometry.

The highest mass stars will eject their outer envelopes into the interstellar medium via supernova explosions at the end of their life. While the supernova explosion itself occurs on short timescales, the resulting supernova remnants are relatively long lived and have characteristic non-thermal spectra produced by synchrotron emission from relativistic cosmic ray electrons moving in galactic-scale magnetic fields. Radio continuum observations at, for example, 5 GHz reveal the extent and detailed morphology of galactic supernova remnants and allow measurement of their structures and dynamics as well as the derivation of their physical parameters, such as their total mass.

2.3.7 Pulsars and Gravitational Waves

One of the most interesting and important discoveries in radio astronomy has been the detection of pulsars. 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 explosion of a supernova. The radio spectra of pulsars indicate a non-thermal mechanism. Pulsars emit strongest at frequencies in the range from ~50 MHz to 2 GHz. Hence, many observations are being performed at such frequencies. However, important observations and surveys for pulsars are being conducted at frequencies up to 10 GHz.

The discovery and the study of pulsars during the past five 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.

The discovery of millisecond binary pulsars has enabled the best experimental tests of general relativity and provided strong evidence for the existence of gravitational radiation. In addition, careful analysis of pulse timing residuals led to the startling discovery of planet-sized bodies in orbit around pulsars—the first detection of extrasolar planets (see also Section 2.2.6). Pulsars also now provide the most accurate timekeeping, surpassing the world's ensemble of atomic clocks for long-term time stability.

Coordinated observations of pulsars at a number of radio observatories, such as those by the NANOGrav project, provide a method to search for Gravitational Wave Radiation (GWR). Specifically, because millisecond pulsars are very stable clocks, coordinated observations of millisecond pulsars provide precise time-of-arrival measurements at each observatory. Fluctuations of time-of-arrival can then be used to detect GWR from the correlation of measured residuals.

2.3.8 Galactic Structure and Dark Matter

Observations of the structure of our own Milky Way are difficult to obtain at optical wavelengths, because these wavelengths of light are blocked by clouds of interstellar dust. Radio waves, however, can penetrate these clouds and allow astronomers to obtain a view of the entire Milky Way galaxy, including the galactic center (see Figure 2.10). Studies of the location and composition of interstellar clouds using radio observations provide fundamental information about the structure and evolution of the galaxy that cannot be obtained by other means. The frequency bands in the 1 to 3 GHz range are important for galactic studies of ionized hydrogen clouds and the general diffuse radiation of the Milky Way. Furthermore, maps

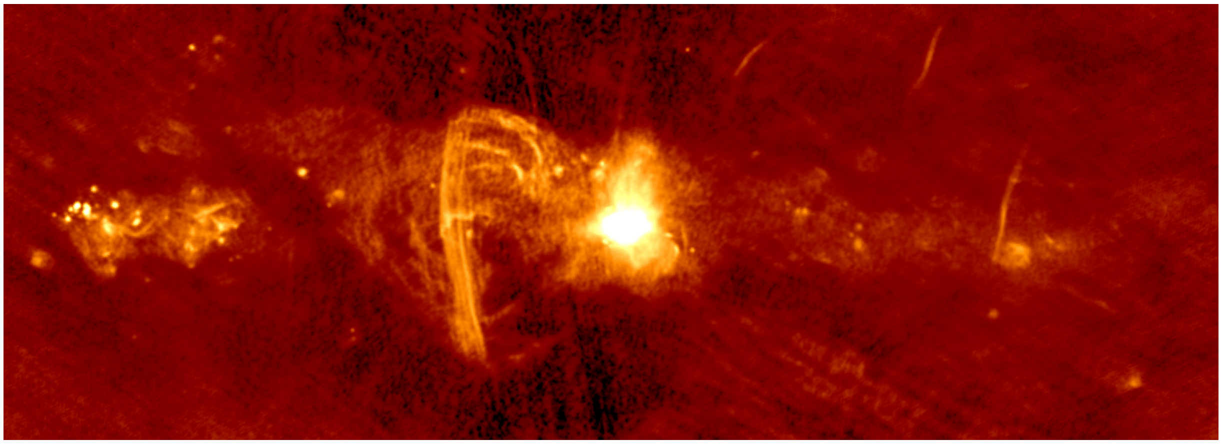

FIGURE 2.10 Radio image of the center of our galaxy at 1.4 GHz from the Very Large Array. The bright core in the center of the image (known as Sgr A) is the area surrounding the Milky Way's supermassive black hole. Other structures in this image include supernova remnants (SNRs) and filamentary arcs tracing magnetic field lines. SOURCE: Courtesy of Elisabeth Mills, NRAO, and Cornelia Lang, University of Iowa; see C.C. Lang, W.M. Goss, C. Cyganowski, and K.I. Clubb, A high-resolution survey of H I absorption toward the central 200 pc of the galactic center, *Astrophysical Journal Supplement Series* 191:275, 2010.

of galactic continuum emission are not only important for the fundamental science associated with studies of structure in our own Milky Way, but also critical to the interpretation of observations of the cosmic microwave background (see Section 2.4.1). Indeed, the most serious hindrance to the full exploitation of existing and future cosmic microwave background data sets is the understanding of the galactic foreground (see Figure 2.1), especially at the frequencies used for these experiments (20-200 GHz).

Observations below 1 GHz are also of great importance in the study of both the thermal and non-thermal 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. Several hundred such galactic clouds appear approximately as blackbodies at frequencies below ~100 MHz.

The structure of our galaxy can also be inferred from the dispersive properties of the diffuse interstellar plasma on the radiation emitted from pulsars. Specifically, because each pulse provides a unique time stamp, it is possible to measure the arrival time of the pulse as a function of frequency and thereby derive the column density of electrons along the path (see Figure 2.11). In addition, the Faraday rotation angle provides a measure of the strength and orientation of the local galactic magnetic field along these same paths. Thus, using pulsars located throughout the galactic disk, pulsar timing experiments have provided some of the best maps of the interstellar medium of the Milky Way to date.

Precision astrometric measurements from interferometric observations of galactic sources also provide the opportunity to trace galactic structure. For example, the distance to the Pleiades star cluster was recently revised based on stellar parallax measurements, with sub-milliarcsecond positional precision, derived from VLBI observations at 8.4 GHz. Similarly, high spatial resolution monitoring observations of sources near the center of our galaxy are used to trace their orbital motions and thereby provide a kinematic estimate of the mass of the central black hole. Furthermore, high spatial resolution observations of atomic and molecular gas trace the circumnuclear accretion disk and provide insight into the feeding and feedback of the supermassive black hole at the center of our galaxy.

As mentioned in Section 2.3.1, the 21 cm HI line has been used extensively to trace the atomic gas component of the Milky Way and other galaxies (e.g., see Figure 2.12). Using the Doppler shift to trace the kinematics of the gas, observations of atomic and molecular transitions are also used to learn about the gravitational potential of galaxies. Results from this work led to the realization that a substantial fraction of the mass of every galaxy is composed 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. In addition, 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. 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.

2.3.9 Extragalactic Distance Estimates

One of the critical parameters in astronomical studies is the distance to astronomical objects. Geometric methods provide the most accurate distance estimates, but are typically only feasible for the near-

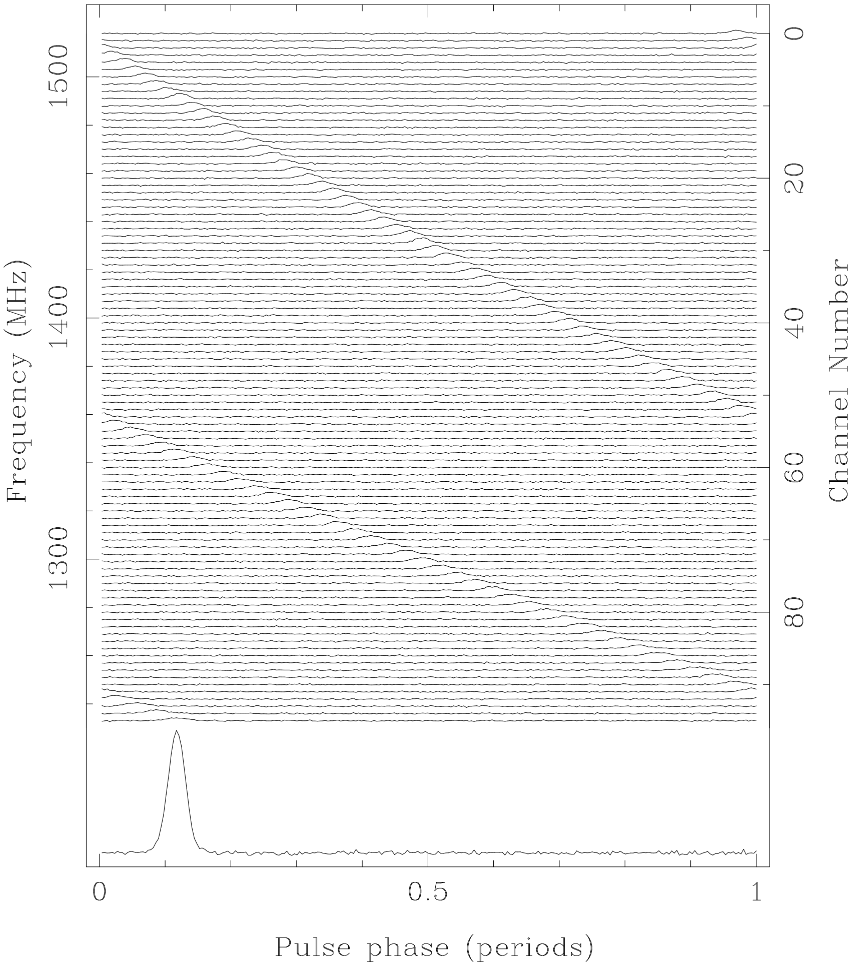

FIGURE 2.11 Pulse dispersion shown in observations of the 128 ms pulsar B1356-61 with the Parkes Radio Telescope. The pulse arrives first at higher frequencies because of the dispersive nature of the plasma in the interstellar medium. The delay is proportional to the inverse square of the frequency. Broad bandwidths allow the detection of multiple pulses simultaneously, increasing the signal-to-noise ratio and permitting analysis of the pulse shape. This observation is centered at 1380 MHz with a bandwidth of 288 MHz. SOURCE: Courtesy of Andrew Lyne, University of Manchester.

est objects (i.e., within the Milky Way) because the angular resolution required is inversely proportional to the distance of the source. However, recent advances in precision astrometry of H_2O masers in nearby galaxies has opened a new window on extragalactic distance measurements. From parallax measurements of the galaxies in the Local Group, to measurements of the orbital motions of masers around the centers of nearby galaxies, these high spatial resolution observations provide accurate distance estimates that form a robust basis for the extragalactic distance ladder.

More traditional extragalactic distance measurements come from galaxy scaling relations, such as the Tully-Fisher relation. The Tully-Fisher relation correlates a galaxy's intrinsic luminosity with its rotation velocity. Because the observed rotation velocity is distance independent, a distance can be

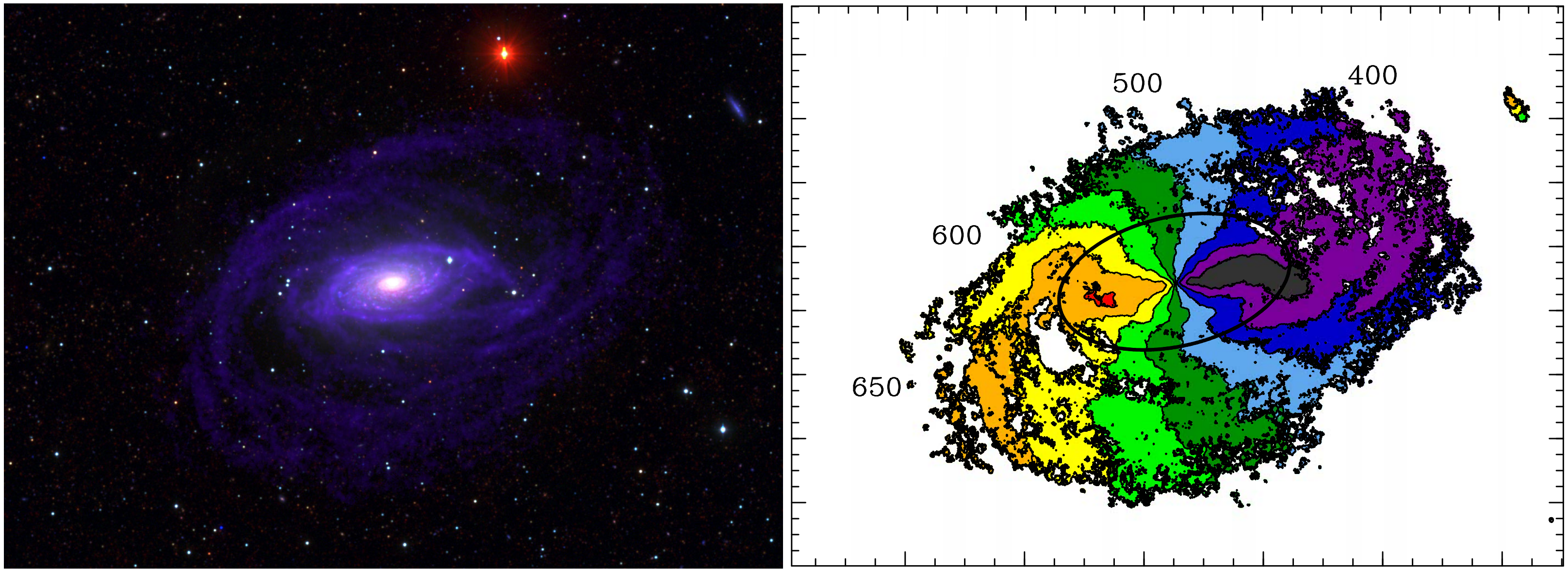

FIGURE 2.12 Combined ultraviolet, optical, infrared, and radio images of M63 (Sunflower Galaxy) and the corresponding neutral hydrogen velocity field. *Left:* The false-color image is a combination of data obtained with GALEX, the WIYN 0.9 m telescope, the Spitzer Space Telescope, and the Very Large Array. The spiral arms are well defined by both the stellar and gaseous components. *Right:* The Doppler shifted neutral hydrogen line traces the galaxy kinematics and is used to derive the rotation speed as a function of radius. Discrepancies between the observed rotation speed of galaxies and that predicted based on observed stellar and gaseous distributions led to the hypothesis that galaxies are embedded in extended halos of unobservable material, known as dark matter. SOURCE: Courtesy of Liese van Zee, Indiana University.

calculated based on the observed flux and the predicted intrinsic luminosity. Traditionally, the Tully-Fisher relation has relied on linewidth measurements of the neutral hydrogen line in the protected band at 21 cm. However, new applications of the Tully-Fisher relation to more distant galaxies has pushed these observations into lower frequency (non-protected) bands.

2.4 ACTIVE GALAXIES

In recent years, astronomers have discovered a surprising level of activity due to the rapid formation of new stars, violent supernovae, and the presence of a supermassive black hole (SMBH) in the center of almost all galaxies. These SMBHs have masses in the range of 10^6 to 10^{10} times the mass of the Sun, which can lead to extraordinary levels of radio luminosity. The levels of radio emission from SMBHs as well as from star formation appears to increase rapidly with distance, suggesting that SMBH activity and star formation were more prominent in the early universe.

2.4.1 Radio Galaxies, Quasars, and Active Galactic Nuclei

About 10 percent of quasars and galaxies with active galactic nuclei (AGN) are very strong radio sources with luminosities ranging up to 10^{27} W/Hz. Other galaxies, quasars, and AGN are much weaker radio sources with luminosities as faint as 10^{19} W/Hz. The radio emission is due to synchrotron radiation from relativistic electrons with energies of the order of 10 GeV moving in magnetic fields of about 10^{-5} Gauss. The total energy contained in particles and magnetic fields is huge and can be as much as 10^{61} ergs. Most radio sources (such as radio galaxies, quasars, and supernova remnants) have non-thermal radio spectra characteristic of a power law electron energy distribution of the form $N(E) \propto \mathrm{E}^{-\gamma}$ with $\gamma \sim 2.5$. As shown in Figure 2.3 the corresponding radio flux density spectra are also closely described by power law of the form $S(\nu) \propto \nu^{\alpha}$ with $\alpha \sim -0.8$. Because of electron energy radiation losses, which are proportional to the square of the electron energy, the radio spectrum often steepens toward high frequencies.

The powerful radio emission from quasars and radio galaxies is driven by a "central engine," thought to be the SMBH located at the galactic nucleus, which accretes matter from the dense interstellar medium surrounding the galactic nucleus. Highly relativistic plasma is then ejected in narrow beams, which transport their energy to the giant radio lobes often associated with radio galaxies. However, the manner by which the relativistic plasma is formed, collimated, and accelerated to form radio jets is not well understood. Figure 2.13 shows a high spatial resolution radio image of the powerful radio galaxy known as Hercules A, obtained with the VLA. The image was made by observing in the full frequency range from 1 to 9 GHz and shows the optically invisible highly collimated relativistic jets,which extend more than 1 million light-years from the visible galaxy from which they emerge. The jets are composed of plasma beams that are ejected at nearly the speed of light from the vicinity of a supermassive black hole located at the center of the galaxy. The outer portions of both jets show ring-like structures, suggesting a history of multiple outbursts from the supermassive black hole.

The study of the continuum emission of radio sources requires observations throughout a very wide frequency range, including the Very high frequency (VHF), Ultra high frequency (UHF), microwave, and millimeter bands, to determine the physical parameters. Many extragalactic radio sources show a "break" or peak in their non-thermal spectrum in their radio emission because of electron energy losses at high frequencies or to self absorption at low frequencies. Continuum measurements throughout this range are essential to define accurately such spectral characteristics.

The radio emission from most quasars and active galactic nuclei come from such small regions that the synchrotron radiation becomes synchrotron self-absorbed from relativistic electrons within

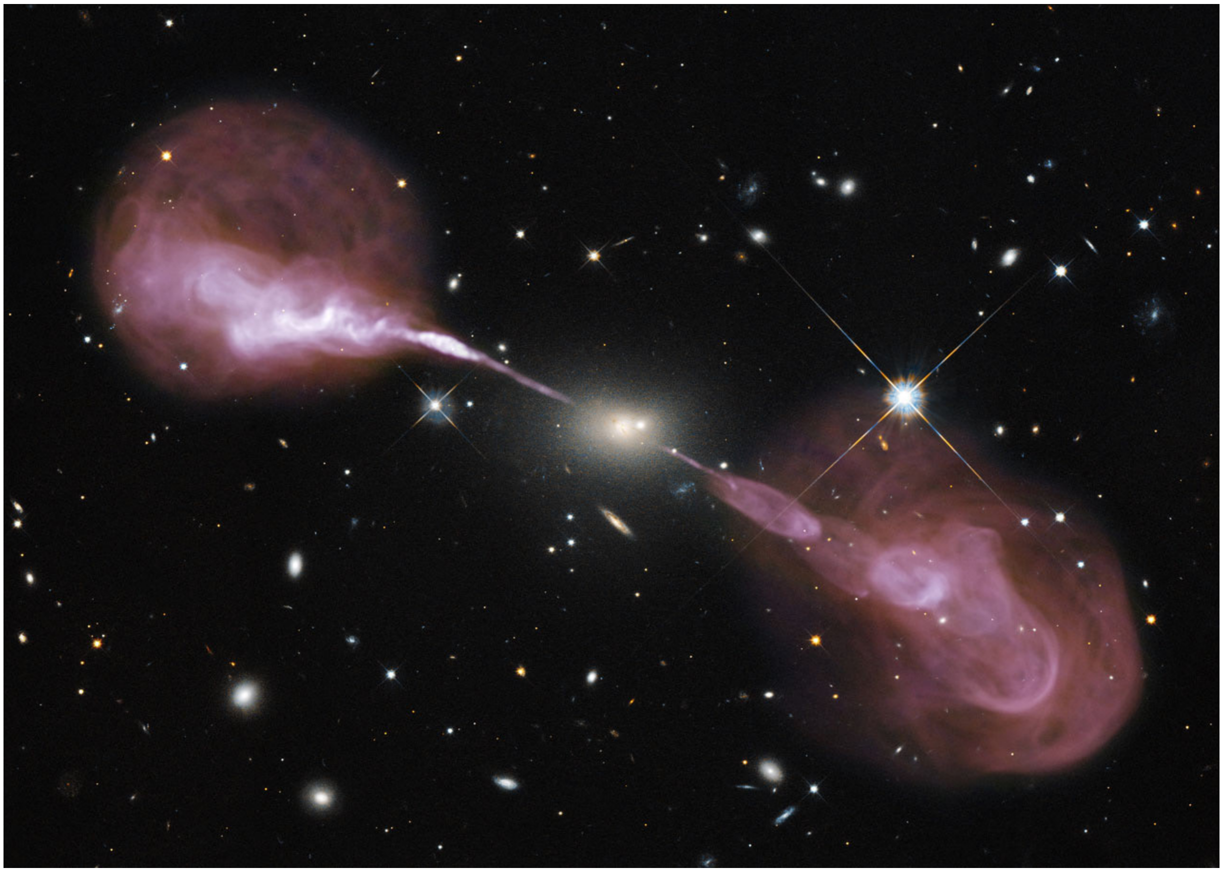

FIGURE 2.13 The Very Large Array (VLA) radio image (pink) superimposed on a Hubble Space Telescope optical image of the powerful radio galaxy known as Hercules A. This image was made using the frequency band from 1 to 9 GHz and interferometer spacings from 36 meters to 36 km to produce this extraordinarily detailed picture with a resolution of only 0.3 arcseconds. Narrow band and short duration pulsating interference signals within the VLA passbands were rejected during data processing. This image illustrates the additional information gained by observing astronomical sources at different wavelengths. Note the sharp contrast between the light emitted at optical wavelengths (Hercules A is the diffuse fuzzy galaxy at the center of the image) and radio wavelengths (the two powerful radio jets are 1.5 million light-years long and extend well beyond the optical galaxy). The optical image is dominated by the thermal emission from starlight, whereas the radio image is dominated by emission from high-energy plasma beams ejected at close to the speed-of-light in the vicinity of the central black hole. SOURCE: Courtesy of NASA, ESA, S. Baum and C. O'Dea (RIT), R. Perley and W. Cotton (NRAO/AUI/NSF), and the Hubble Heritage Team (STScI/AURA); see NRAO, "Image Release: A Radio-Optical View of the Galaxy Hercules A," November 29, 2012, http://www.nrao.edu/pr/2012/herca.

the source. This causes the emerging radiation to be "cut-off" at frequencies below what is called the synchrotron self-absorption cutoff frequency, which depends on the magnetic field strength, source size, and flux density. These peaks may be found between 100 MHz and 100 GHz depending on the electron energy population and the magnetic field strength, so measurements of the spectrum surrounding the cutoff frequency as well as at frequencies well above and well below the cutoff frequency provide a powerful technique to study the physics of these small, yet remarkably powerful, relativistic plasmas.

Many compact radio sources, particularly those associated with quasars and active galactic nuclei are variable, typically showing outbursts on timescales of a few weeks to a few years. Repeated observations at multiple wavelengths sampled with appropriate cadence give further insight to the nature of these sources, and specifically on the way that relativistic electrons are accelerated. Some sources are so small that they “scintillate” in a manner analogous to the optical twinkling of stars, but the scintillations typically occur on timescales of hours requiring frequent time sampling to define the variability. Unlike optical twinkling which occurs in the Earth’s atmosphere, the intra-day radio variability is due to scattering in the ionized gas in interstellar space, so the observations of how the flux density changes with frequency and time also gives information on the nature of the ionized interstellar medium.

Many of the non-thermal synchrotron sources are only detectable at higher frequencies. The frequency range of 10-100 GHz is important for monitoring the variability of the radio emission from quasars. At this frequency range, it is also possible to observe emission from dust in extremely dense cores, which are opaque at higher frequencies.

2.4.2 Starburst Galaxies

Other galaxies with radio emission, particularly the less luminous sources, are found to be spiral galaxies where stars are still being formed. Certain young stars may undergo supernova explosions, which are exceedingly bright for a few days. The stellar explosion generates a shock wave that, as it expands, can accelerate the surrounding interstellar material to relativistic velocities, and the electron component becomes a source of synchrotron radiation. Although the relation is not well understood, there is a close connection between the radio and far infrared luminosity of these star-forming regions. However, it is only at radio wavelengths that the radiation from star forming regions is not obscured by interstellar matter, so radio observations are a uniquely powerful way of determining the rate of star formation in galaxies and how it evolves with cosmic time.

At the extreme end of star forming galaxies are the so-called submillimeter galaxies, which are 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 a burst of newly formed stars in the system. Because this emission is intrinsically strong at infrared wavelengths 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 submillimeter wavelengths (see Box 2.2). ALMA and other modern facilities are able to measure submillimeter galaxies out to very large redshifts giving further insight to the evolutionary history of the development of galaxies and the star formation that occurs within them. This includes the measurement of dust emission, CO rotational lines, and also atomic lines of ionized carbon and nitrogen.

2.4.3 Cosmic Magnetic Fields

The radio emission from active galaxies generally is highly polarized, and so can be used as probes of the gas and magnetic fields through which their radiation propagates. The magnetic fields of clusters of galaxies, individual galaxies, the interstellar medium of our own Milky Way, and even the solar corona have all been estimated from their observed Faraday rotation. The degree of polarization of radio waves is highest at higher frequencies, but the influence of the ionized interstellar medium is greatest at lower frequencies. The frequency range from 30 MHz to 10 GHz is especially important for these polarization measurements.

2.5 COSMOLOGY AND STRUCTURE OF THE UNIVERSE

Cosmology is the study of the history of the universe from its fiery beginning to the way it is today. Radio astronomy has made many critical contributions to cosmology.

2.5.1 Cosmic Microwave Background

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 cosmic microwave background (CMB) is uniform to 1 part in 10^5 and fills the sky. This radiation, which is a remnant of the Big Bang, follows the Planck law at a present-day temperature of 2.73 K. It represents emission as the ionized material recombined 380,000 years after the initiation of the Big Bang. The existence of weak density fluctuations in the microwave background was revealed by NASA's Cosmic Background Explorer (COBE) mission and imaged by NASA's Wilkinson Microwave Anisotropy Probe (WMAP) and the European Space Agency/NASA Planck satellite (see Figure 2.14). All of these satellites operate at radio frequencies. Ground-based and balloon-borne CMB experiments also continue to play vital roles in the study of the angular distribution, spectral energy distribution, polarization, and small-scale structure of the CMB. While observations of the cosmic background from the ground are severely limited by the strongly variable intensity of atmospheric emission near the continuum peak (see Figure 2.6), observations in the 1.2 mm (200-300 GHz) window are important for such fundamental measurement as the

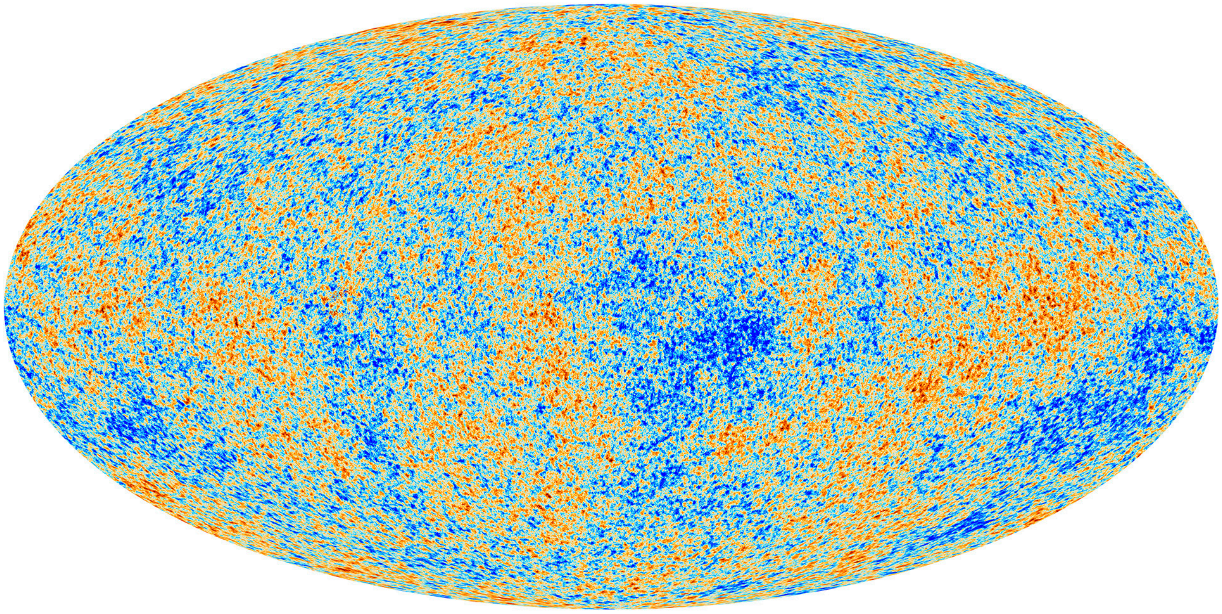

FIGURE 2.14 The anisotropies of the cosmic microwave background (CMB) as observed by the European Space Agency (ESA)/NASA Planck satellite. The foreground emission has been removed, leaving fluctuations at the level of 10^{-5} relative to the mean temperature of the signal. The CMB is a snapshot of the oldest light in our universe, imprinted on the sky when the universe was just 380,000 years old. It shows tiny temperature fluctuations that correspond to regions of slightly different densities, representing the seeds of all future structure: the stars and galaxies of today. SOURCE: ESA, "Plank CMB," March 21, 2013, http://www.esa.int/spaceinimages/Images/2013/03/Planck_CMB; courtesy of ESA and the Planck Collaboration.

velocity of the galaxy with respect to the background radiation field and the rotation and symmetry of the universe.

Furthermore, while the CMB intensity fluctuations have been mapped extremely deeply by the Planck mission, there is additional information encoded in the CMB that will require additional observations. Most importantly, it is possible to infer the existence of gravitational waves from the Big Bang and probe the process of cosmic inflation through study of the polarization of the CMB. These so called B-mode signals are currently unknown in amplitude, but are expected to be another factor of 10 to 100 smaller than the intensity fluctuations mapped by WMAP and Planck. At this exquisitely small level (below 1 micro-Kelvin), foreground signals will likely dominate any background fluctuation. Thus, to create images of only the CMB, measurements at multiple frequencies spanning 40-200 GHz will be required to identify and remove foreground synchrotron emission at low frequencies and foreground dust emission at higher frequencies. Indisputably, radio observations serve as the best way to study the CMB, which has yielded a remarkable picture of the initial conditions of the universe (see Figure 2.2).

2.5.2 Dark Energy, Dark Matter, and Cosmic Evolution

The history of radio astronomy has been one of increasing sensitivity and angular resolution and now reaches sources with flux densities as faint as 10^{-32} W/m^2/Hz (1 micro-Jansky), which can be localized in the sky to an accuracy better than a milliarcsecond. The way in which the number of radio sources is detected as a function of flux density is related to their intrinsic luminosity function, the geometry of the universe, and the evolution with cosmic time of their luminosity and space density. Indeed the first evidence for cosmic evolution came from the early number counts of radio galaxies, which was dramatically confirmed with the discovery of the CMB. Currently, with the aid of a powerful new generation of high-energy, optical, and infrared telescopes, sources detected in radio surveys are identified with a variety of galaxy and active galactic nuclei types, and their redshifts (distances) determined (see Box 2.2). In this way, astronomers are able to study the different cosmic populations, including the relation between supermassive black holes and star formation and how they evolve with cosmic time. The radio surveys used for these studies are conducted at frequencies between 1 and 10 GHz using large bandwidths in order to obtain the highest possible sensitivity.

Galaxies can also be detected in the radio by the 21 cm emission from the hyperfine transition of neutral hydrogen (see Section 2.3.1). At present, discrete galaxies can be detected only at low redshift, but several experiments are under construction or planned to detect the integrated emission from many galaxies (so-called “intensity mapping”) up to redshifts of 2.5 or more. This requires observations at as many frequencies as possible between 400 and 1400 MHz. The technique traces the distribution of hydrogen gas, and thus matter, in the universe. Imprinted in the distribution of matter is a standard ruler with which to measure the universe’s expansion history: the “baryonic acoustic oscillation” (BAO) length scale, which is related to the distance sound could travel between the Big Bang and the time when the universe changed from plasma to neutral hydrogen. The goal is to measure the apparent size of the BAO scale as a function of cosmic epoch and hence the expansion history of the universe (see Figure 2.2), which depends on the density of mass and dark energy. Other experiments are looking for neutral hydrogen at even higher redshifts at frequencies below 200 MHz. These frequencies probe the Epoch of Reionization (EoR, see Section 2.5.5), the period in the history of the universe during which the predominately neutral intergalactic medium was re-ionized by the emergence of the first luminous sources. These observations will help us understand the origin of the first stars, galaxies, and quasars. Intensity mapping of redshifted spectral lines of carbon monoxide and ionized carbon at frequencies between 15 and 200 GHz are also being planned, and will provide a complementary probe of the history of the universe.

Surveys of the radio sky also reveal examples of cosmic sources that are gravitationally lensed (see Figure 2.15). Strong gravitational lenses occur when there is sufficient mass in front of a source such that the light rays are bent to create multiple images. The lens also magnifies the background source, providing a natural method to amplify weak signals from the distant universe. The orientation and spatial separation of the multiple images are used to create a mass model for the lensing system, independent of the visible matter. Thus, gravitational lenses provide significant insight into the distribution of matter, both luminous and dark. Although gravitational lensing requires a fortuitous alignment of source and lens, both the number of and the properties of lensed systems provide a measure of cosmological parameters, including the expansion rate of the universe and the mean density. Combined with timing experiments of the variability of the background source, gravitational lenses also provide insight into the acceleration of the expansion rate of the universe (see Figure 2.2) and dark energy. Observations of gravitational lenses can be conducted at any radio frequency; large bandwidths are preferred in order to obtain the highest possible sensitivity.

2.5.3 Clusters of Galaxies

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.

Observations of galaxy clusters at centimeter wavelengths can reveal information about their magnetic field strengths either through the observations of synchrotron emission, or via studies of Faraday rotation. The origin of these cluster magnetic fields is an area of active research.

2.5.4 Galaxies in the Early Universe

To study the nature of early galaxies as well as other objects, astronomers use radio astronomy data synergistically with optical data from the Hubble Space Telescope, infrared data from the Spitzer Space Telescope, and x-ray data from the Chandra X-ray Observatory (see Figure 2.16). The class of high redshift objects known as submillimeter galaxies are detected with the use of ultra-wideband continuum detectors and bolometers, which make use of most of the available frequency space within the millimeter and submillimeter atmospheric windows (see Figure 2.6). Because the sensitivity of these measurements is greatly enhanced by the use of wide bandwidths, this places a premium on continuous, interference-free allocations for radio astronomy observations. Moreover, it is important to measure the redshift of these objects to determine their distance (see Box 2.2). These radio redshift determinations are made using 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 large portions of the spectrum to allow this fundamental information to be measured.

2.5.5 Epoch of Re-ionization

Studies are just beginning of the EoR, during which radiation from the first generation of stars and galaxies (re)ionized the universe (see Figure 2.2). Observations of HI at redshifts of $z = 6$ to 15 (88-200

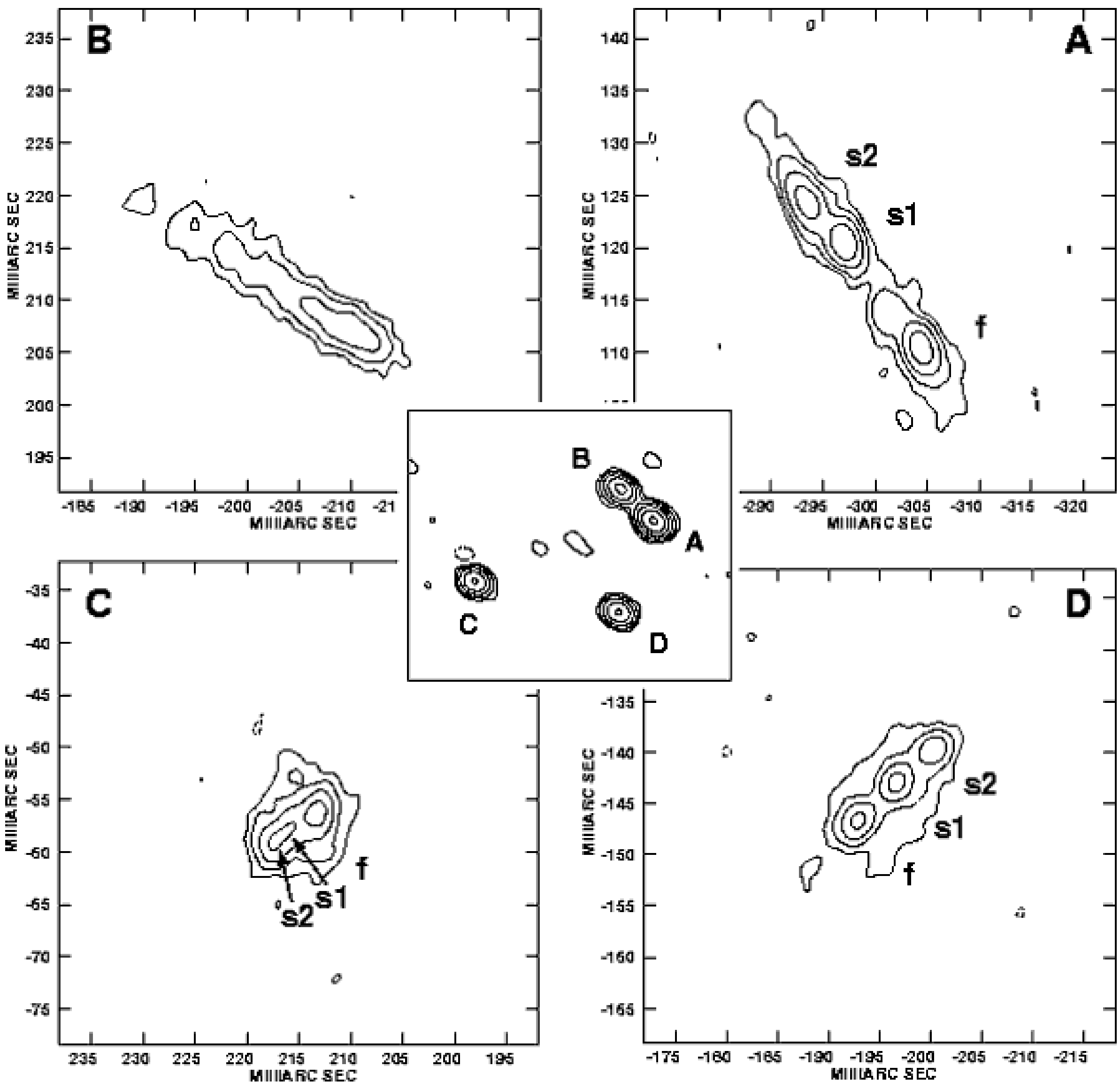

FIGURE 2.15 Very Long Baseline Array 5-GHz maps of the gravitational lens system CLASS B0128+437. This is formed by the deflection of the light from a distant ($z = 3.12$) quasar by an intervening galaxy (the lens), resulting in four images of the quasar being seen from Earth (MERLIN map—middle). The high resolution of the VLBA reveals that the lensed source consists of at least three sub-components. The detection of sub-structure in the lensed image enables models of the mass distribution in the lensed galaxy to be tightly constrained. SOURCE: A. Biggs, I. Browne, N. Jackson, T. York, M. Norbury, J. McKean, and P. Phillips, “The Gravitational Lens System CLASS B0128+437,” NRAO, March 2004, http://www.vlba.nrao.edu/imgmonth/CLASS_B0128_437/.

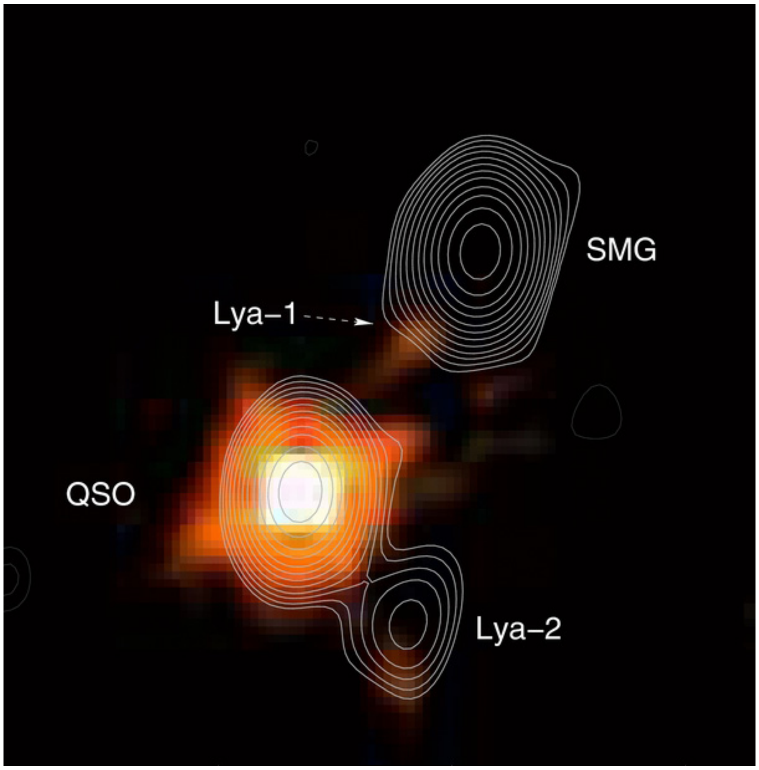

FIGURE 2.16 Radio and optical image of the 4.7 redshift quasar known as BR 1202-07 showing the galaxy at 814 nm (color) observed with the Hubble Space Telescope overlaid by 340 GHz contours observed with the Atacama Large Millimeter Array (ALMA) radio telescope. Also seen in the radio is a bright submillimeter galaxy lying to the northwest of the quasar that is obscured in the optical, and two faint Lyman-α emission regions, one of which is a strong 340 GHz radio source. SOURCE: Courtesy of NRAO/AUI; see C.L. Carilli, D. Riechers, F. Walter, R. Maiolino, J. Wagg, L. Lentati, R. McMahon, and A. Wolfe, The anatomy of an extreme starburst within 1.3 Gyr of the Big Bang revealed by ALMA, *The Astrophysical Journal* 763:120, 2013.

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). An advantage of this approach is that the HI is optically thin, allowing the gas distribution to be measured throughout the universe. Detection and subsequent observations of redshifted hydrogen from this epoch are expected to yield valuable insights into the energetics of the early universe and the processes of initial galaxy formation. A detection of neutral hydrogen from this epoch would place strong constraints on the spin temperature of the hydrogen gas, the neutral fraction, and the timeline of the re-ionization.

3

Scientific Background: Earth Exploration Satellite Service

3.1 INTRODUCTION

The Earth Exploration Satellite Service (EESS) is dedicated to monitoring and studying phenomena that affect habitat of our planet Earth and its environmental quality. These services use spaceborne active and/or passive microwave sensors to provide valuable measurements of atmosphere, land, and sea, for both research and operational purposes. Because all matter emits, absorbs, and scatters electromagnetic energy to varying degrees, these sensors detect variations in Earth's environment. Spaceborne sensors operating at radio frequencies (RF) can detect these variations under all weather conditions because of their longer wavelengths, and with penetration depths not possible at optical or infrared wavelengths. RF used for EESS are usually designated either as "windows" used for observing Earth's surface or as "opaque" used for observing the atmosphere (Figure 3.1). However, it should be noted that all window channels exhibit some atmospheric absorption and emission, and even atmospheric resonant frequencies or absorption bands are often not completely opaque. Hence, most sensors incorporate both window and opaque channels.

Spaceborne sensors can monitor environmental conditions repetitively on a global scale. They measure temperature, humidity, cloud, and trace gas profiles in the atmosphere; moisture, roughness, and biomass at the land surface; salinity, temperature, surface wave height, and sea state in the oceans; and water content and melt character of ice and snow. These measurements are critical to predicting and monitoring of weather and severe storms; managing water resources, land, and biota; and understanding changes in global climate and atmospheric chemistry. As mentioned in Section 1.6, 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 in the operation of businesses and industries that are dependent on knowledge of local weather and changes in climate. Each year many thousands of lives are saved, globally, through advance warning of dangerously inclement weather, for example, hurricanes, tornadoes, severe thunderstorms, flash floods, and droughts.

In addition to using spectrum for spaceborne active and passive sensing, the Earth science services use spectrum for command, tracking, data acquisition, and communications and for ground-based radiometry of the atmosphere (see Section 1.5). Ground-based passive and active microwave sensors

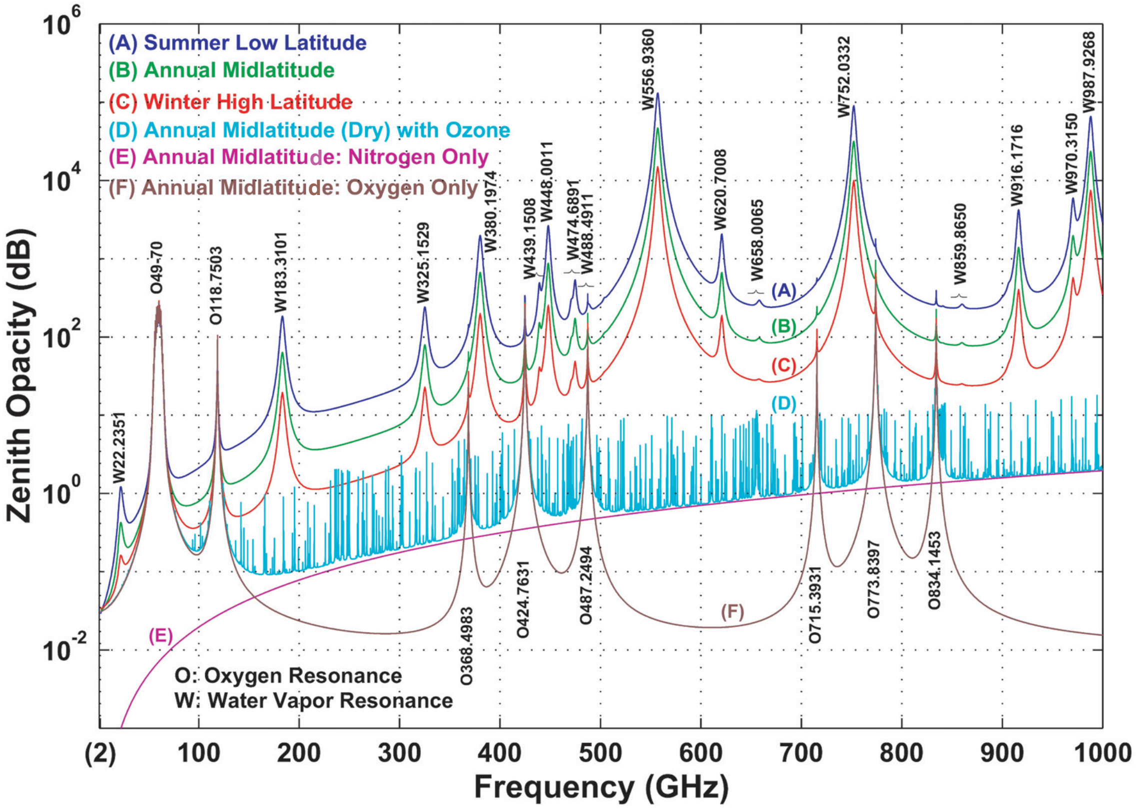

FIGURE 3.1 Atmospheric zenith opacity in the radio spectrum commonly used for the EESS. SOURCE: A.J. Gasiewski and M. Klein, The sensitivity of millimeter and sub-millimeter frequencies to atmospheric temperature and water vapor variations, *Journal of Geophysical Research-Atmospheres* 13:178481-17511, 2000, copyright 2001 by the American Geophysical Union.

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

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 sensors provide key meteorological data sets, including the Advanced Microwave Sounding Unit (AMSU) and instruments on the Defense Meteorological Satellite Program's (DMSP's) passive microwave weather satellites (the Special Sensor Microwave/Imager [SSM/I] and Special Sensor Microwave/Temperature [SSM/T]). Remote sensing satellite missions such as NASA's Earth Observing System (EOS), European Space Agency's (ESA's) Soil Moisture and Ocean Salinity (SMOS), NASA/Japan Aerospace Exploration Agency's (JAXA's) Global Precipitation Measurement (GPM), and NASA's Soil Moisture Active/Passive (SMAP) are providing information about water, rainfall, and ocean salinity on a global basis 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, multibillion-dollar missions are international in scope, reflecting the interests of many countries in continued availability of accurate meteorological, hydrological, and oceanographic data and measurements of land-surface features and trace gases in the atmosphere. It is critical to ensure continued data availability for these important applications. For example, the Tropical Rainfall Measurement Mission (TRMM) reached the end of its life in 2015 after providing unprecedented rainfall data for nearly two decades, much longer than its expected mission life of 3 years. In early 2014, the GPM was launched to provide continued and improved rainfall mapping and forecasting.

3.1.1 Passive Sensing

Techniques

Passive sensors have receivers that measure the electromagnetic energy emitted and scattered by Earth's surface and the constituents of Earth's atmosphere. Measurements at "opaque" frequencies are affected by the absorption and emission of the waves and are strong functions of frequency due to resonant absorption by atmospheric gases. Atmospheric gases emit and absorb microwave energy at discrete resonant frequency bands described by the laws of quantum mechanics, necessitating atmospheric observations in those bands (Figure 3.1). For example, atmospheric molecules of H_2O have resonances at 22.235 and 183.3101 GHz, and 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. Oxygen lines around 55 GHz are used to obtain atmospheric temperature profiles, and water lines are used to obtain atmospheric humidity profiles. The frequency allocations needed for these measurements are rigidly determined by the location of the resonant frequency bands.

The choice of frequencies for measurements of Earth's surface by passive sensors is not as tightly constrained as that for atmospheric measurements. If Earth were an ideal blackbody, then it would emit radio emission of intensity proportional to its temperature, and that is all that could be determined. However, the actual emission depends on the surface characteristics of land and water, such as roughness, soil moisture, and wind speed (see Figures 3.2 and 3.3). The sensing of many surface phenomena requires simultaneous measurements at several frequencies because the energy emitted at any given frequency is determined by several overlapping geophysical phenomena. Multiple frequencies either help separate the property of interest or provide a correction for competing factors such as variations in the sea surface temperature to estimate wind speed or absorption in the atmosphere. Within a set of approximately octave-spaced bands (Appendix B), suitable for particular applications, the precise frequencies to be used for sensing Earth's surface are not critical. The selection of specific frequency is typically based upon the feasibility of sharing frequencies with other allocated radio services. Because passive radio astronomy services (Chapter 2) use these same windows to observe the universe from the ground, there is much spectrum compatibility between the two sciences. However, below 20 GHz, constraints on the parameters of active radio services may be needed to make spectrum sharing feasible.

The energy emitted from Earth's surface is a function of frequency, surface roughness and dielectric properties, polarization, angle of incidence and aspect, and subsurface microstructure. A few underlying physical principles characterize the capabilities of most passive microwave techniques used in the "window" channels to observe Earth's surface. First, lower-frequency waves generally penetrate intervening media better and sense deeper beneath the surface. Thus low frequencies such as those at L-band (e.g., 1.4 GHz, Appendix B) are preferred when sensing subsurface soil moisture beneath vegetative canopies. Second, the influence of surface roughness tends to be largest when the length scales of the roughness are comparable to the electromagnetic wavelength. This fact motivates the use of X-band (e.g., 10.7 GHz)

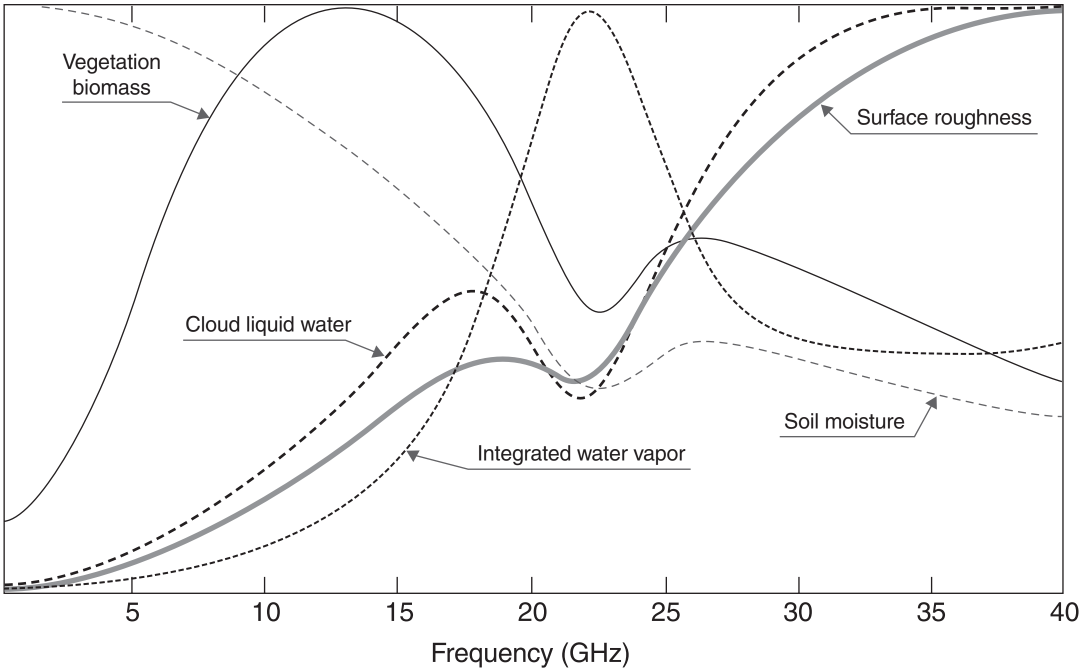

FIGURE 3.2 Relative sensitivity of brightness temperature to geophysical parameters over land surfaces as a function of frequency.

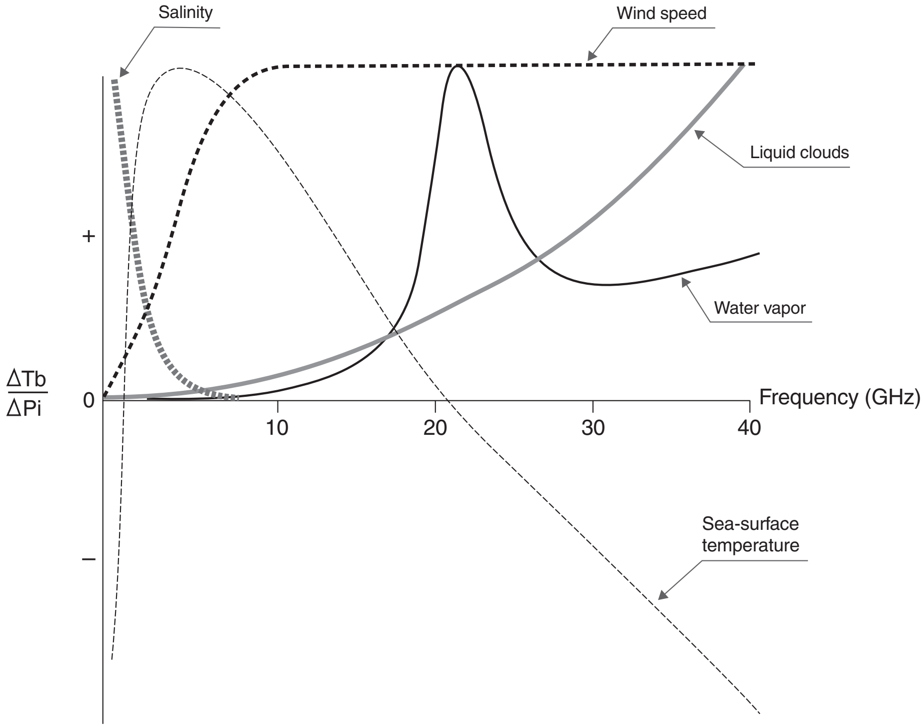

FIGURE 3.3 Relative sensitivity of brightness temperature to geophysical parameters over ocean as a function of frequency. SOURCE: Original figure by Thomas T. Wilheit, NASA Goddard Space Flight Center.

or higher frequencies in attempting to sense the short sea waves, such as the capillary waves, that are the most sensitive to sea surface winds at low wind speeds. Third, water in its various phases of ice, liquid, and vapor exhibits particularly strong characteristic absorption, emission, and scattering features in the radio spectrum. The dielectric constant of water is a strong function of frequency, temperature, and the water's phase. Frequencies below approximately 2 GHz are the most sensitive to sea surface salinity, while the frequencies closer to 5-10 GHz are the most sensitive to sea surface temperature.

Sensors

A major tool of Earth remote sensing systems is the microwave radiometer. These passive sensors are similar in their basic design to radio astronomy receivers. The instrument sensitivity needed varies with the accuracy required for the physical property. For example, determination of open-ocean salinity, with typical values between 30 to 36 parts per thousand, requires accuracies on the order of 0.2 parts per thousand for use in numerical ocean models. In the 1-2 GHz range, where salinity is measured, this translates to a measurement sensitivity of about 0.1 K. Determination of soil moisture, which is also measured in this frequency range, requires accuracies of about 4 percent water by volume, with data availability every 2 to 3 days for meaningful use in weather prediction models. The sensitivity in this frequency band is about 1 to 3 K per percent soil moisture (hence a measurement requirement of about 4 to 12 K).

Scientists have conducted extensive studies to identify the frequencies needed for passive sensor measurements and to quantify the performance criteria of the sensors used by EESS, and to inform and complement the regulations formulated by the International Telecommunications Union's Radiocommunication Section (ITU-R). The resulting frequencies are documented in Recommendation ITU-R RS.515 and the necessary bandwidths and sensitivities 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 EESS on an exclusive basis, it has been determined by the ITU that "all emissions shall be prohibited" (see Radio Regulation 5.340).

3.1.2 Active Sensing

Techniques

Active microwave sensing involves radars. Radars receive signals that they have transmitted after these signals have been reflected by land or ocean surfaces or by water or ice particles in Earth's atmosphere. Because the reflected signal 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 (Appendix B), similar to those for the surface measurements using passive techniques and for the radio astronomy continuum measurements. The precise frequency used within the required octave-wide band is not critical, and the allocations are based upon other services within that band. The sharing of these bands, while not incurring or causing interference with other sources, is an important modern-day consideration. For instance, sharing between active spaceborne sensors and terrestrial radars (the radiolocation service, in ITU parlance) has been shown to be feasible with certain design constraints, and the bands allocated for active sensing are all also allocated to the radiolocation service. The frequency bands to accommodate active sensor measurements range from below 1 GHz for surface measurements up to 150 GHz for cloud measurements. Applications of active sensors include the measurement of soil moisture and roughness, snow, ice, rain, clouds, atmospheric pressure, and ocean wave parameters, and the mapping of geologic and geodetic features and vegetation. Similar to passive requirements, the active sensor frequency and bandwidth requirements have been studied extensively by scientists, the results from which have informed the regulations at the ITU-R. These requirements can be found in Recommendation ITU-R RS.577.

Sensors

Major types of active sensors include spaceborne scatterometers and image-forming radars such as synthetic aperture radars (SARs) and Interferometric SAR (InSAR). SARs and InSARs are capable of determining topography and surface change over large geographic regions to unprecedented accuracy. Bandwidth requirements for active sensors vary with the type of application. For example, scatterometers are typically narrowband, low-resolution devices requiring about 1 MHz of bandwidth. Most 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. However, altimeters and a few very-high resolution SARs require wide bandwidth, typically up to 600 MHz or more, to achieve desired measurement accuracies. Ultra-wide band radars for snow-depth profiling are now in experimental development and require several GHz of bandwidth but operate over a limited spatial extent.

Multispectral images obtained by SARs operating at 432-438 MHz, 1215-1300 MHz, 3100-3300 MHz, 5250-5570 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 GPM uses precipitation radars in the 13.4-14 GHz and 35-36 GHz bands to provide data on global rainfall. 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. These criteria 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 these sensors can be found in Recommendation ITU-R RS.1166.

In the following sections, the radio frequencies used by EESS for applications in atmosphere, terrestrial hydrology, cryosphere, oceans, and solid Earth and biosphere are discussed in more detail.

3.2 ATMOSPHERE

Systems for sensing atmospheric properties can be designed to exploit atmospheric absorption and emission resonances. There are a vast and growing number of applications that benefit from atmospheric measurements obtained by microwave and millimeter wave sounding instruments spanning research areas that include meteorology, oceanography, geology, and ecology. Measurements of the atmosphere using microwave radiometry have provided a benchmark climate record of temperature trends dating back to the first operational use of the Microwave Sounding Unit (MSU) in 1979, which began operation in 1979. MSU was followed by the Advance Microwave Sounding Unit, which began operation in 1998. The Advanced Technology Microwave Sounder (ATMS) is the first in a series of new cross-track scanning sounders developed for the Joint Polar Satellite System (JPSS). ATMS was launched on October 28, 2011, on the Suomi National Polar Partnership satellite. The Special Sensor Microwave Imager/Sounder (SSMIS), launched in 2003 on a DMSP satellite, observed atmospheric temperature up into the mesosphere as well as surface phenomena such as near-surface wind speed and sea surface temperature. The first Microwave Limb Sounder (MLS) was aboard the Upper Atmosphere Research Satellite (UARS), which was launched in 1991. The MLS provides measurements of stratospheric ClO, O_3, and H_2O, upper tropospheric H_2O vapor and cloud ice, stratospheric HNO, and temperature variances associated with atmospheric gravity waves, as shown in Figure 3.4.

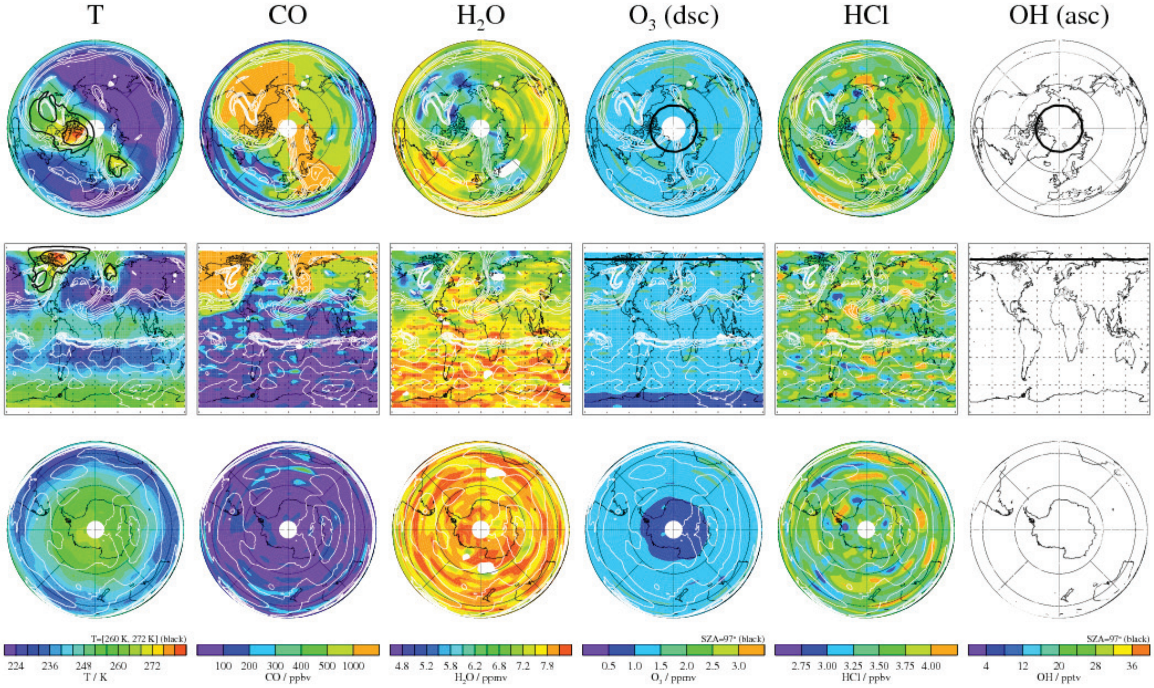

FIGURE 3.4 Daily observations of temperature, CO, H_2O, O_3, HCl, and OH from the Microwave Limb Sounder on the Earth Observing System-Aura satellite January 3, 2015. NOTE: Produced on February 25, 2015 12:47:48 using plot version 1.34. Courtesy of NASA/JPL; produced by the MLS Science Team at the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA, from EOS MLS and GMAO data: JPL Clearance CL#05-3463.

Observations of molecular absorption lines between 118 GHz and 2.5 THz, through the limb of the atmosphere provide key information on atmospheric chemistry from the upper troposphere through the stratosphere. Observations of O_3 play an important role in monitoring the recovery of the ozone hole

In this section, we review the frequencies used for the atmospheric applications in the following areas: temperature and water vapor profiling, precipitation, atmospheric chemistry, clouds, and ionospheric sensing.

3.2.1 Temperature Profiling

Atmospheric profiles of temperature, that is, temperature as a function of altitude, from polar-orbiting satellites are required to initialize and to update the current and emerging global ocean-atmosphere models that provide essential global meteorological and oceanographic predictions for many civil and military applications. High measurement accuracies are essential for the proper operation of these prediction models. For example, it has been shown that for temperature profile inputs not meeting the uncertainty criterion of 1 to 3 K (depending on altitude), 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 and seriously degrade the forecast.

Currently, the temperature profiles are measured using low Earth orbit (LEO) satellite microwave sounders operating in the O_2 absorption band from 50-62 GHz. A number of present-day technological developments are enabling the future deployment of geostationary orbiting microwave temperature sounders. The atmospheric attenuation on a clear day typically varies from ~1 dB near 50 GHz to >200 dB in the region 58 to 62 GHz. Atmospheric temperature profiles can be measured with an uncertainty of 1 to 3 K with vertical resolution ranging from 2 to 5 km (depending on altitude). The Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave Imager Sounder (SSMIS) uses frequencies between 60.4 and 61.2 GHz and a separate channel near 63 GHz to obtain mesospheric temperature profiles. The same oxygen resonance frequency that enables these measurements also leads to the strong absorption of terrestrial anthropogenic emissions. In many (albeit not all) cases, the spectrum from approximately 58 to 62 GHz can be shared with terrestrial ground-based active systems, such as point-to-point communication systems.

The atmospheric temperature profiles can also 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 band by providing independent measurements, albeit with reduced sensitivity at higher altitudes and less penetration 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 the data from 50-60 GHz. As a result, channels near 118 GHz are being considered for use in sounding and imaging from geostationary microwave sensors. 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.

3.2.2 Water Vapor Profiling

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. Much of the atmospheric moisture is concentrated close to Earth's surface in the lowest ~1.5 to 2.5 km 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. The global water vapor measurements are essential to initialize and to update meteorological forecasting and climatological models that provide the global meteorological and oceanographic predictions necessary for civil and military operations. Comparisons of model simulations indicate that if the measurement accuracies of moisture profiles are less than threshold values (typically set to 20 to 35 percent of the root mean square mass mixing ratio), then the remotely sensed profile data that are used as input corrupt the model. Combined microwave and infrared spectral data can yield what is nearly all-weather global performance, even in most cloudy conditions. 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.

Radar observations are strongly dependent on unknown drop size distributions, and optical sensors do not penetrate clouds well; thus microwave radiometers on all types of platforms (satellite, aircraft, ships, and ground sites) are essential to making water vapor measurements. 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 approximately 20 to 35 mb. Two different types of microwave observations are used: those in transparent bands within which the warmer water vapor absorption stands out (1) against the colder ocean background (ocean partially reflects the extremely cold cosmic background radiation (see Section 2.5.1) or (2) against that of cold low-emissivity land.[1] No profile information is usually retrieved—only an estimate of the column integrated abundance. The frequencies most often used for this purpose include 18.7, 22, 23.8, 31.4, 37, and 89 GHz. To improve retrieval accuracies, these channels are often dual-polarized (horizontal and vertical) and scanned at a near-constant angle of incidence (e.g., GPM Microwave Imager [GMI], Special Sensor Microwave/Imager [SSM/I], Special Sensor Microwave/Imager Sounder [SSMIS], WindSat, and Advanced Microwave Scanning Radiometer [ASMR]-E). In addition, the opaque water vapor resonance near 183 GHz is often used by measurements in the adjacent transmission window at the EESS-allocated bands of 150-151 GHz or 164-168 GHz; these can also be used in combination with temperature profile information to yield the most accurate results (e.g., AMSU, SSMIS). Figure 3.5 shows the water vapor derived from the SSM/I. Instruments retrieving water vapor profiles are generally used to retrieve other parameters simultaneously, such as cloud water content, precipitation rate, and ice and snow cover information.

3.2.3 Integrated Precipitable Water

Integrated precipitable water or total precipitable water (TPW), that is, the total atmospheric water vapor from the surface to 30 mb, 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 (Appendix B). These measurements are of major use for meteorological research and forecasting and for astronomical and military applications. Radiowave propagation delays due to atmospheric water vapor can also be derived from radiometric measurements in the spectral region near 22 GHz.

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[1] For background regarding EESS for water vapor profiling, see the following: J.R. Wang, P. Racette, and L.A Chang, MIR measurements of atmospheric water vapor profiles, *IEEE Transactions of Geoscience Remote Sensing* 35(2):212-223, 1997.

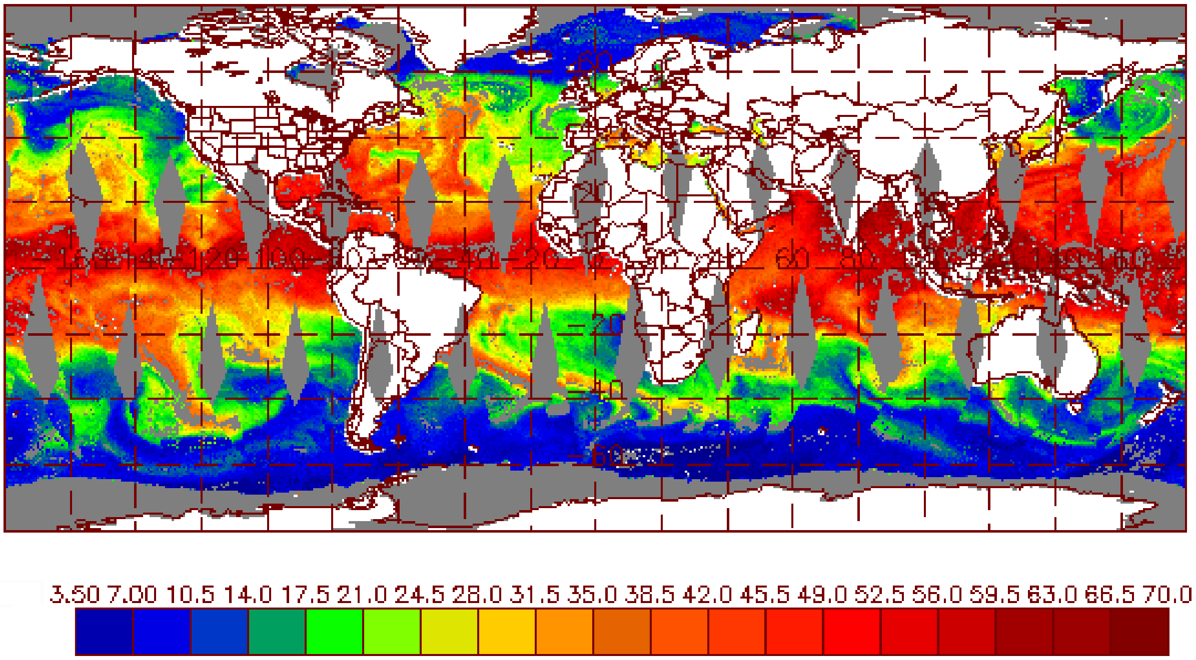

FIGURE 3.5 Operational water vapor (in kg/m^2) product over ocean for June 13, 2015. The data derived from the SSM/I sensor on the DMSP satellites relies on measurements at 19.35, 22.235, and 37 GHz. SOURCE: Courtesy of NOAA Office of Satellite and Product Operations, National Environmental Satellite, Data, and Information Service; see "SSM/IS Products" at http://www.ospo.noaa.gov/Products/land/spp/ssmis.html.

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 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 TPW (see Figure 3.6) and path delay. 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 TPW from the surface of Earth. These ground-based sensors are becoming widely used around the globe to help initialize and update 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, because they view water vapor against a strong contrasting background caused by the cold cosmic emission temperature of 2.73 K (see Section 2.5.1).

3.2.4 Precipitation

Accurate measurement of spatial and temporal variations of rainfall around the globe, particularly over the vast and under-sampled Southern Hemisphere, and oceanic and tropical areas, is one of the most difficult and important problems in 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.[2] Rainfall and snowfall rates and total amounts of

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[2] For background information regarding EESS for precipitation and clouds, see the following: G.L. Stephens and C.D. Kummerow, The remote sensing of clouds and precipitation from space: A review, *Journal of Atmospheric Science* 64:3742-3765, 2007.

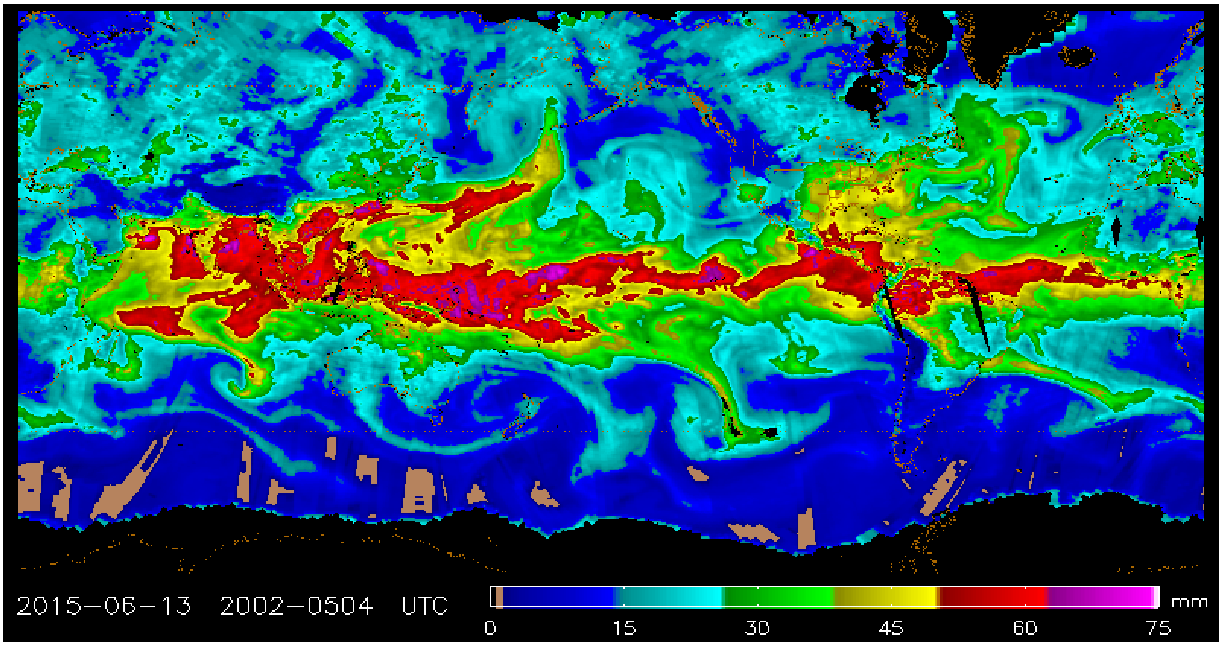

FIGURE 3.6 Total precipitable global water product. Data from multiple satellites are merged to produce global nearly continuous products which track the flow of water vapor and are key to weather forecasting. SOURCE: Courtesy of NOAA Office of Satellite and Product Operations, National Environmental Satellite, Data, and Information Service; see "The NESDIS Operational Blended TPW Products" at http://www.ospo.noaa.gov/Products/bTPW/TPW_Animation.html?product=GLOBAL_TPW.

precipitation are highly valuable measurements that can be determined by on-orbit and ground-based microwave and millimeter wave radiometers. Knowledge of these quantities is important to the prediction of floods, crop health and yield, and catchment replenishment for hydroelectric, irrigation, and domestic uses, and for other societal benefits and impacts. The link between precipitation and clouds provides important constraints on climate variability through the Earth radiation budget. Precipitation measurements using microwave remote sensing may utilize both active and passive sensing. Rain mapping using radar reveals the three-dimensional structure of precipitation, such as the observations from the GPM as shown in Figures 3.7 and 3.8. These radar observations can be used to develop statistical cloud and rain-cell models and to provide improved calibration of rainfall measurements derived using passive radiometry alone. In general, microwave radiometric measurements within the bands at 6, 10, 18, 23, 37, and 89 GHz are of primary interest for rainfall measurement. Active measurements of precipitation are carried out near 13.6, 35.5, and 94 GHz.

Passive microwave measurements near the 89 GHz atmospheric window play an important role in the retrieval of precipitation data, particularly over land. Owing to the combination of high emissivity, thickness, and temperature of clouds 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 89 GHz observations to play an important role in determining rain rate over land.

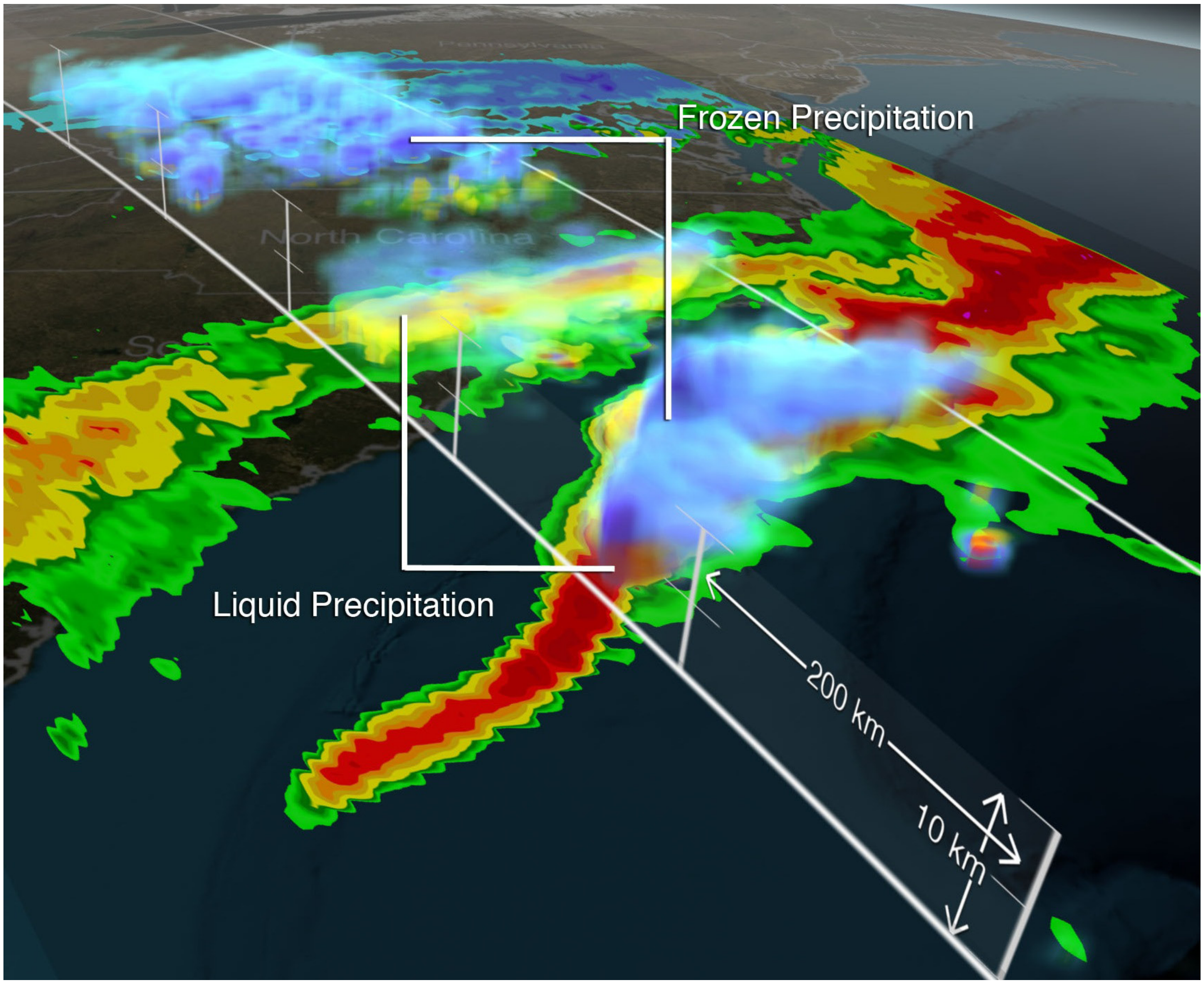

FIGURE 3.7 A storm in the eastern United States observed by the NASA/JAXA Global Precipitation Measurement (GPM) Core Observatory on March 17, 2014. A full range of precipitation, from rain to snow was revealed by the GPM measurements. SOURCE: Courtesy of NASA/JAXA; see NASA GSFC, “GPM Data from March 2014 East Coast Snowstorm,” image, March 17, 2014, http://pmm.nasa.gov/image-gallery/gpm-data-march-2014-east-coast-snowstorm.

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 convective and anvil clouds, which contain frozen particles. Specific frequencies currently used include 150 GHz, 166 GHz, 183.31 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 rates over land surfaces. Furthermore, because 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 observations may also be possible with high spatial resolution using a geostationary microwave sounder at frequencies of ~50, 89, 118, 183, 340, 380, and 424 GHz.

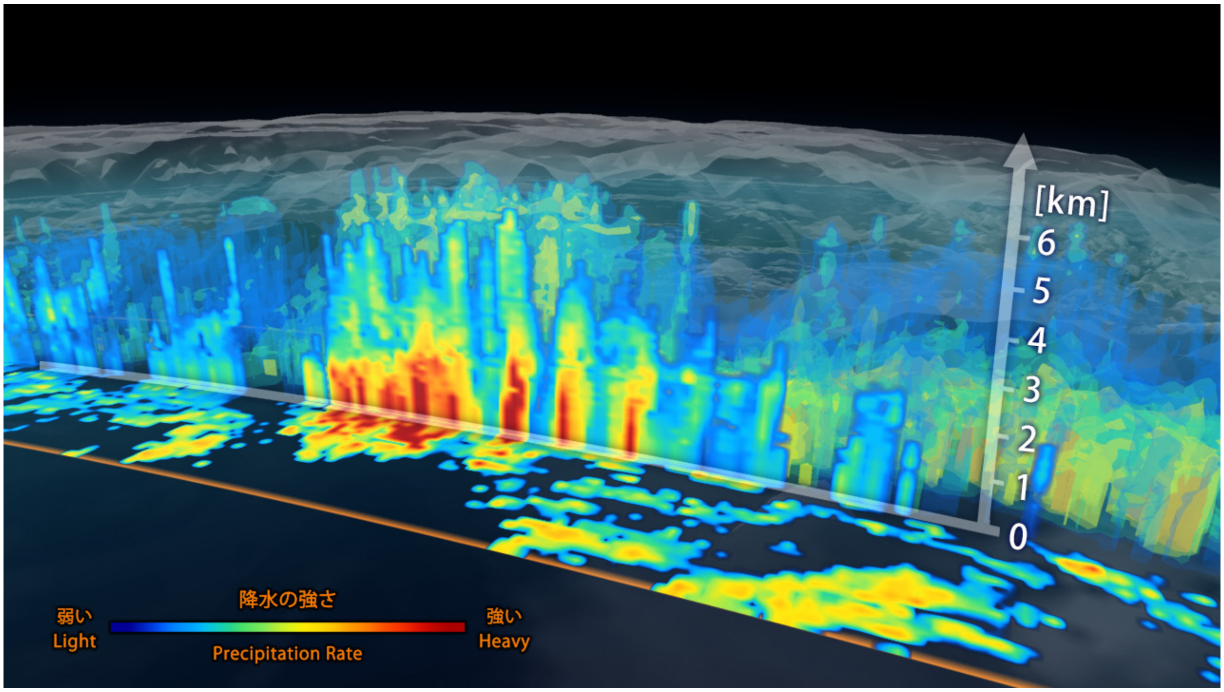

FIGURE 3.8 The Global Precipitation Measurement mission's dual-frequency precipitation radar observed a three dimensional structure of precipitation, inside an extra-tropical cyclone off the coast of Japan on March 10, 2014. The image shows rain rates across a vertical cross-section approximately 4.4 miles (7 kilometers) high. The red areas indicate heavy rainfall while yellow and blue indicate less intense rainfall. SOURCE: Courtesy of JAXA/NASA; see NASA, "First Images Available from NASA-JAXA Global Rain and Snowfall Satellite," Release 14-086, March 25, 2014, http://www.nasa.gov/press/2014/march/first-images-available-from-nasa-jaxa-global-rain-and-snowfall-satellite/#.VhakDflVhBe.

3.2.5 Atmospheric Chemistry

Among the most important of human influences on climate is the production of greenhouse gases, including CO_2, methane (CH_4), and various chlorofluorocarbon (CFC; hydrochlorofluorocarbon [HCFC]) and hydrofluorocarbon (HFC) compounds. Of these, CO_2 and CH_4 rapidly become well mixed in the lower atmosphere and affect Earth's radiation budget by trapping infrared radiation that would otherwise be expelled to space. Although CO_2 and CH_4 are themselves potent greenhouse gases and the primary cause of observed global warming, their indirect influence on atmospheric water vapor—a more potent and less predictable greenhouse gas—is perhaps even more important. Tropospheric water vapor provides a feedback mechanism through which increased global warming adds to the capacity of the atmosphere to contain water vapor while simultaneously elevating evaporation rates. The monitoring of water vapor and cloud water content and their effects on global radiation fluxes is thus critical to understanding the causes of climate change and predicting future climates. Currently, cloud coverage and type are the most significant sources of uncertainty in global climate modeling. Climate is also strongly affected by trace gases in the upper troposphere, stratosphere, and mesosphere; some of these trace gases also facilitate the destruction of stratospheric ozone. A diminished ozone layer allows harmful ultraviolet-B (UV-B) radiation from the Sun to reach Earth's surface, where it significantly enhances the probability of the occurrence of basal and squamous cell skin cancers and cataracts. The underlying chemical reactions that cause ozone depletion require chlorine and bromine to be present in sufficient quantities in the stratosphere.

Passive microwave observations provide a uniquely valuable means for monitoring the distribution and concentration of ozone and other trace gases including source, reservoir and active forms of key ozone-depleting substances, other species involved in ozone layer chemistry, and long-lived tracers used to track motions of air parcels. 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 (ClO), water vapor, ozone (O_3), and sulfur dioxide (SO_2). ClO is a key reactant in the chlorine chemical cycle that destroys O_3. A second generation 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. Instruments making passive observations Earth's atmospheric composition under development use frequencies listed above, plus the 320-360 GHz spectral region. Mesospheric O_3 can be measured using an 11.072 GHz line using radiometer techniques and measurements from 50 to 80 km and 80 to 104 km can be made using ground-based receivers.

3.2.6 Clouds

As described earlier, clouds play an important role in both Earth's water and radiation budgets. Determination of the composition, structure, and location of clouds is of critical importance for numerical weather and climate modeling and analysis. Microwave radiometric measurements within the bands at 6, 10, 18, 23, 31, 37, and 89 GHz are of primary interest for clouds. Active measurements of clouds are carried out near 13.6, 35.5, 78.5, and 94 GHz. It is important to have knowledge of cirrus clouds and the frozen particles in convective and anvil clouds for several reasons: (1) 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 are extremely useful for urban management.

Cloud ice water path (CIWP) is the vertically summed mass of cloud-borne ice particles per unit of area. As ice clouds can reflect a significant amount of sunlight, their impact on global radiative energy fluxes, and hence climate change is considerable. Future global CIWP measurements from space, using passive microwave techniques at frequencies from 89 GHz up to approximately 1 THz (e.g., 150, 166, 183, ~220, and ~340 GHz) could characterize the coupling of the global hydrologic and energy cycles through upper tropospheric cloud processes. 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. Such measurements would enable the development and testing of new self-consistent parameterizations of ice cloud processes and cloud systems, which could in turn guide improvements in ice cloud representation in global Earth system models. These improvements will significantly advance the understanding of the hydrological cycle and climate predictability. 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.

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 (Appendix B) has provided information on the vertical structure of highly dynamic cloud systems to provide global measurements of cloud properties, as shown in Figure 3.9. These measurements have helped 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.

For non-precipitating 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 approximately 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

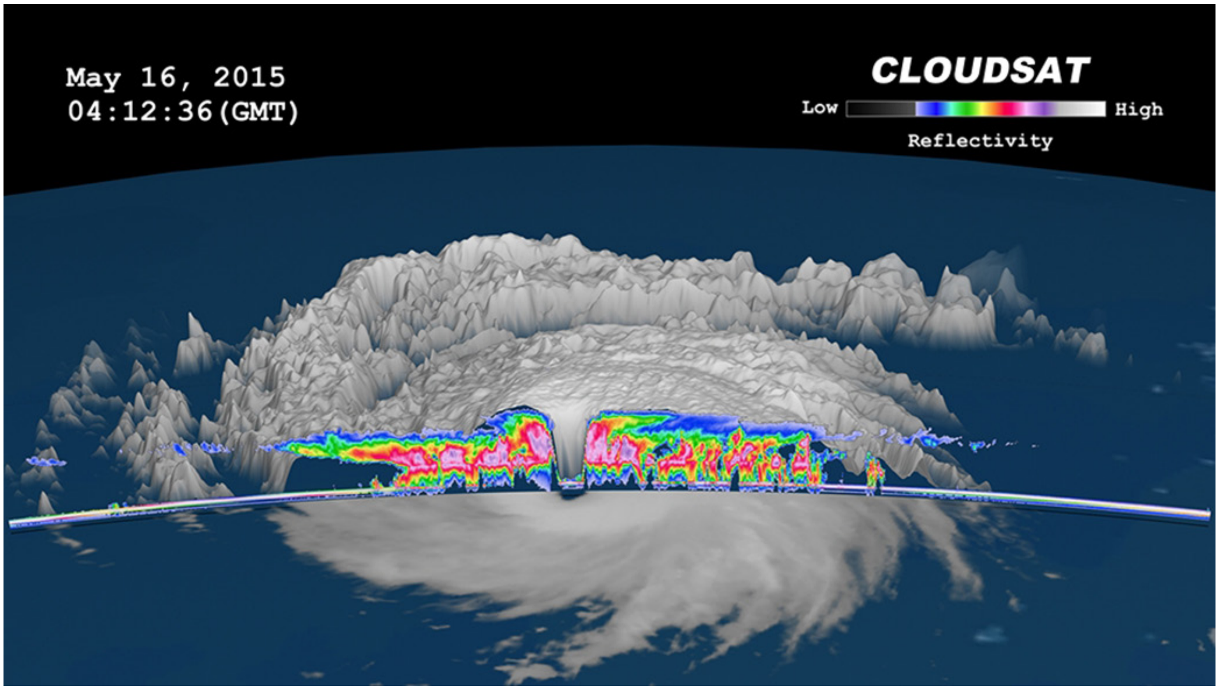

FIGURE 3.9 Combined imagery from Cloudsat and Japanese Multifunctional Transport Satellite (MTSAT) of Typhoon Dolphin in the West Pacific on May 16, 2015. SOURCE: Courtesy of NASA/JPL-Caltech/Colorado State University; see NASA, "Dolphin (was 07W/System 93W - NW Pacific Ocean)," May 21, 2015, http://www.nasa.gov/feature/dolphin-was-07wsystem-93w-nw-pacific-ocean.

modeling the influences of short-wave 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 (see Section 2.5.1) background. Widespread global deployment of these sensors is occurring.

3.2.7 Ionosphere

Radio frequencies are used to understand the physical state of the ionosphere, characterize irregularities, detect large-scale structures, and enable the real-time monitoring and prediction of propagation conditions and space weather effects. Such understanding enables important scientific and commercial applications including communications, precision navigation, environmental remote sensing, and national defense. Techniques for remote sensing of the ionosphere include study of ionospheric coupling to the lower atmosphere below and the larger heliospheric environment above, using both passive and active techniques over a wide range of frequency bands. In this section, we briefly survey ongoing work and point out the wide range of frequencies below 3 GHz that are used for ionospheric sensing.

Passive microwave techniques involve monitoring of the radio spectrum, radio imaging and interferometry, precision measurement of radio noise, and passive use of transmitters of opportunity (natural or man made) to measure ionospheric phenomena. Riometers (relative ionospheric opacity meters) such as IRIS, KAIRA, and EDGES, measure ionospheric absorption and provide images of ionospheric structures in the frequency range of 20-70 MHz. Frequencies lower than 20 MHz tend to be contaminated by broadcast signals, while those higher than 70 MHz have high absorptions in the D- and F-regions of the ionosphere.

Radio scintillation is used for real-time amplitude and phase fluctuations detection of ionospheric conditions such as plasma parameter gradients and embedded irregularities. These impact trans-ionospheric propagation and detection of heliospheric phenomena. Interplanetary scintillation is used for detection of electron densities and magnetic field of coronal mass ejections at distances <1AU. It is measured at a variety of frequencies from HF to S-band (Appendix B). Satellite and ground-based phase coherent radio beacons measure total electron content (TEC) and the amplitude and phase fluctuations in the trans-ionospheric signals (i.e., scintillations) related to the irregularities along the propagation path. Example frequencies of the currently on-orbit beacons operate at 150.012, 300-400, 400.032, 1066.752, and 2360-2380 MHz; and on-ground beacons operate at 401.25 MHz and 2036.25 MHz. Examples of space-based receiver frequencies include 150, 400, and1067 MHz. Both active transmissions from satellites and observation of radio star scintillation (RSS) are routinely conducted. Global Navigation Satellite System use navigation signals in L1 (1575.42 MHz), L2 (1227.6 MHz), and L5 (1176.45 MHz) bands to estimate ionospheric delay.

In the low frequency ranges, VLF sounding techniques are used for magnetosphere-ionosphere coupling, field-aligned TEC, wave perturbations, wave-particle interactions, and lightning locations. ELF from 1-800 Hz are used to explore Schumann resonances in the Earth-ionosphere waveguide cavity and are important for Q-bursts due to "super-bolt" lightning strikes and "sprites" associated with these large strikes. The ULF from 10^{-4} to 1 MHz are used for magnetosphere-ionosphere coupling, provide remote sensing of natural wave modes, and magnetospheric resonances. Low frequency radio telescopes (e.g., LOFAR, MWA, VLA, or LWA) produce calibration products that provide very accurate all-sky map of relative line integrated electron density between baselines. Existing systems with frequency ranges of 10-300 MHz and future systems such as SKA and RAPID can be used to study small-scale ionospheric waves and structures. Satellite-based HF receivers are used to study manmade and natural

HF waves such as radar propagation, lightning pulses, HF scatter from ocean, and high-power HF interactions in the ionosphere at 0-18 MHz range (e.g., ePOP and CARINA).

Passive radar observations of the ionosphere uses transmitters of opportunity such as AM and FM radio, and HDTV, to produce radar observations. These observations are used to study propagation and scattering in the ionosphere, ionospheric turbulence, natural plasma irregularities, and meteor trails. White space bands between stations are often useful for passive propagation measurements in bi-static and multi-static receiver configurations. In-band on channel digital radio, such as used with FM, acts to jam these configurations.

Active techniques are also used for ionospheric sounding, noise and absorption measurements, and radio propagation-based techniques (both ground-to-ground and ground-to-space). Incoherent scatter radar provides precise measurement of the thermal ionospheric plasma. Primary measurements include electron density, electron temperature, ion temperature, and ionospheric drifts and provide information on electric fields, neutral winds, and ion compositions. Typical HF/VHF/UHF/L-band center frequencies, with up to 30 MHz bandwidth on receive and typically up to 1 MHz bandwidth on transmit, are used in existing systems. Up to 10 MHz bandwidth is planned for future systems. Significant power aperture is required, with most systems being multi-megawatt class that have antennae sizes between 25 and 300 meters. Current active systems operate at 46.5, 47, 49.92, 53.5, 154-162, 224, 430, 440, 440.2, 440.4, 442.5, 449.3, 500, 933, 1290, and 2380 MHz, with future systems planned at 220 and 233 MHz.

Ionospheric sounders or ionosondes provide direct measurement of ionospheric electron density profiles using transmissions that experience total reflection at the local plasma/Langmuir frequency. Because electron density and hence the resonance frequency is altitude dependent, these systems must span a significant range (e.g., ~ 1 to 15 MHz), which is time-dependent based upon geophysical conditions. Altitude coverage is limited by the peak ionospheric cut-off frequency. Higher frequencies beyond the local plasma frequency can be used for oblique sounding up to 30 MHz. The pseudorandom transmission radar sounders with low emission levels that produce minimum electromagnetic interference levels (~ 1 W) and low power noise-like radar transmissions can be used to produce HF range-Doppler radar measurements and even ionosonde measurements. This type of radar, which is currently being developed, would cause less interference to other users of the already crowded HF band. They operate from 2-30 MHz with typical bandwidths of 100 kHz. Transmission at low power covering the entire frequency range can be very useful for high measurement speeds. Similar to ionosondes, they provide measurements of electron density and reflection height, wave measurements, meteor trails, and Doppler radar measurement of coherent scattering structures.

The mesosphere/stratosphere/troposphere radar systems measure the lower boundary of the Geospace environment and its coupling to the ionosphere and lower atmosphere. They operate at 30-60 MHz, VHF/UHF, and S-bands. The Mesosphere/Lower Thermosphere (MLT) dynamics radars provide measurements of the mesosphere regions. The mesosphere is a crucial atmospheric layer and is quite difficult to observe by techniques other than meteor radar (MR) and medium frequency (MF) radar that operate at 2-3 MHz. These radar measurements have widely been used to detect mean winds and tides and to get insight into the seasonal, interannual, and long-term behavior of the MLT circulation including long-term trends. In addition, MR and MF radar measurements have been combined to analyze properties of planetary waves and estimate wind parameters. Meteor radars, operating at 30-50 MHz, with some systems operating from 2-100 MHz, provide neutral wind measurements by measuring the Doppler frequency of a drifting meteor trail after the meteor has ablated in the upper atmosphere.

Radars at 2-10 MHz (some specific examples, 2.8, 3.5, 3.85, 5.1, 8.175 MHz) are used to heat the ionosphere at an altitude where the critical frequency corresponds to the transmission frequency. The measurements can be used to investigate fundamental plasma physics primary and secondary wave modes in the plasma, and to measure ionospheric parameters inaccessible by other means. High-power HF have produced artificial aurora, enhanced ionization, field-aligned irregularities, and stimulated electromagnetic emissions.

HF radar operating between 5-50 MHz is used for over the horizon observations of a variety of targets and for ionospheric measurements. Wide-Sweep Backscatter Ionograms are used by over-the-horizon radars to map the HF propagation conditions over ~1000 km in range. Measurement of coherent scattering structures at HF allows detailed study of ionospheric irregularities and plasma physics. Propagation and surface scattering effects, ionospheric waves from earthquakes, or just traveling ionospheric disturbance and Alfven waves can also be investigated.

3.3 TERRESTRIAL HYDROLOGY

3.3.1 Soil Moisture

Soil moisture (SM) is a key component of the land-surface hydrospheric state and is vital to weather and climate prediction research. It is essential in estimating latent heat and carbon fluxes at the land-atmosphere boundary. SM is also a key parameter in forecasting relating to agriculture, drought, and flooding and for predicting vegetative stress and establishing related government policies. Accurate knowledge of the parameters of SM has been shown to improve forecasts of local storms and seasonal climate anomalies. Atmospheric models tend to use sea surface temperatures (SSTs) as their primary boundary condition because so much of Earth's surface is ocean. However, models just using SSTs are unable to capture seasonal climate anomalies in the middle of large continents. However, if SM data are incorporated, atmospheric models can accurately predict the seasonal anomalies in extreme weather.

Passive microwave radiometers operating at frequencies of 10 GHz and lower are sensitive to variations in soil density, type, and moisture content and are needed for SM measurements.[3] Radiometry in the 1-2 GHz range is arguably the best means for measuring subsurface soil moisture on a national or global basis. A combination of active and/or passive microwave measurements can be used to remotely sense SM under moderately vegetated areas, with up to ~5 kg/m^2 of vegetation water content. These measurements provide SM information with an uncertainty of 0.04 m^3/m^3. Passive measurements rely on the dependence of the microwave emissivity of soil to its water content. 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, such as those at 1.26 GHz, rely on the dependence of soil backscatter on water content and are complicated by surface roughness and scattering by vegetation cover. Active measurements can, however, provide finer spatial resolution than is possible with passive techniques. Thus, a combination of active and passive measurements, such as those from the NASA SMAP mission, can be used to separate the effects of surface roughness and vegetation scattering from the soil-moisture signature while providing the desired spatial resolution, as shown in Figure 3.10. Passive microwave measurements in the C-band region, near 6.8 GHz, such as those from AMSR-E and AMSR2, can be used to infer soil moisture in the top 1cm of the surface layer under bare soil and lightly vegetated areas with water content up to ~2 kg/m^2, to an approximate accuracy of 0.10 m^3/m^3.

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[3] For background information regarding EESS for soil moisture see the following: W. Wagner, P. Pampaloni, J.-C. Calvet, B. Bazzari, J.P. Wigneron, and Y. Kerr, Operational readiness of microwave remote sensing of soil moisture for hydrologic applications, *Nordic Hydrology* 38(1):1-20, 2007; J. Judge, Microwave remote sensing of soil water: Recent advances and issues, *Transactions of the American Society of Agricultural Engineers–Centennial Edition* 50(5):1645-1649, 2007.

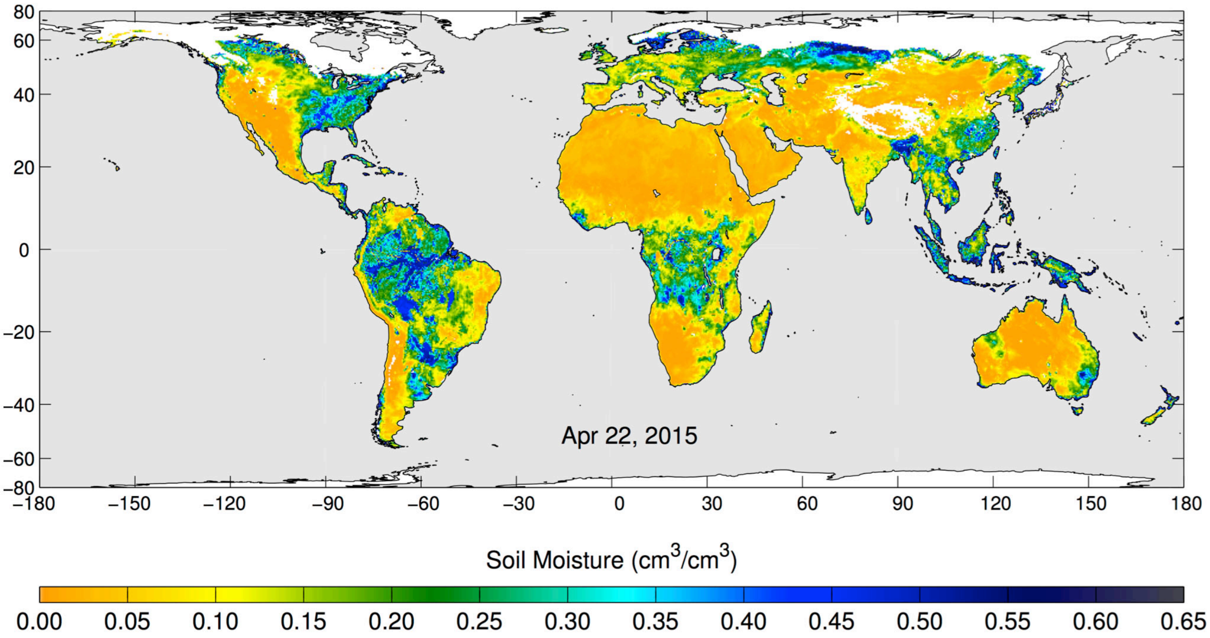

FIGURE 3.10 Global soil moisture from L-band observations of the NASA SMAP mission at a spatial resolution of 10 km obtained by combining passive measurements at a spatial resolution of 36 km with active measurements at a spatial resolution of 3 km. SOURCE: Courtesy of NASA/JPL-Caltech/GSFC; see NASA/JPL, "SMAP's Radiometer Captures Views of Global Soil Moisture" April 22, 2015, http://smap.jpl.nasa.gov/resources/87/.

3.3.2 Freeze/Thaw

The seasonal freeze-thaw transition of the Northern Hemisphere is a significant source and sink of atmospheric CO_2. The exact timing of the spring thaw and the resulting length of the growing season can fundamentally affect the net carbon exchange budget between land and atmosphere. The thawing of polar tundra also results in more solar absorption and heating, with the possible runaway production of methane from the anaerobic decomposition of sub-surface biomass. Because microwave signatures are directly sensitive to the liquid and the solid phase of water, both active and passive observations are well suited for monitoring global freeze-thaw. The radar response to the freeze-thaw transition dominates the response due to any other factors such as changes in canopy structure, biomass, or precipitation. Typically, time series change detection approaches have been used to obtain freeze-thaw information from scatterometers operating at L-band (1.2 GHz; Figure 3.11), C-band (at 5.3 GHz), or Ku band (at 13.4 GHz). The passive approaches rely on the differing sensitivities among various frequencies to liquid moisture and volume scattering, thus requiring multi-frequency observations. Spectral gradients between various frequency combinations at 6, 10, 18, 22, and 37 GHz have been used to obtain freeze-thaw.

3.3.3 Surface Water

Fresh water is essential to all life forms. Our ability to measure, monitor, and predict the global supply of fresh water is increasingly valuable as many countries face critical challenges in meeting demands for clean water supplies partly because of growing and shifting populations. Knowledge of the location, extent, and changes of surface water bodies such as rivers, lakes, reservoirs, floodplains, and wetlands is

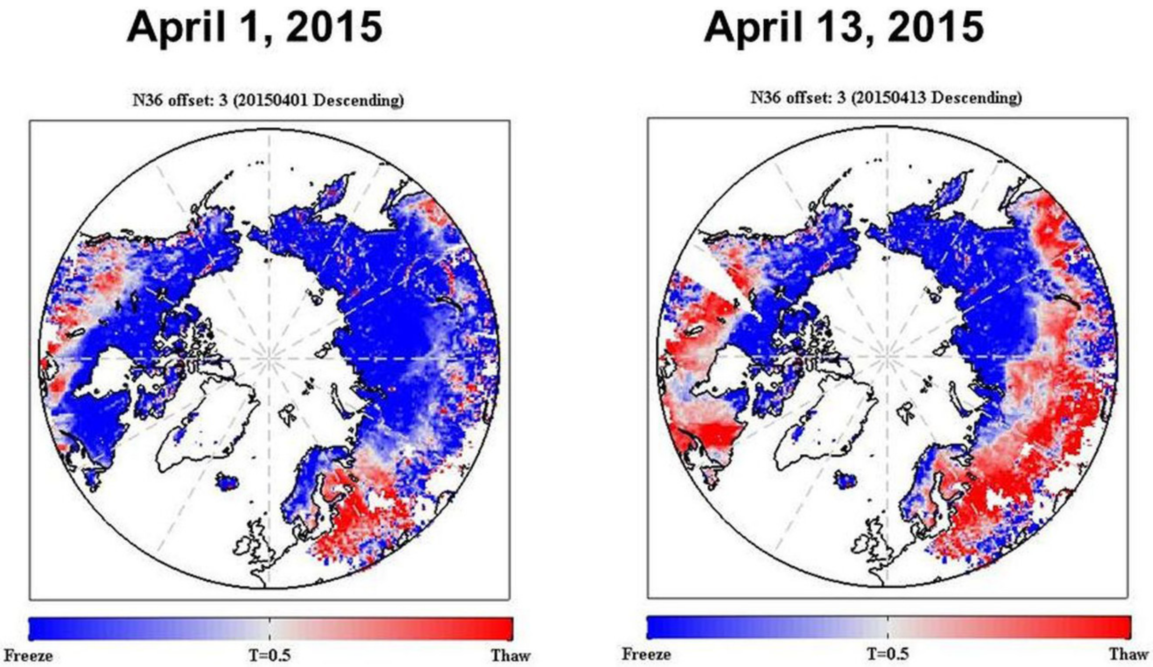

FIGURE 3.11 Spring thaw as observed by the radar at L-band aboard the NASA SMAP mission. SOURCE: Courtesy of NASA/JPL-Caltech; see "SMAP Shows Progression of Spring Thaw," April 2015, http://smap.jpl.nasa.gov/resources/85/.

also important for predicting impacts of extreme hydrological events such as floods. In addition, inundated areas such as the wetlands contribute about 25 percent of the annual CH_4 emissions to the atmosphere, affecting the carbon budget. To date, our ability to measure, monitor, and predict the spatial extent and variability of fresh water at the global scale is surprisingly poor. Specific measurements that are needed to obtain such knowledge are the elevation of the water surface, its slope, extent, and temporal change.

Satellite-based microwave sensors are well suited for measuring these parameters. For example, radars operating at L, C, Ku, and Ka bands have been used to measure surface water extent, elevation, and temporal variations using combinations of altimetry, imaging, and interferometric techniques. Sensors at L- and C-bands, in particular, can also provide information regarding seasonal inundation extents in floodplains and wetlands using both active and passive measurement techniques. At L- and C- band, passive signatures typically decrease with increasing inundation, while active signatures are typically low over flat, open water, but high where dense vegetation is inundated because tree trunks act as corner reflectors.

3.4 CRYOSPHERE

The cryosphere consists of components of the Earth system that contain water in a frozen state. Glaciers, ice sheets, snow cover, lake and river ice, and permafrost make up the terrestrial elements of the cryosphere. Sea ice, frozen sea-bed, and icebergs constitute the oceanic elements of the cryosphere. This definition of Earth's cryosphere implies that substantial portions of Earth's land and ocean surfaces are directly subject in some fashion to cryospheric processes. As such, observations of the cryosphere are necessary to predict future variability in Earth's ice cover, and its interaction with other Earth systems must be made on commensurate spatial and temporal scales. Moreover many measurements must be made

TABLE 3.1 Radio-Frequency Sensors Supporting Cryosphere Research

Platform/Sensor	Example Cryo Application	Center Frequency
Currently Operational Spaceborne		
SMAP/Radiometer	Sea ice and ice sheet	1.41 GHz
GCOM/AMSR-2	Sea ice concentration, snow cover, wet/dry snow, dry snow water equivalent	18.7, 36.5, 89.0 GHz (Cryo used) Possible 6.925 app
DMSP/SSMI	Sea ice concentration, snow cover, wet/dry snow, dry snow water equivalent	19.35, 37, 85 GHz
SMOS/MIRAS	Sea ice thickness, ice sheet morphology, seasonal snow cover	1.41 GHz
Sentinal	Sea ice monitoring, glacier/ice sheet motion	5.405 GHz
Radarsat 2	Lake/river ice monitoring, sea ice monitoring, glacier/ice sheet motion	5.405 GHz
ALOS-2/Palsar-2	Sea ice concentration, ice sheet/glacier motion	1.2575, 1.2365, 1.2785 selectable
TerraSAR	Glacier/ice sheet surface elevation and motion,	9.65 GHz
Cryosat/SIRAL	Sea thickness, glacier/ice sheet surface elevation	13.575 GHz
Planned		
BIOMASS	Potential subsurface mapping of glaciers and ice sheets	435 MHz
Example Operational Airborne Systems		
MCoRDS	Glacier/ice sheet thickness	195 MHz
Kansas KU Band	Ice elevation	15 GHz
Snow Radar	Sea ice snow cover	5 GHz
Accumulation Radar	Ice sheet accumulation	750 MHz
Planned		
UWBRAD Radiometer	Subsurface temperature	0.5-2 GHz

NOTE: Airborne radars referenced are by University of Kansas. Other similar systems are operated by numerous other groups. UWBRAD system is by Ohio State University.

under the environmental restrictions of the long polar night and the frequently cloud-covered conditions at the poles. Consequently, airborne and spaceborne radio-frequency technologies play a key role in acquiring data necessary to understand the important physical processes and Earth system interactions that govern the cryosphere.[4] Table 3.1 provides current RF sensors supporting cryosphere research.

3.4.1 Glaciers and Ice Sheets

Glaciers and ice sheets are reservoirs of fresh water with greater than 90 percent of Earth's fresh water bound in the Antarctic Ice Sheet. If released, the melting ice will have profound implications for

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[4] For background information regarding technical information on EESS for cryosphere applications, see the following: IGOS, Integrated Global Observing Strategy Cryosphere Theme Report-For the Monitoring of Our Environment from Space and from Earth, WMO/TD-No. 1405, World Meteorological Organization, Geneva, 2007; K.C. Jezek, Cryosphere: Spaceborne and airborne measurements/monitoring, pp. 280-298 in *Encyclopedia of Sustainability Science and Technology* (R.A. Meyers, ed.), Springer Science+Business Media, 2012.

coastal communities experiencing sea level rise. Indirect approaches for identifying whether ice sheets are losing mass include use of proxy indicators such as surface melt area and duration—both measureable using passive microwave techniques. For example, the SSM/I instrument of the DMSP (19.35 and 37 GHz channels) and Japan's AMSR-2 (18.7 and 36.5 GHz) provide useful, frequent measurement of ice sheet surface melt. More directly, there are two primary radio-frequency techniques currently used to explicitly assess the changing volume (or mass) of ice contained in glaciers. The first involves an estimate of the difference between the annual net accumulation of mass on the surface of the glacier and the flux of ice lost from the terminus. Surface accumulation has been estimated using the European Space Agency (ESA) Earth Remote Sensing Satellite (ERS-1) C-band SAR and passive microwave data using relationships between accumulation rate, snow grain growth, and grain scattering. Wide-band airborne radars (750 MHz) can map individual annual layers in the near surface from which accumulation rate can be estimated. The flux from the terminus is calculated using the measured ice thickness from airborne radar and the surface velocity from InSAR. Airborne radars, such as those developed as part of NASA's operation IceBridge, operating at 195 MHz, are capable of sounding the deepest polar ice with thickness accuracies of 10-20 m. Lower frequency (1-5 MHz) systems mounted on surface or airborne platforms are used to measure the thickness of temperate ice where volumetric distributions of water inclusions become strong scatters at higher frequencies. Japanese Phased Array L-band SAR (Palsar-2 at 1.2576 GHz), Canadian Space Agency (CSA) and ESA C-band (Radarsat-2 and Sentinel at 5.4 GHz), and German X-band (TerraSAR-X at 9.65 GHz) are all operational SARs capable of interferometry and are used to successfully measure ice surface motion.

The second approach for estimating reservoir change is to repeatedly measure surface elevation change. This has been accomplished with several earlier spaceborne radar altimeters and most recently with ESA's CryoSAT-2 (13.58 GHz). CyroSAT-2 uses synthetic aperture and interferometric processing to provide fine-scale resolution of ice surface elevation near the ice margin where surface slopes are high. Elevation and elevation change have also been measured with ERS-1, NASA's Shuttle Radar Topographic Mapper (SRTM), and Germany's Tandem-X. However, these data tend to be more useful for glacier dynamics studies that rely on estimates of the surface slope to compute the stress driving the glacier forward.

Regional mapping of glaciers and ice sheets focuses on delineating physical characteristics such as glacier termini, glacier snow lines, crevasse patterns, and snow-rock boundaries. For example, active and passive observations at L-band are sensitive to melt onset on ice sheets. An ERS-1 SAR mosaic of Greenland revealed the existence of a long ice stream in northeast Greenland. In 1997, Radarsat-1 SAR data were successfully acquired over the entirety of Antarctica. The coverage was complete and was used to create the first, high-resolution (25 m) radar image mosaic of Antarctica. Subsequent to 1997, regional mapping has been repeated by Radarsat-2 (Figure 3.12) and also with TerraSAR-X. Measurements using Sentinal-1 are now under way.

Internal ice sheet temperature, critical to accurately characterizing ice sheet flow at depth, remains an elusive objective for remote sensing techniques. Recently, airborne wide-band radiometry in the 0.5 to 2 GHz band has been suggested as a possible approach to ice sheet thermometry. Comparisons between modeled and SMOS measured brightness temperatures at 1.4 GHz offer some support for the hypothesis.

3.4.2 Sea Ice and Icebergs

Sea ice modulates polar climate by restricting the oceanic heat flow to the atmosphere and by reflecting incoming solar radiation back into the atmosphere. Sea ice impedes surface navigation and

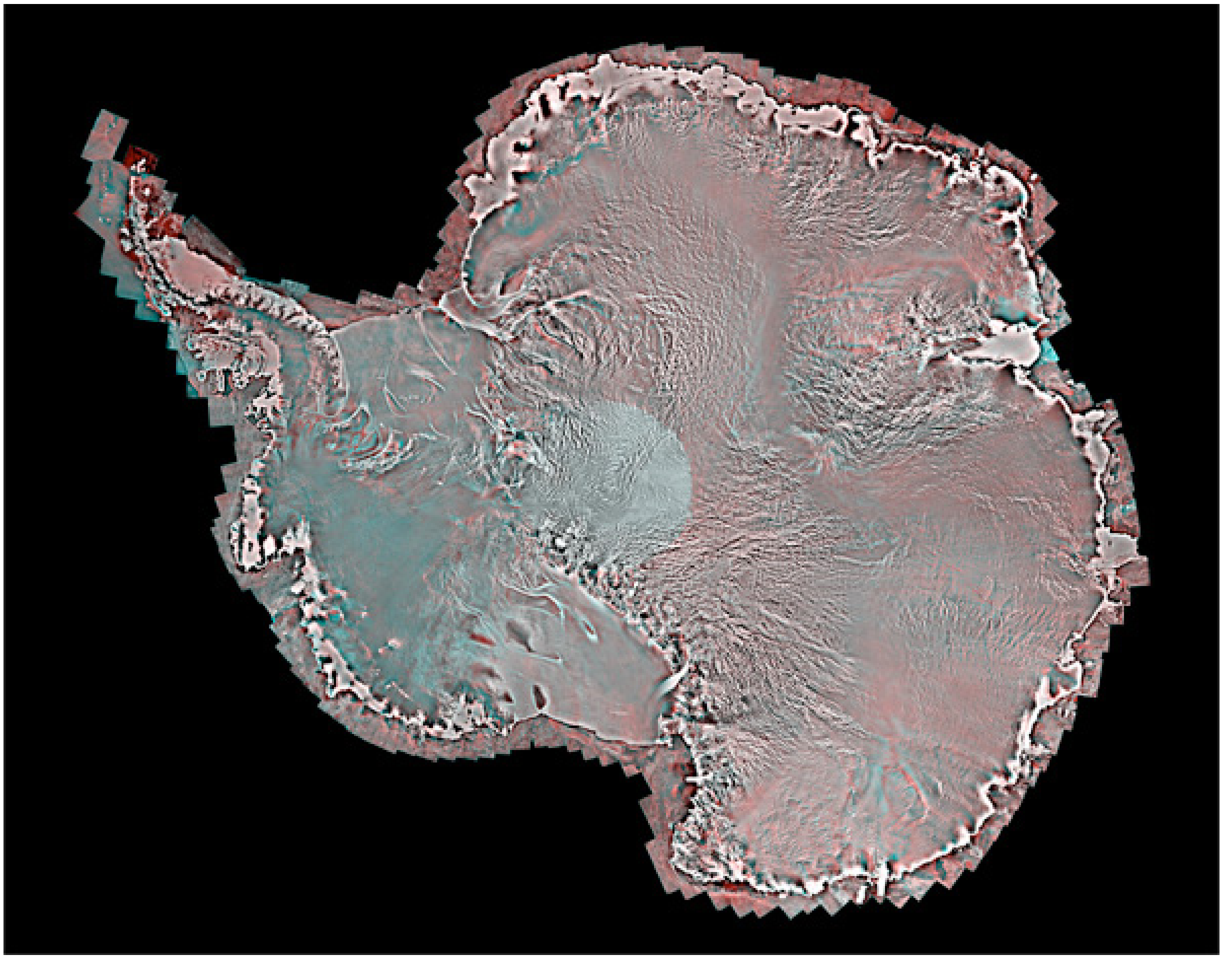

FIGURE 3.12 Radarsat-2 multipolariztion, C-band image of Antarctica collected as part of the International Polar Year. SOURCE: Courtesy of the Canadian Space Agency (for additional background information see M. Drinkwater, K. Jezek, E. Sarukhanian, and T. Mohr, IPY Satellite Observation Program, Chapter 3.1 in *Understanding Earth's Polar Challenges: International Polar Year 2007-2008*, Summary Report by the IPY Joint Committee, WMO/ICSU, 2011).

shrinking sea ice cover has important consequences for future development of the Arctic. Cloud cover and the long polar night dictate the use of all-weather, day/night passive microwave radiometers for monitoring sea ice age, extent, and concentration. Older, multiyear sea ice is thicker and is structurally different from new sea ice. The lower salinity and generally rougher multiyear ice can be mapped with scatterometers and radiometers at L-band. Detailed measurements of ice extent are made using passive microwave image data at frequencies of about 18, 37, and 85 GHz. These data document the dramatic decrease in Arctic sea ice cover and the changing dates of melt onset. Visualization of northern sea ice retreat represent some of the most compelling and straightforward demonstration of the changing climate at high latitudes (Figure 3.13).

Sea ice floes in the Arctic are sufficiently large to enable motion estimates from repeat passive microwave images. Better results are obtained with increasing resolution (tens of meters) achievable

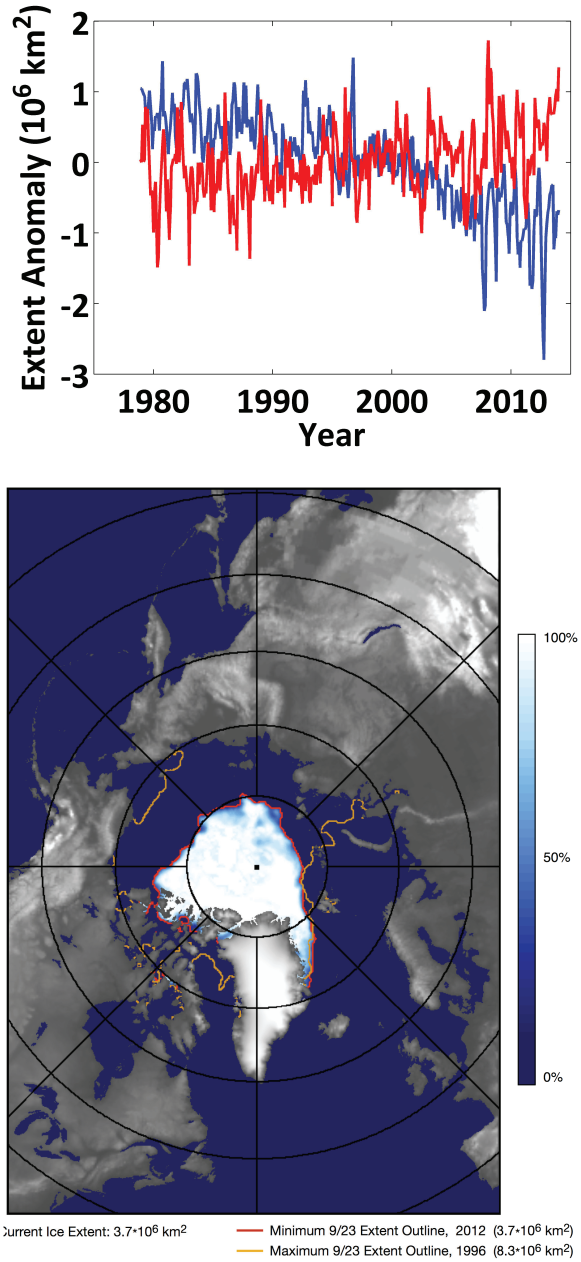

FIGURE 3.13 *Top:* Sea ice areal extent anomaly for the arctic (blue) and antarctic (red) from 1978 through 2013. Extent is calculated using the NASA team algorithm applied to spaceborne passive microwave data. Anomalies are deviations from the mean for the period of observations. Arctic sea ice has retreated over the period of observations. More rapid shrinkage of the ice cover began in about 2000, and that trend is continuing through the present. Conversely, Antarctic sea ice is slowly expanding over the Southern Ocean. Differences in the two trends can be attributed in part to the distinct geographies of the north and south polar regions. Nevertheless, sustained retreat of the northern ice pack is a clear indication of a warming Arctic. *Bottom:* Sea ice extent around the summer minimum, on September 23, 2012, from SSM/I and historical extent on the same day in 1996 from SSM/I and SMMR. SOURCE: *Top:* Data were provided by the National Snow and Ice Data Center; image generated by Kenneth Jezek, Ohio State University. *Bottom:* Courtesy of Robert Gersten and Josefino Comiso, NASA Goddard Space Flight Center.

with C-band SAR (ERS-1 and -2, Radarsat-1 and -2, and Sentinal-1). Similar to ice sheets, a net flux of sea ice across the ocean can be computed given the motion results and an estimate of ice thickness. Ice thickness is presently obtained by computing the ice surface elevation-above-sea-level as measured by Cyrosat-2 and earlier radar altimeters. Snow layer thickness obtained using airborne radars operating at 5 GHz with a 6 MHz bandwidth provides key information about insulating snow layer. Most recently, ESA SMOS L-band emission data have also been used to compute sea ice thickness.

Icebergs are a measure of the ice lost from glaciers and ice sheets by calving at the ice margin. They also represent obvious hazards to navigation. The largest (tens of kilometers) icebergs formed from long fractures through Antarctic ice shelves can be tracked with passive microwave imagers (such as SSM/I using the 18 and 37 GHz channels). Smaller icebergs can be identified and tracked with C-band SAR (such as Radarsat-1 and -2).

3.4.3 Seasonal Snow Pack

Seasonal snow cover plays an important role in regional hydrology and water resource management. Rapid melting of the seasonal snow pack can result in catastrophic flooding. The bright snow surface also serves as an effective mirror for returning incoming solar radiation back into space thus modulating the planetary heat budget.

Snow thickness and, indirectly, the mass of snow are key variables for estimating the volume of water available in a reservoir and potentially releasable as runoff. The most successful techniques to date have relied on microwave-based algorithms. One approach for estimating snow thickness is to difference 19 and 37 GHz brightness temperature data that along with a proportionality constant yields an estimate of the snow thickness. The algorithm is based on the fact that 19 GHz radiation tends to minimize variations in ground temperature because it is less affected by the snow pack. The 37 GHz radiation is strongly scattered by the snow grains, and brightness temperature at this frequency decreases rapidly with snow thickness/snow water equivalent.

Information about the seasonal onset of snow melt is important in river discharge and glacier mass balance studies. It can be obtained from microwave data. A few percent increase in the amount of free water in the snow pack causes the snow emissivity to approach unity, resulting in a dramatic increase in passive microwave brightness temperature. This fact has been successfully used to track the annual melt extent on the ice sheets and also to track the springtime melt progression across the Arctic. Higher resolution estimates of melt extent can be obtained with scatterometer and SAR data. These data generally show an earlier springtime date for the beginning of melt onset and a later date for the fall freeze.

3.4.4 Lake and River Ice

Lake and river ice form seasonally at mid- and high-latitudes and high elevations. River ice forms under the flow of turbulent water, which governs its thickness. The combination of ice jams on rivers with increased water flow during springtime snow melt can result in catastrophic floods. The start of ice formation and the start of springtime ice breakup are proxy indicators for changes in local climate as well as impacts on the ability to navigate these waterways. On larger lakes, passive microwave radiometry is effective for monitoring lake ice growth and decay in much the same way as the technique is applied to sea ice.

Streams, rivers, and lakes of all sizes dot the landscape. Locally, ice cover observations can be made from aircraft. Regionally or globally, river and lake ice monitoring is challenging because physical dimensions (long but narrow rivers) often require high-resolution instruments such as SAR to resolve details. Moreover, because the exact date of key processes, such as the onset of ice formation or river ice breakup are unknown, voluminous data sets are required to support large-scale studies.

3.4.5 Permafrost

Permafrost presents one of the greatest challenges for regional remote sensing technologies. The near surface active layer, the shallow zone where seasonal temperature swings allow for annual freeze and thaw, is complicated by different soil types and vegetative cover. This combination tends to hide the underlying persistently frozen ground from the usual airborne and spaceborne techniques mentioned above. SAR interferometry has been suggested as another tool that can be used to monitor terrain for slumping associated with thawing permafrost. For example, lakes and depressions left by drained lakes are densely distributed across the tundra and are diagnostic of permafrost conditions. SAR intensity images have been used to determine that most of these small lakes freeze completely to the bottom during the winter months. Airborne electrical resistivity measurements at kHz frequencies seem to offer a more direct approach to estimating active layer thickness and the presence/absence of permafrost.

3.5 OCEANS

Microwave remote sensing of the oceans is important both for understanding the oceans themselves (e.g., ocean circulation and currents) and for understanding the global hydrologic cycle and the impact of the oceans on weather and climate. It is also important for commercial applications such as monitoring fisheries and directing ship traffic. Passive measurements (radiometry) require measurement of weak thermal emissions. These measurements are generally performed at a primary frequency that is sensitive to the parameter of interest (e.g., 6.8 GHz for remote sensing of SST) and secondary frequencies necessary for correcting for effects such as attenuation along the propagation path and changes in emissivity of the surface due to roughness (waves). The same is true for active (radar) remote sensing of the oceans, although active sensors are somewhat more flexible because there is control of the transmitted signal. However, the signals are small and the systems often require passive measurements to correct for path delay (e.g., in measurements of ocean topography). Table 3.2 provides a list of the parameters of interest and the primary and secondary frequencies most commonly obtained by passive and active microwave sensors in space.

Both passive and active remote sensing techniques are limited by the availability of noise-free bandwidth. The signals are small, and bandwidth is needed to reduce noise (natural thermal noise). As

TABLE 3.2 Ocean Parameters of Interest and the Primary (black circles) and Secondary (open circles) Frequencies Most Commonly Obtained by Passive and Active Microwave Sensors in Space

	Frequency of Observation (GHz)							
Parameter	1.4	5.3	6.8	10.7	13.6	18.7	23.8	37.0
Passive								
Sea surface temperature			●	○		○	○	○
Sea surface winds			○	●		○	○	
Sea surface salinity	●							
Active								
Surface topography		○			●	○	○	○

the sensor technology improves, the potential for more accurate measurements and new applications increases. Given the limitations on available bandwidth, progress requires careful protection of the available bandwidth from encouragement by manmade RF interference (RFI).

3.5.1 Sea Surface Temperature

Global maps of SST are important for predicting weather and understanding climate and climate change and for commercial applications such as fishery assessment. For example, knowledge of SST is important for modeling the coupling between ocean and atmosphere and for understanding the heat exchange across the boundary. Temperature together with salinity determines water density, and the density-driven circulation (thermohaline circulation) moves large amounts of water and heat around the globe.

Prior to the launch of the microwave imager (TMI) on the TRMM satellite in 1997, global maps of SST were produced from infrared measurements. Since then, data from passive microwave instruments on satellites such as AMSR-E, AMSR-2, Windsat, and GPM are being used to produce global maps of SST.[5] The microwave measurements are not as limited by cloud cover and have proven particularly important for helping to forecast storms and for monitoring areas of persistent cloud cover. For example, this is the case in economically important areas off the coast of Washington and Oregon cannot be imaged in the infrared for weeks at a time because of such cloud cover.

Passive observations of the surface (i.e., measurement of the natural thermal radiation from the surface) respond to changes in SST with peak sensitivity to changes in temperature near 5-7 GHz (Figure 3.14). In this frequency range it is necessary to account for surface roughness (waves) and attenuation in the atmosphere. Modern microwave instruments generally use a combination of frequencies to retrieve SST: A primary channel near 6.8 GHz and channels near 10 GHz (to mitigate effects of waves); channels near 18 and 21 GHz to correct for attenuation by water vapor; and a frequency near 37 GHz to help correct for liquid water (note Figure 3.3). The frequencies of the microwave imager (GMI) on the recently launched GPM are 10.65, 18.70, 23.80, 36.50, and 89.00. These are bands with primary allocation for passive use, but they are shared with other active services. The AMSR series of satellites included a channel at 6.8 GHz better suited for measurement of SST. This channel is near the peak in sensitivity and critical for the measurement of SST. However, the 6.7-7.25 GHz band is not protected for passive use. ITU-R Footnote 5.458 recognizes its use for passive measurements over oceans and urges administrations to be mindful of such use.

3.5.2 Sea Surface Salinity

The salinity of ocean water is important for understanding ocean circulation and its impact on weather and climate. Salinity, together with temperature, determines water density, which is important for understanding water circulation. Ocean circulation in turn is responsible for moving large amounts of heat around the globe with an impact on local weather and climate. Sea surface salinity is also important for understanding the global hydrologic cycle. Changes in salinity in the open ocean are an indication of the change in the balance between evaporation and precipitation. For example, Figure 3.15 shows the mean surface salinity field as observed by the NASA/CONAE Aquarius mission, which is very similar to a map of the global distribution of the difference between evaporation and precipitation. On a short timescale this is an indication of local precipitation, and on a longer timescale it provides important

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[5] For background information on EESS for SST, see the following: F. Wentz, C. Gentemann, D. Smith, and D. Chelton, Satellite measurements of sea surface temperature through clouds, *Science* 288(5467):847-850, 2000.

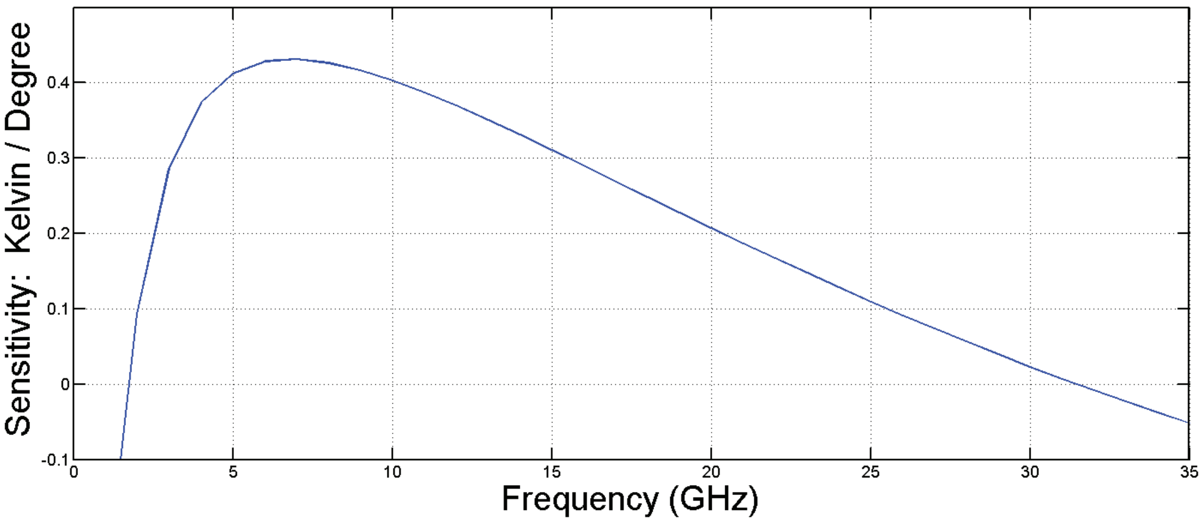

FIGURE 3.14 Sensitivity of brightness temperature to physical temperature (nadir and sea surface salinity = 30 psu). SOURCE: Courtesy of David Le Vine, NASA Goddard Space Flight Center.

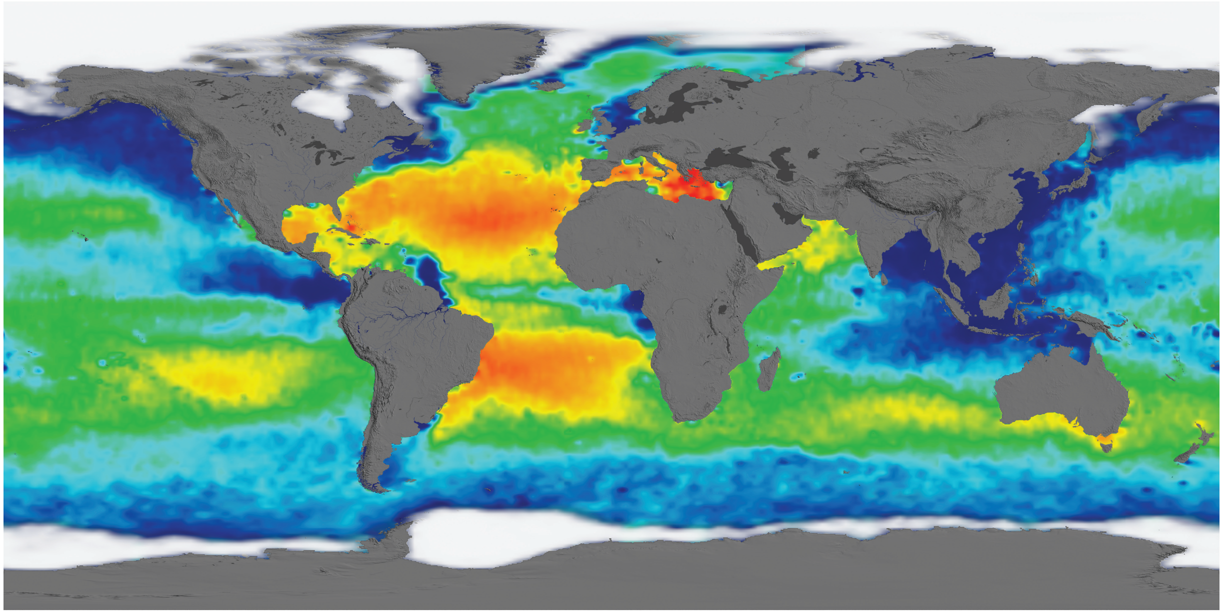

FIGURE 3.15 Remote sensing of sea surface salinity is important to improve understanding of ocean circulation and the global water cycle, and their role in climate and climate change. This image is an example of data produced by Aquarius. It shows the general features of the distribution of ocean salinity (e.g., saltier Atlantic than Pacific; and salty mid-latitudes separated by fresher water created by rain in the tropics). However, the maps are produced weekly and also show the dynamics of the salinity field including short-term changes associated with river runoff and longer term effects (e.g., seasonal and inter-annual) associated with the evolution of the mean field. SOURCE: Courtesy of the Aquarius Project; see NASA Aquarius, “Climatology Maps of Aquarius Data (V.4.0),” Gallery: Climatology, http://aquarius.umaine.edu/cgi/gal_climatology.htm.

boundary conditions for understanding ocean-atmosphere coupling. Changes in salinity in the northern latitudes (e.g., Labrador Sea and Irminger Sea) are indications of freshwater input from melting ice and can be an indicator of climate change. As important as salinity is to ocean dynamics, it is relatively poorly measured. Historically, it has been measured by ships and more recently by a system of floats and buoys (e.g., Argo floats). However, even thousands of point measurements provide poor sampling of the spatial and temporal variations in the vast oceans.

Surface salinity can be measured remotely from space by detecting changes in the natural (i.e., thermal) emission from the surface. The conductivity of seawater depends on the salt content, which changes the dielectric constant and emissivity at the surface (salty water has a higher conductivity and lower emissivity). The change is small (about 0.5 K/psu at 1.4 GHz) but is detectable with modern microwave radiometers. One issue for remote sensing is that the sensitivity is frequency dependent and decreases very rapidly (Figure 3.16). Antenna size and the ionosphere limit measurements to frequencies above about 1 GHz, and the sensitivity is too low above 2-3 GHz. Without the protected spectral window at 1.413 GHz and its radiometers, this measurement would not be practical.

Another important issue is surface roughness (waves). Wind-driven waves can cause a change in emission almost as large as that due to changes in salinity. As a result sensors such as Aquarius that are designed to monitor surface salinity globally from space, include a radar (scatterometer) to help correct for roughness. The Aquarius scatterometer operated at 1.26 GHz in a shared band is an example of combined active/passive microwave remote sensing.[6] Data from both sensors are needed for an accurate measurement.

Measuring sea surface salinity also depends on ancillary information such as surface temperature, atmospheric attenuation, and knowledge of radiation from other sources (e.g., the Sun and galactic background) that are also products of microwave remote sensing and other scientific applications requiring noise-free access to the spectrum. To make these measurements (i.e., SST) requires a sensor with bands at 6.8, 10.65, 18.70, 23.80, and 36.50 (e.g., AMSR).

3.5.3 Sea Surface Winds

Winds at the ocean surface are important for weather forecasts, such as monitoring and developing warnings for storms and to provide boundary conditions in numerical weather forecast models. Information on surface winds is also used in operational applications such as predicting sea state, routing of ships, tracking buoys, and supporting ocean-based defense operations (navy operations).

Surface winds can be monitored with passive microwave instruments because of the coupling of winds to waves and the effect of waves on the emissivity of the surface. In the microwave spectrum the sensitivity to surface roughness increases with frequency until about 10 GHz, after which it is roughly constant. Passive measurement of surface winds generally requires several frequencies. For example, Windsat uses channels at 6.8, 10.7, 18.7, 23.8, and 37.0 GHz. The channel at 6.8 GHz helps to mitigate the effects of SST, and the channels at 18.7 and 23.8 GHz to help correct for attenuation in atmosphere. Instruments scanning in azimuthal directions can also provide wind direction because of differences in along-wind and crosswind emissivity and dependence on polarization.

Surface winds can also be monitored with active microwave instruments. Backscatter from instruments such as NSCAT, QuickSCAT, and RapidSCAT, which operate near 13.5 GHz, responds to surface roughness and, by looking in multiple directions, produce wind speed and direction. Winds have also been retrieved successfully with scatterometers operating at L-band (1.26 GHz). Active/passive combinations

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[6] For technical information on EESS for measuring ocean salinity, see the following: D.M. Le Vine, G.S.E. Lagerloef, and S. Torrusio, Aquarius and remote sensing of sea surface salinity from space, *Proceedings of the IEEE* 98(5):688-703, 2010.

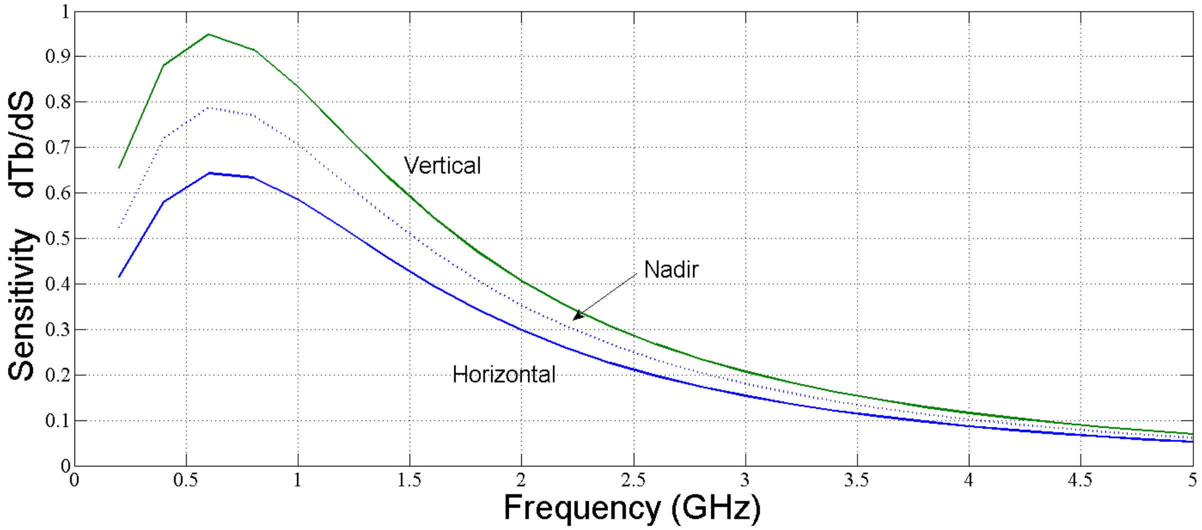

FIGURE 3.16 The sensitivity of brightness temperature of an ideal ocean surface (no waves) to changes in salinity as a function of frequency for nadir (broken curve) and at 40 degrees (solid curves). The calculations are for a surface with sea surface salinity = 35 psu and sea surface temperature = 20°C. SOURCE: Courtesy of David Le Vine, NASA Goddard Space Flight Center.

have also been employed (e.g., Aquarius and SMAP) where the radar (1.26 GHz) provides a correction for roughness and an independent estimate roughness or winds needed by the passive sensor (1.41 GHz).

Both active (radar) and passive (radiometer) measurements require highly sensitive instruments operating in a noise-free environment. However, the bands available are generally shared with other services (e.g., the radar band at 1.26 GHz).

3.5.4 Sea Topography

Details of the surface of the ocean provide information for several important ocean, weather, and climate applications. For example, roughness is related to sea state and surface winds. Sea level (e.g., height and topography) changes with water temperature, and variations in sea level provide estimates of the upper-level heat content. Water velocity is also related to surface height (geostrophic current), and maps of the surface topography can be used to study ocean circulation.

Microwave radar altimeters in orbit are used to provide global maps of the ocean surface to support these applications. The altimeter is essentially a short-pulse, nadir-looking radar. By looking at the shape of the returned signal and the travel time, it is possible to infer information about the sea surface topography (e.g., height and roughness). Radar altimeters have been operating in space since the early 1990s including Topex/Poseidon, Jason-1, and the Ocean Surface Topography Mission (OSTM) on Jason-2. These instruments operate at 13.6 GHz with a channel at 5.3 GHz and also include a radiometer to help correct for path delay. Typically, radiometer channels are at 18.7, 23.8, and 34.0 GHz. After 20 years of experience in orbit, the modern science objectives for spaceborne altimetry are impressive:

- Estimates of the transport of heat, water mass, nutrients, and salt by the oceans;
- Increased understanding of ocean circulation and how it changes with time;

- Estimates of significant wave height and wind speed;
- Improved knowledge of ocean tides and open-ocean tide models;
- Improved forecasting of climatic events like El Niño;
- Improved understanding of the variation of global mean sea level and its relation to global and climate change.

The radar altimeter also has potential for applications over land, for example in monitoring changes in ice cover and mapping properties of the surface. But the measurements require high accuracy and operating in shared and/or partially protected frequency bands raises the problem of interference.

3.6 SOLID EARTH AND BIOSPHERE

The science of the solid Earth and biosphere covers a variety of applications related to Earth's surfaces and those systems that inhabit it. For these applications the RF spectrum is used either passively, to observe variations in black body radiation and target emissivity (whose signature is regulated by moisture content), or actively, which allows for measures of relative reflected power, signal phase, and time of flight to be made and related to physical characteristics of the target.

In many of these applications, access to specific frequencies is less important than having some degree of frequency (and wavelength) diversity because remote sensing of terrestrial targets is most sensitive to the target's broad structural and shape characteristics, as well as dielectric and surface roughness contrasts with respect to surrounding areas. In all, the sensitivity to these characteristics is maximized when the physical scale of the variations is similar to the observing wavelength.

For active systems, bandwidth is used to better determine the target range. RFI-free bandwidths permit passive systems to achieve a more accurate thermal/emissivity signature for the target being observed.

Because of the non-frequency specific nature of the described applications, RF spectrum requirements occur at octave-level intervals. Historically, such spectrum, often coincident with atmospheric windows, has been available for these systems The frequencies where most solid Earth and biosphere measurements are obtained are listed in Table 3.3.

The long history of observations made in these bands allows the temporal evolution of the phenomena to be observed. Observation systems themselves have also benefited from historical resources,

TABLE 3.3 Frequencies Where Most of the Active Science-Application Systems Operate for Studying the Solid Earth and Biosphere

Band Designation	Passive Spectra	Active Spectra	Role
P-band		432-438 MHz	Biomass imaging, root zone soil moisture, below-canopy surface topography
L-band	1.42 GHz	1215-1300 MHz	Biomass imaging, forest change detection, surface motion and subsidence
S-band		3100-3300 MHz	Agricultural monitoring
C-band		5250-5570 MHz	Agricultural monitoring, surface change detection
X-band		8550-8650 MHz, 9300-9900 MHz	Vegetation and elevation mapping
Ka-band		35.5-36 GHz	Surface water and elevation mapping

such as standardized parts and existing infrastructure. The development of technology and observational capabilities in these areas relies on a stable and predictable RF spectral environment.

A more in-depth discussion for three areas of solid Earth and the biosphere is presented below: (1) surface dynamics and deformation, (2) agricultural productivity, and (3) terrestrial carbon storage. Indeed, there are many more applications than this short list can provide, or that can be discussed in the space provided here. In each however, the use of the RF spectrum is often divided up into active and passive applications, the details of which are related to the configuration of the sensing system and the physics of the electromagnetic interaction that is being exploited to extract physical parameters of interest.

3.6.1 Surface Dynamics and Deformation

Earth's solid surface is often undergoing change. This change occurs through incremental events, such as land subsidence and soil erosion/deposition, or changes driven by drastic and short-lived events such as earthquakes, volcanic eruptions, and landslides.[7]

The types of remote sensing that are applied to these types of changes often make use of the coherent nature of electromagnetic signals, especially in the microwave region extending on the low-frequency radar side from L-band up to X-band. In this context, low-frequency signals have the advantage of penetrating through ground cover and reflecting primarily from the solid surface, whereas higher frequency signals have the advantage of increased sensitivity to change, because of the wavelength-dependent nature for the coherent detection of this change. At the low-frequency extreme of observation (e.g., P-band), the interaction of the ionosphere with the signal causes variations in the signal phase that can be difficult to extract from the desired surface deformation signature. At the higher frequency extremes, X-band and above, physical changes in the surface geometry on the order of a wavelength and electromagnetic characteristics (e.g., dielectric changes) will cause the signal to decorrelate over time, and similarly obscure the sought-after deformation signature.

Airborne and especially spaceborne remote sensing play a role in solid Earth science because of their ability to make repeated measurements over long time periods. Often these measurements are made in the high-resolution configuration of SAR, which allows for three-dimensional maps to be made of the deformation. The resolution of SAR systems is dictated by the signal bandwidth (typically on the range of 10 MHz to 100 MHz) and the size of the antenna aperture in the along-track direction of the flight platform. If interference occurs in this bandwidth, then it can be dealt with through filtering of the signal in the frequency domain. However, because of the high sensitivity of deformation measurements to signal phase, the implementation of these filters has a deleterious effect on the deformation measure, and for that reason, notch-filters (those with a steep frequency response) are generally avoided.

3.6.2 Agricultural Productivity

Agricultural production is important for human health and safety. Agricultural productivity changes from year to year as the local environment changes and in response to government policies, so it is important to track these changes. While much of this monitoring takes place through direct interaction between the sources of production and government organizations such as the U.S. Department of Agri-

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[7] For background regarding EESS in understanding surface dynamics and deformation, see the following: D. Massonnet and K.L. Feigl, Radar interferometry and its application to changes in the Earth's surface, *Reviews of Geophysics* 36(4):441-500, 1998.

culture, the factors governing production, such as soil moisture and water availability, and the outputs of the production as they manifest themselves in crop health monitoring, are important components as well.

Both passive and active remote sensing are used in this context for monitoring changes in soil moisture and groundcover. Employing passive remote sensing to measure soil moisture requires the use of C-band frequencies and below in order for the signal to penetrate through the crop and directly sense the soil surface. Measurements such as these, made from either spaceborne or airborne platforms, use real-aperture antennas and have resolutions ranging from tens of meters up to tens of kilometers. For this reason, moisture measurements are made over large regions, consisting of many crops and land management practices.

Active remote sensing of agriculture crops makes use of the improved resolution (along- and cross-track) that these systems can achieve with an active signal.[8] High-frequency observations (e.g., X-band), sensitive to small plant structures and the upper part of an agricultural canopy, are important for monitoring early growth and estimating water resources available to the sun-gathering components of the canopy. Lower frequency signals (C-, S-, and L-band) are used for estimating bulk characteristics of the canopy. Calibrated ratios of power between these frequencies (which differentiate crop type and crop density) are important factors in estimating crop yield and for detecting the early detection of crop disease and drought. The lowest frequency observations of crops (L- or P-band), when combined with estimates of surface roughness, canopy height, and time-series measurements, can be used for making high-resolution estimates of soil moisture, an important component in overall crop health. Thus, because farming practices vary widely around the world, these applications benefit greatly from high-bandwidth and high-resolution observations.

3.6.3 Terrestrial Carbon Storage

Earth's vegetation canopy, or biomass, is a significant component of the global carbon inventory and a source of its greatest uncertainty. It is also a major contributor to the net long-wave/short-wave albedo of the planet and hence to Earth's energy balance and temperature. For these reasons, climate change can both be affected by and can itself affect the global distribution of biomass.

The ability to perform comprehensive inventories of biomass from space is recognized as a critical step toward modeling and understanding Earth's climate system. Passive microwave observations operating in all of the primary atmospheric window channels between 1.4 and 90 GHz are valuable for monitoring the full range of vegetation canopy water content found in nature and are complementary to optical and synthetic aperture radar techniques. Improved techniques for biomass estimation using passive microwave methods are continuously being developed (Figure 3.17).

Active sensing of the vegetation canopy makes use of the volume scattering component of the canopy and is used as a signature for the height of the canopy and to estimate the amount of aboveground biomass stored in the vegetation.[9] Such measures are important for characterizing animal and plant habitats, for detecting natural or manmade changes in the land cover, and for better understanding the global carbon budget.

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[8] For background in active EESS in agricultural monitoring, see the following: J.M. Lopez-Sanchez and J.D. Ballester-Berman, Potentials of polarimetric SAR interferometry for agriculture monitoring, *Radiation Science* 44, 2010; H. McNairn and B. Brisco, The application of C-band polarimetric SAR for agriculture: A review, *Canadian Journal of Remote Sensing* 30(3):525-542, 2004.

[9] For background on active EESS for forest studies, see the following: R. Ahmed, P. Siqueira, S. Hensley, B. Chapman, and K. Bergen. A survey of temporal decorrelation from spaceborne L-Band repeat-pass InSAR, *Remote Sensing of Environment* 115(11):2887-2896, 2011.

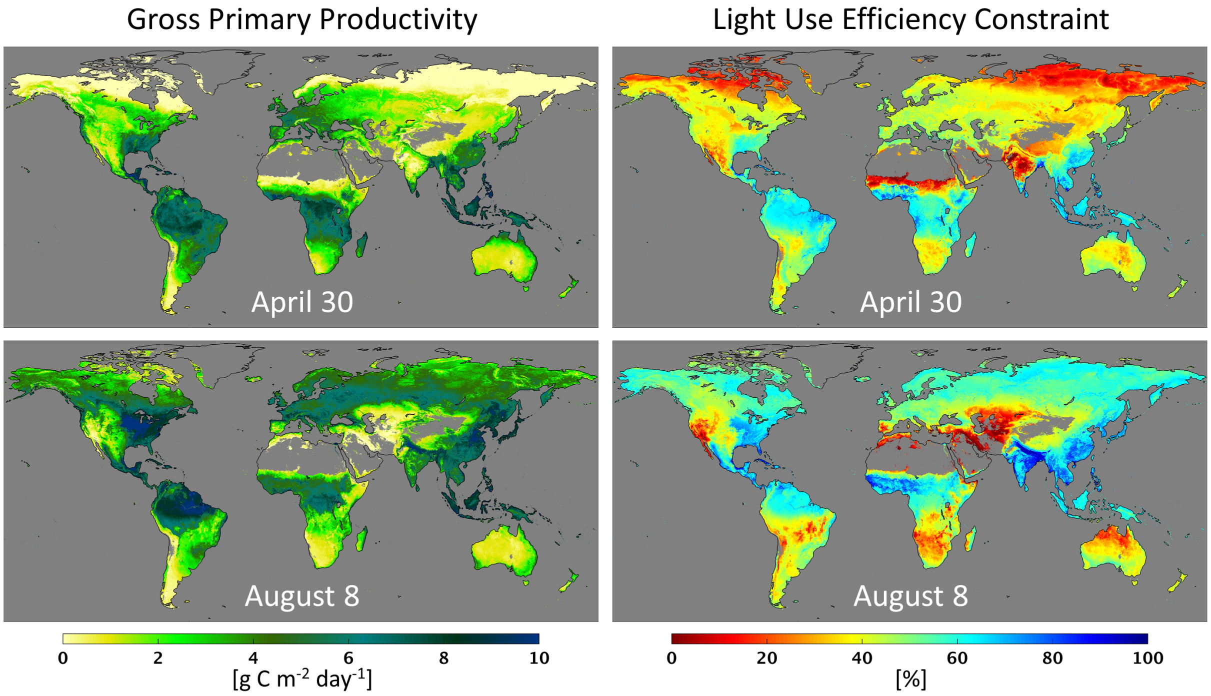

FIGURE 3.17 Vegetation gross primary production (GPP, g C m^{-2} day^{-1}) and the proportion (%) of estimated daily GPP to potential growth from the NASA SMAP (Soil Moisture Active Passive) mission Level 4 Carbon (L4_C) product; GPP defines the photosynthetic rate of green plants and conversion of atmosphere carbon dioxide (CO_2) to plant biomass, including forest, rangeland, and agricultural productivity. The proportional reduction in daily GPP shows where environmental conditions are less than optimal for plant growth (including areas with frozen temperatures and low soil moisture levels determined from SMAP active and passive microwave remote sensing; observed GPP reduction map ranges from optimal (100%) to fully constrained (0%) growth conditions). The L4_C results are shown for April 13 and May 25, 2015, and capture the northerly migration of spring green-up and associated onset of the growing season across the Northern Hemisphere; the onset of GPP in spring coincides with a seasonal shift to favorable growth conditions from thawing temperatures and relatively abundant soil moisture conditions from April to May. Strong GPP reductions from potential growth conditions are also observed over many (red shaded) areas, including the African Sahel, northern India and southwest United States, stemming from regional drought. SOURCE: Courtesy of John Kimball and Lucas Jones, University of Montana.

The physical mechanisms for this active sensing typically take on one of three forms. These are (1) measure of the frequency-dependent radar backscattered power, (2) measure of the polarimetric scattering characteristics of the target, and (3) use of single- and repeat-pass SAR interferometry for determining the target volume scattering characteristics, which can be related to the vegetation height and vertical density profile. In all of these applications, the frequency determines the depth of penetration into the vegetation canopy; different frequencies (or wavelengths) are chosen such that they are primarily sensitive to the upper or lower parts of the vegetation layer. Frequencies that are of primary interest for this application range from P-band up to X-band. Multiple-frequency observations and their ratios are used to remove systematic variations that occur due to weather, moisture, and topographic conditions, and assess the underlying structural components of the vegetation that are of interest.

4

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

Unlike active users of the radio spectrum, the passive services do not interfere with other passive users and therefore can share spectrum efficiently with each other. However, as the passive services are dependent on the absence of transmissions, they cannot make their presence known to active users. Thus, they require negotiations to reserve those portions of the radio-frequency (RF) environment that are critical to their needs and to resolve conflicts when that spectrum is infringed upon by active services. As discussed in the previous chapters, frequency allocations for the passive services generally include allocations for specific molecular and atomic transitions, and allocations spaced approximately every octave for continuum and Earth observations. However, under the fast-paced development of technology and the subsequent increasing appetite for wireless communications and radio distancing devices that were once under only the purview of specialized sectors of commercial, government and academic institutions, the radio environment has become increasingly crowded. An example of this is the 2010 Presidential memorandum that directed the Secretary of Commerce, working through the National Telecommunications and Information Administration, to collaborate with the Federal Communications Commission (FCC) to make available a total of 500 MHz of federal and nonfederal spectrum over the next 10 years for mobile and fixed wireless broadband use. More recently, in 2012, the President's Council of Advisors on Science and Technology (PCAST) recommended that 1000 MHz of federal and non-federal spectrum be freed up over the next 10 years and shared with private industry in order to meet the country's needs for mobile and fixed wireless broadband access. This increase in use of the radio spectrum will likely be geographically diverse and less regulated compared to previous practice when broadcast installations were more specialized and access to the spectrum more tightly controlled. Hence, the effects of RF interference (RFI) on the passive services will likely increase in the upcoming decade thus creating new challenges and hopefully offering new solutions for addressing this changing landscape.

Radio spectrum usage can act as a zero-sum game: use by one application can exclude use by another. The key issue in allocation and use is to avoid this conundrum and to find balance by utilizing the best tools at hand to maximize the benefits of spectrum use. The suite of tools can be very different in different parts of the spectrum, and will change as time goes on and as technology changes.

Early documentation of the negative consequences of radio interference to the passive use of the radio spectrum for radio astronomy was performed 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 (05/03), *Protection Criteria for Radioastronomical Measurements*,[2] which provides recommendations and guidelines on protection of the spectrum for radio astronomical measurements. Protections such as these are increasingly important as airborne-, ground-, and space-based use of the RF spectrum increase and as the potential for aggregate interference increases due to the proliferation of electronic devices.

4.1 RADIO-FREQUENCY INTERFERENCE

4.1.1 Radio Astronomy Considerations

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:

- *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 editing 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 $\lambda^2/4\pi$,

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[1] The CCIR has 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,* Volume IV, Geneva, 1963, 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* 43(5):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* 44(3):540-548, 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* 44(7, Pt. 2):1974-1985.

[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). Because 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 F 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.

where λ is the wavelength. The choice of the 0 dBi level is discussed in Chapter 4 of the *ITU Handbook on Radio Astronomy* (2013 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.[6] 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. Both criteria must be met, unless the band is designated exclusively for either continuum or spectral line use. 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 Section 4.3.5. However, such instruments are not suitable for observations 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 Considerations

In contrast to radio telescopes that point from Earth to space, Earth Exploration Satellite Service (EESS) sensors point in the opposite direction, from space to Earth. Hence, radio sources on Earth, particularly those transmitting toward space, and which may be benign to radio astronomers, are typically incompatible with spaceborne EESS sensors. The rapid motion of satellite-based sensors through space for EESS remote sensing limits the integration time available for sensor measurements to seconds, compared with the longer integration times used by stationary radio telescopes. Hence when interference does occur to the sensor, it is more difficult to correct or compensate and so the data is often flagged simply as being lost.

Because Earth-observing satellite sensors typically point their antennas toward Earth's surface, they are also particularly sensitive to ground-based interference sources. While some of the effects of RFI can be improved through front-end filtering prior to amplification and higher gain antennas that are better able to geographically isolate interfering sources, fundamental limitations on satellite resources such as size, weight, and power make most of those solutions impractical to implement.

There are two basic levels of remote sensing that utilize the RF spectrum: (1) active remote sensing, which is typically associated with the use of radars that make use of the physics of microwave scattering to infer physical characteristics about the targets being imaged, and (2) passive remote sensing,

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[5] International Telecommunication Union, *ITU Handbook on Radio Astronomy,* 2nd ed., Geneva, Switzerland, 2013.

[6] Appendices 3 and 4 of the *ITU Handbook on Radio Astronomy* provide a useful guide on converting units used by radio astronomers to those used by others in the radio communications sector. The IUCAF (the Scientific Committee on Frequency Allocations for Radio Astronomy and Space Science) has available many useful lectures on these topics on its website at http://www.iucaf.org/.

which uses thermal emissions, radiative transfer theory, and models for the scattering albedo and surface emissivity to infer dielectric and emission properties of the natural environment.

While both of these remote sensing applications are vulnerable to RFI, the passive remote sensing measurements are more 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 provides the interference criteria that are compatible with those performance objectives by defining the maximum permissible interference level within a reference bandwidth that 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 EESS sensor data should exceed 95 percent from all locations in the sensor service area in the case where the loss occurs randomly, and that it should 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 Section 3.1.1, "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, as are Earth-observing satellites that view geographic regions for only brief periods of time as the satellite passes overhead. In radio astronomy, 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.[7] Nontransient observations can be interfered with by intermodulation and harmonic 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

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[7] See S.W. Ellingson and G.A. Hampson, Mitigation of radar interference in L-band radio astronomy, *Astrophysical Journal Supplement Series* 147(1):167-176, 2003.

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* (2013 edition).

Interference from satellites in GEO presents a special problem, because a constellation of interfering satellites distributed along the orbit could preclude science 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.611). 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* (2013 edition).

Examples of interference from non-geostationary orbit satellites (non-GSO) can be found with the 24 satellite Russian Global Navigation Satellite System (GLONASS; 1602.5625-1615.5 MHz) and the 66 satellite Iridium constellation (1618.25-1626.5 MHz) that interfere with Radio Astronomy Service (RAS) operations in the 1610.6-1613.8 MHz and 1660-1670 MHz bands. Interferences of this type have been due to out of band emissions from lack of pulse shaping, poor control of modulation sidelobes in the frequency domain, and intermodulation products generated on the satellite caused by driving the transmitter amplifiers into compression in order to improve on efficiency. Because of their constant motion, constellations of non-GSO satellites such as these have the potential for being particularly disruptive to the passive services because of their constantly changing configuration and their near-constant coverage of Earth's surface.

In the case of GLONASS, improvements have been made by no longer launching spacecraft with frequency capacity higher than 1610 MHz, and those that do launch, all are equipped with out-of-band filters. As such, after 1999, the out-of-band emissions from GLONASS in the 1612 MHz radio astronomy band have been eliminated. Unfortunately, this cannot be said of the Iridium system.

4.1.4 Percentage of Time Lost to Interference

Recognizing that interference to radio astronomy is difficult to avoid at all times (see Figure 4.1), the ITU recommends that the fraction of time during which transmissions from any one service into a

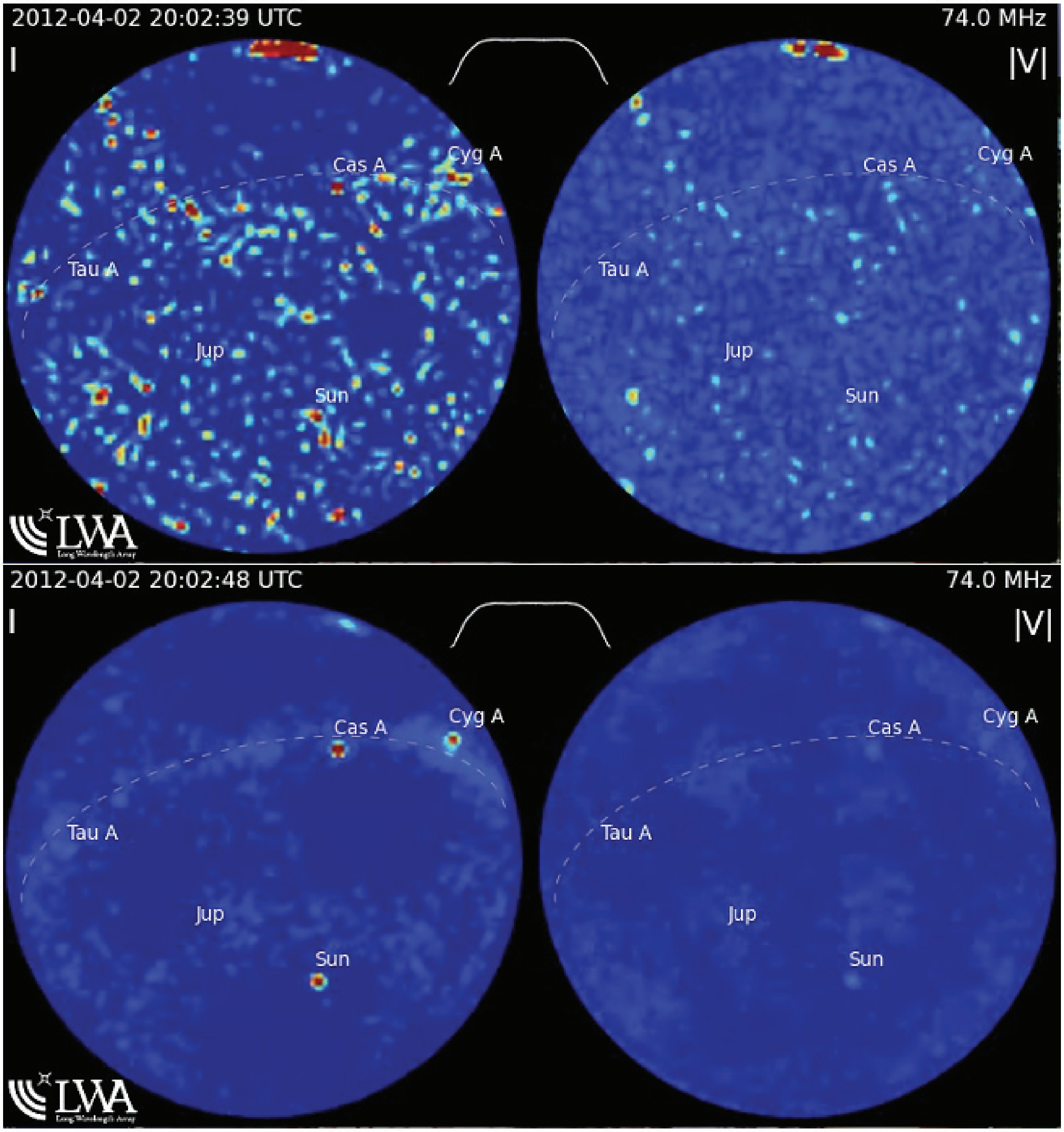

FIGURE 4.1 Illustration of the effects of radio frequency interference (RFI) on a Radio Astronomy Service (RAS) VHF passive-only band taken by the Long Wavelength Array (LWA1; Taylor et al., 2012). Shown above are two pairs of images taken 10 seconds apart. Each row shows the radiometric intensity, I (*left*), and absolute circular polarization, |V| (*right*), for a part of the celestial sky that includes the Sun and Cas A, two very strong radio sources. As can be seen in the time stamp of the images in their upper left-hand corner, the top row of images was collected just 10 seconds prior to the bottom row. Effects of RFI in the protected RAS band from 73.0-74.6 MHz on the 100 kHz bandwidth images shown in the top row (centered at 74.0 MHz) completely obscure the strongest astronomical sources seen in the image, which are clearly visible in the bottom row. SOURCE: Courtesy of Greg Taylor and the Long Wavelength Array.

radio astronomy band exceeding 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.

While these time restrictions are useful for fixed installations such as radio astronomical observatories, they are less useful for EESS radiometric observations, which have a strict linkage between the geographic-temporal aspects of coverage due to the fundamental mechanics of satellite orbits. Such sources of RFI can be particularly problematic because the antennas of the Earth-observing satellites are pointed such that maximum gain is obtained from Earth's surface, and hence, ground-based sources of interference will have a maximal impact on the satellite instrument during the time that it is observing the geographic region where the interferer is located (Figure 4.2)

4.2 SEPARATION OF INCOMPATIBLE SERVICES

Several techniques enable active and passive users of the radio spectrum to share this limited resource. First, multiple users may share the same spectral allocation provided that they are spatially located at a sufficient distance, or with sufficient blockage (e.g., mountains), such that the line-of-sight propagation falls below threshold limits. Second, spectral allocations can recognize the incompatible nature of the various services and designate some spectral regions as protected for passive service use only. Finally, multiple users may effectively share the same spectral allocation if none need to use it continuously and all are able to coordinate the use of the spectral allocation based on local demand. Thus, while sharing of the radio spectrum is often considered a zero sum game, where use by one service excludes use by another, effective spectrum management includes consideration of location and time, as well as the specific spectral allocation.

4.2.1 Geographic 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. Earth stations in both EESS and Space Research Service receive weak signals: EESS from Earth-orbiting satellites and the deep space network from interplanetary spacecraft with extremely low signal levels. An important degree of protection from ground-based transmitters can be obtained by choosing observatory sites and Earth stations 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 difficult 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 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.

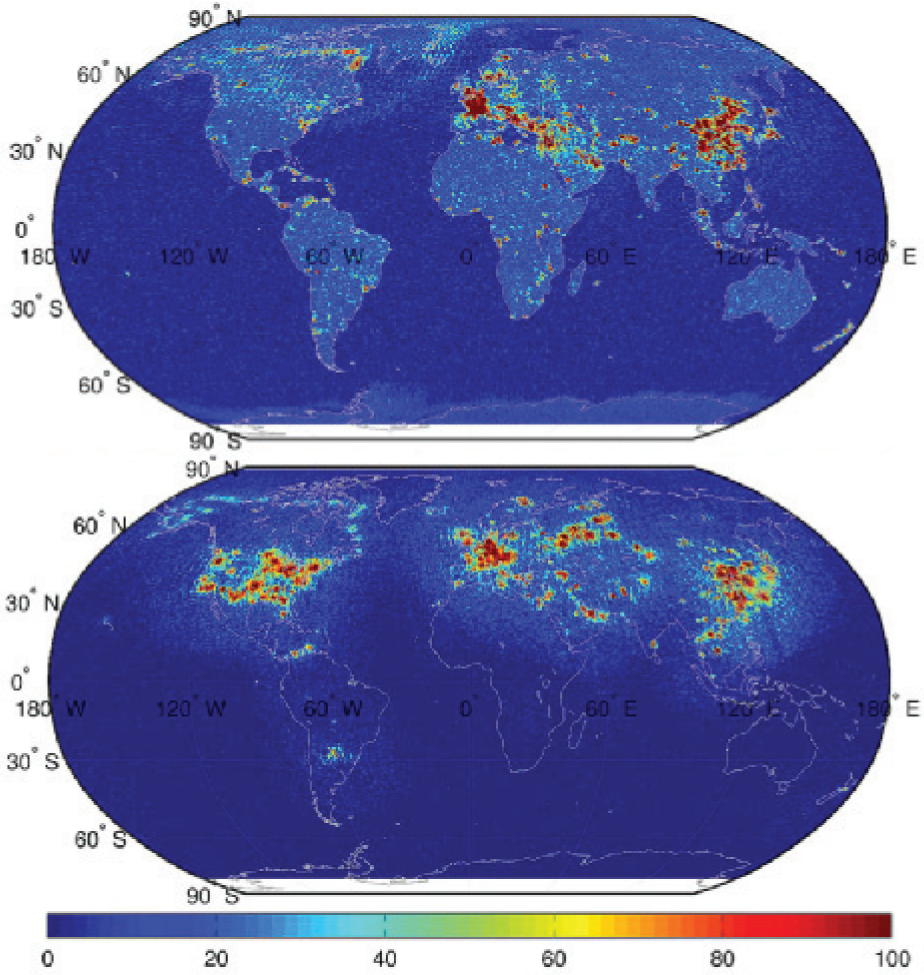

FIGURE 4.2 Percentage of radio frequency interference (RFI)-flagged samples in the passive and active bands of the radio spectrum. The top image shows the passive part of the spectrum between 1400-1427 MHz, which is a protected passive band. The lower image is collected at 1.26 GHz and shows the effects of ground-based radar stations on the observations. Ground-based RFI such as that shown here cause a degradation or loss of data that are important for weather, food security, and climate-prediction models that are supported by the Earth Exploration Satellite Service. SOURCE: Data shown above are from NASA's Aquarius satellite, launched in 2011. Image courtesy of David LeVine, NASA Goddard Space Flight Center.

Defining the boundaries of a zone requires knowledge of the radiated powers in the direction of the observatory or Earth station and a determination of the transmission loss in various directions with respect to the observatory or Earth station. The transmission loss for propagation over terrain is calculable from terrain profiles. Major observatories and Earth stations 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 or Earth station 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

BOX 4.1
Footnote US385

US385 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, and in the band 2655-2690 MHz on a secondary 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 and 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 miles) radius centered on:

	Latitude (North)	Longitude (West)
Brewster, WA	48° 08′	119° 41′
Fort Davis, TX	30° 38′	103° 57′
Hancock, NH	42° 56′	71° 59′
Kitt Peak, AZ	31° 57′	111° 37′
Los Alamos, NM	35° 47′	106° 15′
Mauna Kea, HI	19° 48′	155° 27′
North Liberty, IA	41° 46′	91° 34′
Owens Valley, CA	37° 14′	118° 17′
Pie Town, NM	34° 18′	108° 07′
Saint Croix, VI	17° 45′	64° 35′

Owens Valley Radio Observatory, Big Pine, California: Two contiguous rectangles, one 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, May 2015.

zone, then coordination between the transmitting service and the observatory/Earth station is required. Protection of the observatory or Earth station may be possible by various means, such as placing a null in the pattern of the transmitter in the direction of the observatory or Earth station or, if the allocated transmitter frequency is outside the radio astronomy band or spacecraft communication 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 of the passive 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.

The 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.

4.2.3 Temporal Separation

A third strategy for mitigating interference between active and passive users of the radio spectrum is with dynamic frequency allocations based on local demand. For example, with increasing demand for access to the radio spectra by commercial services (e.g., the communications industry) and a freeing up of the part of the spectrum once occupied by analog broadcast television (from 470-790 MHz), there has been a significant degree of activity in finding innovative ways for better accessing the RF spectrum in order to allow autonomous users to make use of the spectrum without interfering with one another and in compliance with FCC regulations. One example of this type of activity is in the area of cognitive radios that are meant to sense the local radio environment and dynamically create a communication channel that does not interfere with other users in that part of the spectrum.

In order to make best use of the spectrum, cognitive radios and other users wishing to access radio frequencies require knowledge of all current users in the geographic area. The Internet provides a unique opportunity to serve as the information backbone that supports this increased efficiency. For example, the IEEE Geosciences and Remote Sensing Technical Committee on Frequency Allocations in Remote Sensing (FARS) has created a geographic database that can be accessed through the Internet that combines satellite observations of the RF spectrum with ITU and FCC regulations. Other efforts being encouraged by the FCC result in commercially run databases that dynamically map the TV white space spectrum and can be used by cognitive radios for improving communications performance. Taken to its logical extension, databases such as these will likely be combined in the future and cover the wider RF spectrum to provide an up-to-date picture of spectrum use and provide a mechanism for dynamically allocating licenses to use the spectrum in accordance with ITU and FCC regulations and on a non-interfering basis. Such a database will be useful for scientific, governmental, and commercial users of the spectrum because it will allow for a more flexible approach to accessing parts of the spectrum that have been nominally precluded from use because of more traditional methods for spectrum licensing.

4.3 MITIGATION TECHNIQUES FOR RADIO ASTRONOMY

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.[8] 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* (2013 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

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[8] See F.H. Briggs and J. Kocz, Overview of technical approaches to radio frequency interference mitigation, *Radio Science* 40(5), 2005, and other articles in this issue; S.W. Ellingson, RFI mitigation and the SKA, *Experimental Astronomy* 17(1-3):261-267, 2004; R. Weber, G. Hellbourg, C. Dumez-Viou, A.J. Boonstra, S. Torchinsky, C. Capdessus, and K. Abed-Meriam, RFI mitigation in radio astronomy: An overview, *Les Journees Scientifiques d'URSI-France L'electromagnetisme*, Paris, France, 2013.

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* (2013 edition), including calculations based on these limits as applied to non-GSO and GEO satellites.

4.3.1 Advanced Modulation

A basic modulation scheme used in communications is digital phase-shift keying. In its simplest implementation, the power spectrum is in the form of $[\sin(\pi\Delta f)/\pi\Delta f]^2$, where Δf 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 Δf. For many years these sidelobes in GLONASS (Section 4.1.3) caused serious interference to observations in the 1610.6-1613.8 MHz and 1660-1670 MHz radio astronomy bands. 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, 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. Because 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 that 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 geographically distributed 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* (2013 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, because the fringe periods decrease. As the interference response is decreased, the corresponding detrimental threshold is increased.

For example, for the 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 the 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 the 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) and as the frequency goes down.

4.4 MITIGATION TECHNIQUES FOR PASSIVE REMOTE SENSING

Increased occurrences of 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. Like RAS, passive remote sensing is also effected by out-of-band emission (as discussed in Section 4.3). Most satellite-based remote sensing applications are not stationary however and hence do not observe a fixed geographic region for extended periods of time. For this reason there is more tolerance for interferers in EESS than RAS, but the geographic reach of these sensors is global (or nearly so) by design and therefore the effect of OOBE and other sources of interference must be controlled over much larger geographic areas.

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. Over the oceans, the ITU recognizes the passive microwave EESS usage between 6.425 and 7.075 GHz through Radio Regulation 5.458, but offers no formal protection other than asking administrations to keep the EESS needs in mind.

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, then the input can be effectively blanked during the pulse period with little impact to the radiometric sensitivity and accuracy. It should be noted however that narrow-band interfering signals will be broad in time, and thus are difficult to remove using this technique.

4.5 GOALS FOR ADDITIONAL PROTECTION

4.5.1 Bandwidths

In general, a 1 to 2 percent bandwidth (which is the norm for most RAS allocations) is the minimum practical allocation for passive use, as dictated by the ability to filter OOBE from the receiver front-ends. However, given the impracticality of implementing narrowband filters that provide high transmission and significant out-of-band suppression, such as superconducting filters, a 5 percent bandwidth is preferred for the continuum bands. This need is strongly reinforced by the new and rapidly increasing requirements for bandwidth allocation at all frequencies, and it addresses interference 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 Milky Way 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.

In addition, access to bandwidths much greater than the FCC-allocated bands are needed to exploit the capabilities of modern radio telescopes for both continuum and spectral line observations. At UHF and higher frequencies, propagation is limited to only a few multiples of the line of sight distance. Because radio telescopes are generally located in remote areas and are somewhat shielded by the surrounding terrain from ground-based RFI, protection to the RAS while needed over very broad bands, is only necessary for relatively small geographic areas surrounding each operational radio telescope. While radio astronomy needs protection over large segments of the radio spectrum, some degree of time sharing with active users, enabled by the Internet and dynamic frequency allocation, may be possible to make more efficient use of the overall spectrum (See Section 4.2). The problem is similar for EESS, although the requirements for sharing are different. In particular, Earth-viewing sensors in low Earth orbits map the entire globe, but may need only a few seconds of spectrum every other day for a given location. EESS sensors in geostationary orbit view the same area on the surface continuously, and time-sharing may not be feasible. Thus, while reserved frequency allocations are still a critical component for scientific use of the radio spectrum, where shared use of the spectrum is necessary, additional approaches must be considered.

4.5.2 Unwanted Emissions

The EESS and RAS 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.[9] Passive services are particularly sensitive to spurious, out-of-band, and harmonic emissions from other services. “Guard bands” proportional to frequency (or fractional bandwidth specified) should be maintained around the passive and shared bands, prohibiting services with an inherent inability to adequately filter transmissions from leaking into adjacent bands. 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 RAS and EESS. This is particularly the case with airborne and satellite transmitters because of the potential clear line of sight between a passive user and unlicensed devices. As technology

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

improves, new applications in RAS and EESS will require lower noise floors and will benefit from new and wider bandwidth, which could be made available by improved rules for sharing.

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 molecular weight 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 the detection of a number of radio lines.

EESS environmental products (e.g., temperature and atmospheric pressure profiles) derived from passive radiometry would benefit from additional frequencies in the millimeter-wave bands. Specifically, additional allocations in the millimeter-band will permit multi-band passive radiometry to probe different depths of the atmosphere because of the varying penetration depths. Consequently, observations are desired either in, or adjacent to, bands allocated to other services. If unwanted emissions are minimized, the new science will be enabled.

At the other extreme of the frequency spectrum, the European Space Agency (ESA) is planning to launch the BIOMASS mission (432-438 MHz) in 2020 to map the biomass and carbon stored in the world's forests. The longer wavelength at this frequency allows for better penetration into the vegetation canopy and hence a means for estimating the total forest volume. Because Europe and North America operate a missile warning and space-surveillance system in this band, this $500 million mission will not collect data in this part of the world. If some coordination between the satellite and these systems were possible, even on a very limited basis during the brief overpass of the satellite over these installations, then new observations over these geographic regions will be possible.

4.5.4 Dynamic Scheduling and Access Coordination

Although the advance of technology and widespread use of the spectrum has created challenges for passive users, it offers the potential to solve long-term RFI issues. The telecommunications industry and the FCC have been experimenting with dynamic allocation of bandwidth. In 2014, the FCC held a workshop on the Spectrum Access System, a pilot program where the spectrum at 3.5 GHz is dynamically scheduled based on priorities such as demand from primary and secondary users, geographic location, and transmitted power. A database of licensed use is maintained, and, at any given time, an unlicensed user may query the database and, if the band is unoccupied, may transmit in the band. The importance of this development cannot be understated, because it replaces the licensed use process, which has inherent inefficiencies—particularly regarding disputes between users—with one where permitted use is managed by software. Although this system is still in its infant stage and many important details need to be worked out, the potential to expand the use well beyond the 3.5 GHz band is intriguing. An observer wishing to utilize a previously unprotected band, could receive the required protection for the time needed to observe. Examples of this might include an observatory that wants to use a band dedicated to a space-Earth telecom service, or an EESS satellite that needs a clear band only when overhead. It is clear that this approach has the potential to revolutionize spectral access by taking advantage of the most important aspect of the spectrum as a resource—its nearly instantaneous renewability.

However, frequency coordination must take into account the rapid timescale at which radio telescopes operate. Most modern radio telescopes are equipped with multiple receivers and instruments, spanning a wide range of radio frequencies. In the cases of telescopes operating at higher frequencies where clear, dry skies under stable nighttime conditions may be required for highest quality data, observatories have been employing dynamic scheduling. This enables the use of the telescope under the best possible conditions for the frequency being observed. Because weather conditions may change rapidly, a telescope schedule may change rapidly to observing projects requiring stronger degrees of spectrum protection. Even when weather conditions are stable, instrument failures or newly discovered hazardous asteroids may motivate changes in set observing schedules.

An additional factor in time-sensitive spectrum use is the coordination of simultaneous observations between two or more facilities. Radar observations of the moon or near-Earth asteroids transmit a radar signal from one station and receive at another, a bistatic operation. Because radar signal returns decrease rapidly in strength with more distant objects, the receiving station is highly vulnerable to RFI. Coordination with spacecraft, for radio science investigations, space-to-ground bistatic experiments, or for detections of safe landings or homing signals, also requires very specific timing of observations. Similarly, VLBI observations use a variety of telescopes worldwide and require interference-free access to the radio spectrum at all locations simultaneously. Thus, dynamic scheduling and frequency coordination must take into account both the local spectral environment and also those of the associated facilities in order to enable productive scientific use of the radio spectrum.

5

Science Service Allocations

This chapter lists radio spectrum allocations for both passive and active science services described in Chapters 1, 2, and 3. For spectrum allocation purposes, the Radio Regulations of the International Telecommunication Union (ITU) divide the world into three regions, as shown in Figure 5.1. The United States (U.S.) is in Region 2. As of June 2015, the spectrum allocations are established only for frequencies below 275 GHz. Nonetheless, while no formal allocations are established above 275 GHz, the ITU Radio Regulation 5.565 urges administrations to take all practicable steps to protect passive services from harmful interference in the frequency range of 275-1000 GHz and states that 1000-3000 GHz may be used by both passive and active services.[1]

Frequency allocations and footnotes relevant to the science services in Radio Astronomy, Earth Exploration, Space Research and Operation, and Meteorological Aids and Satellite are listed in Table 5.1. The allocations presented in this chapter are based upon the Table of Frequency Allocations published by the U.S. Federal Communications Commission (FCC) on May 15, 2015, and codified at Section 2.106 of the Commission's Rules. Table 5.1 consists of the International Table of Frequency Allocations ("International Table") and the U.S. Table of Frequency Allocations ("United States Table"). The International Table is subdivided into allocations for the three regions (Columns 1, 2, and 3). The U.S. Table is subdivided into the allocations for federal government services (Column 4) established by the National Telecommunications and Information Administration (NTIA) and non-federal government services (Column 5) established by the FCC. Some of the pertinent rules or rule parts[2] for non-federal allocated services established by the FCC are provided in Column 6. In addition, Column 7 lists key areas of study enabled by the scientific services, along with corresponding section numbers from Chapters 1, 2, and 3 where these services are described in detail.

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[1] The full text of ITU Radio Regulation 5.565 is provided at the end of Table 5.1.

[2] A selected list of these rules and regulations that are particularly relevant to Radio Astronomy Service and Earth Exploration Satellite Service are given in Appendix G. The full rules and regulations 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 https://www.fcc.gov/encyclopedia/rules-regulations-title-47.

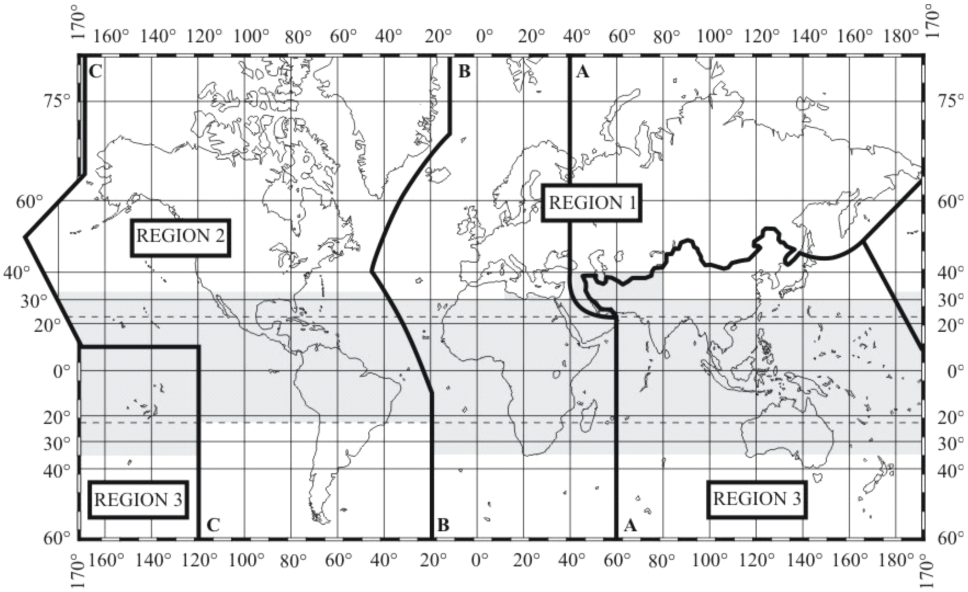

FIGURE 5.1 The regions in Article 5 of the Radio Regulations of the International Telecommunication Union. The shaded part represents the Tropical Zone. SOURCE: National Telecommunications and Information Administration, *Manual of Regulations and Procedures for Federal Radio Frequency Management* (Redbook), May 2013 edition, revised May 2014. See http://www.itu.int/ITU-R/ for more information.

Each row in Table 5.1 consists of the frequency range covered and the services allocated in that range. The table lists frequency ranges that are relevant to the science services and includes all other services that are allocated in those ranges. The services marked in all capital letters (such as "EARTH EXPLORATION SATELLITE") indicate a primary allocation, where entities properly authorized to operate in that service are entitled to protection from harmful interference from any other services in that frequency range. The services with the first letter capitalized (such as "Radio astronomy") indicate that the allocation is on a secondary basis. The ITU rules require that "*stations of secondary services*: *i) shall not cause harmful interference to stations of a primary service to which frequencies are already assigned or may be assigned at a later date; ii) cannot claim protection from harmful interference from stations of a primary service to which frequencies are already assigned or may be assigned at a later date; and iii) can claim protection, however, from harmful interference from stations of a same or other secondary service(s) to which frequencies may be assigned at a later date*." Along with the primary and secondary services, each row has numbers such as "5.340" in the International Table, indicating footnotes to the allocation table. If the footnote appears directly next to the service, then it applies only to that service. If it appears at the bottom of the row, then it applies to all the services in the frequency range. Footnotes are important and may place significant restrictions on specific services or provide for additional allocations in the frequency range. For example, in the International Table, footnote 5.340 provides exclusive protection for the passive services in several frequency ranges. In the U.S. Table, the footnotes are marked with prefixes such as "US," "NG," or "G," indicating applicability of the footnotes to both federal and non-federal operations, only to non-federal operations, or only to federal operations, respectively. All the footnotes relevant to the Radio Astronomy Service (RAS) and the Earth Exploration

Satellite Service (EESS) described in Chapters 2 and 3 are set in boldface. The frequency allocations that contain footnotes relevant to science services are explicitly marked as “Regulations relevant to science services” in Column 7. Full texts of all the footnotes used in the allocations table are reprinted from the FCC Table of Frequency Allocations and provided at the end of Table 5.1.

Any radio astronomy or Earth remote sensing station observing in a band in which RAS or EESS is allocated is urged to register its operations so that the regulator is aware of its presence and can provide interference protection. For RAS sites, registration is typically done through the National Science Foundation’s Electromagnetic Spectrum Management office; for EESS sites, registration is typically done through the NASA Space Communications and Navigation Directorate’s Spectrum Management office or the National Oceanic and Atmospheric Administration’s Radio Frequency Management Division.

Because regulations, allocations, and footnotes can change, the reader is advised to consult NTIA’s *Manual of Regulations and Procedures for Federal Radio Frequency Management* (Redbook) or the FCC’s *Online Table of Frequency Allocations*, the Radio Regulations, and the ITU Radiocommunication Sector (ITU-R) recommendations for the latest information. The Redbook can be found at http://www.ntia.doc.gov/osmhome/redbook/redbook.html, the FCC’s document can be found at http://www.fcc.gov/oet/spectrum/table/fcctable.pdf, and the ITU-R recommendations are at http://www.itu.int/opb/.

TABLE 5.1 Table of Frequency Allocations for the Scientific Services based on the FCC Online Table of Frequency Allocations, 47 C.F.R. Section 2.106, Revised on May 15, 2015

Table of Frequency Allocations	**0-137.8 kHz (VLF/LF)**					
International Table			**United States Table**		**FCC Rule Part(s)**	**Current Science Usage**
Region 1 Table	**Region 2 Table**	**Region 3 Table**	**Federal Table**	**Non-Federal Table**		
			Below 9 kHz (Not Allocated) 5.53 5.54			3.2.7 Ionosphere
8.3-9 kHz METEOROLOGICAL AIDS 5.54A 5.54B 5.54C						1.5.1 Meteorological aids service
9-11.3 kHz METEOROLOGICAL AIDS 5.54A RADIONAVIGATION			9-14 kHz RADIONAVIGATION US18 US2			1.5.1 Meteorological aids service
19.95-20.05 kHz STANDARD FREQUENCY AND TIME SIGNAL (20 kHz)			19.95-20.05 kHz STANDARD FREQUENCY AND TIME SIGNAL (20 kHz) US2			1.5.3 Standard Frequency and time signal-satellite service
20.05-70 kHz FIXED MARITIME MOBILE 5.57 5.56 5.58						
			59-61 kHz STANDARD FREQUENCY AND TIME SIGNAL (60 kHz) US2			1.5.3 Standard Frequency and time signal-satellite service

Table of Frequency Allocations	**1800-3230 kHz (MF/HF)**					
	2000-2065 kHz FIXED MOBILE		2000-2065 kHz FIXED MOBILE US340	2000-2065 kHz MARITIME MOBILE US340 NG7	Maritime (80) Private Land Mobile (90)	3.2.7 Ionosphere
2025-2045 kHz FIXED MOBILE except aeronautical mobile (R) Meteorological aids 5.104 5.92 5.103						1.5.1 Meteorological aids service 3.2.7 Ionosphere

	2495-2501 kHz STANDARD FREQUENCY AND TIME SIGNAL (2500 kHz)	2495-2505 kHz STANDARD FREQUENCY AND TIME SIGNAL (2500 kHz) US1 US340		1.5.2 Space research service 1.5.3 Standard Frequency and time signal-satellite service 3.2.7 Ionosphere
2498-2501 kHz STANDARD FREQUENCY AND TIME SIGNAL (2500 kHz)				1.5.3 Standard Frequency and time signal-satellite service 3.2.7 Ionosphere
2501-2502 kHz STANDARD FREQUENCY AND TIME SIGNAL Space research				1.5.2 Space research service 1.5.3 Standard Frequency and time signal-satellite service 3.2.7 Ionosphere
2502-2625 kHz FIXED MOBILE except aeronautical mobile (R) 5.92 5.103 5.114	2502-2505 kHz STANDARD FREQUENCY AND TIME SIGNAL			1.5.3 Standard Frequency and time signal-satellite service 3.2.7 Ionosphere

Table of Frequency Allocations	**3.23-5.9 MHz (HF)**					
			3.5-4 MHz US340	3.5-4 MHz AMATEUR US340	Amateur Radio (97)	3.2.7 Ionosphere
	3.75-4 MHz AMATEUR FIXED MOBILE except aeronautical mobile (R) 5.122 5.125					3.2.7 Ionosphere
3.95-4 MHz FIXED BROADCASTING		3.95-4 MHz FIXED BROADCASTING 5.126				1.5.3 Standard Frequency and time signal-satellite service 3.2.7 Ionosphere

Table of Frequency Allocations **3.23-5.9 MHz (HF)** ***continued***

International Table			United States Table		FCC Rule Part(s)	Current Science Usage
Region 1 Table	**Region 2 Table**	**Region 3 Table**	**Federal Table**	**Non-Federal Table**		
4.995-5.003 MHz STANDARD FREQUENCY AND TIME SIGNAL (5 MHz)			4.995-5.005 MHz STANDARD FREQUENCY AND TIME SIGNAL (5 MHz) US1 US340			1.5.3 Standard Frequency and time signal-satellite service 3.2.7 Ionosphere
5.003-5.005 MHz STANDARD FREQUENCY AND TIME SIGNAL Space research						1.5.2 Space research service 1.5.3 Standard Frequency and time signal-satellite service 3.2.7 Ionosphere

Table of Frequency Allocations **5.9-11.175 MHz (HF)**

9.995-10.003 MHz STANDARD FREQUENCY AND TIME SIGNAL (10 MHz) 5.111			9.995-10.005 MHz STANDARD FREQUENCY AND TIME SIGNAL (10 MHz) 5.111 US1 US340			1.5.2 Space research service 1.5.3 Standard Frequency and time signal-satellite service 3.2.7 Ionosphere
10.003-10.005 MHz STANDARD FREQUENCY AND TIME SIGNAL Space research 5.111						1.5.2 Space research service 1.5.3 Standard Frequency and time signal-satellite service 3.2.7 Ionosphere

Table of Frequency Allocations **11.175-15.1 MHz (HF)**

13.36-13.41 MHz FIXED RADIO ASTRONOMY **5.149**			13.36-13.41 MHz RADIO ASTRONOMY **US342** G115	13.36-13.41 MHz RADIO ASTRONOMY **US342**		2.2.1 Sun 2.2.5 Jupiter 2.3 Interstellar medium 2.4 Steep spectrum sources 3.2.7 Ionosphere
14.99-15.005 MHz STANDARD FREQUENCY AND TIME SIGNAL (15 MHz) 5.111			14.99-15.01 MHz STANDARD FREQUENCY AND TIME SIGNAL (15 MHz) 5.111 US1 US340			1.5.2 Space research service 1.5.3 Standard Frequency and time signal-satellite service 3.2.7 Ionosphere
15.005-15.01 MHz STANDARD FREQUENCY AND TIME SIGNAL Space research						1.5.2 Space research service 1.5.3 Standard Frequency and time signal-satellite service 3.2.7 Ionosphere

Table of Frequency Allocations	**15.1-22.855 MHz (HF)**		
	18.03-18.068 MHz FIXED US340	Maritime (80) Private Land Mobile (90)	3.2.7 Ionosphere
18.052-18.068 MHz FIXED Space research			1.5.2 Space research service 3.2.7 Ionosphere
19.99-19.995 MHz STANDARD FREQUENCY AND TIME SIGNAL Space research 5.111	19.99-20.01 MHz STANDARD FREQUENCY AND TIME SIGNAL (20 MHz) 5.111 US1 US340		1.5.2 Space research service 1.5.3 Standard Frequency and time signal-satellite service 3.2.7 Ionosphere
19.995-20.01 MHz STANDARD FREQUENCY AND TIME SIGNAL (20 MHz) 5.111			1.5.3 Standard Frequency and time signal-satellite service 3.2.7 Ionosphere

Table of Frequency Allocations	**22.855-27.41 MHz (HF)**		
24.99-25.005 MHz STANDARD FREQUENCY AND TIME SIGNAL (25 MHz)	24.99-25.01 MHz STANDARD FREQUENCY AND TIME SIGNAL (25 MHz) US1 US340		1.5.2 Space research service 1.5.3 Standard Frequency and time signal-satellite service 3.2.7 Ionosphere
25.005-25.01 MHz STANDARD FREQUENCY AND TIME SIGNAL Space research			1.5.2 Space research service 1.5.3 Standard Frequency and time signal-satellite service 3.2.7 Ionosphere
25.55-25.67 MHz RADIO ASTRONOMY **5.149**	25.55-25.67 MHz RADIO ASTRONOMY **US74** **US342**		2.2.1 Sun 2.2.5 Jupiter 2.3 Interstellar medium 2.4 Steep spectrum sources 2.3.7 Pulsars 3.2.7 Ionosphere

Table of Frequency Allocations	**27.41-42 MHz (HF/VHF)**			
	27.41-27.54 MHz US340	27.41-27.54 MHz FIXED LAND MOBILE US340	Private Land Mobile (90)	3.2.7 Ionosphere

Table of Frequency Allocations **27.41-42 MHz (HF/VHF)** ***continued***

International Table			United States Table		FCC Rule Part(s)	Current Science Usage
Region 1 Table	**Region 2 Table**	**Region 3 Table**	**Federal Table**	**Non-Federal Table**		
27.5-28 MHz METEOROLOGICAL AIDS FIXED MOBILE						1.5.1 Meteorological aids service 3.2.7 Ionosphere
			27.54-28 MHz FIXED MOBILE US298 US340	27.54-28 MHz US298 US340		3.2.7 Ionosphere
			30-30.56 MHz FIXED MOBILE			3.2.7 Ionosphere
30.005-30.01 MHz SPACE OPERATION (satellite identification) FIXED MOBILE SPACE RESEARCH						1.5.2 Space research service 3.2.7 Ionosphere
37.5-38.25 MHz FIXED MOBILE Radio astronomy **5.149**			37.5-38 MHz Radio astronomy **US342**	37.5-38 MHz LAND MOBILE Radio astronomy **US342** NG59 NG124	37-38 Private Land Mobile (90)	2.2.1 Sun 2.2.5 Jupiter 2.3 Interstellar medium 2.4 Steep spectrum sources 2.3.7 Pulsars 3.2.7 Ionosphere
			38-38.25 MHz FIXED MOBILE RADIO ASTRONOMY US81 **US342**	38-38.25 MHz RADIO ASTRONOMY US81 **US342**		2.2.1 Sun 2.2.5 Jupiter 2.3 Interstellar medium 2.4 Steep spectrum sources 2.3.7 Pulsars 3.2.7 Ionosphere
				39-40 MHz LAND MOBILE NG124	Private Land Mobile (90)	3.2.7 Ionosphere
39.986-40.02 MHz FIXED MOBILE Space research		39.986-40 MHz FIXED MOBILE RADIOLOCATION 5.132A Space research				1.5.2 Space research service 3.2.7 Ionosphere

		40-40.02 MHz FIXED MOBILE Space research	40-42 MHz FIXED MOBILE 5.150 US210	40-42 MHz 5.150 US210	ISM Equipment (18) Private Land Mobile (90)	1.5.2 Space research service 3.2.7 Ionosphere
40.98-41.015 MHz FIXED MOBILE Space research 5.160 5.161						1.5.2 Space research service 3.2.7 Ionosphere

Table of Frequency Allocations		**42-117.975 MHz (VHF)**				
				54-72 MHz BROADCASTING NG5 NG14 NG115 NG149	Broadcast Radio (TV)(73) LPTV, TV Translator/ Booster (74G) Low Power Auxiliary (74H)	3.2.7 Ionosphere
68-74.8 MHz FIXED MOBILE except aeronautical mobile **5.149** 5.175 5.177 5.179	68-72 MHz BROADCASTING Fixed Mobile 5.173	68-74.8 MHz FIXED MOBILE **5.149** 5.176 5.179				Regulation relevant to science services
	72-73 MHz FIXED MOBILE			72-73 MHz FIXED MOBILE NG3 NG49 NG56	Public Mobile (22) Maritime (80) Aviation (87) Private Land Mobile (90) Personal Radio (95)	
	73-74.6 MHz RADIO ASTRONOMY 5.178		73-74.6 MHz RADIO ASTRONOMY **US74** US246			2.2.1 Sun 2.3 Interstellar medium 2.4 Steep spectrum sources 2.3.7 Pulsars 2.5.5 Epoch of Reionization
	74.6-74.8 MHz FIXED MOBILE		74.6-74.8 MHz FIXED MOBILE US273		Private Land Mobile (90)	Regulation relevant to science services

Table of Frequency Allocations 117.975-150.8 MHz (VHF)

International Table			United States Table		FCC Rule Part(s)	Current Science Usage
Region 1 Table	**Region 2 Table**	**Region 3 Table**	**Federal Table**	**Non-Federal Table**		
137-137.025 MHz SPACE OPERATION (space-to-Earth) METEOROLOGICAL-SATELLITE (space-to-Earth) MOBILE-SATELLITE (space-to-Earth) **5.208A 5.208B** 5.209 SPACE RESEARCH (space-to-Earth) Fixed Mobile except aeronautical mobile (R) 5.204 5.205 5.206 5.207 5.208			137-137.025 MHz SPACE OPERATION (space-to-Earth) METEOROLOGICAL-SATELLITE (space-to-Earth) MOBILE-SATELLITE (space-to-Earth) US319 US320 SPACE RESEARCH (space-to-Earth) 5.208		Satellite Communications (25)	1.5.1 Meteorological satellite service 1.5.2 Space research service
137.025-137.175 MHz SPACE OPERATION (space-to-Earth) METEOROLOGICAL-SATELLITE (space-to-Earth) SPACE RESEARCH (space-to-Earth) Fixed Mobile-satellite (space-to-Earth) **5.208A 5.208B** 5.209 Mobile except aeronautical mobile (R) 5.204 5.205 5.206 5.207 5.208			137.025-137.175 MHz SPACE OPERATION (space-to-Earth) METEOROLOGICAL-SATELLITE (space-to-Earth) SPACE RESEARCH (space-to-Earth) Mobile-satellite (space-to-Earth) US319 US320 5.208			1.5.1 Meteorological satellite service 1.5.2 Space research service
137.175-137.825 MHz SPACE OPERATION (space-to-Earth) METEOROLOGICAL-SATELLITE (space-to-Earth) MOBILE-SATELLITE (space-to-Earth) **5.208A 5.208B** 5.209 SPACE RESEARCH (space-to-Earth) Fixed Mobile except aeronautical mobile (R) 5.204 5.205 5.206 5.207 5.208			137.175-137.825 MHz SPACE OPERATION (space-to-Earth) METEOROLOGICAL-SATELLITE (space-to-Earth) MOBILE-SATELLITE (space-to-Earth) US319 US320 SPACE RESEARCH (space-to-Earth) 5.208			1.5.1 Meteorological satellite service 1.5.2 Space research service
137.825-138 MHz SPACE OPERATION (space-to-Earth) METEOROLOGICAL-SATELLITE (space-to-Earth) SPACE RESEARCH (space-to-Earth) Fixed Mobile-satellite (space-to-Earth) **5.208A 5.208B** 5.209 Mobile except aeronautical mobile (R) 5.204 5.205 5.206 5.207 5.208			137.825-138 MHz SPACE OPERATION (space-to-Earth) METEOROLOGICAL-SATELLITE (space-to-Earth) SPACE RESEARCH (space-to-Earth) Mobile-satellite (space-to-Earth) US319 US320 5.208			1.5.1 Meteorolgical satellite service 1.5.2 Space research service
138-143.6 MHz AERONAUTICAL MOBILE (OR) 5.210 5.211 5.212 5.214	138-143.6 MHz FIXED MOBILE RADIOLOCATION Space research (space-to-Earth)	138-143.6 MHz FIXED MOBILE Space research (space-to-Earth) 5.207 5.213	138-144 MHz FIXED MOBILE G30			1.5.2 Space research service

143.6-143.65 MHz AERONAUTICAL MOBILE (OR) SPACE RESEARCH (space-to-Earth) 5.211 5.212 5.214	143.6-143.65 MHz FIXED MOBILE RADIOLOCATION SPACE RESEARCH (space-to-Earth)	143.6-143.65 MHz FIXED MOBILE SPACE RESEARCH (space-to-Earth) 5.207 5.213				1.5.2 Space research service
143.65-144 MHz AERONAUTICAL MOBILE (OR) 5.210 5.211 5.212 5.214	143.65-144 MHz FIXED MOBILE RADIOLOCATION Space research (space-to-Earth)	143.65-144 MHz FIXED MOBILE Space research (space-to-Earth) 5.207 5.213				1.5.2 Space research service
148-149.9 MHz FIXED MOBILE except aeronautical mobile (R) MOBILE-SATELLITE (Earth-to-space) 5.209 5.218 5.219 5.221	148-149.9 MHz FIXED MOBILE MOBILE-SATELLITE (Earth-to-space) 5.209 5.218 5.219 5.221		148-149.9 MHz FIXED MOBILE MOBILE-SATELLITE (Earth-to-space) US319 US320 US323 US325 5.218 5.219 G30	148-149.9 MHz MOBILE-SATELLITE (Earth-to-space) US320 US323 US325 5.218 5.219 US319	Satellite Communications (25)	1.5.2 Space research and operation services
149.9-150.05 MHz MOBILE-SATELLITE (Earth-to-space) 5.209 5.224A RADIONAVIGATION-SATELLITE 5.224B 5.220 5.222 5.223			149.9-150.05 MHz MOBILE-SATELLITE (Earth-to-space) US319 US320 RADIONAVIGATION-SATELLITE 5.223			1.5.2 Space research service 3.2.7 Ionosphere
150.05-153 MHz FIXED MOBILE except aeronautical mobile RADIO ASTRONOMY **5.149**	150.05-154 MHz FIXED MOBILE **5.225**		150.05-150.8 MHz FIXED MOBILE US73 G30	150.05-150.8 MHz US73		2.2.1 Sun 2.2.5 Jupiter 2.3 Interstellar medium 2.4 Steep spectrum sources 2.3.7 Pulsars 2.5.5 Epoch of Reionization
150.05-153 MHz FIXED MOBILE except aeronautical mobile RADIO ASTRONOMY **5.149**	150.05-154 MHz FIXED MOBILE **5.225**		150.8-152.855 MHz US73	150.8-152.855 MHz FIXED LAND MOBILE NG4 NG51 NG112 US73 NG124	Public Mobile (22) Private Land Mobile (90) Personal Radio (95)	Regulation relevant to science services

Table of Frequency Allocations		**150.8-174 MHz (VHF)**	***continued***			
International Table			**United States Table**		**FCC Rule Part(s)**	**Current Science Usage**
Region 1 Table	**Region 2 Table**	**Region 3 Table**	**Federal Table**	**Non-Federal Table**		
			152.855-156.2475 MHz	152.855-154 MHz LAND MOBILE NG4 NG124	Remote Pickup (74D) Private Land Mobile (90)	Regulation relevant to science services
153-154 MHz FIXED MOBILE except aeronautical mobile (R) Meteorological aids						1.5.1 Meteorolgical aids service
162.0375-174 MHz FIXED MOBILE except aeronautical mobile 5.226 5.229	162.0375-174 MHz FIXED MOBILE 5.226 5.230 5.231 5.232		162.0375-173.2 MHz FIXED MOBILE US8 US11 **US13** US73 US300 US312 G5	162.0375-173.2 MHz US8 US11 **US13** US73 US300 US312	Remote Pickup (74D) Private Land Mobile (90)	1.5.1 Meteorolgical satellite service 1.5.2 Space operation service

Table of Frequency Allocations	**174-400.15 MHz (VHF/UHF)**					
174-223 MHz BROADCASTING 5.235 5.237 5.243	174-216 MHz BROADCASTING Fixed Mobile 5.234	174-223 MHz FIXED MOBILE BROADCASTING ***5.233***		174-216 MHz BROADCASTING NG5 NG14 NG115 NG149	Broadcast Radio (TV)(73) LPTV, TV Translator/ Booster (74G) Low Power Auxiliary (74H)	3.2.7 Ionosphere
	216-220 MHz FIXED MARITIME MOBILE Radiolocation 5.241 5.242		216-217 MHz Fixed Land mobile US210 US241 G2	216-219 MHz FIXED MOBILE except aeronautical mobile US210 US241 NG173	Maritime (80) Private Land Mobile (90) Personal Radio (95)	Regulation relevant to science services
			217-220 MHz Fixed Mobile US210 US241			Regulation relevant to science services

				219-220 MHz FIXED MOBILE except aeronautical mobile Amateur NG152 US210 US241 NG173	Maritime (80) Private Land Mobile (90) Amateur Radio (97)	Regulation relevant to science services
223-230 MHz BROADCASTING Fixed Mobile 5.246 5.247		223-230 MHz FIXED MOBILE BROADCASTING AERONAUTICAL RADIONAVIGATION Radiolocation **5.250**				Regulation relevant to science services
			225-235 MHz FIXED MOBILE G27			Regulation relevant to science services
230-235 MHz FIXED MOBILE 5.247 5.251 5.252		230-235 MHz FIXED MOBILE AERONAUTICAL RADIONAVIGATION **5.250**				Regulation relevant to science services
267-272 MHz FIXED MOBILE Space operation (space-to-Earth) 5.254 5.257			267-322 MHz FIXED MOBILE G27 G100			1.5.2 Space operation service
272-273 MHz SPACE OPERATION (space-to-Earth) FIXED MOBILE 5.254						1.5.2 Space operation service
322-328.6 MHz FIXED MOBILE RADIO ASTRONOMY **5.149**			322-328.6 MHz FIXED MOBILE **US342** G27	322-328.6 MHz **US342**		2.2.1 Sun 2.3 Interstellar Medium 2.4 Steep spectrum sources 2.3.7 Pulsars 2.5.5 Epoch of Reionization

Table of Frequency Allocations	174-400.15 MHz (VHF/UHF)		*continued*			
International Table			**United States Table**		**FCC Rule Part(s)**	**Current Science Usage**
Region 1 Table	**Region 2 Table**	**Region 3 Table**	**Federal Table**	**Non-Federal Table**		
387-390 MHz FIXED MOBILE Mobile-satellite (space-to-Earth) **5.208A** **5.208B** 5.254 5.255						3.2.7 Ionosphere
400.05-400.15 MHz STANDARD FREQUENCY AND TIME SIGNAL-SATELLITE (400.1 MHz) 5.261 5.262			400.05-400.15 MHz STANDARD FREQUENCY AND TIME SIGNAL-SATELLITE (400.1 MHz) 5.261			1.5.3 Standard Frequency and time signal-satellite service 3.2.7 Ionosphere

Table of Frequency Allocations	400.15-456 MHz (UHF)					
400.15-401 MHz METEOROLOGICAL AIDS METEOROLOGICAL-SATELLITE (space-to-Earth) MOBILE-SATELLITE (space-to-Earth) **5.208A** **5.208B** 5.209 SPACE RESEARCH (space-to-Earth) 5.263 Space operation (space-to-Earth) 5.262 5.264			400.15-401 MHz METEOROLOGICAL AIDS (radiosonde) US70 METEOROLOGICAL-SATELLITE (space-to-Earth) MOBILE-SATELLITE (space-to Earth) US319 US320 US324 SPACE RESEARCH (space-to-Earth) 5.263 Space operation (space-to-Earth) 5.264	400.15-401 MHz METEOROLOGICAL AIDS (radiosonde) US70 MOBILE-SATELLITE (space-to-Earth) US319 US320 US324 SPACE RESEARCH (space-to-Earth) 5.263 Space operation (space-to-Earth) 5.264	Satellite Communications (25)	1.5.1 Meteorological aids and satellite services 1.5.2 Space research and operation services
401-402 MHz METEOROLOGICAL AIDS SPACE OPERATION (space-to-Earth) EARTH EXPLORATION-SATELLITE (Earth-to-space) METEOROLOGICAL-SATELLITE (Earth-to-space) Fixed Mobile except aeronautical mobile			401-402 MHz METEOROLOGICAL AIDS (radiosonde) US70 SPACE OPERATION (space-to-Earth) EARTH EXPLORATION-SATELLITE (Earth-to-space) METEOROLOGICAL-SATELLITE (Earth-to-space) **US64** **US384**	401-402 MHz METEOROLOGICAL AIDS (radiosonde) US70 SPACE OPERATION (space-to-Earth) Earth exploration-satellite (Earth-to-space) Meteorological-satellite (Earth-to-space) US64 **US384**	MedRadio (95I)	1.5.1 Meteorological aids and satellite services 1.5.2 Space operation service 3.2.7 Ionosphere

402-403 MHz METEOROLOGICAL AIDS EARTH EXPLORATION-SATELLITE (Earth-to-space) METEOROLOGICAL-SATELLITE (Earth-to-space) Fixed Mobile except aeronautical mobile		402-403 MHz METEOROLOGICAL AIDS (radiosonde) US70 EARTH EXPLORATION-SATELLITE (Earth-to-space) METEOROLOGICAL-SATELLITE (Earth-to-space) US64 **US384**	402-403 MHz METEOROLOGICAL AIDS (radiosonde) US70 Earth exploration-satellite (Earth-to-space) Meteorological-satellite (Earth-to-space) **US64 US384**		1.5.1 Meteorological aids and satellite services
403-406 MHz METEOROLOGICAL AIDS Fixed Mobile except aeronautical mobile		403-406 MHz METEOROLOGICAL AIDS (radiosonde) US70 **US64 G6**	403-406 MHz METEOROLOGICAL AIDS (radiosonde) US70 **US64**		1.5.1 Meteorological aids service
406.1-410 MHz FIXED MOBILE except aeronautical mobile RADIO ASTRONOMY **5.149**		406.1-410 MHz FIXED MOBILE RADIO ASTRONOMY **US74** **US13 US117** G5 **G6**	406.1-410 MHz RADIO ASTRONOMY **US74** **US13 US117**	Private Land Mobile (90)	1.5.1 Meteorological satellite service 2.2.1 Sun 2.3 Interstellar medium 2.4 Steep spectrum sources 2.3.7 Pulsars
410-420 MHz FIXED MOBILE except aeronautical mobile SPACE RESEARCH (space-to-space) 5.268		410-420 MHz FIXED MOBILE SPACE RESEARCH (space-to-space) 5.268 **US13 US64** G5	410-420 MHz **US13 US64**	Private Land Mobile (90) MedRadio (95I)	1.5.1 Meteorological satellite service 1.5.2 Space research service
		420-450 MHz RADIOLOCATION G2 G129 **US64** US87 US269 US270 **US397** G8	420-450 MHz Amateur US270 5.282 **US64** US87 US269 **US397**	Private Land Mobile (90) MedRadio (95I) Amateur Radio (97)	1.5.1 Meteorological aids and satellite services 3.2.7 Ionosphere 3.4.2 Glacier and ice sheets 3.6.1 Surface topography 3.6.3 Terrestrial carbon – biomass
432-438 MHz AMATEUR RADIOLOCATION Earth exploration-satellite (active) **5.279A** 5.138 5.271 5.276 5.277 5.280 5.281 5.282	432-438 MHz RADIOLOCATION Amateur Earth exploration-satellite (active) **5.279A** 5.271 5.276 5.277 5.278 5.279 5.281 5.282				3.4.2 Glacier and ice sheets 3.6.1 Surface topography 3.6.3 Terrestrial carbon - biomass

Table of Frequency Allocations **456-894 MHz (UHF)**

International Table			United States Table		FCC Rule Part(s)	Current Science Usage
Region 1 Table	**Region 2 Table**	**Region 3 Table**	**Federal Table**	**Non-Federal Table**		
460-470 MHz FIXED MOBILE 5.286AA Meteorological-satellite (space-to-Earth) 5.287 5.288 **5.289** 5.290			460-470 MHz Meteorological-satellite (space-to-Earth) 5.287 US73 US209 US288 **US289**	460-462.5375 MHz FIXED LAND MOBILE US209 **US289** NG124	Private Land Mobile (90)	1.5.1 Meteorological satellite service
				462.5375-462.7375 MHz LAND MOBILE **US289**	Personal Radio (95)	1.5.1 Meteorological satellite service
				462.7375-467.5375 MHz FIXED LAND MOBILE 5.287 US73 US209 US288 **US289** NG124	Maritime (80) Private Land Mobile (90)	1.5.1 Meteorological satellite service
				467.5375-467.7375 MHz LAND MOBILE 5.287 US288 **US289**	Maritime (80) Personal Radio (95)	1.5.1 Meteorological satellite service
				467.7375-470 MHz FIXED LAND MOBILE US73 US288 **US289** NG124	Maritime (80) Private Land Mobile (90)	1.5.1 Meteorological satellite service
470-790 MHz BROADCASTING **5.149** 5.291A 5.294 5.296 5.300 **5.304** **5.306** 5.311A 5.312 5.312A		470-585 MHz FIXED MOBILE BROADCASTING 5.291 5.298				1.5.2 Space research and operation services 3.2.7 Ionosphere
	512-608 MHz BROADCASTING 5.297			512-608 MHz FIXED MOBILE BROADCASTING NG5 NG14 NG115 NG149	Wireless Communications (27) Broadcast Radio (TV)(73) LPTV, TV Translator/ Booster (74G) Low Power Auxiliary (74H)	Regulations relevant to science services

		585-610 MHz FIXED MOBILE BROADCASTING RADIONAVIGATION **5.149** 5.305 **5.306 5.307**				Regulations relevant to science services
	608-614 MHz RADIO ASTRONOMY Mobile-satellite except aeronautical mobile-satellite (Earth-to-space)		608-614 MHz LAND MOBILE (medical telemetry and medical telecommand) RADIO ASTRONOMY **US74** US246		Personal Radio (95)	2.2.1 Sun 2.3 Interstellar medium 2.4 Steep spectrum sources 2.3.7 Pulsars
		610-890 MHz FIXED MOBILE 5.313A 5.317A BROADCASTING **5.149 5.305 5.306 5.307** 5.311A 5.320				Regulations relevant to science services

Table of Frequency Allocations			**894-1400 MHz (UHF)**			
1215-1240 MHz EARTH EXPLORATION-SATELLITE (active) RADIOLOCATION RADIONAVIGATION-SATELLITE (space-to-Earth) (space-to-space) 5.328B 5.329 5.329A SPACE RESEARCH (active) 5.330 5.331 **5.332**			1215-1240 MHz EARTH EXPLORATION-SATELLITE (active) RADIOLOCATION G56 RADIONAVIGATION-SATELLITE (space-to-Earth) (space-to-space) G132 SPACE RESEARCH (active) **5.332**	1215-1240 MHz Earth exploration-satellite (active) Space research (active)		1.5.2 Space research service 3.2.7 Ionosphere 3.3.1 Soil moisture 3.3.2 Freeze/Thaw 3.3.3 Surface water 3.6.1 Surface dynamics and deformation 3.6.3 Terrestrial carbon – biomass

Table of Frequency Allocations **894-1400 MHz (UHF)** ***continued***

International Table			United States Table		FCC Rule Part(s)	Current Science Usage
Region 1 Table	**Region 2 Table**	**Region 3 Table**	**Federal Table**	**Non-Federal Table**		
1240-1300 MHz EARTH EXPLORATION-SATELLITE (active) RADIOLOCATION RADIONAVIGATION-SATELLITE (space-to-Earth) (space-to-space) 5.328B 5.329 5.329A SPACE RESEARCH (active) Amateur 5.282 5.330 5.331 **5.332 5.335 5.335A**			1240-1300 MHz EARTH EXPLORATION-SATELLITE (active) RADIOLOCATION G56 SPACE RESEARCH (active) AERONAUTICAL RADIONAVIGATION **5.332 5.335**	1240-1300 MHz AERONAUTICAL RADIONAVIGATION Amateur Earth exploration-satellite (active) Space research (active) 5.282	Amateur Radio (97)	1.5.2 Space research service 3.2.7 Ionosphere 3.3.1 Soil moisture 3.3.2 Freeze/Thaw 3.3.3 Surface water 3.4.2 Sea ice 3.6.1 Surface dynamics and deformation 3.6.3 Terrestrial carbon – biomass
1300-1350 MHz RADIOLOCATION AERONAUTICAL RADIONAVIGATION 5.337 RADIONAVIGATION-SATELLITE (Earth-to-space) **5.149** 5.337A			1300-1350 MHz AERONAUTICAL RADIONAVIGATION 5.337 Radiolocation G2 **US342**	1300-1350 MHz AERONAUTICAL RADIONAVIGATION 5.337 **US342**	Aviation (87)	2.3 The Milky Way and other galaxies 2.4 Active galaxies 2.3.7 Pulsars and gravitational waves
1350-1400 MHz FIXED MOBILE RADIOLOCATION **5.149** 5.338 5.338A **5.339**	1350-1400 MHz RADIOLOCATION 5.338A **5.149** 5.334 **5.339**		1350-1390 MHz FIXED MOBILE RADIOLOCATION G2 5.334 **5.339 US342 US385** G27 G114	1350-1390 MHz 5.334 **5.339 US342 US385**		1.5.2 Space research service 2.3 The Milky Way and other galaxies 2.4 Active galaxies 2.3.7 Pulsars and gravitational waves
			1390-1395 MHz **5.339** US79 **US342 US385**	1390-1395 MHz FIXED MOBILE except aeronautical mobile **5.339** US79 **US342 US385** NG338A	Wireless Communications (27)	1.5.2 Space research service 2.3 The Milky Way and other galaxies 2.4 Active galaxies 2.3.7 Pulsars and gravitational waves
			1395-1400 MHz LAND MOBILE (medical telemetry and medical telecommand) 5.339 US79 **US342 US385**		Personal Radio (95)	2.3 The Milky Way and other galaxies 2.4 Active galaxies 2.3.7 Pulsars and gravitational waves

Table of Frequency Allocations	**1400-1626.5 MHz (UHF)**				
1400-1427 MHz EARTH EXPLORATION-SATELLITE (passive) RADIO ASTRONOMY SPACE RESEARCH (passive) **5.340 5.341**		1400-1427 MHz EARTH EXPLORATION-SATELLITE (passive) RADIO ASTRONOMY **US74** SPACE RESEARCH (passive) **5.341** US246			**ALL EMISSIONS PROHIBITED** 1.5.2 Space research service 2.2.8 Extraterrestrial intelligence 2.3 Neutral hydrogen in the Milky Way and other galaxies 2.4 Active galaxies 2.3.7 Pulsars and gravitational waves 3.3.1 Soil moisture 3.3.3 Surface water 3.4.2 Sea ice 3.4.3 Snow 3.5.2 Ocean salinity 3.6.1 Surface dynamics and deformation 3.6.3 Terrestrial carbon – biomass
1427-1429 MHz SPACE OPERATION (Earth-to-space) FIXED MOBILE except aeronautical mobile **5.338A 5.341**		1427-1429.5 MHz LAND MOBILE (medical telemetry and medical telecommand) US350 **5.341** US79	1427-1429.5 MHz LAND MOBILE (telemetry and telecommand) Fixed (telemetry) **5.341** US79 US350 NG338A	Private Land Mobile (90) Personal Radio (95)	1.5.2 Space operation service 2.2.8 Extraterrestrial intelligence Regulation relevant to science service (5.338A)
1429-1452 MHz FIXED MOBILE except aeronautical mobile **5.338A 5.341** 5.342	1429-1452 MHz FIXED MOBILE 5.343 **5.338A 5.341**				2.2.8 Extraterrestrial intelligence Regulation relevant to science service (5.338A)
		1429.5-1432 MHz **5.341** US79 US350	1429.5-1432 MHz FIXED (telemetry and telecommand) LAND MOBILE (telemetry and telecommand) **5.341** US79 US350 NG338A		2.2.8 Extraterrestrial intelligence

Table of Frequency Allocations 1400-1626.5 MHz (UHF) *continued*

International Table			United States Table		FCC Rule Part(s)	Current Science Usage
Region 1 Table	**Region 2 Table**	**Region 3 Table**	**Federal Table**	**Non-Federal Table**		
(see previous page)	(see previous page)		1432-1435 MHz **5.341** US83	1432-1435 MHz FIXED MOBILE except aeronautical mobile **5.341** US83 NG338A	Wireless Communications (27)	2.2.8 Extraterrestrial intelligence
			1435-1525 MHz MOBILE (aeronautical telemetry) US338A **5.341** US343		Aviation (87)	2.2.8 Extraterrestrial intelligence
1452-1492 MHz FIXED MOBILE except aeronautical mobile BROADCASTING BROADCASTING-SATELLITE **5.208B** **5.341** 5.342 5.345	1452-1492 MHz FIXED MOBILE 5.343 BROADCASTING BROADCASTING-SATELLITE **5.208B** **5.341** 5.344 5.345					2.2.8 Extraterrestrial intelligence
1492-1518 MHz FIXED MOBILE except aeronautical mobile **5.341** 5.342	1492-1518 MHz FIXED MOBILE 5.343 **5.341** 5.344	1492-1518 MHz FIXED MOBILE **5.341**				2.2.8 Extraterrestrial intelligence
1518-1525 MHz FIXED MOBILE except aeronautical mobile MOBILE-SATELLITE (space-to-Earth) 5.348 5.348A 5.348B 5.351A **5.341** 5.342	1518-1525 MHz FIXED MOBILE 5.343 MOBILE-SATELLITE (space-to-Earth) 5.348 5.348A 5.348B 5.351A **5.341** 5.344	1518-1525 MHz FIXED MOBILE MOBILE-SATELLITE (space-to-Earth) 5.348 5.348A 5.348B 5.351A **5.341**				2.2.8 Extraterrestrial intelligence
1525-1530 MHz SPACE OPERATION (space-to-Earth) FIXED MOBILE-SATELLITE (space-to-Earth) **5.208B** 5.351A	1525-1530 MHz SPACE OPERATION (space-to-Earth) MOBILE-SATELLITE (space-to-Earth) **5.208B** 5.351A Earth exploration-satellite	1525-1530 MHz SPACE OPERATION (space-to-Earth) FIXED MOBILE-SATELLITE (space-to-Earth) **5.208B** 5.351A	1525-1535 MHz MOBILE-SATELLITE (space-to-Earth) US315 US380 **5.341** 5.351		Satellite Communications (25) Maritime (80)	1.5.2 Space operation service 2.2.8 Extraterrestrial intelligence

Earth exploration-satellite Mobile except aeronautical mobile 5.349 **5.341** 5.342 5.350 5.351 5.352A 5.354	Fixed Mobile 5.343 **5.341** 5.351 5.354	Earth exploration-satellite Mobile 5.349 **5.341** 5.351 5.352A 5.354			
1530-1535 MHz SPACE OPERATION (space-to-Earth) MOBILE-SATELLITE (space-to-Earth) **5.208B** 5.351A 5.353A Earth exploration-satellite Fixed Mobile except aeronautical mobile **5.341** 5.342 5.351 5.354	1530-1535 MHz SPACE OPERATION (space-to-Earth) MOBILE-SATELLITE (space-to-Earth) **5.208B** 5.351A 5.353A Earth exploration-satellite Fixed Mobile 5.343 **5.341** 5.351 5.354				1.5.2 Space operation service 2.2.8 Extraterrestrial intelligence
1535-1559 MHz MOBILE-SATELLITE (space-to-Earth) **5.208B** 5.351A **5.341** 5.351 5.353A 5.354 5.355 5.356 5.357 5.357A 5.359 5.362A			1535-1559 MHz MOBILE-SATELLITE (space-to-Earth) US308 US309 US315 US380 **5.341** 5.351 5.356	Satellite Communications (25) Maritime (80) Aviation (87)	2.2.8 Extraterrestrial intelligence
1559-1610 MHz AERONAUTICAL RADIONAVIGATION RADIONAVIGATION-SATELLITE (space-to-Earth) (space-to-space) **5.208B** 5.328B 5.329A **5.341** 5.362B 5.362C			1559-1610 MHz AERONAUTICAL RADIONAVIGATION RADIONAVIGATION-SATELLITE (space-to-Earth) (space-to-space) **5.341** US85 US208 US260	Aviation (87)	2.2.8 Extraterrestrial intelligence 2.3.4 Extragalactic OH Masers 3.2.7 Ionosphere
1610-1610.6 MHz MOBILE-SATELLITE (Earth-to-space) 5.351A AERONAUTICAL RADIONAVIGATION **5.341** 5.355 5.359 5.364 5.366 5.367 5.368 5.369 5.371 **5.372**	1610-1610.6 MHz MOBILE-SATELLITE (Earth-to-space) 5.351A AERONAUTICAL RADIONAVIGATION RADIODETERMINATION-SATELLITE (Earth-to-space) **5.341** 5.364 5.366 5.367 5.368 5.370 **5.372**	1610-1610.6 MHz MOBILE-SATELLITE (Earth-to-space) 5.351A AERONAUTICAL RADIONAVIGATION Radiodetermination-satellite (Earth-to-space) **5.341** 5.355 5.359 5.364 5.366 5.367 5.368 5.369 **5.372**	1610-1610.6 MHz MOBILE-SATELLITE (Earth-to-space) US319 US380 AERONAUTICAL RADIONAVIGATION US260 RADIODETERMINATION-SATELLITE (Earth-to-space) **5.341** 5.364 5.366 5.367 5.368 **5.372** US208	Satellite Communications (25) Aviation (87)	2.2.8 Extraterrestrial intelligence

Table of Frequency Allocations **1400-1626.5 MHz (UHF)** ***continued***

International Table			United States Table		FCC Rule Part(s)	Current Science Usage
Region 1 Table	**Region 2 Table**	**Region 3 Table**	**Federal Table**	**Non-Federal Table**		
1610.6-1613.8 MHz MOBILE-SATELLITE (Earth-to-space) 5.351A RADIO ASTRONOMY AERONAUTICAL RADIONAVIGATION **5.149** **5.341** 5.355 5.359 5.364 5.366 5.367 5.368 5.369 5.371 **5.372**	1610.6-1613.8 MHz MOBILE-SATELLITE (Earth-to-space) 5.351A RADIO ASTRONOMY AERONAUTICAL RADIONAVIGATION RADIODETERMINATION-SATELLITE (Earth-to-space) **5.149** **5.341** 5.364 5.366 5.367 5.368 5.370 **5.372**	1610.6-1613.8 MHz MOBILE-SATELLITE (Earth-to-space) 5.351A RADIO ASTRONOMY AERONAUTICAL RADIONAVIGATION Radiodetermination-satellite (Earth-to-space) **5.149** **5.341** 5.355 5.359 5.364 5.366 5.367 5.368 5.369 **5.372**	1610.6-1613.8 MHz MOBILE-SATELLITE (Earth-to-space) US319 US380 RADIO ASTRONOMY AERONAUTICAL RADIONAVIGATION US260 RADIODETERMINATION-SATELLITE (Earth-to-space) **5.341** 5.364 5.366 5.367 5.368 **5.372** US208 **US342**			2.2.8 Extraterrestrial intelligence 2.3.2 Cold molecular gas (OH)
1613.8-1626.5 MHz MOBILE-SATELLITE (Earth-to-space) 5.351A AERONAUTICAL RADIONAVIGATION Mobile-satellite (space-to-Earth) **5.208B** **5.341** 5.355 5.359 5.364 5.365 5.366 5.367 5.368 5.369 5.371 **5.372**	1613.8-1626.5 MHz MOBILE-SATELLITE (Earth-to-space) 5.351A AERONAUTICAL RADIONAVIGATION RADIODETERMINATION-SATELLITE (Earth-to-space) Mobile-satellite (space-to-Earth) **5.208B** **5.341** 5.364 5.365 5.366 5.367 5.368 5.370 **5.372**	1613.8-1626.5 MHz MOBILE-SATELLITE (Earth-to-space) 5.351A AERONAUTICAL RADIONAVIGATION Mobile-satellite (space-to-Earth) **5.208B** Radiodetermination-satellite (Earth-to-space) **5.341** 5.355 5.359 5.364 5.365 5.366 5.367 5.368 5.369 **5.372**	1613.8-1626.5 MHz MOBILE-SATELLITE (Earth-to-space) US319 US380 AERONAUTICAL RADIONAVIGATION US260 RADIODETERMINATION-SATELLITE (Earth-to-space) Mobile-satellite (space-to-Earth) **5.341** 5.364 5.365 5.366 5.367 5.368 **5.372** US208			2.2.8 Extraterrestrial intelligence

Table of Frequency Allocations **1626.5-2110 MHz (UHF)**

1626.5-1660 MHz MOBILE-SATELLITE (Earth-to-space) 5.351A **5.341** 5.351 5.353A 5.354 5.355 5.357A 5.359 5.362A 5.374 5.375 5.376	1626.5-1660 MHz MOBILE-SATELLITE (Earth-to-space) US308 US309 US315 US380 **5.341** 5.351 5.375	Satellite Communications (25) Maritime (80) Aviation (87)	2.2.8 Extraterrestrial intelligence
1660-1660.5 MHz MOBILE-SATELLITE (Earth-to-space) 5.351A RADIO ASTRONOMY	1660-1660.5 MHz MOBILE-SATELLITE (Earth-to-space) US308 US309 US380	Satellite Communications (25)	2.2.8 Extraterrestrial intelligence 2.3.2 Cold molecular gas (OH)

5.149 5.341 5.351 5.354 5.362A **5.376A**	RADIO ASTRONOMY **5.341** 5.351 **US342**		Aviation (87)	
1660.5-1668 MHz RADIO ASTRONOMY SPACE RESEARCH (passive) Fixed Mobile except aeronautical mobile **5.149 5.341** 5.379 5.379A	1660.5-1668.4 MHz RADIO ASTRONOMY **US74** SPACE RESEARCH (passive) **5.341** US246			1.5.1 Meteorological aids service 1.5.2 Space research service 2.2.8 Extraterrestrial intelligence 2.3.2 Cold molecular gas (OH)
1668-1668.4 MHz MOBILE-SATELLITE (Earth-to-space) 5.351A **5.379B 5.379C** RADIO ASTRONOMY SPACE RESEARCH (passive) Fixed Mobile except aeronautical mobile **5.149 5.341** 5.379 5.379A				1.5.1 Meteorological aids service 1.5.2 Space research service 2.2.8 Extraterrestrial intelligence 2.3.2 Cold molecular gas (OH)
1668.4-1670 MHz METEOROLOGICAL AIDS FIXED MOBILE except aeronautical mobile MOBILE-SATELLITE (Earth-to-space) 5.351A **5.379B 5.379C** RADIO ASTRONOMY **5.149 5.341** 5.379D 5.379E	1668.4-1670 MHz METEOROLOGICAL AIDS (radiosonde) RADIO ASTRONOMY **US74** **5.341** US99 **US342**			1.5.1 Meteorological aids service 2.2.8 Extraterrestrial intelligence 2.3.2 Cold molecular gas (OH)
1670-1675 MHz METEOROLOGICAL AIDS FIXED METEOROLOGICAL-SATELLITE (space-to-Earth) MOBILE MOBILE-SATELLITE (Earth-to-space) 5.351A **5.379B** **5.341** 5.379D 5.379E 5.380A	1670-1675 MHz **5.341 US211** US362	1670-1675 MHz FIXED MOBILE except aeronautical mobile **5.341 US211** US362	Wireless Communications (27)	1.5.1 Meteorological aids and satellite service 2.2.8 Extraterrestrial intelligence
1675-1690 MHz METEOROLOGICAL AIDS FIXED METEOROLOGICAL-SATELLITE (space-to-Earth) MOBILE except aeronautical mobile **5.341**	1675-1695 MHz METEOROLOGICAL AIDS (radiosonde) METEOROLOGICAL-SATELLITE (space-to-Earth) US88 **5.341 US211 US289**			1.5.1 Meteorological aids and satellite services 2.2.8 Extraterrestrial intelligence

Table of Frequency Allocations **1626.5-2110 MHz (UHF)** ***continued***

International Table			United States Table		FCC Rule Part(s)	Current Science Usage
Region 1 Table	**Region 2 Table**	**Region 3 Table**	**Federal Table**	**Non-Federal Table**		
1690-1700 MHz METEOROLOGICAL AIDS METEOROLOGICAL-SATELLITE (space-to-Earth) Fixed Mobile except aeronautical mobile **5.289** **5.341** 5.382	1690-1700 MHz METEOROLOGICAL AIDS METEOROLOGICAL-SATELLITE (space-to-Earth) **5.289** **5.341** 5.381		(see previous page)			1.5.1 Meteorological aids and satellite services 2.2.8 Extraterrestrial intelligence
			1695-1710 MHz METEOROLOGICAL-SATELLITE (space-to-Earth) US88 **5.341**	1695-1710 MHz FIXED MOBILE except aeronautical mobile **5.341** US88	Wireless Communications (27)	Regulations relevant to scientific services 2.2.8 Extraterrestrial intelligence
1700-1710 MHz FIXED METEOROLOGICAL-SATELLITE (space-to-Earth) MOBILE except aeronautical mobile **5.289** **5.341**		1700-1710 MHz FIXED METEOROLOGICAL-SATELLITE (space-to-Earth) MOBILE except aeronautical mobile **5.289** **5.341** 5.384				1.5.1 Meteorological satellite service 1.5.2 Space research service 2.2.8 Extraterrestrial intelligence
1710-1930 MHz FIXED MOBILE 5.384A 5.388A 5.388B **5.149** **5.341** **5.385** 5.386 5.387 5.388			1710-1761 MHz **5.341** US91 US378 **US385**	1710-1780 MHz FIXED MOBILE **5.341** US91 US378 **US385**		1.5.1 Meteorological satellite service 1.5.2 Space research and operation services 2.2.8 Extraterrestrial intelligence 2.3.2 Cold molecular gas (OH)
			1761-1780 MHz SPACE OPERATION (Earth-to-space) G42 US91			1.5.2 Space operation service
			1780-1850 MHz FIXED MOBILE SPACE OPERATION (Earth-to-space) G42	1780-1850 MHz		1.5.2 Space operation service

2025-2110 MHz SPACE OPERATION (Earth-to-space) (space-to-space) EARTH EXPLORATION-SATELLITE (Earth-to-space) (space-to-space) FIXED MOBILE 5.391 SPACE RESEARCH (Earth-to-space) (space-to-space) **5.392**	2025-2110 MHz SPACE OPERATION (Earth-to-space) (space-to-space) EARTH EXPLORATION-SATELLITE (Earth-to-space) (space-to-space) SPACE RESEARCH (Earth-to-space) (space-to-space) FIXED MOBILE 5.391 **5.392 US90** US92 **US222 US346 US347**	2025-2110 MHz FIXED NG118 MOBILE 5.391 **5.392 US90** US92 **US222** **US346 US347**	TV Auxiliary Broadcasting (74F) Cable TV Relay (78) Local TV Transmission (101J)	1.5.2 Space research and operation services 3.2.7 Ionosphere

Table of Frequency Allocations 2110-2483.5 MHz (UHF)

2110-2120 MHz FIXED MOBILE 5.388A 5.388B SPACE RESEARCH (deep space) (Earth-to-space) 5.388	2110-2120 MHz US252	2110-2120 MHz FIXED MOBILE US252	Public Mobile (22) Wireless Communications (27) Fixed Microwave (101)	1.5.2 Space research service
2200-2290 MHz SPACE OPERATION (space-to-Earth) (space-to-space) EARTH EXPLORATION-SATELLITE (space-to-Earth) (space-to-space) FIXED MOBILE 5.391 SPACE RESEARCH (space-to-Earth) (space-to-space) **5.392**	2200-2290 MHz SPACE OPERATION (space-to-Earth) (space-to-space) EARTH EXPLORATION-SATELLITE (space-to-Earth) (space-to-space) FIXED (line-of-sight only) MOBILE (line-of-sight only including aeronautical telemetry, but excluding flight testing of manned aircraft) 5.391 SPACE RESEARCH (space-to-Earth) (space-to-space) **5.392 US303**	2200-2290 MHz **US303**		1.5.2 Space research and operation services

Table of Frequency Allocations 2110-2483.5 MHz (UHF) *continued*

International Table			United States Table		FCC Rule Part(s)	Current Science Usage
Region 1 Table	Region 2 Table	Region 3 Table	Federal Table	Non-Federal Table		
2290-2300 MHz FIXED MOBILE except aeronautical mobile SPACE RESEARCH (deep space) (space-to-Earth)			2290-2300 MHz FIXED MOBILE except aeronautical mobile SPACE RESEARCH (deep space) (space-to-Earth)	2290-2300 MHz SPACE RESEARCH (deep space) (space-to-Earth)		1.5.2 Space research service
2300-2450 MHz FIXED MOBILE 5.384A Amateur Radiolocation 5.150 5.282 5.395	2300-2450 MHz FIXED MOBILE 5.384A RADIOLOCATION Amateur 5.150 5.282 5.393 5.394 5.396					2.2.4 Radar astronomy 3.2.7 Ionosphere
			2305-2310 MHz US97 G122	2305-2310 MHz FIXED MOBILE except aeronautical mobile RADIOLOCATION Amateur US97	Wireless Communications (27) Amateur Radio (97)	2.2.4 Radar astronomy
			2310-2320 MHz Fixed Mobile US100 Radiolocation G2 US97 US327	2310-2320 MHz FIXED MOBILE BROADCASTING-SATELLITE RADIOLOCATION 5.396 US97 US100 US327	Wireless Communications (27)	2.2.4 Radar astronomy

Table of Frequency Allocations 2483.5-3500 MHz (UHF/SHF)

2483.5-2500 MHz FIXED MOBILE MOBILE-SATELLITE (space-to-Earth)	2483.5-2500 MHz FIXED MOBILE MOBILE-SATELLITE (space-to-Earth) 5.351A	2483.5-2500 MHz FIXED MOBILE MOBILE-SATELLITE (space-to-Earth)	2483.5-2500 MHz MOBILE-SATELLITE (space-to-Earth) US319 US380 US391 RADIODETERMINATION	2483.5-2495 MHz MOBILE-SATELLITE (space-to-Earth) US380 RADIODETERMINATION SATELLITE (space-to-	ISM Equipment (18) Satellite Communi-cations (25)	Regulation relevant to science services

5.351A RADIODETERMINATION-SATELLITE (space-to-Earth) 5.398 Radiolocation 5.398A 5.150 5.399 5.401 **5.402**	RADIOLOCATION RADIODETERMINATION-SATELLITE (space-to-Earth) 5.398 5.150 **5.402**	5.351A RADIOLOCATION RADIODETERMINATION-SATELLITE (space-to-Earth) 5.398 5.150 5.401 **5.402**	-SATELLITE (space-to-Earth) 5.398 5.150 **5.402** US41	Earth) 5.398 5.150 **5.402** US41 US319 NG147		
				2495-2500 MHz FIXED MOBILE except aeronautical mobile MOBILE-SATELLITE (space-to-Earth) US380 RADIODETERMINATION-SATELLITE (space-to-Earth) 5.398 5.150 **5.402** US41 US319 US391 NG147	ISM Equipment (18) Satellite Communications (25) Wireless Communications (27)	Regulation relevant to science services
2500-2520 MHz FIXED 5.410 MOBILE except aeronautical mobile 5.384A 5.412	2500-2520 MHz FIXED 5.410 FIXED-SATELLITE (space-to-Earth) 5.415 MOBILE except aeronautical mobile 5.384A 5.404	2500-2520 MHz FIXED 5.410 FIXED-SATELLITE (space-to-Earth) 5.415 MOBILE except aeronautical mobile 5.384A MOBILE-SATELLITE (space-to-Earth) 5.351A 5.407 5.414 5.414A 5.404 5.415A	2500-2655 MHz **5.339** US205	2500-2655 MHz FIXED US205 MOBILE except aeronautical mobile **5.339**	Wireless Communications (27)	Regulation relevant to science services
2520-2655 MHz FIXED 5.410 MOBILE except aeronautical mobile 5.384A BROADCASTING-SATELLITE **5.413** 5.416 5.339 5.412 5.417C 5.417D 5.418B 5.418C	2520-2655 MHz FIXED 5.410 FIXED-SATELLITE (space-to-Earth) 5.415 MOBILE except aeronautical mobile 5.384A BROADCASTING-SATELLITE **5.413** 5.416 5.339 5.417C 5.417D 5.418B 5.418C	2520-2535 MHz FIXED 5.410 FIXED-SATELLITE (space-to-Earth) 5.415 MOBILE except aeronautical mobile 5.384A BROADCASTING-SATELLITE **5.413** 5.416 5.403 5.414A 5.415A				Regulation relevant to science services

Table of Frequency Allocations **2483.5-3500 MHz (UHF/SHF)**

International Table			United States Table		FCC Rule Part(s)	Current Science Usage
Region 1 Table	**Region 2 Table**	**Region 3 Table**	**Federal Table**	**Non-Federal Table**		
		2535-2655 MHz FIXED 5.410 MOBILE except aeronautical mobile 5.384A BROADCASTING-SATELLITE **5.413** 5.416 5.339 5.417A 5.417B 5.417C 5.417D 5.418 5.418A 5.418B 5.418C	(see previous page)	(see previous page)		Regulation relevant to science service
2655-2670 MHz FIXED 5.410 MOBILE except aeronautical mobile 5.384A BROADCASTING-SATELLITE **5.208B** **5.413** 5.416 Earth exploration-satellite (passive) Radio astronomy Space research (passive) **5.149** 5.412	2655-2670 MHz FIXED 5.410 FIXED-SATELLITE (Earth-to-space) (space-to-Earth) 5.415 MOBILE except aeronautical mobile 5.384A BROADCASTING-SATELLITE **5.413** 5.416 Earth exploration-satellite (passive) Radio astronomy Space research (passive) **5.149** **5.208B**	2655-2670 MHz FIXED 5.410 FIXED-SATELLITE (Earth-to-space) 5.415 MOBILE except aeronautical mobile 5.384A BROADCASTING-SATELLITE **5.413** 5.416 Earth exploration-satellite (passive) Radio astronomy Space research (passive) **5.149** **5.208B** 5.420	2655-2690 MHz Earth exploration-satellite (passive) Radio astronomy **US385** Space research (passive) US205	2655-2690 MHz FIXED US205 MOBILE except aeronautical mobile Earth exploration-satellite (passive) Radio astronomy Space research (passive) **US385**		1.5.2 Space research service 2.4 Active galaxies 2.5 Cosmology and structure of the universe
2670-2690 MHz FIXED 5.410 MOBILE except aeronautical mobile 5.384A Earth exploration-satellite (passive) Radio astronomy Space research (passive) **5.149** 5.412	2670-2690 MHz FIXED 5.410 FIXED-SATELLITE (Earth-to-space) (space-to-Earth) **5.208B** 5.415 MOBILE except aeronautical mobile 5.384A Earth exploration-satellite (passive) Radio astronomy	2670-2690 MHz FIXED 5.410 FIXED-SATELLITE (Earth-to-space) 5.415 MOBILE except aeronautical mobile 5.384A MOBILE-SATELLITE (Earth-to-space) 5.351A 5.419 Earth exploration-satellite (passive)				1.5.2 Space research service 2.4 Active galaxies 2.5 Cosmology and structure of the universe

	Space research (passive) **5.149**	Radio astronomy Space research (passive) **5.149**				
2690-2700 MHz EARTH EXPLORATION-SATELLITE (passive) RADIO ASTRONOMY SPACE RESEARCH (passive) **5.340 5.422**			2690-2700 MHz EARTH EXPLORATION-SATELLITE (passive) RADIO ASTRONOMY **US74** SPACE RESEARCH (passive) US246			**ALL EMISSIONS PROHIBITED EXCEPT THOSE PROVIDED FOR BY 5.422** 1.5.2 Space research service 2.4 Active galaxies 2.5 Cosmology and structure of the universe
2700-2900 MHz AERONAUTICAL RADIONAVIGATION 5.337 Radiolocation 5.423 5.424			2700-2900 MHz METEOROLOGICAL AIDS AERONAUTICAL RADIONAVIGATION 5.337 US18 Radiolocation G2 5.423 G15	2700-2900 MHz 5.423 US18	Aviation (87)	1.5.1 Meteorological aids service
2900-3100 MHz RADIOLOCATION 5.424A RADIONAVIGATION 5.426 5.425 5.427			2900-3100 MHz RADIOLOCATION 5.424A G56 MARITIME RADIONAVIGATION 5.427 US44 US316	2900-3100 MHz MARITIME RADIONAVIGATION Radiolocation US44 5.427 US316	Maritime (80) Private Land Mobile (90)	1.5.1 Meteorological aids service
3100-3300 MHz RADIOLOCATION Earth exploration-satellite (active) Space research (active) **5.149** 5.428			3100-3300 MHz RADIOLOCATION G59 Earth exploration-satellite (active) Space research (active) **US342**	3100-3300 MHz Earth exploration-satellite (active) Space research (active) Radiolocation **US342**	Private Land Mobile (90)	1.5.2 Space research service 2.3.1 Interstellar medium (CH) 3.6.2 Agriculture
3300-3400 MHz RADIOLOCATION **5.149** 5.429 5.430	3300-3400 MHz RADIOLOCATION Amateur Fixed Mobile **5.149**	3300-3400 MHz RADIOLOCATION Amateur **5.149** 5.429	3300-3500 MHz RADIOLOCATION US108 G2 **US342**	3300-3500 MHz Amateur Radiolocation US108 5.282 **US342**	Private Land Mobile (90) Amateur Radio (97)	Regulation relevant to science services
4200-4400 MHz AERONAUTICAL RADIONAVIGATION **5.438** 5.439 5.440			4200-4400 MHz AERONAUTICAL RADIONAVIGATION 5.440 **US261**		Aviation (87)	1.5.2 Space research service 1.5.3 Standard Frequency and time signal-satellite service

Table of Frequency Allocations **3500-5460 MHz (SHF)**

International Table			United States Table		FCC Rule Part(s)	Current Science Usage
Region 1 Table	**Region 2 Table**	**Region 3 Table**	**Federal Table**	**Non-Federal Table**		
			4400-4940 MHz FIXED MOBILE US113 US245 **US342**			
4800-4990 MHz FIXED MOBILE 5.440A 5.442 Radio astronomy **5.149** 5.339 **5.443**				4800-4940 MHz US113 **US342**		2.3 The Milky Way and other galaxies (formaldehyde – HCOH) 2.4 Active galaxies 2.5 Cosmology and structure of the universe
			4940-4990 MHz 5.339 **US342 US385** G122	4940-4990 MHz FIXED MOBILE except aeronautical mobile 5.339 **US342 US385**	Public Safety Land Mobile (90Y)	2.3 The Milky Way and other galaxies 2.4 Active galaxies 2.5 Cosmology and structure of the universe
4990-5000 MHz FIXED MOBILE except aeronautical mobile RADIO ASTRONOMY Space research (passive) **5.149**			4990-5000 MHz RADIO ASTRONOMY **US74** Space research (passive) US246			1.5.2 Space research service 2.3 The Milky Way and other galaxies 2.4 Active galaxies 2.5 Cosmology and structure of the universe
5000-5010 MHz AERONAUTICAL MOBILE-SATELLITE (R) 5.443AA AERONAUTICAL RADIONAVIGATION RADIONAVIGATION-SATELLITE (Earth-to-space)			5000-5010 MHz AERONAUTICAL RADIONAVIGATION US260 RADIONAVIGATION-SATELLITE (Earth-to-space) **US211** US367		Aviation (87)	Regulation relevant to science services
5010-5030 MHz AERONAUTICAL MOBILE-SATELLITE (R) 5.443AA AERONAUTICAL RADIONAVIGATION RADIONAVIGATION-SATELLITE (space-to-Earth) (space-to-space) 5.328B **5.443B**			5010-5030 MHz AERONAUTICAL RADIONAVIGATION US260 RADIONAVIGATION-SATELLITE (space-to-Earth) (space-to-space) **5.443B** **US211** US367			Regulation relevant to science services
5030-5091 AERONAUTICAL MOBILE (R) 5.443C AERONAUTICAL MOBILE-SATELLITE (R) 5.443D AERONAUTICAL RADIONAVIGATION 5.444			5030-5091 AERONAUTICAL RADIONAVIGATION US260 5.444 **US211** US367			Regulation relevant to science services
5091-5150 MHz AERONAUTICAL MOBILE 5.444B AERONAUTICAL MOBILE-SATELLITE (R) 5.443AA AERONAUTICAL RADIONAVIGATION 5.444 5.444A			5091-5150 MHz AERONAUTICAL MOBILE US111 US444B AERONAUTICAL RADIONAVIGATION US260 **US211** US344 US367 US444 US444A		Satellite Communications (25) Aviation (87)	Regulation relevant to science services

5150-5250 MHz FIXED-SATELLITE (Earth-to-space) 5.447A MOBILE except aeronautical mobile 5.446A 5.446B AERONAUTICAL RADIONAVIGATION 5.446 5.446C 5.447 5.447B 5.447C	5150-5250 MHz AERONAUTICAL RADIONAVIGATION US260 **US211** US307 US344	5150-5250 MHz FIXED-SATELLITE (Earth-to-space) 5.447A US344 AERONAUTICAL RADIONAVIGATION US260 5.447C **US211** US307	RF Devices (15) Satellite Communications (25) Aviation (87)	Regulation relevant to science services
5250-5255 MHz EARTH EXPLORATION-SATELLITE (active) MOBILE except aeronautical mobile 5.446A **5.447F** RADIOLOCATION SPACE RESEARCH 5.447D **5.447E** 5.448 **5.448A**	5250-5255 MHz EARTH EXPLORATION-SATELLITE (active) RADIOLOCATION G59 SPACE RESEARCH (active) 5.447D **5.448A**	5250-5255 MHz Earth exploration-satellite (active) Radiolocation Space research	RF Devices (15) Private Land Mobile (90)	1.5.2 Space research service 3.3.3 Surface water 3.6.1 Surface dynamics and deformation 3.6.2 Agriculture
5255-5350 MHz EARTH EXPLORATION-SATELLITE (active) MOBILE except aeronautical mobile 5.446A **5.447F** RADIOLOCATION SPACE RESEARCH (active) **5.447E** 5.448 **5.448A**	5255-5350 MHz EARTH EXPLORATION-SATELLITE (active) RADIOLOCATION G59 SPACE RESEARCH (active) **5.448A**	5255-5350 MHz Earth exploration-satellite (active) Radiolocation Space research (active) 5.448A		1.5.2 Space research service 3.3.2 Freeze/Thaw 3.3.3 Surface water 3.5.4 Ocean topography 3.6.1 Surface dynamics and deformation 3.6.2 Agriculture
5350-5460 MHz EARTH EXPLORATION-SATELLITE (active) **5.448B** RADIOLOCATION 5.448D AERONAUTICAL RADIONAVIGATION 5.449 SPACE RESEARCH (active) 5.448C	5350-5460 MHz EARTH EXPLORATION-SATELLITE (active) **5.448B** RADIOLOCATION G56 AERONAUTICAL RADIONAVIGATION 5.449 SPACE RESEARCH (active) US390 G130	5350-5460 MHz AERONAUTICAL RADIONAVIGATION 5.449 Earth exploration-satellite (active) **5.448B** Radiolocation Space research (active) US390	Aviation (87) Private Land Mobile (90)	1.5.2 Space research service 3.3.3 Surface water 3.4.1 Glacier and ice sheet 3.4.2 Sea ice 3.4.4 River and lake ice 3.6.1 Surface dynamics and deformation 3.6.2 Agriculture

Table of Frequency Allocations **5460-7145 MHz (SHF)**

International Table			United States Table		FCC Rule Part(s)	Current Science Usage
Region 1 Table	**Region 2 Table**	**Region 3 Table**	**Federal Table**	**Non-Federal Table**		
5460-5470 MHz EARTH EXPLORATION-SATELLITE (active) RADIOLOCATION 5.448D RADIONAVIGATION 5.449 SPACE RESEARCH (active) **5.448B**			5460-5470 MHz EARTH EXPLORATION-SATELLITE (active) RADIOLOCATION G56 RADIONAVIGATION 5.449 US65 SPACE RESEARCH (active) **5.448B** US49 G130	5460-5470 MHz RADIONAVIGATION 5.449 US65 Earth exploration-satellite (active) Radiolocation Space research (active) **5.448B** US49	Maritime (80) Aviation (87) Private Land Mobile (90)	1.5.2 Space research service 3.3.3 Surface water 3.6.1 Surface dynamics and deformation 3.6.2 Agriculture
5470-5570 MHz EARTH EXPLORATION-SATELLITE (active) MOBILE except aeronautical mobile 5.446A 5.450A RADIOLOCATION 5.450B MARITIME RADIONAVIGATION SPACE RESEARCH (active) **5.448B** 5.450 5.451			5470-5570 MHz EARTH EXPLORATION-SATELLITE (active) RADIOLOCATION G56 MARITIME RADIONAVIGATION US65 SPACE RESEARCH (active) **5.448B** US50 G131	5470-5570 MHz RADIOLOCATION MARITIME RADIONAVIGATION US65 Earth exploration-satellite (active) Space research (active) US50	RF Devices (15) Maritime (80) Private Land Mobile (90)	1.5 Ground-based meteorological data 1.5.2 Space research service 3.3.3 Surface water 3.6.1 Surface dynamics and deformation 3.6.2 Agriculture
5570-5650 MHz MOBILE except aeronautical mobile 5.446A 5.450A RADIOLOCATION 5.450B MARITIME RADIONAVIGATION 5.450 5.451 5.452						1.5 Ground-based meteorological data
			5600-5650 MHz METEOROLOGICAL AIDS RADIOLOCATION G56 MARITIME RADIONAVIGATION US65 5.452 US50 G131	5600-5650 MHz METEOROLOGICAL AIDS RADIOLOCATION MARITIME RADIONAVIGATION US65 5.452 US50		1.5.1 Meteorological aids service
5650-5725 MHz MOBILE except aeronautical mobile 5.446A 5.450A RADIOLOCATION Amateur Space research (deep space) 5.282 5.451 5.453 5.454 5.455			5650-5925 MHz RADIOLOCATION G2 5.150 US245	5650-5830 MHz Amateur 5.150 5.282	RF Devices (15) ISM Equipment (18) Amateur Radio (97)	1.5.2 Space research service

5925-6700 MHz FIXED 5.457 FIXED-SATELLITE (Earth-to-space) 5.457A 5.457B MOBILE 5.457C **5.149** 5.440 **5.458**				1.5.2 Space research service 1.5.3 Standard Frequency and time signal-satellite service 2.3.2 Cold molecular gas (methanol) 3.2.6 Clouds 3.3.2 Freeze/Thaw
	6425-6525 MHz 5.440 **5.458**	6425-6525 MHz FIXED-SATELLITE (Earth-to-space) MOBILE 5.440 **5.458**	RF Devices (15) Satellite Communications (25) TV Broadcast Auxiliary (74F) Cable TV Relay (78) Fixed Microwave (101)	1.5.2 Space research service 1.5.3 Standard Frequency and time signal-satellite service
	6525-6700 MHz **5.458 US342**	6525-6700 MHz FIXED FIXED-SATELLITE (Earth-to-space) 5.458 **US342**	RF Devices (15) Satellite Communications (25) Fixed Microwave (101)	1.5.2 Space research service 2.3.2 Cold molecular gas (methanol) 3.2.4 Precipitation
6700-7075 MHz FIXED FIXED-SATELLITE (Earth-to-space) (space-to-Earth) 5.441 MOBILE **5.458 5.458A** 5.458B 5.458C	6700-7125 MHz 5.458	6700-6875 MHz FIXED FIXED-SATELLITE (Earth-to-space) (space-to-Earth) 5.441 5.458 **5.458A** 5.458B		1.5.2 Space research service 3.3.1 Soil moisture 3.3.3 Surface water 3.5.1 Sea surface temperature 3.5.3 Sea surface winds
		6875-7025 MHz FIXED NG118 FIXED-SATELLITE (Earth-to-space) (space-to-Earth) 5.441 MOBILE NG171 5.458 **5.458A** 5.458B	RF Devices (15) Satellite Communications (25) TV Broadcast Auxiliary (74F) Cable TV Relay (78)	Regulation relevant to science services

Table of Frequency Allocations **5460-7145 MHz (SHF)** ***continued***

International Table			United States Table		FCC Rule Part(s)	Current Science Usage
Region 1 Table	**Region 2 Table**	**Region 3 Table**	**Federal Table**	**Non-Federal Table**		
(see previous page)			(see previous page)	7025-7075 MHz FIXED NG118 FIXED-SATELLITE (Earth-to-space) NG172 MOBILE NG171 5.458 **5.458A** 5.458B	RF Devices (15) TV Broadcast Auxiliary (74F) Cable TV Relay (78)	Regulation relevant to science services
7075-7145 MHz FIXED MOBILE **5.458** 5.459				7075-7125 MHz FIXED NG118 MOBILE NG171 5.458		1.5.2 Space research service
			7125-7145 MHz FIXED **5.458** G116	7125-7145 MHz 5.458	RF Devices (15)	1.5.2 Space research service

Table of Frequency Allocations **7145-8650 MHz (SHF)**

7145-7235 MHz FIXED MOBILE SPACE RESEARCH (Earth-to-space) 5.460 **5.458** 5.459			7145-7190 MHz FIXED SPACE RESEARCH (deep space) (Earth-to-space) US262 **5.458** G116	7145-7235 MHz 5.458 US262	RF Devices (15)	1.5.2 Space research service
			7190-7235 FIXED SPACE RESEARCH (Earth-to-space) G133 **5.458** G134			1.5.1 Meteorological satellite service 1.5.2 Space research service
7450-7550 MHz FIXED FIXED-SATELLITE (space-to-Earth) METEOROLOGICAL-SATELLITE (space-to-Earth) MOBILE except aeronautical mobile 5.461A			7450-7550 MHz FIXED FIXED-SATELLITE (space-to-Earth) METEOROLOGICAL-SATELLITE (space-to-Earth) Mobile-satellite (space-to-Earth) G104 G117			1.5.1 Meteorological satellite service

7750-7900 MHz FIXED METEOROLOGICAL-SATELLITE (space-to-Earth) 5.461B MOBILE except aeronautical mobile	7750-7850 MHz FIXED METEOROLOGICAL-SATELLITE (space-to-Earth) 5.461B		1.5.1 Meteorological satellite service
	7850-7900 MHz FIXED		
8025-8175 MHz EARTH EXPLORATION-SATELLITE (space-to-Earth) FIXED FIXED-SATELLITE (Earth-to-space) MOBILE 5.463 **5.462A**	8025-8175 MHz EARTH EXPLORATION-SATELLITE (space-to-Earth) FIXED FIXED-SATELLITE (Earth-to-space) Mobile-satellite (Earth-to-space) (no airborne transmissions) **US258** G117	8025-8400 MHz **US258**	Regulation relevant to science services
8175-8215 MHz EARTH EXPLORATION-SATELLITE (space-to-Earth) FIXED FIXED-SATELLITE (Earth-to-space) METEOROLOGICAL-SATELLITE (Earth-to-space) MOBILE 5.463 **5.462A**	8175-8215 MHz EARTH EXPLORATION-SATELLITE (space-to-Earth) FIXED FIXED-SATELLITE (Earth-to-space) METEOROLOGICAL-SATELLITE (Earth-to-space) Mobile-satellite (Earth-to-space) (no airborne transmissions) **US258** G104 G117		1.5.1 Meteorological satellite service
8215-8400 MHz EARTH EXPLORATION-SATELLITE (space-to-Earth) FIXED FIXED-SATELLITE (Earth-to-space) MOBILE 5.463 **5.462A**	8215-8400 MHz EARTH EXPLORATION-SATELLITE (space-to-Earth) FIXED FIXED-SATELLITE (Earth-to-space) Mobile-satellite (Earth-to-space) (no airborne transmissions) **US258** G117		Regulation relevant to science services

Table of Frequency Allocations **7145-8650 MHz (SHF)** ***continued***

International Table			United States Table		FCC Rule Part(s)	Current Science Usage
Region 1 Table	**Region 2 Table**	**Region 3 Table**	**Federal Table**	**Non-Federal Table**		
8400-8500 MHz FIXED MOBILE except aeronautical mobile SPACE RESEARCH (space-to-Earth) 5.465 5.466			8400-8450 MHz FIXED SPACE RESEARCH (deep space)(space-to-Earth)	8400-8450 MHz Space research (deep space)(space-to-Earth)		1.5.2 Space research service
			8450-8500 MHz FIXED SPACE RESEARCH (space-to-Earth)	8450-8500 MHz SPACE RESEARCH (space-to-Earth)		1.5.2 Space research service
8550-8650 MHz EARTH EXPLORATION-SATELLITE (active) RADIOLOCATION SPACE RESEARCH (active) 5.468 5.469 **5.469A**			8550-8650 MHz EARTH EXPLORATION-SATELLITE (active) RADIOLOCATION G59 SPACE RESEARCH (active)	8550-8650 MHz Earth exploration-satellite (active) Radiolocation Space research (active)	Private Land Mobile (90)	1.5.2 Space research service 2.2.4 Radar astronomy 3.6.3 Terrestrial carbon – vegetation elevation

Table of Frequency Allocations **8.65-12.2 GHz (SHF)**

9.3-9.5 GHz EARTH EXPLORATION-SATELLITE (active) RADIOLOCATION RADIONAVIGATION SPACE RESEARCH (active) 5.427 5.474 5.475 **5.475A** 5.475B **5.476A**			9.3-9.5 GHz EARTH EXPLORATION-SATELLITE (active) RADIOLOCATION G56 RADIONAVIGATION US475 SPACE RESEARCH (active) Meteorological aids 5.427 5.474 **5.475A** 5.475B US67 US71 **US476A**	9.3-9.5 GHz RADIONAVIGATION US475 Meteorological aids Earth exploration-satellite (active) Radiolocation Space research (active) 5.427 5.474 US67 US71 **US476A**	Maritime (80) Aviation (87) Private Land Mobile (90)	1.5.1 Meteorological aids service 1.5.2 Space research service 3.6.3 Terrestrial carbon – vegetation elevation
9.5-9.8 GHz EARTH EXPLORATION-SATELLITE (active) RADIOLOCATION RADIONAVIGATION SPACE RESEARCH (active) **5.476A**			9.5-9.8 GHz EARTH EXPLORATION-SATELLITE (active) RADIOLOCATION SPACE RESEARCH (active)	9.5-9.9 GHz Earth exploration-satellite (active) Radiolocation Space research (active)	Private Land Mobile (90)	1.5.2 Space research service 3.6.3 Terrestrial carbon – vegetation elevation
9.8-9.9 GHz RADIOLOCATION Earth exploration-satellite (active)			9.8-9.9 GHz RADIOLOCATION Earth exploration-satellite			1.5.2 Space research service 3.6.3 Terrestrial carbon – vegetation elevation

Fixed Space research (active) 5.477 5.478 **5.478A 5.478B**			(active) Space research (active)			
9.9-10 GHz RADIOLOCATION Fixed 5.477 5.478 5.479			9.9-10 GHz RADIOLOCATION 5.479	9.9-10 GHz RADIOLOCATION 5.479		1.5.1 Meteorological satellite service
10-10.45 GHz FIXED MOBILE RADIOLOCATION Amateur 5.479	10-10.45 GHz RADIOLOCATION Amateur 5.479 5.480	10-10.45 GHz FIXED MOBILE RADIOLOCATION Amateur 5.479	10-10.5 GHz RADIOLOCATION US108 G32	10-10.45 GHz Amateur Radiolocation US108 5.479 US128 NG50	Private Land Mobile (90) Amateur Radio (97)	1.5.1 Meteorological satellite service
10.45-10.5 GHz	10.45-10.5 GHz	10.45-10.5 GHz		10.45-10.5 GHz		
10.6-10.68 GHz EARTH EXPLORATION-SATELLITE (passive) FIXED MOBILE except aeronautical mobile RADIO ASTRONOMY SPACE RESEARCH (passive) Radiolocation **5.149** 5.482 **5.482A**			10.6-10.68 GHz EARTH EXPLORATION-SATELLITE (passive) SPACE RESEARCH (passive) **US130 US131 US482**	10.6-10.68 GHz EARTH EXPLORATION-SATELLITE (passive) FIXED **US482** SPACE RESEARCH (passive) **US130 US131**		1.5.2 Space research service 2.3 Milky Way & other galaxies 2.4 Active galaxies 2.5 Cosmology and structure of the universe (Continuum, VLBI) 3.2.4 Precipitation 3.2.6 Clouds 3.3.2 Freeze/Thaw
10.68-10.7 GHz EARTH EXPLORATION-SATELLITE (passive) RADIO ASTRONOMY SPACE RESEARCH (passive) **5.340 5.483**			10.68-10.7 GHz EARTH EXPLORATION-SATELLITE (passive) RADIO ASTRONOMY **US74** SPACE RESEARCH (passive) **US131** US246			**ALL EMISSIONS PROHIBITED EXCEPT THOSE PROVIDED FOR BY 5.483** 1.5.2 Space research service 2.3 Milky Way & other galaxies 2.4 Active galaxies 2.5 Cosmology and structure of the universe (Continuum, VLBI) 3.2.4 Precipitation 3.2.6 Clouds 3.3.2 Freeze/Thaw 3.5.1 Sea surface temperature 3.5.3 Sea surface winds
10.7-11.7 GHz FIXED FIXED-SATELLITE (space-to-Earth) 5.441 5.484A (Earth-to-space) 5.484 MOBILE except aeronautical mobile	10.7-11.7 GHz FIXED FIXED-SATELLITE (space-to-Earth) 5.441 5.484A MOBILE except aeronautical mobile		10.7-11.7 GHz **US131 US211**	10.7-11.7 GHz FIXED FIXED-SATELLITE (space-to-Earth) 5.441 **US131 US211** NG52	Satellite Communications (25) Fixed Microwave (101)	3.2.5 Atm. chemistry – mesospheric O_3

Table of Frequency Allocations 12.2-15.4 GHz (SHF)

International Table			United States Table		FCC Rule Part(s)	Current Science Usage
Region 1 Table	Region 2 Table	Region 3 Table	Federal Table	Non-Federal Table		
12.75-13.25 FIXED FIXED-SATELLITE (Earth-to-space) 5.441 MOBILE Space research (deep space) (space-to-Earth)			12.75-13.25 US251	12.75-13.25 FIXED NG118 FIXED-SATELLITE (Earth-to-space) 5.441 NG52 MOBILE US251 NG53	Satellite Communications (25) TV Broadcast Auxiliary (74F) Cable TV Relay (78) Fixed Microwave (101)	1.5.2 Space research service
13.25-13.4 GHz EARTH EXPLORATION-SATELLITE (active) AERONAUTICAL RADIONAVIGATION 5.497 SPACE RESEARCH (active) **5.498A** 5.499			13.25-13.4 GHz EARTH EXPLORATION-SATELLITE (active) AERONAUTICAL RADIONAVIGATION 5.497 SPACE RESEARCH (active) **5.498A**	13.25-13.4 GHz AERONAUTICAL RADIONAVIGATION 5.497 Earth exploration-satellite (active) Space research (active)	Aviation (87)	1.5.2 Space research service 3.3.2 Freeze/Thaw 3.3.3 Surface water 3.6 Solid Earth
13.4-13.75 GHz EARTH EXPLORATION-SATELLITE (active) RADIOLOCATION SPACE RESEARCH 5.501A Standard frequency and time signal-satellite (Earth-to-space) 5.499 5.500 5.501 **5.501B**			13.4-13.75 GHz EARTH EXPLORATION-SATELLITE (active) RADIOLOCATION G59 SPACE RESEARCH 5.501A Standard frequency and time signal-satellite (Earth-to-space) **5.501B**	13.4-13.75 GHz Earth exploration-satellite (active) Radiolocation Space research Standard frequency and time signal-satellite (Earth-to-space)	Private Land Mobile (90)	1.5.2 Space research service 1.5.3 Standard Frequency and time signal-satellite service 3.2.4 Precipitation 3.2.6 Clouds 3.3.2 Freeze/Thaw 3.3.3 Surface water 3.4.1 Glacier and ice sheets 3.4.2 Sea ice 3.5.4 Ocean topography 3.6 Solid Earth
13.75-14 GHz FIXED-SATELLITE (Earth-to-space) 5.484A RADIOLOCATION Earth exploration-satellite Standard frequency and time signal-satellite (Earth-to-space) Space research 5.499 5.500 5.501 5.502 5.503			13.75-14 GHz RADIOLOCATION G59 Standard frequency and time signal-satellite (Earth-to-space) Space research US337 US356 US357	13.75-14 GHz FIXED-SATELLITE (Earth-to-space) US337 Standard frequency and time signal-satellite (Earth-to-space) Space research Radiolocation US356 US357	Satellite Communications (25) Private Land Mobile (90)	1.5.2 Space research service 1.5.3 Standard Frequency and time signal-satellite service 3.3.3 Surface water

14-14.25 GHz FIXED-SATELLITE (Earth-to-space) 5.457A 5.457B 5.484A 5.506 5.506B RADIONAVIGATION 5.504 Mobile-satellite (Earth-to-space) 5.504B 5.504C 5.506A Space research 5.504A 5.505	14-14.2 GHz Space research US133	14-14.2 GHz FIXED-SATELLITE (Earth-to-space) NG55 Mobile-satellite (Earth-to-space) Space research US133	Satellite Communications (25)	1.5.2 Space research service
		14.2-14.47 GHz FIXED-SATELLITE (Earth-to-space) NG55 Mobile-satellite (Earth-to-space)		
14.25-14.3 FIXED-SATELLITE (Earth-to-space) 5.457A 5.457B 5.484A 5.506 5.506B RADIONAVIGATION 5.504 Mobile-satellite (Earth-to-space) 5.504B 5.506A 5.508A Space research 5.504A 5.505 5.508				1.5.2 Space research service
14.4-14.47 GHz FIXED FIXED-SATELLITE (Earth-to-space) 5.457A 5.457B 5.484A 5.506 5.506B MOBILE except aeronautical mobile Mobile-satellite (Earth-to-space) 5.504B 5.506A 5.509A Space research (space-to-Earth) 5.504A	14.4-14.47 GHz Fixed Mobile			1.5.2 Space research service
14.47-14.5 GHz FIXED FIXED-SATELLITE (Earth-to-space) 5.457A 5.457B 5.484A 5.506 5.506B MOBILE except aeronautical mobile Mobile-satellite (Earth-to-space) 5.504B 5.506A 5.509A Radio astronomy **5.149** 5.504A	14.47-14.5 GHz Fixed Mobile **US113** US133 **US342**	14.47-14.5 GHz FIXED-SATELLITE (Earth-to-space) NG55 Mobile-satellite (Earth-to-space) **US113** US133 **US342**		2.3 The Milky Way and other galaxies 2.4 Active galaxies (Formeldahyde)
14.5-14.8 GHz FIXED FIXED-SATELLITE (Earth-to-space) 5.510 MOBILE Space research	14.5-14.7145 GHz FIXED Mobile Space research			1.5.2 Space research service
	14.7145-14.8 GHz MOBILE Fixed Space research			1.5.2 Space research service

Table of Frequency Allocations **12.2-15.4 GHz (SHF)** ***continued***

International Table			United States Table		FCC Rule Part(s)	Current Science Usage
Region 1 Table	**Region 2 Table**	**Region 3 Table**	**Federal Table**	**Non-Federal Table**		
14.8-15.35 GHz FIXED MOBILE Space research 5.339			14.8-15.1365 GHz MOBILE SPACE RESEARCH Fixed US310	14.8-15.1365 GHz US310		1.5.2 Space research service
			15.1365-15.35 GHz FIXED SPACE RESEARCH Mobile 5.339 **US211**	15.1365-15.35 GHz 5.339 **US211**		1.5.2 Space research service
15.35-15.4 GHz EARTH EXPLORATION-SATELLITE (passive) RADIO ASTRONOMY SPACE RESEARCH (passive) **5.340** 5.**511**			15.35-15.4 GHz EARTH EXPLORATION-SATELLITE (passive) RADIO ASTRONOMY **US74** SPACE RESEARCH (passive) US246			**ALL EMISSIONS PROHIBITED EXCEPT THOSE PROVIDED FOR BY 5.511** 1.5.2 Space research service 2.3 The Milky Way and other galaxies 2.4 Active galaxies 2.5 Cosmology and structure of the universe (Continuum, VLBI)

Table of Frequency Allocations **15.4-21.2 GHz (SHF)**

15.4-15.43 GHz RADIOLOCATION 5.511E **5.511F** AERONAUTICAL RADIONAVIGATION 5.511D			15.4-15.43 GHz AERONAUTICAL RADIONAVIGATION US260 **US211**		Aviation (87)	Regulation relevant to science services
15.43-15.63 GHz FIXED-SATELLITE (Earth-to-space) **5.511A** RADIOLOCATION 5.511E **5.511F** AERONAUTICAL RADIONAVIGATION 5.511C			15.43-15.63 GHz AERONAUTICAL RADIONAVIGATION US260 5.511C **US211** US359	15.43-15.63 GHz FIXED-SATELLITE (Earth-to-space) AERONAUTICAL RADIONAVIGATION US260 5.511C **US211** US359	Satellite Communications (25) Aviation (87)	Regulation relevant to science services
15.63-15.7 GHz RADIOLOCATION 5.511E **5.511F** AERONAUTICAL RADIONAVIGATION 5.511D			15.63-15.7 GHz AERONAUTICAL RADIONAVIGATION US260 **US211**		Aviation (87)	Regulation relevant to science services

				15.7-17.2 GHz Radiolocation	Private Land Mobile (90)	
16.6-17.1 GHz RADIOLOCATION Space research (deep space) (Earth-to-space) 5.512 5.513			16.6-17.1 GHz RADIOLOCATION G59 Space research (deep space) (Earth-to-space)			1.5.2 Space research service
17.2-17.3 GHz EARTH EXPLORATION-SATELLITE (active) RADIOLOCATION SPACE RESEARCH (active) 5.512 5.513 **5.513A**			17.2-17.3 GHz EARTH EXPLORATION-SATELLITE (active) RADIOLOCATION G59 SPACE RESEARCH (active)	17.2-17.3 GHz Earth exploration-satellite (active) Radiolocation Space research (active)		1.5.2 Space research service 3.6 Solid Earth and biosphere
17.7-18.1 GHz FIXED FIXED-SATELLITE (space-to-Earth) 5.484A (Earth-to-space) 5.516 MOBILE	17.7-17.8 GHz		17.7-17.8 GHz	17.7-17.8 GHz		1.5.1 Meteorological satellite service
	17.8-18.1 GHz GHz FIXED FIXED-SATELLITE (space-to-Earth) 5.484A (Earth-to-space) 5.516 MOBILE 5.519		17.8-18.3 GHz FIXED-SATELLITE (space-to-Earth) US334 G117 US519	17.8-18.3 GHz FIXED US334 US519	TV Broadcast Auxiliary (74F) Cable TV Relay (78) Fixed Microwave (101)	
18.1-18.4 GHz FIXED FIXED-SATELLITE (space-to-Earth) 5.484A 5.516B (Earth-to-space) 5.520 MOBILE 5.519 5.521			18.3-18.4 GHz	18.3-18.4 GHz		1.5.1 Meteorological satellite service
18.6-18.8 GHz EARTH EXPLORATION-SATELLITE (passive) FIXED FIXED-SATELLITE (space-to-Earth) 5.522B MOBILE except aeronautical mobile Space research (passive) 5.522A 5.522C	18.6-18.8 GHz EARTH EXPLORATION-SATELLITE (passive) FIXED FIXED-SATELLITE (space-to-Earth) 5.516B 5.522B MOBILE except aeronautical mobile SPACE RESEARCH (passive) 5.522A	18.6-18.8 GHz EARTH EXPLORATION-SATELLITE (passive) FIXED FIXED-SATELLITE (space-to-Earth) 5.522B MOBILE except aeronautical mobile Space research (passive) 5.522A	18.6-18.8 GHz EARTH EXPLORATION-SATELLITE (passive) FIXED-SATELLITE (space-to-Earth) US255 US334 G117 SPACE RESEARCH (passive) US139 US254	18.6-18.8 GHz EARTH EXPLORATION-SATELLITE (passive) FIXED-SATELLITE (space-to-Earth) US255 NG164 SPACE RESEARCH (passive) US139 US254 US334		1.5.2 Space research service 3.2.2 Atm. water vapor 3.2.4 Precipitation 3.2.6 Clouds 3.3.2 Freeze/Thaw 3.4.2 Sea ice 3.4.3 Snow 3.5.1 Sea surface temperature 3.5.3 Sea surface winds 3.5.4 Ocean topography

Table of Frequency Allocations **15.4-21.2 GHz (SHF)** ***continued***

International Table			United States Table		FCC Rule Part(s)	Current Science Usage
Region 1 Table	**Region 2 Table**	**Region 3 Table**	**Federal Table**	**Non-Federal Table**		
20.2-21.2 GHz FIXED-SATELLITE (space-to-Earth) MOBILE-SATELLITE (space-to-Earth) Standard frequency and time signal-satellite (space-to-Earth) 5.524			20.2-21.2 GHz FIXED-SATELLITE (space-to-Earth) MOBILE-SATELLITE (space-to-Earth) Standard frequency and time signal-satellite (space-to-Earth) G117	20.2-21.2 GHz Standard frequency and time signal-satellite (space-to-Earth)		1.5.3 Standard Frequency and time signal-satellite service

Table of Frequency Allocations **21.2-27 GHz (SHF)**

Region 1 Table	Region 2 Table	Region 3 Table	Federal Table	Non-Federal Table	FCC Rule Part(s)	Current Science Usage
21.2-21.4 GHz EARTH EXPLORATION-SATELLITE (passive) FIXED MOBILE SPACE RESEARCH (passive)			21.2-21.4 GHz EARTH EXPLORATION-SATELLITE (passive) FIXED MOBILE SPACE RESEARCH (passive) **US532**		Fixed Microwave (101)	1.5.2 Space research service
21.4-22 GHz FIXED MOBILE BROADCASTING-SATELLITE **5.208B** 5.530A 5.530B 5.530C 5.530D	21.4-22 GHz FIXED MOBILE 5.530A 5.530C	21.4-22 GHz FIXED MOBILE BROADCASTING-SATELLITE **5.208B** 5.530A 5.530B 5.530C 5.530D 5.531	21.4-22 GHz FIXED MOBILE			Regulation relevant to science services
22-22.21 GHz FIXED MOBILE except aeronautical mobile **5.149**			22-22.21 GHz FIXED MOBILE except aeronautical mobile **US342**			2.3 Milky Way & other galaxies 2.4 Active galaxies (extragalactic water) 3.2.2 Atm. water vapor 3.3.2 Freeze/Thaw 3.2.3 Integrated precipitable water
22.21-22.5 GHz EARTH EXPLORATION-SATELLITE (passive) FIXED MOBILE except aeronautical mobile RADIO ASTRONOMY SPACE RESEARCH (passive) **5.149 5.532**			22.21-22.5 GHz EARTH EXPLORATION-SATELLITE (passive) FIXED MOBILE except aeronautical mobile RADIO ASTRONOMY SPACE RESEARCH (passive) **US342 US532**			1.5.2 Space research service 2.3 The Milky Way and other galaxies (Water masers) 3.2.2 Atm. water vapor 3.2.3 Integrated precipitable water

22.5-22.55 GHz FIXED MOBILE	22.5-22.55 GHz FIXED MOBILE **US211**			2.3 The Milky Way and other galaxies (Water masers)
22.55-23.15 GHz FIXED INTER-SATELLITE 5.338A MOBILE SPACE RESEARCH (Earth-to-space) 5.532A **5.149**	22.55-23.55 GHz FIXED INTER-SATELLITE US145 US278 MOBILE **US342**		Satellite Communications (25) Fixed Microwave (101)	1.5.2 Space research service 2.3 The Milky Way and other galaxies (Water masers) 2.5 Cosmology and structure of the universe (Cosmic Microwave Background) 3.2.4 Precipitation 3.2.6 Clouds
23.15-23.55 GHz FIXED INTER-SATELLITE 5.338A MOBILE				2.3 The Milky Way and 0ther galaxies (Water masers)
23.6-24 GHz EARTH EXPLORATION-SATELLITE (passive) RADIO ASTRONOMY SPACE RESEARCH (passive) **5.340**	23.6-24 GHz EARTH EXPLORATION-SATELLITE (passive) RADIO ASTRONOMY **US74** SPACE RESEARCH (passive) US246			**ALL EMISSIONS PROHIBITED** 1.5.2 Space research service 2.3 Milky Way & other galaxies (ammonia) 3.2.2 Atm. water vapor 3.5.1 Sea surface temperature 3.5.3 Sea surface winds 3.5.4 Ocean topography
24-24.05 GHz AMATEUR AMATEUR-SATELLITE 5.150	24-24.05 GHz 5.150 **US211**	24-24.05 GHz AMATEUR AMATEUR-SATELLITE 5.150 **US211**	ISM Equipment (18) Amateur Radio (97)	Regulation relevant to science services
24.05-24.25 GHz RADIOLOCATION Amateur Earth exploration-satellite (active) 5.150	24.05-24.25 GHz RADIOLOCATION G59 Earth exploration-satellite (active) 5.150	24.05-24.25 GHz Amateur Earth exploration-satellite (active) Radiolocation 5.150	RF Devices (15) ISM Equipment (18) Private Land Mobile (90) Amateur Radio (97)	Regulation relevant to science services
25.25-25.5 GHz FIXED INTER-SATELLITE **5.536** MOBILE Standard frequency and time signal-satellite (Earth-to-space)	25.25-25.5 GHz FIXED INTER-SATELLITE **5.536** MOBILE Standard frequency and time signal-satellite (Earth-to-space)	25.25-25.5 GHz Inter-satellite **5.536** Standard frequency and \ time signal-satellite (Earth-to-space)	RF Devices (15)	1.5.2 Space research service 1.5.3 Standard Frequency and time signal-satellite service

Table of Frequency Allocations **21.2-27 GHz (SHF)** ***continued***

International Table			United States Table		FCC Rule Part(s)	Current Science Usage
Region 1 Table	**Region 2 Table**	**Region 3 Table**	**Federal Table**	**Non-Federal Table**		
25.5-27 GHz EARTH EXPLORATION-SATELLITE (space-to-Earth) **5.536B** FIXED INTER-SATELLITE **5.536** MOBILE SPACE RESEARCH (space-to-Earth) 5.536C Standard frequency and time signal-satellite (Earth-to-space) **5.536A**			25.5-27 GHz EARTH EXPLORATION-SATELLITE (space-to-Earth) FIXED INTER-SATELLITE **5.536** MOBILE SPACE RESEARCH (space-to-Earth) Standard frequency and time signal-satellite (Earth-to-space) **5.536A US258**	25.5-27 GHz Inter-satellite **5.536** Standard frequency and time signal-satellite (Earth-to-space) **5.536A US258**		1.5.2 Space research service 1.5.3 Standard Frequency and time signal-satellite service

Table of Frequency Allocations **27-34.7 GHz (SHF/EHF)**

27-27.5 GHz FIXED INTER-SATELLITE **5.536** MOBILE	27-27.5 GHz FIXED FIXED-SATELLITE (Earth-to-space) INTER-SATELLITE **5.536** 5.537 MOBILE		27-27.5 GHz FIXED INTER-SATELLITE **5.536** MOBILE	27-27.5 GHz Inter-satellite **5.536**	RF Devices (15)	1.5.2 Space research service
28.5-29.1 GHz FIXED FIXED-SATELLITE (Earth-to-space) 5.484A 5.516B 5.523A 5.539 MOBILE Earth exploration-satellite (Earth-to-space) **5.541** 5.540						Regulation relevant to science services
29.1-29.5 GHz FIXED FIXED-SATELLITE (Earth-to-space) 5.516B 5.523C 5.523E 5.535A 5.539 5.541A MOBILE Earth exploration-satellite (Earth-to-space) **5.541** 5.540						Regulation relevant to science services
29.5-29.9 GHz FIXED-SATELLITE (Earth-to-space) 5.484A 5.516B 5.539 Earth exploration-satellite (Earth-to-space) **5.541**	29.5-29.9 GHz FIXED-SATELLITE (Earth-to-space) 5.484A 5.516B 5.539 MOBILE-SATELLITE (Earth-to-space)	29.5-29.9 GHz FIXED-SATELLITE (Earth-to-space) 5.484A 5.516B 5.539 Earth exploration-satellite (Earth-to-space) **5.541**		29.5-30 GHz FIXED-SATELLITE (Earth-to-space) MOBILE-SATELLITE (Earth-to-space) 5.525 5.526 5.527	Satellite Communications (25)	Regulation relevant to science services

Mobile-satellite (Earth-to-space) 5.540 5.542	Earth exploration-satellite (Earth-to-space) **5.541** 5.525 5.526 5.527 5.529 5.540 5.542	Mobile-satellite (Earth-to-space) 5.540 5.542		5.529 **5.543**		
29.9-30 GHz FIXED-SATELLITE (Earth-to-space) 5.484A 5.516B 5.539 MOBILE-SATELLITE (Earth-to-space) Earth exploration-satellite (Earth-to-space) **5.541 5.543** 5.525 5.526 5.527 5.538 5.540 5.542						Regulation relevant to science services
30-31 GHz FIXED-SATELLITE (Earth-to-space) 5.338A MOBILE-SATELLITE (Earth-to-space) Standard frequency and time signal-satellite (space-to-Earth) 5.542			30-31 GHz FIXED-SATELLITE (Earth-to-space) MOBILE-SATELLITE (Earth-to-space) Standard frequency and time signal-satellite (space-to-Earth) G117	30-31 GHz Standard frequency and time signal-satellite (space-to-Earth)		1.5.3 Standard Frequency and time signal-satellite service 2.5 Cosmology and structure of the universe (Cosmic Microwave Background) 3.2.6 Clouds
31-31.3 GHz FIXED 5.338A **5.543A** MOBILE Standard frequency and time signal-satellite (space-to-Earth) Space research 5.544 5.545 **5.149**			31-31.3 GHz Standard frequency and time signal-satellite (space-to-Earth) **US211 US342**	31-31.3 GHz FIXED **NG60** MOBILE Standard frequency and time signal-satellite (space-to-Earth) **US211 US342**	Fixed Microwave (101)	1.5.2 Space research service 1.5.3 Standard Frequency and time signal-satellite service 3.2.6 Clouds
31.3-31.5 GHz EARTH EXPLORATION-SATELLITE (passive) RADIO ASTRONOMY SPACE RESEARCH (passive) **5.340**			31.3-31.8 GHz EARTH EXPLORATION-SATELLITE (passive) RADIO ASTRONOMY **US74** SPACE RESEARCH (passive) US246			**ALL EMISSIONS PROHIBITED** 1.5.2 Space research service 2.3 The Milky Way and other galaxies (complex organic molecules)

Table of Frequency Allocations **27-34.7 GHz (SHF/EHF)** ***continued***

International Table			United States Table		FCC Rule Part(s)	Current Science Usage
Region 1 Table	**Region 2 Table**	**Region 3 Table**	**Federal Table**	**Non-Federal Table**		
31.5-31.8 GHz EARTH EXPLORATION-SATELLITE (passive) RADIO ASTRONOMY SPACE RESEARCH (passive) Fixed Mobile except aeronautical mobile **5.149** 5.546	31.5-31.8 GHz EARTH EXPLORATION-SATELLITE (passive) RADIO ASTRONOMY SPACE RESEARCH (passive) **5.340**	31.5-31.8 GHz EARTH EXPLORATION-SATELLITE (passive) RADIO ASTRONOMY SPACE RESEARCH (passive) Fixed Mobile except aeronautical mobile **5.149**	(see previous page)			**ALL EMISSIONS PROHIBITED IN REGION 2** 1.5.2 Space research service 3.2.2 Atm. water vapor 3.2.4 Precipitation 3.4.2 Sea ice 3.5.3 Sea surface winds
31.8-32 GHz FIXED **5.547**A RADIONAVIGATION SPACE RESEARCH (deep space) (space-to-Earth) **5.547** **5.547**B 5.548			31.8-32.3 GHz RADIONAVIGATION US69 SPACE RESEARCH (deep space) (space-to-Earth) US262 5.548 **US211**	31.8-32.3 GHz SPACE RESEARCH (deep space) (space-to-Earth) US262 5.548 **US211**		1.5.2 Space research service
32-32.3 GHz FIXED **5.547**A RADIONAVIGATION SPACE RESEARCH (deep space) (space-to-Earth) **5.547** **5.547**C 5.548						1.5.2 Space research service 2.5 Cosmology and Structure of the Universe (Cosmic Microwave Background)
34.2-34.7 GHz RADIOLOCATION SPACE RESEARCH (deep space) (Earth-to-space) 5.549			34.2-34.7 GHz RADIOLOCATION SPACE RESEARCH (deep space) (Earth-to-space) US262 US360 G34 G117	34.2-34.7 GHz Radiolocation Space research (deep space) (Earth-to-space) US262 US360		1.5.1 Meteorological satellite 1.5.2 Space research service

Table of Frequency Allocations **34.7-46.9 GHz (EHF)**

34.7-35.2 GHz RADIOLOCATION Space research 5.550 5.549			34.7-35.5 GHz RADIOLOCATION US360 G117	34.7-35.5 GHz Radiolocation US360		1.5.2 Space research service
35.2-35.5 GHz METEOROLOGICAL AIDS RADIOLOCATION 5.549						1.5.1 Meteorological aids service

35.5-36 GHz METEOROLOGICAL AIDS EARTH EXPLORATION-SATELLITE (active) RADIOLOCATION SPACE RESEARCH (active) 5.549 **5.549A**	35.5-36 GHz EARTH EXPLORATION-SATELLITE (active) RADIOLOCATION SPACE RESEARCH (active) US360 G117	35.5-36 GHz Earth exploration-satellite (active) Radiolocation Space research (active) US360		1.5.1 Meteorological aids service 1.5.2 Space research service 3.2.4 Precipitation 3.2.6 Clouds 3.3.3 Surface water
36-37 GHz EARTH EXPLORATION-SATELLITE (passive) FIXED MOBILE SPACE RESEARCH (passive) **5.149 5.550A**	36-37 GHz EARTH EXPLORATION-SATELLITE (passive) FIXED MOBILE SPACE RESEARCH (passive) **US342 US550A**			1.5.2 Space research service 2.3 The Milky Way and other galaxies (complex organic molecules) 3.2.2 Atm. water vapor 3.2.4 Precipitation 3.2.6 Clouds 3.3.2 Freeze/Thaw 3.4.2 Sea ice 3.4.4 Snow 3.5.1 Sea surface temperature 3.5.3 Sea surface winds 3.5.4 Ocean topography
37-37.5 GHz FIXED MOBILE except aeronautical mobile SPACE RESEARCH (space-to-Earth) **5.547**	37-38 GHz FIXED MOBILE SPACE RESEARCH (space-to-Earth)	37-37.5 GHz FIXED MOBILE		1.5.2 Space research service 3.2.2 Atm. water vapor 3.2.4 Precipitation
37.5-38 GHz FIXED FIXED-SATELLITE (space-to-Earth) MOBILE except aeronautical mobile SPACE RESEARCH (space-to-Earth) Earth exploration-satellite (space-to-Earth) **5.547**		37.5-38.6 GHz FIXED FIXED-SATELLITE (space-to-Earth) MOBILE	Satellite Communications (25)	1.5.2 Space research service
38-39.5 GHz FIXED FIXED-SATELLITE (space-to-Earth) MOBILE Earth exploration-satellite (space-to-Earth) **5.547**	38-38.6 GHz FIXED MOBILE			Regulation relevant to science services
	38.6-39.5 GHz	38.6-39.5 GHz FIXED FIXED-SATELLITE (space-to-Earth) MOBILE NG175	Satellite Communications (25) Fixed Microwave (101)	

Table of Frequency Allocations **34.7-46.9 GHz (EHF)** ***continued***

International Table			United States Table		FCC Rule Part(s)	Current Science Usage
Region 1 Table	**Region 2 Table**	**Region 3 Table**	**Federal Table**	**Non-Federal Table**		
39.5-40 GHz FIXED FIXED-SATELLITE (space-to-Earth) 5.516B MOBILE MOBILE-SATELLITE (space-to-Earth) Earth exploration-satellite (space-to-Earth) **5.547**			39.5-40 GHz FIXED-SATELLITE (space-to-Earth) MOBILE-SATELLITE (space-to-Earth) US382 G117	39.5-40 GHz FIXED FIXED-SATELLITE (space-to-Earth) MOBILE NG175 US382		Regulation relevant to science services
40-40.5 GHz EARTH EXPLORATION-SATELLITE (Earth-to-space) FIXED FIXED-SATELLITE (space-to-Earth) 5.516B MOBILE MOBILE-SATELLITE (space-to-Earth) SPACE RESEARCH (Earth-to-space) Earth exploration-satellite (space-to-Earth)			40-40.5 GHz EARTH EXPLORATION-SATELLITE (Earth-to-space) FIXED-SATELLITE (space-to-Earth) MOBILE-SATELLITE (space-to-Earth) SPACE RESEARCH (Earth-to-space) Earth exploration-satellite (space-to-Earth) G117	40-40.5 GHz FIXED-SATELLITE (space-to-Earth) MOBILE-SATELLITE (space-to-Earth)	Satellite Communications (25)	1.5.2 Space research service
40.5-41 GHz FIXED FIXED-SATELLITE (space-to-Earth) BROADCASTING BROADCASTING-SATELLITE Mobile **5.547**	40.5-41 GHz FIXED FIXED-SATELLITE (space-to-Earth) 5.516B BROADCASTING BROADCASTING-SATELLITE Mobile Mobile-satellite (space-to-Earth) **5.547**	40.5-41 GHz FIXED FIXED-SATELLITE (space-to-Earth) BROADCASTING BROADCASTING-SATELLITE Mobile **5.547**	40.5-41 GHz FIXED-SATELLITE (space-to-Earth) Mobile-satellite (space-to-Earth) **US211** G117	40.5-41 GHz FIXED-SATELLITE (space-to-Earth) BROADCASTING BROADCASTING-SATELLITE Fixed Mobile Mobile-satellite (space-to-Earth) **US211**		Regulation relevant to science services
41-42.5 GHz FIXED FIXED-SATELLITE (space-to-Earth) 5.516B BROADCASTING BROADCASTING-SATELLITE Mobile **5.547** 5.551F **5.551H** 5.551I			41-42.5 GHz **US211**	41-42 GHz FIXED FIXED-SATELLITE (space-to-Earth) MOBILE BROADCASTING BROADCASTING-SATELLITE **US211**		2.5 Cosmology and structure of the universe (Cosmic Microwave Background)

		42-42.5 GHz FIXED MOBILE BROADCASTING BROADCASTING-SATELLITE **US211**		
42.5-43.5 GHz FIXED FIXED-SATELLITE (Earth-to-space) 5.552 MOBILE except aeronautical mobile RADIO ASTRONOMY **5.149 5.547**	42.5-43.5 GHz FIXED FIXED-SATELLITE (Earth-to-space) MOBILE except aeronautical mobile RADIO ASTRONOMY **US342**	42.5-43.5 GHz RADIO ASTRONOMY **US342**		2.3 The Milky Way and other galaxies (complex organic molecules, SiO masers) 2.5 Cosmology and structure of the universe (Cosmic Microwave Background)

Table of Frequency Allocations	**46.9-59 GHz (EHF)**			
48.2-48.54 GHz FIXED FIXED-SATELLITE (Earth-to-space) 5.552 (space-to-Earth) 5.516B 5.554A 5.555B MOBILE	48.2-50.2 GHz FIXED FIXED-SATELLITE (Earth-to-space) 5.338A 5.516B 5.552 MOBILE **5.149 5.340 5.555**	48.2-50.2 GHz FIXED FIXED-SATELLITE (Earth-to-space) US156 US297 MOBILE US264 **5.555 US342**		**ALL EMISSIONS PROHIBITED FROM AIRBORNE STATIONS IN 48.94 – 49.04 GHz** 2.3 The Milky Way and other galaxies (CS)
48.54-49.44 GHz FIXED FIXED-SATELLITE (Earth-to-space) 5.552 MOBILE **5.149 5.340 5.555**				
49.44-50.2 GHz FIXED FIXED-SATELLITE (Earth-to-space) 5.338A 5.552 (space-to-Earth) 5.516B 5.554A 5.555B MOBILE				3.2.4 Precipitation
50.2-50.4 GHz EARTH EXPLORATION-SATELLITE (passive) SPACE RESEARCH (passive) **5.340 5.340.1**		50.2-50.4 GHz EARTH EXPLORATION-SATELLITE (passive) SPACE RESEARCH (passive) US246		**ALL EMISSIONS PROHIBITED** 1.5.2 Space research service 3.2.1 Atm. temperature profile

Table of Frequency Allocations **46.9-59 GHz (EHF)** ***continued***

International Table			United States Table		FCC Rule Part(s)	Current Science Usage
Region 1 Table	**Region 2 Table**	**Region 3 Table**	**Federal Table**	**Non-Federal Table**		
50.4-51.4 GHz FIXED FIXED-SATELLITE (Earth-to-space) 5.338A MOBILE Mobile-satellite (Earth-to-space)			50.4-51.4 GHz FIXED FIXED-SATELLITE (Earth-to-space) US156 MOBILE MOBILE-SATELLITE (Earth-to-space) G117	50.4-51.4 GHz FIXED FIXED-SATELLITE (Earth-to-space) US156 MOBILE MOBILE-SATELLITE (Earth-to-space)		3.2.1 Atm. temperature profile
51.4-52.6 GHz FIXED 5.338A MOBILE **5.547** 5.556			51.4-52.6 GHz FIXED US157 MOBILE			3.2.1 Atm. temperature profile
52.6-54.25 EARTH EXPLORATION-SATELLITE (passive) SPACE RESEARCH (passive) **5.340** 5.556			52.6-54.25 EARTH EXPLORATION-SATELLITE (passive) SPACE RESEARCH (passive) US246			**ALL EMISSIONS PROHIBITED** 1.5.2 Space research service 2.3 The Milky Way and other galaxies (Interstellar Oxygen) 3.2.1 Atm. temperature profile
54.25-55.78 GHz EARTH EXPLORATION-SATELLITE (passive) INTER-SATELLITE 5.556A SPACE RESEARCH (passive) 5.556B			54.25-55.78 GHz EARTH EXPLORATION-SATELLITE (passive) INTER-SATELLITE 5.556A SPACE RESEARCH (passive)		Satellite Communications (25)	1.5.2 Space research service 3.2.1 Atm. temperature profile
55.78-56.9 GHz EARTH EXPLORATION-SATELLITE (passive) FIXED **5.557A** INTER-SATELLITE 5.556A MOBILE 5.558 SPACE RESEARCH (passive) **5.547** 5.557			55.78-56.9 GHz EARTH EXPLORATION-SATELLITE (passive) FIXED **US379** INTER-SATELLITE 5.556A MOBILE 5.558 SPACE RESEARCH (passive) US353 **US532**			1.5.2 Space research service 3.2.1 Atm. temperature profile
56.9-57 GHz EARTH EXPLORATION-SATELLITE (passive) FIXED INTER-SATELLITE 5.558A MOBILE 5.558 SPACE RESEARCH (passive) **5.547** 5.557			56.9-57 GHz EARTH EXPLORATION-SATELLITE (passive) FIXED INTER-SATELLITE G128 MOBILE 5.558 SPACE RESEARCH (passive) **US532**	56.9-57 GHz EARTH EXPLORATION-SATELLITE (passive) FIXED MOBILE 5.558 SPACE RESEARCH (passive) **US532**		1.5.2 Space research service 3.2.1 Atm. temperature profile

57-58.2 GHz EARTH EXPLORATION-SATELLITE (passive) FIXED INTER-SATELLITE 5.556A MOBILE 5.558 SPACE RESEARCH (passive) **5.547** 5.557	57-58.2 GHz EARTH EXPLORATION-SATELLITE (passive) FIXED INTER-SATELLITE 5.556A MOBILE 5.558 SPACE RESEARCH (passive) **US532**	RF Devices (15) Satellite Communications (25)	1.5.2 Space research service 3.2.1 Atm. temperature profile
58.2-59 GHz EARTH EXPLORATION-SATELLITE (passive) FIXED MOBILE SPACE RESEARCH (passive) **5.547** 5.556	58.2-59 GHz EARTH EXPLORATION-SATELLITE (passive) FIXED MOBILE SPACE RESEARCH (passive) US353 US354	RF Devices (15)	1.5.2 Space research service 3.2.1 Atm. temperature profile

Table of Frequency Allocations	**59-86 GHz (EHF)**			
59-59.3 GHz EARTH EXPLORATION-SATELLITE (passive) FIXED INTER-SATELLITE 5.556A MOBILE 5.558 RADIOLOCATION 5.559 SPACE RESEARCH (passive)	59-59.3 GHz EARTH EXPLORATION-SATELLITE (passive) FIXED INTER-SATELLITE 5.556A MOBILE 5.558 RADIOLOCATION 5.559 SPACE RESEARCH (passive) US353	59-59.3 EARTH EXPLORATION-SATELLITE (passive) FIXED MOBILE 5.558 RADIOLOCATION 5.559 SPACE RESEARCH (passive) US353		1.5.2 Space research service 3.2.1 Atm. temperature profile
59.3-64 GHz FIXED INTER-SATELLITE MOBILE 5.558 RADIOLOCATION 5.559 5.138	59.3-64 GHz FIXED INTER-SATELLITE MOBILE 5.558 RADIOLOCATION 5.559 5.138 US353	59.3-64 GHz FIXED MOBILE 5.558 RADIOLOCATION 5.559 5.138 US353	RF Devices (15) ISM Equipment (18)	2.5 Cosmology and structure of the universe (Cosmic Microwave Background) 3.2.1 Atm. temperature profile 3.2.5 Atm. chemistry – ClO, H_2O, SO_2, O_3
64-65 GHz FIXED INTER-SATELLITE MOBILE except aeronautical mobile **5.547** 5.556	64-65 GHz FIXED INTER-SATELLITE MOBILE except aeronautical mobile	64-65 GHz FIXED MOBILE except aeronautical mobile		Regulation relevant to science services

Table of Frequency Allocations **59-86 GHz (EHF)** ***continued***

International Table			United States Table		FCC Rule Part(s)	Current Science Usage
Region 1 Table	**Region 2 Table**	**Region 3 Table**	**Federal Table**	**Non-Federal Table**		
65-66 GHz EARTH EXPLORATION-SATELLITE FIXED INTER-SATELLITE MOBILE except aeronautical mobile SPACE RESEARCH **5.547**			65-66 GHz EARTH EXPLORATION-SATELLITE FIXED MOBILE except aeronautical mobile SPACE RESEARCH	65-66 GHz EARTH EXPLORATION-SATELLITE FIXED INTER-SATELLITE MOBILE except aeronautical mobile SPACE RESEARCH	Satellite Communications (25)	1.5.2 Space research service
74-76 GHz FIXED FIXED-SATELLITE (space-to-Earth) MOBILE BROADCASTING BROADCASTING-SATELLITE Space research (space-to-Earth) 5.561			74-76 GHz FIXED FIXED-SATELLITE (space-to-Earth) MOBILE Space research (space-to-Earth) US389	74-76 GHz FIXED FIXED-SATELLITE (space-to-Earth) MOBILE BROADCASTING BROADCASTING-SATELLITE Space research (space-to-Earth) US389	RF Devices (15) Fixed Microwave (101)	1.5.2 Space research service 2.3 The Milky Way and other Galaxies (complex organic molecules $HCNH^+$, N_2O, H_2CO) 2.5 Cosmology and structure of the Universe (Cosmic Microwave Background)
76-77.5 GHz RADIO ASTRONOMY RADIOLOCATION Amateur Amateur-satellite Space research (space-to-Earth) **5.149**			76-77.5 GHz RADIO ASTRONOMY RADIOLOCATION Space research (space-to-Earth) **US342**	76-77 GHz RADIO ASTRONOMY RADIOLOCATION Amateur Space research (space-to-Earth) **US342**	RF Devices (15)	1.5.2 Space research service 2.3 The Milky Way and other galaxies (Deuterated water HDO)
				77-77.5 RADIO ASTRONOMY RADIOLOCATION Amateur Amateur-satellite Space research (space-to-Earth) **US342**	RF Devices (15) Amateur Radio (97)	1.5.2 Space research service 2.3 The Milky Way and other galaxies (Deuterated water HDO)
77.5-78 GHz AMATEUR AMATEUR-SATELLITE Radio astronomy Space research (space-to-Earth)			77.5-78 GHz Radio astronomy Space research (space-to-Earth) **US342**	77.5-78 GHz AMATEUR AMATEUR-SATELLITE Radio astronomy Space research (space-		1.5.2 Space research service 2.3 The Milky Way and other galaxies (Complex organic molecules)

5.149		to-Earth) **US342**		
78-79 GHz RADIOLOCATION Amateur Amateur-satellite Radio astronomy Space research (space-to-Earth) **5.149 5.560**	78-79 GHz RADIO ASTRONOMY RADIOLOCATION Space research (space-to-Earth) **5.560 US342**	78-79 GHz RADIO ASTRONOMY RADIOLOCATION Amateur Amateur-satellite Space research (space-to-Earth) **5.560 US342**		1.5.2 Space research service 2.3 The Milky Way and other galaxies (Complex organic molecules) 3.2.6 Clouds
79-81 GHz RADIO ASTRONOMY RADIOLOCATION Amateur Amateur-satellite Space research (space-to-Earth) **5.149**	79-81 GHz RADIO ASTRONOMY RADIOLOCATION Space research (space-to-Earth) **US342**	79-81 GHz RADIO ASTRONOMY RADIOLOCATION Amateur Amateur-satellite Space research (space-to-Earth) **US342**		1.5.2 Space research service 2.3 The Milky Way and other galaxies (Complex organic molecules)
81-84 GHz FIXED 5.338A FIXED-SATELLITE (Earth-to-space) MOBILE MOBILE-SATELLITE (Earth-to-space) RADIO ASTRONOMY Space research (space-to-Earth) **5.149** 5.561A	81-84 GHz FIXED FIXED-SATELLITE (Earth-to-space) US297 MOBILE MOBILE-SATELLITE (Earth-to-space) RADIO ASTRONOMY Space research (space-to-Earth) US161 **US342** US389		RF Devices (15) Fixed Microwave (101)	1.5.2 Space research service 2.3 The Milky Way and other galaxies (Complex organic molecules such as C_3H_2 and HC_3N)
84-86 GHz FIXED 5.338A FIXED-SATELLITE (Earth-to-space) 5.561B MOBILE RADIO ASTRONOMY **5.149**	84-86 GHz FIXED FIXED-SATELLITE (Earth-to-space) MOBILE RADIO ASTRONOMY US161 **US342** US389			2.3 The Milky Way and other galaxies (Complex organic molecules such as NH_2D and CH_3CCH)

Table of Frequency Allocations **86-130 GHz (EHF)**

International Table			United States Table		FCC Rule Part(s)	Current Science Usage
Region 1 Table	**Region 2 Table**	**Region 3 Table**	**Federal Table**	**Non-Federal Table**		
86-92 GHz EARTH EXPLORATION-SATELLITE (passive) RADIO ASTRONOMY SPACE RESEARCH (passive) **5.340**			86-92 GHz EARTH EXPLORATION-SATELLITE (passive) RADIO ASTRONOMY **US74** SPACE RESEARCH (passive) US246			**ALL EMISSIONS PROHIBITED** 1.5.2 Space research service 2.3 The Milky Way and other galaxies (Complex organic molecules such as SiO, $H^{13}CO^+$, HCO^+, HCN, CCH, HNC, CH_3CN, $HC^{15}N$, $H^{13}CN$, $HN^{13}C$, HCO) 3.2.2 Atm. water vapor 3.2.4 Precipitation 3.2.6 Clouds 3.4.2 Sea ice 3.4.4 Snow
92-94 GHz FIXED 5.338A MOBILE RADIO ASTRONOMY RADIOLOCATION **5.149**			92-94 GHz FIXED MOBILE RADIO ASTRONOMY RADIOLOCATION US161 **US342**		RF Devices (15) Fixed Microwave (101)	2.3 The Milky Way and other galaxies (Complex organic molecules such as ^{13}CS,NH_2^+, AINC) 2.5 Cosmology and structure of the universe (Cosmic Microwave Background)
94-94.1 GHz EARTH EXPLORATION-SATELLITE (active) RADIOLOCATION SPACE RESEARCH (active) Radio astronomy **5.562 5.562A**			94-94.1 GHz EARTH EXPLORATION-SATELLITE (active) RADIOLOCATION SPACE RESEARCH (active) Radio astronomy **5.562 5.562A**	94-94.1 GHz RADIOLOCATION Radio astronomy **5.562A**	RF Devices (15)	1.5.2 Space research service 3.2.4 Precipitation 3.2.6 Clouds
94.1-95 GHz FIXED MOBILE RADIO ASTRONOMY RADIOLOCATION **5.149**			94.1-95 GHz FIXED MOBILE RADIO ASTRONOMY RADIOLOCATION US161 **US342**		RF Devices (15) Fixed Microwave (101)	Regulation relevant to science services
95-100 GHz FIXED MOBILE RADIO ASTRONOMY RADIOLOCATION			95-100 GHz FIXED MOBILE RADIO ASTRONOMY RADIOLOCATION			2.3 The Milky Way and other galaxies (Complex organic Molecules such as CS, SO, $C^{34}S$, MgNC)

RADIONAVIGATION RADIONAVIGATION-SATELLITE **5.149** 5.554	RADIONAVIGATION RADIONAVIGATION-SATELLITE 5.554 **US342**		
100-102 GHz EARTH EXPLORATION-SATELLITE (passive) RADIO ASTRONOMY SPACE RESEARCH (passive) **5.340 5.341**	100-102 GHz EARTH EXPLORATION-SATELLITE (passive) RADIO ASTRONOMY **US74** SPACE RESEARCH (passive) **5.341** US246		**ALL EMISSIONS PROHIBITED** 1.5.2 Space research service 2.2.8 Extraterrestrial intelligence 2.3 The Milky Way and other galaxies (Complex organic molecules such as extragalactic CO, HC_3N) 2.5 Cosmology and structure of the universe (Cosmic Microwave Background)
102-105 GHz FIXED MOBILE RADIO ASTRONOMY **5.149 5.341**	102-105 GHz FIXED MOBILE RADIO ASTRONOMY **5.341 US342**		2.2.8 Extraterrestrial intelligence 2.3 The Milky Way and other galaxies (Complex organic molecules such as CH_3CCH)
105-109.5 GHz FIXED MOBILE RADIO ASTRONOMY SPACE RESEARCH (passive) **5.562B** **5.149 5.341**	105-109.5 GHz FIXED MOBILE RADIO ASTRONOMY SPACE RESEARCH (passive) **5.562B** **5.341 US342**		2.2.8 Extraterrestrial intelligence 1.5.2 Space research service 2.3 The Milky Way and other galaxies (Complex organic molecules such as SO, CN, CO,^{13}CO, $C^{18}O$, $C^{17}O$, ^{13}CN)
109.5-111.8 GHz EARTH EXPLORATION-SATELLITE (passive) RADIO ASTRONOMY SPACE RESEARCH (passive) **5.340 5.341**	109.5-111.8 GHz EARTH EXPLORATION-SATELLITE (passive) RADIO ASTRONOMY **US74** SPACE RESEARCH (passive) **5.341** US246		**ALL EMISSIONS PROHIBITED** 1.5.2 Space research service 2.2.8 Extraterrestrial intelligence 2.3 The Milky Way and other galaxies (Complex organic molecules such as SO, CN, CO, ^{13}CO, $C^{18}O$, $C^{17}O$, ^{13}CN)
111.8-114.25 GHz FIXED MOBILE RADIO ASTRONOMY SPACE RESEARCH (passive) **5.562B** **5.149 5.341**	111.8-114.25 GHz FIXED MOBILE RADIO ASTRONOMY SPACE RESEARCH (passive) **5.562B** **5.341 US342**		1.5.2 Space research service 2.2.8 Extraterrestrial intelligence 2.3 The Milky Way and other galaxies (Complex organic molecules such as SO, CN, CO, ^{13}CO, $C^{18}O$, $C^{17}O$, ^{13}CN) 3.2.1 Atm temperature profile 3.2.5 Atm. chemistry

Table of Frequency Allocations **86-130 GHz (EHF)** ***continued***

International Table			United States Table		FCC Rule Part(s)	Current Science Usage
Region 1 Table	**Region 2 Table**	**Region 3 Table**	**Federal Table**	**Non-Federal Table**		
114.25-116 GHz EARTH EXPLORATION-SATELLITE (passive) RADIO ASTRONOMY SPACE RESEARCH (passive) **5.340 5.341**			114.25-116 GHz EARTH EXPLORATION-SATELLITE (passive) RADIO ASTRONOMY **US74** SPACE RESEARCH (passive) **5.341** US246			**ALL EMISSIONS PROHIBITED** 1.5.2 Space research service 2.2.8 Extraterrestrial intelligence 2.3 The Milky Way and other galaxies (Complex organic molecules such as SO, CN, CO, ^{13}CO, C^{18}O, C^{17}O, ^{13}CN) 3.2.1 Atm temperature profile 3.2.5 Atm. chemistry
116-119.98 GHz EARTH EXPLORATION-SATELLITE (passive) INTER-SATELLITE 5.562C SPACE RESEARCH (passive) **5.341**			116-122.25 GHz EARTH EXPLORATION-SATELLITE (passive) INTER-SATELLITE 5.562C SPACE RESEARCH (passive) 5.138 **5.341 US211**		ISM Equipment (18)	1.5.2 Space research service 2.2.8 Extraterrestrial intelligence 3.2.1 Atm. temperature profile 3.2.4 Precipitation
119.98-122.25 GHz EARTH EXPLORATION-SATELLITE (passive) INTER-SATELLITE 5.562C SPACE RESEARCH (passive) 5.138 **5.341**						1.5.2 Space research service 2.2.8 Extraterrestrial intelligence
123-130 GHz FIXED-SATELLITE (space-to-Earth) MOBILE-SATELLITE (space-to-Earth) RADIONAVIGATION RADIONAVIGATION-SATELLITE Radio astronomy **5.562D** **5.149** 5.554			123-130 GHz FIXED-SATELLITE (space-to-Earth) MOBILE-SATELLITE (space-to-Earth) RADIONAVIGATION RADIONAVIGATION-SATELLITE Radio astronomy 5.554 **US211 US342**			Regulation relevant to science services

Table of Frequency Allocations **130-200 GHz (EHF)**

International Table			United States Table		FCC Rule Part(s)	Current Science Usage
130-134 GHz EARTH EXPLORATION-SATELLITE (active) **5.562E** FIXED INTER-SATELLITE MOBILE 5.558 RADIO ASTRONOMY **5.149 5.562A**			130-134 GHz EARTH EXPLORATION-SATELLITE (active) **5.562E** FIXED INTER-SATELLITE MOBILE 5.558 RADIO ASTRONOMY **5.562A US342**			Regulation relevant to science services
134-136 GHz AMATEUR			134-136 GHz Radio astronomy	134-136 GHz AMATEUR	Amateur Radio (97)	Regulation relevant to science services

AMATEUR-SATELLITE Radio astronomy		AMATEUR-SATELLITE Radio astronomy		
136-141 GHz RADIO ASTRONOMY RADIOLOCATION Amateur Amateur-satellite **5.149**	136-141 GHz RADIO ASTRONOMY RADIOLOCATION **US342**	136-141 GHz RADIO ASTRONOMY RADIOLOCATION Amateur Amateur-satellite **US342**		2.3 The Milky Way and other galaxies (Complex organic molecules such as H_2CO)
141-148.5 GHz FIXED MOBILE RADIO ASTRONOMY RADIOLOCATION **5.149**	141-148.5 GHz FIXED MOBILE RADIO ASTRONOMY RADIOLOCATION **US342**			2.3 The Milky Way and other galaxies (Complex organic molecules such as H_2CO, DCN, $DC0^+$) 2.5 Cosmology and structure of the universe (Cosmic Microwave Background)
148.5-151.5 GHz EARTH EXPLORATION-SATELLITE (passive) RADIO ASTRONOMY SPACE RESEARCH (passive) **5.340**	148.5-151.5 GHz EARTH EXPLORATION-SATELLITE (passive) RADIO ASTRONOMY **US74** SPACE RESEARCH (passive) US246			**ALL EMISSIONS PROHIBITED** 1.5.2 Space research service 2.3 The Milky Way and other galaxies (Complex organic molecules such as NO, H_2CO) 3.2.2 Atm. water vapor 3.2.4 Precipitation-Hydrometeor 3.2.6 Clouds
151.5-155.5 GHz FIXED MOBILE RADIO ASTRONOMY RADIOLOCATION **5.149**	151.5-155.5 GHz FIXED MOBILE RADIO ASTRONOMY RADIOLOCATION **US342**			2.3 The Milky Way and other galaxies (Complex organic molecules such as CS, CH_3CN, CH_3CCH)
155.5-158.5 GHz EARTH EXPLORATION-SATELLITE (passive) FIXED MOBILE RADIO ASTRONOMY SPACE RESEARCH (passive) **5.562B** **5.149** **5.562F** 5.562G	155.5-158.5 GHz EARTH EXPLORATION-SATELLITE (passive) FIXED MOBILE RADIO ASTRONOMY SPACE RESEARCH (passive) **5.562B** **5.562F** 5.562G **US342**			1.5.2 Space research service 3.2.2 Atm water vapor 3.2.4 Precipitation 3.2.6 Clouds
158.5-164 GHz FIXED FIXED-SATELLITE (space-to-Earth) MOBILE MOBILE-SATELLITE (space-to-Earth)	158.5-164 GHz FIXED FIXED-SATELLITE (space-to-Earth) MOBILE MOBILE-SATELLITE (space-to-Earth) **US211**			Regulation relevant to science services

Table of Frequency Allocations **130-200 GHz (EHF)** ***continued***

International Table			United States Table		FCC Rule Part(s)	Current Science Usage
Region 1 Table	**Region 2 Table**	**Region 3 Table**	**Federal Table**	**Non-Federal Table**		
164-167 GHz EARTH EXPLORATION-SATELLITE (passive) RADIO ASTRONOMY SPACE RESEARCH (passive) **5.340**			164-167 GHz EARTH EXPLORATION-SATELLITE (passive) RADIO ASTRONOMY **US74** SPACE RESEARCH (passive) US246			**ALL EMISSIONS PROHIBITED** 1.5.2 Space research service 2.3 The Milky Way and other galaxies (Complex organic molecules such as H_2S at 168.7 GHz) 3.2.2 Atm. water vapor 3.2.4 Precipitation-Hydrometeor 3.2.6 Clouds
167-174.5 GHz FIXED FIXED-SATELLITE (space-to-Earth) INTER-SATELLITE MOBILE 5.558 **5.149 5.562D**			167-174.5 GHz FIXED FIXED-SATELLITE (space-to-Earth) INTER-SATELLITE MOBILE 5.558 **US211 US342**			2.3 The Milky Way and other galaxies (Complex organic molecules such as H_2S at 168.7 GHz) 3.2.2 Atm. water vapor
174.8-182 GHz EARTH EXPLORATION-SATELLITE (passive) INTER-SATELLITE 5.562H SPACE RESEARCH (passive)			174.8-182 GHz EARTH EXPLORATION-SATELLITE (passive) INTER-SATELLITE 5.562H SPACE RESEARCH (passive)			1.5.2 Space research service 3.2.2 Atm. water vapor
182-185 GHz EARTH EXPLORATION-SATELLITE (passive) RADIO ASTRONOMY SPACE RESEARCH (passive) **5.340**			182-185 GHz EARTH EXPLORATION-SATELLITE (passive) RADIO ASTRONOMY SPACE RESEARCH (passive) US246			**ALL EMISSIONS PROHIBITED** 1.5.2 Space research service 3.2.2 Atm. water vapor 3.2.4 Precipitation-Hydrometeor 3.2.5 Atm. chemistry – ClO, H_2O, SO_2, O_3, HNO_3 3.2.6 Clouds
185-190 GHz EARTH EXPLORATION-SATELLITE (passive) INTER-SATELLITE 5.562H SPACE RESEARCH (passive)			185-190 GHz EARTH EXPLORATION-SATELLITE (passive) INTER-SATELLITE 5.562H SPACE RESEARCH (passive)			1.5.2 Space research service 3.2.2 Atm. water vapor 3.2.5 Atm. chemistry – HNO_3
190-191.8 GHz EARTH EXPLORATION-SATELLITE (passive) SPACE RESEARCH (passive) **5.340**			190-191.8 GHz EARTH EXPLORATION-SATELLITE (passive) SPACE RESEARCH (passive) US246			**ALL EMISSIONS PROHIBITED** 1.5.2 Space research service 3.2.2 Atm. water vapor 3.2.5 Atm. chemistry – HNO_3
191.8-200 GHz FIXED INTER-SATELLITE			191.8-200 GHz FIXED INTER-SATELLITE			2.2.8 Extraterrestrial intelligence

MOBILE 5.558 MOBILE-SATELLITE RADIONAVIGATION RADIONAVIGATION-SATELLITE **5.149 5.341** 5.554	MOBILE 5.558 MOBILE-SATELLITE RADIONAVIGATION RADIONAVIGATION-SATELLITE **5.341** 5.554 **US211 US342**		

Table of Frequency Allocations	**200-1000 GHz (EHF)**		
200-209 GHz EARTH EXPLORATION-SATELLITE (passive) RADIO ASTRONOMY SPACE RESEARCH (passive) **5.340 5.341** 5.563A	200-209 GHz EARTH EXPLORATION-SATELLITE (passive) RADIO ASTRONOMY **US74** SPACE RESEARCH (passive) **5.341** 5.563A US246		**ALL EMISSIONS PROHIBITED** 1.5.2 Space research service 2.2.8 Extraterrestrial intelligence 3.2.5 Atm. chemistry – ClO, H_2O, SO_2, O_3 3.2.6 Clouds
209-217 GHz FIXED FIXED-SATELLITE (Earth-to-space) MOBILE RADIO ASTRONOMY **5.149 5.341**	209-217 GHz FIXED FIXED-SATELLITE (Earth-to-space) MOBILE RADIO ASTRONOMY **5.341 US342**		2.2.8 Extraterrestrial intelligence
217-226 GHz FIXED FIXED-SATELLITE (Earth-to-space) MOBILE RADIO ASTRONOMY SPACE RESEARCH (passive) 5.562B **5.149 5.341**	217-226 GHz FIXED FIXED-SATELLITE (Earth-to-space) MOBILE RADIO ASTRONOMY SPACE RESEARCH (passive) 5.562B **5.341 US342**		1.5.2 Space research service 2.2.8 Extraterrestrial intelligence 2.5 Cosmology and structure of the universe (Cosmic Microwave Background) 3.2.4 Precipitation-Hydrometeor
226-231.5 GHz EARTH EXPLORATION-SATELLITE (passive) RADIO ASTRONOMY SPACE RESEARCH (passive) **5.340**	226-231.5 GHz EARTH EXPLORATION-SATELLITE (passive) RADIO ASTRONOMY SPACE RESEARCH (passive) US246		**ALL EMISSIONS PROHIBITED** 1.5.2 Space research service 2.3 The Milky Way and other galaxies (Common organic molecules such as ^{12}CO)
235-238 GHz EARTH EXPLORATION-SATELLITE (passive) FIXED-SATELLITE (space-to-Earth) SPACE RESEARCH (passive) 5.563A **5.563B**	235-238 GHz EARTH EXPLORATION-SATELLITE (passive) FIXED-SATELLITE (space-to-Earth) SPACE RESEARCH (passive) 5.563A **5.563B**		1.5.2 Space research service 3.2.6 Clouds

Table of Frequency Allocations **200-1000 GHz (EHF)** ***continued***

International Table			United States Table		FCC Rule Part(s)	Current Science Usage
Region 1 Table	**Region 2 Table**	**Region 3 Table**	**Federal Table**	**Non-Federal Table**		
238-240 GHz FIXED FIXED-SATELLITE (space-to-Earth) MOBILE RADIOLOCATION RADIONAVIGATION RADIONAVIGATION-SATELLITE			238-240 GHz FIXED FIXED-SATELLITE (space-to-Earth) MOBILE RADIOLOCATION RADIONAVIGATION RADIONAVIGATION- SATELLITE			3.2.5 Atm chemistry – O_3 3.2.6 Clouds
241-248 GHz RADIO ASTRONOMY RADIOLOCATION Amateur Amateur-satellite 5.138 **5.149**			241-248 GHz RADIO ASTRONOMY RADIOLOCATION 5.138 **US342**	241-248 GHz RADIO ASTRONOMY RADIOLOCATION Amateur Amateur-satellite 5.138 **US342**	ISM Equipment (18) Amateur Radio (97)	Regulation relevant to science services
248-250 GHz AMATEUR AMATEUR-SATELLITE Radio astronomy **5.149**			248-250 GHz Radio astronomy **US342**	248-250 GHz AMATEUR AMATEUR-SATELLITE Radio astronomy **US342**	Amateur Radio (97)	Regulation relevant to science services
250-252 GHz EARTH EXPLORATION-SATELLITE (passive) RADIO ASTRONOMY SPACE RESEARCH (passive) **5.340** 5.563A			250-252 GHz EARTH EXPLORATION-SATELLITE (passive) RADIO ASTRONOMY **US74** SPACE RESEARCH (passive) 5.563A US246			**ALL EMISSIONS PROHIBITED** 1.5.2 Space research service 2.3 The Milky Way and other galaxies (Common organic molecules such as NO) 3.2.6 Clouds
252-265 GHz FIXED MOBILE MOBILE-SATELLITE (Earth-to-space) RADIO ASTRONOMY RADIONAVIGATION RADIONAVIGATION-SATELLITE **5.149** 5.554			252-265 GHz FIXED MOBILE MOBILE-SATELLITE (Earth-to-space) RADIO ASTRONOMY RADIONAVIGATION RADIONAVIGATION-SATELLITE 5.554 **US211** **US342**			2.3 The Milky Way and other galaxies (Common organic molecules such as HCN, CCH)
265-275 GHz FIXED FIXED-SATELLITE (Earth-to-space) MOBILE RADIO ASTRONOMY **5.149** 5.563A			265-275 GHz FIXED FIXED-SATELLITE (Earth-to-space) MOBILE RADIO ASTRONOMY 5.563A **US342**			2.3 The Milky Way and other galaxies (Organic molecules such as HCO^+) 3.2.6 Clouds

275-3000 GHz (Not allocated) **5.565**	275-1000 GHz (Not allocated) **US565**	Amateur Radio (97)	1.5.2 Space research service 2.3 The Milky Way and other galaxies (Organic molecules such as N_2H+, CO, CS, CN, HCO^+, HCN, MgH, H_3O^+, SiO) 2.5 Cosmology and structure of the universe (Cosmic Microwave Background) 3.2.4 Precipitation-Hydrometeor 3.2.5 Atm chemistry – O_3 and stratosphere studies; atmospheric composition 3.2.6 Clouds

INTERNATIONAL FOOTNOTES

5.53 Administrations authorizing the use of frequencies below 8.3 kHz shall ensure that no harmful interference is caused to services to which the bands above 8.3 kHz are allocated. (WRC-12)

5.54 Administrations conducting scientific research using frequencies below 8.3 kHz are urged to advise other administrations that may be concerned in order that such research may be afforded all practicable protection from harmful interference. (WRC-12)

5.54A Use of the 8.3-11.3 kHz frequency band by stations in the meteorological aids service is limited to passive use only. In the band 9-11.3 kHz, meteorological aids stations shall not claim protection from stations of the radionavigation service submitted for notification to the Bureau prior to 1 January 2013. For sharing between stations of the meteorological aids service and stations in the radionavigation service submitted for notification after this date, the most recent version of Recommendation ITU-R RS.1881 should be applied. (WRC-12)

5.54B *Additional allocation:* in Algeria, Saudi Arabia, Egypt, the United Arab Emirates, the Russian Federation, Iraq, Lebanon, Morocco, Qatar, the Syrian Arab Republic, Sudan and Tunisia, the frequency band 8.3-9 kHz is also allocated to the radionavigation, fixed and mobile services on a primary basis. (WRC-12)

5.54C *Additional allocation:* in China, the frequency band 8.3-9 kHz is also allocated to the maritime radionavigation and maritime mobile services on a primary basis. (WRC-12)

5.57 The use of the bands 14-19.95 kHz, 20.05-70 kHz and 70-90 kHz (72-84 kHz and 86-90 kHz in Region 1) by the maritime mobile service is limited to coast radiotelegraph stations (A1A and F1B only). Exceptionally, the use of class J2B or J7B emissions is authorized subject to the necessary bandwidth not exceeding that normally used for class A1A or F1B emissions in the band concerned.

5.56 The stations of services to which the bands 14-19.95 kHz and 20.05-70 kHz and in Region 1 also the bands 72-84 kHz and 86-90 kHz are allocated may transmit standard frequency and time signals. Such stations shall be afforded protection from harmful interference. In Armenia, Azerbaijan, Belarus, the Russian Federation, Georgia, Kazakhstan, Kyrgyzstan, Tajikistan and Turkmenistan, the frequencies 25 kHz and 50 kHz will be used for this purpose under the same conditions. (WRC-12)

5.58 *Additional allocation:* in Armenia, Azerbaijan, the Russian Federation, Georgia, Kazakhstan, Kyrgyzstan, Tajikistan and Turkmenistan, the band 67-70 kHz is also allocated to the radionavigation service on a primary basis.

5.92 Some countries of Region 1 use radiodetermination systems in the bands 1606.5-1625 kHz, 1635-1800 kHz, 1850-2160 kHz, 2194-2300 kHz, 2502-2850 kHz and 3500-3800 kHz, subject to agreement obtained under No. 9.21. The radiated mean power of these stations shall not exceed 50 W.

5.103 In Region 1, in making assignments to stations in the fixed and mobile services in the bands 1850-2045 kHz, 2194-2498 kHz, 2502-2625 kHz and 2650-2850 kHz, administrations should bear in mind the special requirements of the maritime mobile service.

5.104 In Region 1, the use of the band 2025-2045 kHz by the meteorological aids service is limited to oceanographic buoy stations.

5.111 The carrier frequencies 2182 kHz, 3023 kHz, 5680 kHz, 8364 kHz and the frequencies 121.5 MHz, 156.525 MHz, 156.8 MHz and 243 MHz may also be used, in accordance with the procedures in force for terrestrial radiocommunication services, for search and rescue operations concerning manned space vehicles. The conditions for the use of the frequencies are prescribed in Article 31.

The same applies to the frequencies 10003 kHz, 14993 kHz and 19993 kHz, but in each of these cases emissions must be confined in a band of ± 3 kHz about the frequency. (WRC-07)

5.114 *Alternative allocation:* in Denmark and Iraq, the band 2502-2625 kHz is allocated to the fixed and mobile, except aeronautical mobile, services on a primary basis. (WRC-12)

5.122 *Alternative allocation:* in Bolivia, Chile, Ecuador, Paraguay, Peru and Uruguay, the band 3750-4000 kHz is allocated to the fixed and mobile, except aeronautical mobile, services on a primary basis. (WRC-07)

5.125 *Additional allocation:* in Greenland, the band 3950-4000 kHz is also allocated to the broadcasting service on a primary basis. The power of the broadcasting stations operating in this band shall not exceed that necessary for a national service and shall in no case exceed 5 kW.

5.126 In Region 3, the stations of those services to which the band 3995-4005 kHz is allocated may transmit standard frequency and time signals.

5.132A Stations in the radiolocation service shall not cause harmful interference to, or claim protection from, stations operating in the fixed or mobile services. Applications of the radiolocation service are limited to oceanographic radars operating in accordance with Resolution 612 (Rev.WRC-12). (WRC-12)

5.138 The following bands:

6765-6795 kHz (centre frequency 6780 kHz),
433.05-434.79 MHz (centre frequency 433.92 MHz) in Region 1 except in the countries mentioned in No. 5.280,
61-61.5 GHz (centre frequency 61.25 GHz),
122-123 GHz (centre frequency 122.5 GHz), and
244-246 GHz (centre frequency 245 GHz)

are designated for industrial, scientific and medical (ISM) applications. The use of these frequency bands for ISM applications shall be subject to special authorization by the administration concerned, in agreement with other administrations whose radiocommunication services might be affected. In applying this provision, administrations shall have due regard to the latest relevant ITU-R Recommendations.

5.149 In making assignments to stations of other services to which the bands:

13360-13410 kHz,
25550-25670 kHz,
37.5-38.25 MHz,
73-74.6 MHz in Regions 1 and 3,
150.05-153 MHz in Region 1,
322-328.6 MHz,
406.1-410 MHz,
608-614 MHz in Regions 1 and 3,
1330-1400 MHz,
1610.6-1613.8 MHz,
1660-1670 MHz,
1718.8-1722.2 MHz,
2655-2690 MHz,
3260-3267 MHz,
3332-3339 MHz,
3345.8-3352.5 MHz,
4825-4835 MHz,
4950-4990 MHz,
4990-5000 MHz,
6650-6675.2 MHz,
10.6-10.68 GHz,
14.47-14.5 GHz,
22.01-22.21 GHz,
22.21-22.5 GHz,
22.81-22.86 GHz,
23.07-23.12 GHz,
31.2-31.3 GHz,
31.5-31.8 GHz in Regions 1 and 3,
36.43-36.5 GHz,
42.5-43.5 GHz,
48.94-49.04 GHz,
76-86 GHz,
92-94 GHz,
94.1-100 GHz,
102-109.5 GHz,
111.8-114.25 GHz,
128.33-128.59 GHz,
129.23-129.49 GHz,
130-134 GHz,
136-148.5 GHz,
151.5-158.5 GHz,
168.59-168.93 GHz,
171.11-171.45 GHz,
172.31-172.65 GHz,
173.52-173.85 GHz,
195.75-196.15 GHz,
209-226 GHz,
241-250 GHz,
252-275 GHz

are allocated, administrations are urged to take all practicable steps to protect the radio astronomy service from harmful interference. Emissions from spaceborne or airborne stations can be particularly serious sources of interference to the radio astronomy service (see Nos. 4.5 and 4.6 and Article 29). (WRC-07)

5.150 The following bands:

13553-13567 kHz (centre frequency 13560 kHz),
26957-27283 kHz (centre frequency 27120 kHz),
40.66-40.70 MHz (centre frequency 40.68 MHz),
902-928 MHz in Region 2 (centre frequency 915 MHz),
2400-2500 MHz (centre frequency 2450 MHz),
5725-5875 MHz (centre frequency 5800 MHz), and
24-24.25 GHz (centre frequency 24.125 GHz)

are also designated for industrial, scientific and medical (ISM) applications. Radiocommunication services operating within these bands must accept harmful interference which may be caused by these applications. ISM equipment operating in these bands is subject to the provisions of No. 15.13.

5.160 *Additional allocation:* in Botswana, Burundi, Dem. Rep. of the Congo and Rwanda, the band 41-44 MHz is also allocated to the aeronautical radionavigation service on a primary basis. (WRC-12)

5.161 *Additional allocation:* in Iran (Islamic Republic of) and Japan, the band 41-44 MHz is also allocated to the radiolocation service on a secondary basis.

5.173 *Different category of service:* in the French overseas departments and communities in Region 2, Guyana, Jamaica and Mexico, the allocation of the band 68-72 MHz to the fixed and mobile services is on a primary basis (see No. 5.33).

5.175 *Alternative allocation:* in Armenia, Azerbaijan, Belarus, the Russian Federation, Georgia, Kazakhstan, Moldova, Uzbekistan, Kyrgyzstan, Tajikistan, Turkmenistan and Ukraine, the bands 68-73 MHz and 76-87.5 MHz are allocated to the broadcasting service on a primary basis. In Latvia and Lithuania, the bands 68-73 MHz and 76-87.5 MHz are allocated to the broadcasting and mobile, except aeronautical mobile, services on a primary basis. The services to which these bands are allocated in other countries and the broadcasting service in the countries listed above are subject to agreements with the neighbouring countries concerned. (WRC-07)

5.176 *Additional allocation:* in Australia, China, Korea (Rep. of), the Philippines, the Dem. People's Rep. of Korea and Samoa, the band 68-74 MHz is also allocated to the broadcasting service on a primary basis. (WRC-07)

5.177 *Additional allocation:* in Armenia, Azerbaijan, Belarus, the Russian Federation, Georgia, Kazakhstan, Uzbekistan, Kyrgyzstan, Tajikistan, Turkmenistan and Ukraine, the band 73-74 MHz is also allocated to the broadcasting service on a primary basis, subject to agreement obtained under No. 9.21. (WRC-07)

5.178 *Additional allocation:* in Colombia, Cuba, El Salvador, Guatemala, Guyana, Honduras and Nicaragua, the band 73-74.6 MHz is also allocated to the fixed and mobile services on a secondary basis. (WRC-12)

5.179 *Additional allocation:* in Armenia, Azerbaijan, Belarus, China, the Russian Federation, Georgia, Kazakhstan, Lithuania, Mongolia, Kyrgyzstan, Tajikistan, Turkmenistan and Ukraine, the bands 74.6-74.8 MHz and 75.2-75.4 MHz are also allocated to the aeronautical radionavigation service, on a primary basis, for ground-based transmitters only. (WRC-12)

5.204 *Different category of service:* in Afghanistan, Saudi Arabia, Bahrain, Bangladesh, Brunei Darussalam, China, Cuba, the United Arab Emirates, India, Indonesia, Iran (Islamic Republic of), Iraq, Kuwait, Montenegro, Oman, Pakistan, the Philippines, Qatar, Serbia, Singapore, Thailand and Yemen, the band 137-138 MHz is allocated to the fixed and mobile, except aeronautical mobile (R), services on a primary basis (see No. 5.33). (WRC-07)

5.205 *Different category of service:* in Israel and Jordan, the allocation of the band 137-138 MHz to the fixed and mobile, except aeronautical mobile, services is on a primary basis (see No. 5.33).

5.206 *Different category of service:* in Armenia, Azerbaijan, Belarus, Bulgaria, Egypt, the Russian Federation, Finland, France, Georgia, Greece, Kazakhstan, Lebanon, Moldova, Mongolia, Uzbekistan, Poland, Kyrgyzstan, the Syrian Arab Republic, Slovakia, the Czech Rep., Romania, Tajikistan, Turkmenistan and Ukraine, the allocation of the band 137-138 MHz to the aeronautical mobile (OR) service is on a primary basis (see No. 5.33).

5.207 *Additional allocation:* in Australia, the band 137-144 MHz is also allocated to the broadcasting service on a primary basis until that service can be accommodated within regional broadcasting allocations.

5.208 The use of the band 137-138 MHz by the mobile-satellite service is subject to coordination under No. 9.11A.

5.208A In making assignments to space stations in the mobile-satellite service in the bands 137-138 MHz, 387-390 MHz and 400.15-401 MHz, administrations shall take all practicable steps to protect the radio astronomy service in the bands 150.05-153 MHz, 322-328.6 MHz, 406.1-410 MHz and 608-614 MHz from harmful interference from unwanted emissions. The threshold levels of interference detrimental to the radio astronomy service are shown in the relevant ITU-R Recommendation. (WRC-07)

5.208B In the bands:

137-138 MHz,
387-390 MHz,
400.15-401 MHz,
1452-1492 MHz,
1525-1610 MHz,
1613.8-1626.5 MHz,
2655-2690 MHz,
21.4-22 GHz,

Resolution 739 (Rev.WRC-07) applies. (WRC-07) (FCC)

5.209 The use of the bands 137-138 MHz, 148-150.05 MHz, 399.9-400.05 MHz, 400.15-401 MHz, 454-456 MHz and 459-460 MHz by the mobile-satellite service is limited to non-geostationary-satellite systems.

5.210 *Additional allocation:* in Italy, the Czech Rep. and the United Kingdom, the bands 138-143.6 MHz and 143.65-144 MHz are also allocated to the space research service (space-to-Earth) on a secondary basis. (WRC-07)

5.211 *Additional allocation:* in Germany, Saudi Arabia, Austria, Bahrain, Belgium, Denmark, the United Arab Emirates, Spain, Finland, Greece, Ireland, Israel, Kenya, Kuwait, The Former Yugoslav Republic of Macedonia, Lebanon, Liechtenstein, Luxembourg, Mali, Malta, Montenegro, Norway, the Netherlands, Qatar, Slovakia, the United Kingdom, Serbia, Slovenia, Somalia, Sweden, Switzerland, Tanzania, Tunisia and Turkey, the band 138-144 MHz is also allocated to the maritime mobile and land mobile services on a primary basis. (WRC-12)

5.212 *Alternative allocation:* in Angola, Botswana, Cameroon, the Central African Rep., Congo (Rep. of the), Gabon, Gambia, Ghana, Guinea, Iraq, Jordan, Lesotho, Liberia, Libya, Malawi, Mozambique, Namibia, Niger, Oman, Uganda, Syrian Arab Republic, the Dem. Rep. of the Congo, Rwanda, Sierra Leone, South Africa, Swaziland, Chad, Togo, Zambia and Zimbabwe, the band 138-144 MHz is allocated to the fixed and mobile services on a primary basis. (WRC-12)

5.213 *Additional allocation:* in China, the band 138-144 MHz is also allocated to the radiolocation service on a primary basis.

5.214 *Additional allocation:* in Eritrea, Ethiopia, Kenya, The Former Yugoslav Republic of Macedonia, Montenegro, Serbia, Somalia, Sudan, South Sudan and Tanzania, the band 138-144 MHz is also allocated to the fixed service on a primary basis. (WRC-12)

5.218 *Additional allocation:* the band 148-149.9 MHz is also allocated to the space operation service (Earth-to-space) on a primary basis, subject to agreement obtained under No. 9.21. The bandwidth of any individual transmission shall not exceed ± 25 kHz.

5.219 The use of the band 148-149.9 MHz by the mobile-satellite service is subject to coordination under No. 9.11A. The mobile-satellite service shall not constrain the development and use of the fixed, mobile and space operation services in the band 148-149.9 MHz.

5.220 The use of the bands 149.9-150.05 MHz and 399.9-400.05 MHz by the mobile-satellite service is subject to coordination under No. 9.11A. The mobile-satellite service shall not constrain the development and use of the radionavigation-satellite service in the bands 149.9-150.05 MHz and 399.9-400.05 MHz.

5.221 Stations of the mobile-satellite service in the band 148-149.9 MHz shall not cause harmful interference to, or claim protection from, stations of the fixed or mobile services operating in accordance with the Table of Frequency Allocations in the following countries: Albania, Algeria, Germany, Saudi Arabia, Australia, Austria, Bahrain, Bangladesh, Barbados, Belarus, Belgium, Benin, Bosnia and Herzegovina, Botswana, Brunei Darussalam, Bulgaria, Cameroon, China, Cyprus, Congo (Rep. of the), Korea (Rep. of), Côte d'Ivoire, Croatia, Cuba, Denmark, Djibouti, Egypt, the United Arab Emirates, Eritrea, Spain, Estonia, Ethiopia, the Russian Federation, Finland, France, Gabon, Ghana, Greece, Guinea, Guinea Bissau, Hungary, India, Iran (Islamic Republic of), Ireland, Iceland, Israel, Italy, Jamaica, Japan, Jordan, Kazakhstan, Kenya, Kuwait, The Former Yugoslav Republic of Macedonia, Lesotho, Latvia, Lebanon, Libya, Liechtenstein, Lithuania, Luxembourg, Malaysia, Mali, Malta, Mauritania, Moldova, Mongolia, Montenegro, Mozambique, Namibia, Norway, New Zealand, Oman, Uganda, Uzbekistan, Pakistan, Panama, Papua New Guinea, Paraguay, the Netherlands, the Philippines, Poland, Portugal, Qatar, the Syrian Arab Republic, Kyrgyzstan, Dem. People's Rep. of Korea, Slovakia, Romania, the United Kingdom, Senegal, Serbia, Sierra Leone, Singapore, Slovenia, Sudan, Sri Lanka, South Africa, Sweden, Switzerland, Swaziland, Tanzania, Chad, Thailand, Togo, Tonga, Trinidad and Tobago, Tunisia, Turkey, Ukraine, Viet Nam, Yemen, Zambia and Zimbabwe. (WRC-12)

5.222 Emissions of the radionavigation-satellite service in the bands 149.9-150.05 MHz and 399.9-400.05 MHz may also be used by receiving Earth stations of the space research service.

5.223 Recognizing that the use of the band 149.9-150.05 MHz by the fixed and mobile services may cause harmful interference to the radionavigation-satellite service, administrations are urged not to authorize such use in application of No. 4.4.

5.224A The use of the bands 149.9-150.05 MHz and 399.9-400.05 MHz by the mobile-satellite service (Earth-to-space) is limited to the land mobile-satellite service (Earth-to-space) until 1 January 2015.

5.224B The allocation of the bands 149.9-150.05 MHz and 399.9-400.05 MHz to the radionavigation-satellite service shall be effective until 1 January 2015.

5.225 *Additional allocation:* in Australia and India, the band 150.05-153 MHz is also allocated to the radio astronomy service on a primary basis.

5.226 The frequency 156.525 MHz is the international distress, safety and calling frequency for the maritime mobile VHF radiotelephone service using digital selective calling (DSC). The conditions for the use of this frequency and the band 156.4875-156.5625 MHz are contained in Articles 31 and 52, and in Appendix 18.

The frequency 156.8 MHz is the international distress, safety and calling frequency for the maritime mobile VHF radiotelephone service. The conditions for the use of this frequency and the band 156.7625-156.8375 MHz are contained in Article 31 and Appendix 18.

In the bands 156-156.4875 MHz, 156.5625-156.7625 MHz, 156.8375-157.45 MHz, 160.6-160.975 MHz and 161.475-162.05 MHz, each administration shall give priority to the maritime mobile service on only such frequencies as are assigned to stations of the maritime mobile service by the administration (see Articles 31 and 52, and Appendix 18).

Any use of frequencies in these bands by stations of other services to which they are allocated should be avoided in areas where such use might cause harmful interference to the maritime mobile VHF radiocommunication service.

However, the frequencies 156.8 MHz and 156.525 MHz and the frequency bands in which priority is given to the maritime mobile service may be used for radiocommunications on inland waterways subject to agreement between interested and affected administrations and taking into account current frequency usage and existing agreements. (WRC-07)

5.229 *Alternative allocation:* in Morocco, the band 162-174 MHz is allocated to the broadcasting service on a primary basis. The use of this band shall be subject to agreement with administrations having services, operating or planned, in accordance with the Table which are likely to be affected. Stations in existence on 1 January 1981, with their technical characteristics as of that date, are not affected by such agreement.

5.230 *Additional allocation:* in China, the band 163-167 MHz is also allocated to the space operation service (space-to-Earth) on a primary basis, subject to agreement obtained under No. 9.21.

5.231 *Additional allocation:* in Afghanistan and China, the band 167-174 MHz is also allocated to the broadcasting service on a primary basis. The introduction of the broadcasting service into this band shall be subject to agreement with the neighbouring countries in Region 3 whose services are likely to be affected. (WRC-12)

5.232 *Additional allocation:* in Japan, the band 170-174 MHz is also allocated to the broadcasting service on a primary basis.

5.233 *Additional allocation:* in China, the band 174-184 MHz is also allocated to the space research (space-to-Earth) and the space operation (space-to-Earth) services on a primary basis, subject to agreement obtained under No. 9.21. These services shall not cause harmful interference to, or claim protection from, existing or planned broadcasting stations.

5.234 *Different category of service:* in Mexico, the allocation of the band 174-216 MHz to the fixed and mobile services is on a primary basis (see No. 5.33).

5.235 *Additional allocation:* in Germany, Austria, Belgium, Denmark, Spain, Finland, France, Israel, Italy, Liechtenstein, Malta, Monaco, Norway, the Netherlands, the United Kingdom, Sweden and Switzerland, the band 174-223 MHz is also allocated to the land mobile service on a primary basis. However, the stations of the land mobile service shall not cause harmful interference to, or claim protection from, broadcasting stations, existing or planned, in countries other than those listed in this footnote.

5.237 *Additional allocation:* in Congo (Rep. of the), Egypt, Eritrea, Ethiopia, Gambia, Guinea, Libya, Mali, Sierra Leone, Somalia and Chad, the band 174-223 MHz is also allocated to the fixed and mobile services on a secondary basis. (WRC-12)

5.241 In Region 2, no new stations in the radiolocation service may be authorized in the band 216-225 MHz. Stations authorized prior to 1 January 1990 may continue to operate on a secondary basis.

5.242 *Additional allocation:* in Canada, the band 216-220 MHz is also allocated to the land mobile service on a primary basis.

5.243 *Additional allocation:* in Somalia, the band 216-225 MHz is also allocated to the aeronautical radionavigation service on a primary basis, subject to not causing harmful interference to existing or planned broadcasting services in other countries.

5.246 *Alternative allocation:* in Spain, France, Israel and Monaco, the band 223-230 MHz is allocated to the broadcasting and land mobile services on a primary basis (see No. 5.33) on the basis that, in the preparation of frequency plans, the broadcasting service shall have prior choice of frequencies; and allocated to the fixed and mobile, except land mobile, services on a secondary basis. However, the stations of the land mobile service shall not cause harmful interference to, or claim protection from, existing or planned broadcasting stations in Morocco and Algeria.

5.247 *Additional allocation:* in Saudi Arabia, Bahrain, the United Arab Emirates, Jordan, Oman, Qatar and Syrian Arab Republic, the band 223-235 MHz is also allocated to the aeronautical radionavigation service on a primary basis.

5.250 *Additional allocation:* in China, the band 225-235 MHz is also allocated to the radio astronomy service on a secondary basis.

5.251 *Additional allocation:* in Nigeria, the band 230-235 MHz is also allocated to the aeronautical radionavigation service on a primary basis, subject to agreement obtained under No. 9.21.

5.252 *Alternative allocation:* in Botswana, Lesotho, Malawi, Mozambique, Namibia, South Africa, Swaziland, Zambia and Zimbabwe, the bands 230-238 MHz and 246-254 MHz are allocated to the broadcasting service on a primary basis, subject to agreement obtained under No. 9.21.

5.254 The bands 235-322 MHz and 335.4-399.9 MHz may be used by the mobile-satellite service, subject to agreement obtained under No. 9.21, on condition that stations in this service do not cause harmful interference to those of other services operating or planned to be operated in accordance with the Table of Frequency Allocations except for the additional allocation made in footnote No. 5.256A.

5.255 The bands 312-315 MHz (Earth-to-space) and 387-390 MHz (space-to-Earth) in the mobile-satellite service may also be used by non-geostationary-satellite systems. Such use is subject to coordination under No. 9.11A.

5.257 The band 267-272 MHz may be used by administrations for space telemetry in their countries on a primary basis, subject to agreement obtained under No. 9.21.

5.261 Emissions shall be confined in a band of ± 25 kHz about the standard frequency 400.1 MHz.

5.262 *Additional allocation:* in Saudi Arabia, Armenia, Azerbaijan, Bahrain, Belarus, Botswana, Colombia, Cuba, Egypt, the United Arab Emirates, Ecuador, the Russian Federation, Georgia, Hungary, Iran (Islamic Republic of), Iraq, Israel, Jordan, Kazakhstan, Kuwait, Liberia, Malaysia, Moldova, Oman, Uzbekistan, Pakistan, the Philippines, Qatar, the Syrian Arab Republic, Kyrgyzstan, Singapore, Somalia, Tajikistan, Chad, Turkmenistan and Ukraine, the band 400.05-401 MHz is also allocated to the fixed and mobile services on a primary basis. (WRC-12)

5.263 The band 400.15-401 MHz is also allocated to the space research service in the space-to-space direction for communications with manned space vehicles. In this application, the space research service will not be regarded as a safety service.

5.264 The use of the band 400.15-401 MHz by the mobile-satellite service is subject to coordination under No. 9.11A. The power flux-density limit indicated in Annex 1 of Appendix 5 shall apply until such time as a competent world radiocommunication conference revises it.

5.268 Use of the band 410-420 MHz by the space research service is limited to communications within 5 km of an orbiting, manned space vehicle. The power flux-density at the surface of the Earth produced by emissions from extra-vehicular activities shall not exceed -153 dB(W/m^2) for $0° \leq \delta \leq 5°$, $-153 + 0.077 (\delta - 5)$ dB(W/m^2) for $5° \leq \delta \leq 70°$ and -148 dB(W/m^2) for $70° \leq \delta \leq 90°$, where δ is the angle of arrival of the radio-frequency wave and the reference bandwidth is 4 kHz. No. 4.10 does not apply to extra-vehicular activities. In this frequency band the space research (space-to-space) service shall not claim protection from, nor constrain the use and development of, stations of the fixed and mobile services.

5.271 *Additional allocation:* in Belarus, China, India, Kyrgyzstan and Turkmenistan, the band 420-460 MHz is also allocated to the aeronautical radionavigation service (radio altimeters) on a secondary basis. (WRC-07)

5.276 *Additional allocation:* in Afghanistan, Algeria, Saudi Arabia, Bahrain, Bangladesh, Brunei Darussalam, Burkina Faso, Djibouti, Egypt, the United Arab Emirates, Ecuador, Eritrea, Ethiopia, Greece, Guinea, India, Indonesia, Iran (Islamic Republic of), Iraq, Israel, Italy, Jordan, Kenya, Kuwait, Libya, Malaysia, Niger, Nigeria, Oman, Pakistan, the Philippines, Qatar, the Syrian Arab Republic, the Dem. People's Rep. of Korea, Singapore, Somalia, Sudan, Switzerland, Tanzania, Thailand, Togo, Turkey and Yemen, the band 430-440 MHz is also allocated to the fixed service on a primary basis and the bands 430-435 MHz and 438-440 MHz are also allocated to the mobile, except aeronautical mobile, service on a primary basis. (WRC-12)

5.277 *Additional allocation:* in Angola, Armenia, Azerbaijan, Belarus, Cameroon, Congo (Rep. of the), Djibouti, the Russian Federation, Georgia, Hungary, Israel, Kazakhstan, Mali, Mongolia, Uzbekistan, Poland, the Dem. Rep. of the Congo, Kyrgyzstan, Slovakia, Romania, Rwanda, Tajikistan, Chad, Turkmenistan and Ukraine, the band 430-440 MHz is also allocated to the fixed service on a primary basis. (WRC-12)

5.278 *Different category of service:* in Argentina, Colombia, Costa Rica, Cuba, Guyana, Honduras, Panama and Venezuela, the allocation of the band 430-440 MHz to the amateur service is on a primary basis (see No. 5.33).

5.279 *Additional allocation:* in Mexico, the bands 430-435 MHz and 438-440 MHz are also allocated on a primary basis to the land mobile service, subject to agreement obtained under No. 9.21.

5.279A The use of this band by sensors in the Earth exploration-satellite service (active) shall be in accordance with Recommendation ITU-R RS.1260-1. Additionally, the Earth exploration-satellite service (active) in the band 432-438 MHz shall not cause harmful interference to the aeronautical radionavigation service in China. The provisions of this footnote in no way diminish the obligation of the Earth exploration-satellite service (active) to operate as a secondary service in accordance with Nos. 5.29 and 5.30.

5.280 In Germany, Austria, Bosnia and Herzegovina, Croatia, The Former Yugoslav Republic of Macedonia, Liechtenstein, Montenegro, Portugal, Serbia, Slovenia and Switzerland, the band 433.05-434.79 MHz (centre frequency 433.92 MHz) is designated for industrial, scientific and medical (ISM) applications. Radiocommunication services of these countries operating within this band must accept harmful interference which may be caused by these applications. ISM equipment operating in this band is subject to the provisions of No. 15.13. (WRC-07)

5.281 *Additional allocation:* in the French overseas departments and communities in Region 2 and India, the band 433.75-434.25 MHz is also allocated to the space operation service (Earth-to-space) on a primary basis. In France and in Brazil, the band is allocated to the same service on a secondary basis.

5.282 In the bands 435-438 MHz, 1260-1270 MHz, 2400-2450 MHz, 3400-3410 MHz (in Regions 2 and 3 only) and 5650-5670 MHz, the amateur-satellite service may operate subject to not causing harmful interference to other services operating in accordance with the Table (see No. 5.43). Administrations authorizing such use shall ensure that any harmful interference caused by emissions from a station in the amateur-satellite service is immediately eliminated in accordance with the provisions of No. 25.11. The use of the bands 1260-1270 MHz and 5650-5670 MHz by the amateur-satellite service is limited to the Earth-to-space direction.

5.286AA The band 450-470 MHz is identified for use by administrations wishing to implement International Mobile Telecommunications (IMT). See Resolution 224 (Rev.WRC-12). This identification does not preclude the use of this band by any application of the services to which it is allocated and does not establish priority in the Radio Regulations. (FCC)

5.287 In the maritime mobile service, the frequencies 457.525 MHz, 457.550 MHz, 457.575 MHz, 467.525 MHz, 467.550 MHz and 467.575 MHz may be used by on-board communication stations. Where needed, equipment designed for 12.5 kHz channel spacing using also the additional frequencies 457.5375 MHz, 457.5625 MHz, 467.5375 MHz and 467.5625 MHz may be introduced for on-board communications. The use of these frequencies in territorial waters may be subject to the national regulations of the administration concerned. The characteristics of the equipment used shall conform to those specified in Recommendation ITU-R M.1174-2. (WRC-07)

5.288 In the territorial waters of the United States and the Philippines, the preferred frequencies for use by on-board communication stations shall be 457.525 MHz, 457.550 MHz, 457.575 MHz and 457.600 MHz paired, respectively, with 467.750 MHz, 467.775 MHz, 467.800 MHz and 467.825 MHz. The characteristics of the equipment used shall conform to those specified in Recommendation ITU-R M.1174-2. (WRC-03)

5.289 Earth exploration-satellite service applications, other than the meteorological-satellite service, may also be used in the bands 460-470 MHz and 1690-1710 MHz for space-to-Earth transmissions subject to not causing harmful interference to stations operating in accordance with the Table.

5.290 *Different category of service:* in Afghanistan, Azerbaijan, Belarus, China, the Russian Federation, Japan, Kyrgyzstan, Tajikistan and Turkmenistan, the allocation of the band 460-470 MHz to the meteorological-satellite service (space-to-Earth) is on a primary basis (see No. 5.33), subject to agreement obtained under No. 9.21. (WRC-12)

5.291 *Additional allocation:* in China, the band 470-485 MHz is also allocated to the space research (space-to-Earth) and the space operation (space-to-Earth) services on a primary basis subject to agreement obtained under No. 9.21 and subject to not causing harmful interference to existing and planned broadcasting stations.

5.291A *Additional allocation:* in Germany, Austria, Denmark, Estonia, Finland, Liechtenstein, Norway, Netherlands, the Czech Rep. and Switzerland, the band 470-494 MHz is also allocated to the radiolocation service on a secondary basis. This use is limited to the operation of wind profiler radars in accordance with Resolution 217 (WRC-97).

5.294 *Additional allocation:* in Saudi Arabia, Cameroon, Côte d'Ivoire, Egypt, Ethiopia, Israel, Kenya, Libya, the Syrian Arab Republic, South Sudan, Chad and Yemen, the band 470-582 MHz is also allocated to the fixed service on a secondary basis. (WRC-12)

5.296 *Additional allocation:* in Albania, Germany, Saudi Arabia, Austria, Bahrain, Belgium, Benin, Bosnia and Herzegovina, Burkina Faso, Cameroon, Congo (Rep. of the), Côte d'Ivoire, Croatia, Denmark, Djibouti, Egypt, United Arab Emirates, Spain, Estonia, Finland, France, Gabon, Ghana, Iraq, Ireland, Iceland, Israel, Italy, Jordan, Kuwait, Latvia, The Former Yugoslav Republic of Macedonia, Libya, Liechtenstein, Lithuania, Luxembourg, Mali, Malta, Morocco, Moldova, Monaco, Niger, Norway, Oman, the Netherlands, Poland, Portugal, Qatar, the Syrian Arab Republic, Slovakia, the Czech Republic, the United Kingdom, Sudan, Sweden, Switzerland, Swaziland, Chad, Togo, Tunisia and Turkey, the band 470-790 MHz, and in Angola, Botswana, Lesotho, Malawi, Mauritius, Mozambique, Namibia, Nigeria, South Africa, Tanzania, Zambia and Zimbabwe, the band 470-698 MHz are also allocated on a secondary basis to the land mobile service, intended for applications ancillary to broadcasting. Stations of the land mobile service in the countries listed in this footnote shall not cause harmful interference to existing or planned stations operating in accordance with the Table in countries other than those listed in this footnote. (WRC-12)

5.297 *Additional allocation:* in Canada, Costa Rica, Cuba, El Salvador, the United States, Guatemala, Guyana, Honduras, Jamaica and Mexico, the band 512-608 MHz is also allocated to the fixed and mobile services on a primary basis, subject to agreement obtained under No. 9.21. (WRC-07)

5.298 *Additional allocation:* in India, the band 549.75-550.25 MHz is also allocated to the space operation service (space-to-Earth) on a secondary basis.

5.300 *Additional allocation:* in Saudi Arabia, Cameroon, Egypt, United Arab Emirates, Israel, Jordan, Libya, Oman, Qatar, the Syrian Arab Republic, Sudan and South Sudan, the band 582-790 MHz is also allocated to the fixed and mobile, except aeronautical mobile, services on a secondary basis. (WRC-12)

5.304 *Additional allocation:* in the African Broadcasting Area (see Nos. 5.10 to 5.13), the band 606-614 MHz is also allocated to the radio astronomy service on a primary basis.

5.305 *Additional allocation:* in China, the band 606-614 MHz is also allocated to the radio astronomy service on a primary basis.

5.306 *Additional allocation:* in Region 1, except in the African Broadcasting Area (see Nos. 5.10 to 5.13), and in Region 3, the band 608-614 MHz is also allocated to the radio astronomy service on a secondary basis.

5.307 *Additional allocation:* in India, the band 608-614 MHz is also allocated to the radio astronomy service on a primary basis.

5.311A For the frequency band 620-790 MHz, see also Resolution 549 (WRC-07). (WRC-07)

5.312 *Additional allocation:* in Armenia, Azerbaijan, Belarus, the Russian Federation, Georgia, Kazakhstan, Uzbekistan, Kyrgyzstan, Tajikistan, Turkmenistan and Ukraine, the band 645-862 MHz, in Bulgaria the bands 646-686 MHz, 726-758 MHz, 766-814 MHz and 822-862 MHz, in Romania the band 830-862 MHz, and in Poland, the band 830-860 MHz until 31 December 2012 and the band 860-862 MHz until 31 December 2017, are also allocated to the aeronautical radionavigation service on a primary basis. (WRC-12)

5.312A In Region 1, the use of the band 694-790 MHz by the mobile, except aeronautical mobile, service is subject to the provisions of Resolution 232 (WRC-12). See also Resolution 224 (Rev.WRC-12). (WRC-12)

5.313A The band, or portions of the band 698-790 MHz, in Bangladesh, China, Korea (Rep. of), India, Japan, New Zealand, Pakistan, Papua New Guinea, Philippines and Singapore are identified for use by these administrations wishing to implement International Mobile Telecommunications (IMT). This identification does not preclude the use of these bands by any application of the services to which they are allocated and does not establish priority in the Radio Regulations. In China, the use of IMT in this band will not start until 2015. (WRC-12)

5.317A Those parts of the band 698-960 MHz in Region 2 and the band 790-960 MHz in Regions 1 and 3 which are allocated to the mobile service on a primary basis are identified for use by administrations wishing to implement International Mobile Telecommunications (IMT)—see Resolutions 224 (Rev.WRC-12) and 749 (Rev.WRC-12), as appropriate. This identification does not preclude the use of these bands by any application of the services to which they are allocated and does not establish priority in the Radio Regulations. (WRC-12)

5.320 *Additional allocation:* in Region 3, the bands 806-890 MHz and 942-960 MHz are also allocated to the mobile-satellite, except aeronautical mobile-satellite (R), service on a primary basis, subject to agreement obtained under No. 9.21. The use of this service is limited to operation within national boundaries. In seeking such agreement, appropriate protection shall be afforded to services operating in accordance with the Table, to ensure that no harmful interference is caused to such services.

5.328B The use of the bands 1164-1300 MHz, 1559-1610 MHz and 5010-5030 MHz by systems and networks in the radionavigation-satellite service for which complete coordination or notification information, as appropriate, is received by the Radiocommunication Bureau after 1 January 2005 is subject to the application of the provisions of Nos. 9.12, 9.12A and 9.13. Resolution 610 (WRC-03) shall also apply; however, in the case of radionavigation-satellite service (space-to-space) networks and systems, Resolution 610 (WRC-03) shall only apply to transmitting space stations. In accordance with No. 5.329A, for systems and networks in the radionavigation-satellite service (space-to-space) in the bands 1215-1300 MHz and 1559-1610 MHz, the provisions of Nos. 9.7, 9.12, 9.12A and 9.13 shall only apply with respect to other systems and networks in the radionavigation-satellite service (space-to-space). (WRC-07)

5.329 Use of the radionavigation-satellite service in the band 1215-1300 MHz shall be subject to the condition that no harmful interference is caused to, and no protection is claimed from, the radionavigation service authorized under No. 5.331. Furthermore, the use of the radionavigation-satellite service in the band 1215-1300 MHz shall be subject to the condition that no harmful interference is caused to the radiolocation service. No. 5.43 shall not apply in respect of the radiolocation service. Resolution 608 (WRC-03) shall apply.

5.329A Use of systems in the radionavigation-satellite service (space-to-space) operating in the bands 1215-1300 MHz and 1559-1610 MHz is not intended to provide safety service applications, and shall not impose any additional constraints on radionavigation-satellite service (space-to-Earth) systems or on other services operating in accordance with the Table of Frequency Allocations. (WRC-07)

5.330 *Additional allocation:* in Angola, Saudi Arabia, Bahrain, Bangladesh, Cameroon, China, Djibouti, Egypt, the United Arab Emirates, Eritrea, Ethiopia, Guyana, India, Indonesia, Iran (Islamic Republic of), Iraq, Israel, Japan, Jordan, Kuwait, Nepal, Oman, Pakistan, the Philippines, Qatar, the Syrian Arab Republic, Somalia, Sudan, South Sudan, Chad, Togo and Yemen, the band 1215-1300 MHz is also allocated to the fixed and mobile services on a primary basis. (WRC-12)

5.331 *Additional allocation:* in Algeria, Germany, Saudi Arabia, Australia, Austria, Bahrain, Belarus, Belgium, Benin, Bosnia and Herzegovina, Brazil, Burkina Faso, Burundi, Cameroon, China, Korea (Rep. of), Croatia, Denmark, Egypt, the United Arab Emirates, Estonia, the Russian Federation, Finland, France, Ghana, Greece, Guinea, Equatorial Guinea, Hungary, India, Indonesia, Iran (Islamic Republic of), Iraq, Ireland, Israel, Jordan, Kenya, Kuwait, The Former Yugoslav Republic of Macedonia, Lesotho, Latvia, Lebanon, Liechtenstein, Lithuania, Luxembourg, Madagascar, Mali, Mauritania, Montenegro, Nigeria, Norway, Oman, Pakistan, the Netherlands, Poland, Portugal, Qatar, the Syrian Arab Republic, Dem. People’s Rep. of Korea, Slovakia, the United Kingdom, Serbia, Slovenia, Somalia, Sudan, South Sudan, Sri Lanka, South Africa, Sweden, Switzerland, Thailand, Togo, Turkey, Venezuela and Viet Nam, the band 1215-1300 MHz is also allocated to the radionavigation service on a primary basis. In Canada and the United States, the band 1240-1300 MHz is also allocated to the radionavigation service, and use of the radionavigation service shall be limited to the aeronautical radionavigation service. (WRC-12)

5.332 In the band 1215-1260 MHz, active spaceborne sensors in the Earth exploration-satellite and space research services shall not cause harmful interference to, claim protection from, or otherwise impose constraints on operation or development of the radiolocation service, the radionavigation-satellite service and other services allocated on a primary basis.

5.334 *Additional allocation:* in Canada and the United States, the band 1350-1370 MHz is also allocated to the aeronautical radionavigation service on a primary basis.

5.335 In Canada and the United States in the band 1240-1300 MHz, active spaceborne sensors in the Earth exploration-satellite and space research services shall not cause interference to, claim protection from, or otherwise impose constraints on operation or development of the aeronautical radionavigation service.

5.335A In the band 1260-1300 MHz, active spaceborne sensors in the Earth exploration-satellite and space research services shall not cause harmful interference to, claim protection from, or otherwise impose constraints on operation or development of the radiolocation service and other services allocated by footnotes on a primary basis.

5.337 The use of the bands 1300-1350 MHz, 2700-2900 MHz and 9000-9200 MHz by the aeronautical radionavigation service is restricted to ground-based radars and to associated airborne transponders which transmit only on frequencies in these bands and only when actuated by radars operating in the same band.

5.337A The use of the band 1300-1350 MHz by Earth stations in the radionavigation-satellite service and by stations in the radiolocation service shall not cause harmful interference to, nor constrain the operation and development of, the aeronautical-radionavigation service.

5.338 In Kyrgyzstan, Slovakia and Turkmenistan, existing installations of the radionavigation service may continue to operate in the band 1350-1400 MHz. (WRC-12)

5.338A In the bands 1350-1400 MHz, 1427-1452 MHz, 22.55-23.55 GHz, 30-31.3 GHz, 49.7-50.2 GHz, 50.4-50.9 GHz, 51.4-52.6 GHz, 81-86 GHz and 92-94 GHz, Resolution 750 (Rev.WRC-12) applies. (WRC-12)

5.339 The bands 1370-1400 MHz, 2640-2655 MHz, 4950-4990 MHz and 15.20-15.35 GHz are also allocated to the space research (passive) and Earth exploration-satellite (passive) services on a secondary basis.

5.340 All emissions are prohibited in the following bands:

1400-1427 MHz,
2690-2700 MHz, except those provided for by
  No. 5.422,
10.68-10.7 GHz, except those provided for by
  No. 5.483,
15.35-15.4 GHz, except those provided for by
  No. 5.511,
23.6-24 GHz,
31.3-31.5 GHz,
31.5-31.8 GHz, in Region 2,
48.94-49.04 GHz, from airborne stations
50.2-50.4 GHz,[3]
52.6-54.25 GHz,
86-92 GHz,
100-102 GHz,
109.5-111.8 GHz,
114.25-116 GHz,
148.5-151.5 GHz,
164-167 GHz,
182-185 GHz,
190-191.8 GHz,
200-209 GHz,
226-231.5 GHz,
250-252 GHz.

5.341 In the bands 1400-1727 MHz, 101-120 GHz and 197-220 GHz, passive research is being conducted by some countries in a programme for the search for intentional emissions of extraterrestrial origin.

5.342 *Additional allocation:* in Armenia, Azerbaijan, Belarus, the Russian Federation, Uzbekistan, Kyrgyzstan and Ukraine, the band 1429-1535 MHz, and in Bulgaria the band 1525-1535 MHz, are also allocated to the aeronautical mobile service on a primary basis exclusively for the purposes of aeronautical telemetry within the national territory. As of 1 April 2007, the use of the band 1452-1492 MHz is subject to agreement between the administrations concerned. (WRC-12)

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[3] **5.340**.1 The allocation to the Earth exploration-satellite service (passive) and the space research service (passive) in the band 50.2-50.4 GHz should not impose undue constraints on the use of the adjacent bands by the primary allocated services in those bands.

5.343 In Region 2, the use of the band 1435-1535 MHz by the aeronautical mobile service for telemetry has priority over other uses by the mobile service.

5.344 *Alternative allocation:* in the United States, the band 1452-1525 MHz is allocated to the fixed and mobile services on a primary basis (see also No. 5.343).

5.345 Use of the band 1452-1492 MHz by the broadcasting-satellite service, and by the broadcasting service, is limited to digital audio broadcasting and is subject to the provisions of Resolution 528 (Rev.WRC-03). (FCC)

5.348 The use of the band 1518-1525 MHz by the mobile-satellite service is subject to coordination under No. 9.11A. In the band 1518-1525 MHz stations in the mobile-satellite service shall not claim protection from the stations in the fixed service. No. 5.43A does not apply.

5.348A In the band 1518-1525 MHz, the coordination threshold in terms of the power flux-density levels at the surface of the Earth in application of No. 9.11A for space stations in the mobile-satellite (space-to-Earth) service, with respect to the land mobile service use for specialized mobile radios or used in conjunction with public switched telecommunication networks (PSTN) operating within the territory of Japan, shall be -150 dB(W/m^2) in any 4 kHz band for all angles of arrival, instead of those given in Table 5-2 of Appendix 5. In the band 1518-1525 MHz stations in the mobile-satellite service shall not claim protection from stations in the mobile service in the territory of Japan. No. 5.43A does not apply.

5.348B In the band 1518-1525 MHz, stations in the mobile-satellite service shall not claim protection from aeronautical mobile telemetry stations in the mobile service in the territory of the United States (see Nos. 5.343 and 5.344) and in the countries listed in No. 5.342. No. 5.43A does not apply.

5.349 *Different category of service:* in Saudi Arabia, Azerbaijan, Bahrain, Cameroon, Egypt, France, Iran (Islamic Republic of), Iraq, Israel, Kazakhstan, Kuwait, The Former Yugoslav Republic of Macedonia, Lebanon, Morocco, Qatar, Syrian Arab Republic, Kyrgyzstan, Turkmenistan and Yemen, the allocation of the band 1525-1530 MHz to the mobile, except aeronautical mobile, service is on a primary basis (see No. 5.33). (WRC-07)

5.350 *Additional allocation:* in Azerbaijan, Kyrgyzstan and Turkmenistan, the band 1525-1530 MHz is also allocated to the aeronautical mobile service on a primary basis.

5.351 The bands 1525-1544 MHz, 1545-1559 MHz, 1626.5-1645.5 MHz and 1646.5-1660.5 MHz shall not be used for feeder links of any service. In exceptional circumstances, however, an Earth station at a specified fixed point in any of the mobile-satellite services may be authorized by an administration to communicate via space stations using these bands.

5.351A For the use of the bands 1518-1544 MHz, 1545-1559 MHz, 1610-1645.5 MHz, 1646.5-1660.5 MHz, 1668-1675 MHz, 1980-2010 MHz, 2170-2200 MHz, 2483.5-2520 MHz and 2670-2690 MHz by the mobile-satellite service, see Resolutions 212 (Rev.WRC-07) and 225 (Rev.WRC-12). (FCC)

5.352A In the band 1525-1530 MHz, stations in the mobile-satellite service, except stations in the maritime mobile-satellite service, shall not cause harmful interference to, or claim protection from, stations of the fixed service in Algeria, Saudi Arabia, Egypt, France and French overseas communities of Region 3, Guinea, India, Israel, Italy, Jordan, Kuwait, Mali, Morocco, Mauritania, Nigeria, Oman, Pakistan, the Philippines, Qatar, Syrian Arab Republic, Tanzania, Viet Nam and Yemen notified prior to 1 April 1998. (WRC-12)

5.353A In applying the procedures of Section II of Article 9 to the mobile-satellite service in the bands 1530-1544 MHz and 1626.5-1645.5 MHz, priority shall be given to accommodating the spectrum requirements for distress, urgency and safety communications of the Global Maritime Distress and Safety System (GMDSS). Maritime mobile-satellite distress, urgency and safety communications shall have priority access and immediate availability over all other mobile satellite communications operating within a network. Mobile-satellite systems shall not cause unacceptable interference to, or claim protection from, distress, urgency and safety communications of the GMDSS. Account shall be taken of the priority of safety-related communications in the other mobile-satellite services. (The provisions of Resolution 222 (Rev.WRC-12) shall apply.) (FCC)

5.354 The use of the bands 1525-1559 MHz and 1626.5-1660.5 MHz by the mobile-satellite services is subject to coordination under No. 9.11A.

5.355 *Additional allocation:* in Bahrain, Bangladesh, Congo (Rep. of the), Djibouti, Egypt, Eritrea, Iraq, Israel, Kuwait, Qatar, Syrian Arab Republic, Somalia, Sudan, South Sudan, Chad, Togo and Yemen, the bands 1540-1559 MHz, 1610-1645.5 MHz and 1646.5-1660 MHz are also allocated to the fixed service on a secondary basis. (WRC-12)

5.356 The use of the band 1544-1545 MHz by the mobile-satellite service (space-to-Earth) is limited to distress and safety communications (see Article 31).

5.357 Transmissions in the band 1545-1555 MHz from terrestrial aeronautical stations directly to aircraft stations, or between aircraft stations, in the aeronautical mobile (R) service are also authorized when such transmissions are used to extend or supplement the satellite-to-aircraft links.

5.357A In applying the procedures of Section II of Article 9 to the mobile-satellite service in the frequency bands 1545-1555 MHz and 1646.5-1656.5 MHz, priority shall be given to accommodating the spectrum requirements of the aeronautical mobile-satellite (R) service providing transmission of messages with priority 1 to 6 in Article 44. Aeronautical mobile-satellite (R) service communications with priority 1 to 6 in Article 44 shall have priority access and immediate availability, by pre-emption if necessary, over all other mobile-satellite communications operating within a network. Mobile-satellite systems shall not cause unacceptable interference to, or claim protection from, aeronautical mobile-satellite (R) service communications with priority 1 to 6 in Article 44. Account shall be taken of the priority of safety-related communications in the other mobile-satellite services. (The provisions of Resolution 222 (Rev.WRC-12) shall apply.) (WRC-12)

5.359 *Additional allocation:* in Germany, Saudi Arabia, Armenia, Austria, Azerbaijan, Belarus, Benin, Cameroon, the Russian Federation, France, Georgia, Greece, Guinea, Guinea-Bissau, Jordan, Kazakhstan, Kuwait, Lithuania, Mauritania, Uganda, Uzbekistan, Pakistan, Poland, the Syrian Arab Republic, Kyrgyzstan, the Dem. People's Rep. of Korea, Romania, Tajikistan, Tanzania, Tunisia, Turkmenistan and Ukraine, the bands 1550-1559 MHz, 1610-1645.5 MHz and 1646.5-1660 MHz are also allocated to the fixed service on a primary basis. Administrations are urged to make all practicable efforts to avoid the implementation of new fixed-service stations in these bands. (WRC-12)

5.362A In the United States, in the bands 1555-1559 MHz and 1656.5-1660.5 MHz, the aeronautical mobile-satellite (R) service shall have priority access and immediate availability, by pre-emption if necessary, over all other mobile-satellite communications operating within a network. Mobile-satellite systems shall not cause unacceptable interference to, or claim protection from, aeronautical mobile-satellite (R) service communications with priority 1 to 6 in Article 44. Account shall be taken of the priority of safety-related communications in the other mobile-satellite services.

5.362B *Additional allocation:* The band 1559-1610 MHz is also allocated to the fixed service on a secondary basis in Algeria, Saudi Arabia, Armenia, Azerbaijan, Belarus, Benin, Cameroon, Russian Federation, Gabon, Georgia, Guinea, Guinea-Bissau, Jordan, Kazakhstan, Libya, Lithuania, Mali, Mauritania, Nigeria, Uzbekistan, Pakistan, Poland, the Syrian Arab Republic, Kyrgyzstan, Dem. People's Rep. of Korea, Romania, Senegal, Tajikistan, Tanzania, Tunisia, Turkmenistan and Ukraine until 1 January 2015, at which time this allocation shall no longer be valid. Administrations are urged to take all practicable steps to protect the radionavigation-satellite service and the aeronautical radionavigation service and not authorize new frequency assignments to fixed-service systems in this band. (WRC-12)

5.362C *Additional allocation:* in Congo (Rep. of the), Eritrea, Iraq, Israel, Jordan, Qatar, the Syrian Arab Republic, Somalia, Sudan, South Sudan, Chad, Togo and Yemen, the band 1559-1610 MHz is also allocated to the fixed service on a secondary basis until 1 January 2015, at which time this allocation shall no longer be valid. Administrations are urged to take all practicable steps to protect the radionavigation-satellite service and not authorize new frequency assignments to fixed-service systems in this band. (WRC-12)

5.364 The use of the band 1610-1626.5 MHz by the mobile-satellite service (Earth-to-space) and by the radiodetermination-satellite service (Earth-to-space) is subject to coordination under No. 9.11A. A mobile Earth station operating in either of the services in this band shall not produce a peak e.i.r.p. density in excess of –15 dB(W/4 kHz) in the part of the band used by systems operating in accordance with the provisions of No. 5.366 (to which No. 4.10 applies), unless otherwise agreed by the affected administrations. In the part of the band where such systems are not operating, the mean e.i.r.p. density of a mobile Earth station shall not exceed –3 dB(W/4 kHz). Stations of the mobile-satellite service shall not claim protection from stations in the aeronautical radionavigation service, stations operating in accordance with the provisions of No. 5.366 and stations in the fixed service operating in accordance with the provisions of No. 5.359. Administrations responsible for the coordination of mobile-satellite networks shall make all practicable efforts to ensure protection of stations operating in accordance with the provisions of No. 5.366.

5.365 The use of the band 1613.8-1626.5 MHz by the mobile-satellite service (space-to-Earth) is subject to coordination under No. 9.11A.

5.366 The band 1610-1626.5 MHz is reserved on a worldwide basis for the use and development of airborne electronic aids to air navigation and any directly associated ground-based or satellite-borne facilities. Such satellite use is subject to agreement obtained under No. 9.21.

5.367 *Additional allocation*: The frequency band 1610-1626.5 MHz is also allocated to the aeronautical mobile-satellite (R) service on a primary basis, subject to agreement obtained under No. 9.21. (WRC-12)

5.368 With respect to the radiodetermination-satellite and mobile-satellite services the provisions of No. 4.10 do not apply in the band 1610-1626.5 MHz, with the exception of the aeronautical radionavigation-satellite service.

5.369 *Different category of service:* in Angola, Australia, China, Eritrea, Ethiopia, India, Iran (Islamic Republic of), Israel, Lebanon, Liberia, Madagascar, Mali, Pakistan, Papua New Guinea, Syrian Arab Republic, the Dem. Rep. of the Congo, Sudan, South Sudan, Togo and Zambia, the allocation of the band 1610-1626.5 MHz to the radiodetermination-satellite service (Earth-to-space) is on a primary basis (see No. 5.33), subject to agreement obtained under No. 9.21 from countries not listed in this provision. (WRC-12)

5.370 *Different category of service:* in Venezuela, the allocation to the radiodetermination-satellite service in the band 1610-1626.5 MHz (Earth-to-space) is on a secondary basis.

5.371 *Additional allocation:* in Region 1, the band 1610-1626.5 MHz (Earth-to-space) is also allocated to the radiodetermination-satellite service on a secondary basis, subject to agreement obtained under No. 9.21. (WRC-12)

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).

5.374 Mobile Earth stations in the mobile-satellite service operating in the bands 1631.5-1634.5 MHz and 1656.5-1660 MHz shall not cause harmful interference to stations in the fixed service operating in the countries listed in No. 5.359.

5.375 The use of the band 1645.5-1646.5 MHz by the mobile-satellite service (Earth-to-space) and for inter-satellite links is limited to distress and safety communications (see Article 31).

5.376 Transmissions in the band 1646.5-1656.5 MHz from aircraft stations in the aeronautical mobile (R) service directly to terrestrial aeronautical stations, or between aircraft stations, are also authorized when such transmissions are used to extend or supplement the aircraft-to-satellite links.

5.376A Mobile Earth stations operating in the band 1660-1660.5 MHz shall not cause harmful interference to stations in the radio astronomy service.

5.379 *Additional allocation:* in Bangladesh, India, Indonesia, Nigeria and Pakistan, the band 1660.5-1668.4 MHz is also allocated to the meteorological aids service on a secondary basis.

5.379A Administrations are urged to give all practicable protection in the band 1660.5-1668.4 MHz for future research in radio astronomy, particularly by eliminating air-to-ground transmissions in the meteorological aids service in the band 1664.4-1668.4 MHz as soon as practicable.

5.379B The use of the band 1668-1675 MHz by the mobile-satellite service is subject to coordination under No. 9.11A. In the band 1668-1668.4 MHz, Resolution 904 (WRC-07) shall apply. (WRC-07)

5.379C In order to protect the radio astronomy service in the band 1668-1670 MHz, the aggregate power flux-density values produced by mobile Earth stations in a network of the mobile-satellite service operating in this band shall not exceed –181 dB(W/m^2) in 10 MHz and −194 dB(W/m^2) in any 20 kHz at any radio astronomy station recorded in the Master International Frequency Register, for more than 2% of integration periods of 2000 s.

5.379D For sharing of the band 1668.4-1675 MHz between the mobile-satellite service and the fixed and mobile services, Resolution 744 (Rev.WRC-07) shall apply. (WRC-07)

5.379E In the band 1668.4-1675 MHz, stations in the mobile-satellite service shall not cause harmful interference to stations in the meteorological aids service in China, Iran (Islamic Republic of), Japan and Uzbekistan. In the band 1668.4-1675 MHz, administrations are urged not to implement new systems in the meteorological aids service and are encouraged to migrate existing meteorological aids service operations to other bands as soon as practicable.

5.380A In the band 1670-1675 MHz, stations in the mobile-satellite service shall not cause harmful interference to, nor constrain the development of, existing Earth stations in the meteorological-satellite service notified before 1 January 2004. Any new assignment to these Earth stations in this band shall also be protected from harmful interference from stations in the mobile-satellite service. (WRC-07)

5.381 *Additional allocation:* in Afghanistan, Cuba, India, Iran (Islamic Republic of) and Pakistan, the band 1690-1700 MHz is also allocated to the fixed and mobile, except aeronautical mobile, services on a primary basis. (WRC-12)

5.382 *Different category of service:* in Saudi Arabia, Armenia, Azerbaijan, Bahrain, Belarus, Congo (Rep. of the), Egypt, the United Arab Emirates, Eritrea, Ethiopia, the Russian Federation, Guinea, Iraq, Israel, Jordan, Kazakhstan, Kuwait, the Former Yugoslav Republic of Macedonia, Lebanon, Mauritania, Moldova, Mongolia, Oman, Uzbekistan, Poland, Qatar, the Syrian Arab Republic, Kyrgyzstan, Somalia, Tajikistan, Tanzania, Turkmenistan, Ukraine and Yemen, the allocation of the band 1690-1700 MHz to the fixed and mobile, except aeronautical mobile, services is on a primary basis (see No. 5.33), and in the Dem. People's Rep. of Korea, the allocation of the band 1690-1700 MHz to the fixed service is on a primary basis (see No. 5.33) and to the mobile, except aeronautical mobile, service on a secondary basis. (WRC-12)

5.384 *Additional allocation:* in India, Indonesia and Japan, the band 1700-1710 MHz is also allocated to the space research service (space-to-Earth) on a primary basis.

5.384A The bands, or portions of the bands, 1710-1885 MHz, 2300-2400 MHz and 2500-2690 MHz, are identified for use by administrations wishing to implement International Mobile Telecommunications (IMT) in accordance with Resolution 223 (Rev.WRC-12). This identification does not preclude the use of these bands by any application of the services to which they are allocated and does not establish priority in the Radio Regulations. (FCC)

5.385 *Additional allocation:* the band 1718.8-1722.2 MHz is also allocated to the radio astronomy service on a secondary basis for spectral line observations.

5.386 *Additional allocation:* the band 1750-1850 MHz is also allocated to the space operation (Earth-to-space) and space research (Earth-to-space) services in Region 2, in Australia, Guam, India, Indonesia and Japan on a primary basis, subject to agreement obtained under No. 9.21, having particular regard to troposcatter systems.

5.387 *Additional allocation:* in Belarus, Georgia, Kazakhstan, Kyrgyzstan, Romania, Tajikistan and Turkmenistan, the band 1770-1790 MHz is also allocated to the meteorological-satellite service on a primary basis, subject to agreement obtained under No. 9.21. (WRC-12)

5.388 The bands 1885-2025 MHz and 2110-2200 MHz are intended for use, on a worldwide basis, by administrations wishing to implement International Mobile Telecommunications (IMT). Such use does not preclude the use of these bands by other services to which they are allocated. The bands should be made available for IMT in accordance with Resolution 212 (Rev.WRC-07). (See also Resolution 223 (Rev.WRC-12).) (WRC-12) (FCC)

5.388A In Regions 1 and 3, the bands 1885-1980 MHz, 2010-2025 MHz and 2110-2170 MHz and, in Region 2, the bands 1885-1980 MHz and 2110-2160 MHz may be used by high altitude platform stations as base stations to provide International Mobile Telecommunications (IMT), in accordance with Resolution 221 (Rev.WRC-07). Their use by IMT applications using high altitude platform stations as base stations does not preclude the use of these bands by any station in the services to which they are allocated and does not establish priority in the Radio Regulations. (WRC-12)

5.388B In Algeria, Saudi Arabia, Bahrain, Benin, Burkina Faso, Cameroon, Comoros, Côte d'Ivoire, China, Cuba, Djibouti, Egypt, United Arab Emirates, Eritrea, Ethiopia, Gabon, Ghana, India, Iran (Islamic Republic of), Israel, Jordan, Kenya, Kuwait, Libya, Mali, Morocco, Mauritania, Nigeria, Oman, Uganda, Pakistan, Qatar, the Syrian Arab Republic, Senegal, Singapore, Sudan, South Sudan, Tanzania, Chad, Togo, Tunisia, Yemen, Zambia and Zimbabwe, for the purpose of protecting fixed and mobile services, including IMT mobile stations, in their territories from co-channel interference, a high altitude platform station (HAPS) operating as an IMT base station in neighbouring countries, in the bands referred to in No. 5.388A, shall not exceed a co-channel power flux-density of -127 dB(W/(m^2 · MHz)) at the Earth's surface outside a country's borders unless explicit agreement of the affected administration is provided at the time of the notification of HAPS. (WRC-12)

5.391 In making assignments to the mobile service in the bands 2025-2110 MHz and 2200-2290 MHz, administrations shall not introduce high-density mobile systems, as described in Recommendation ITU-R SA.1154, and shall take that Recommendation into account for the introduction of any other type of mobile system.

5.392 Administrations are urged to take all practicable measures to ensure that space-to-space transmissions between two or more non-geostationary satellites, in the space research, space operations and Earth exploration-satellite services in the bands 2025-2110 MHz and 2200-2290 MHz, shall not impose any constraints on Earth-to-space, space-to-Earth and other space-to-space transmissions of those services and in those bands between geostationary and non-geostationary satellites.

5.393 *Additional allocation:* in Canada, the United States, India and Mexico, the band 2310-2360 MHz is also allocated to the broadcasting-satellite service (sound) and complementary terrestrial sound broadcasting service on a primary basis. Such use is limited to digital audio broadcasting and is subject to the provisions of Resolution 528 (Rev.WRC-03), with the exception of *resolves* 3 in regard to the limitation on broadcasting-satellite systems in the upper 25 MHz. (WRC-07)

5.394 In the United States, the use of the band 2300-2390 MHz by the aeronautical mobile service for telemetry has priority over other uses by the mobile services. In Canada, the use of the band 2360-2400 MHz by the aeronautical mobile service for telemetry has priority over other uses by the mobile services. (WRC-07)

5.395 In France and Turkey, the use of the band 2310-2360 MHz by the aeronautical mobile service for telemetry has priority over other uses by the mobile service.

5.396 Space stations of the broadcasting-satellite service in the band 2310-2360 MHz operating in accordance with No. 5.393 that may affect the services to which this band is allocated in other countries shall be coordinated and notified in accordance with Resolution 33 (Rev.WRC-03). Complementary terrestrial broadcasting stations shall be subject to bilateral coordination with neighbouring countries prior to their bringing into use. (FCC)

5.398 In respect of the radiodetermination-satellite service in the band 2483.5-2500 MHz, the provisions of No. 4.10 do not apply.

5.398A *Different category of service:* In Armenia, Azerbaijan, Belarus, the Russian Federation, Kazakhstan, Uzbekistan, Kyrgyzstan, Tajikistan and Ukraine, the band 2483.5-2500 MHz is allocated on a primary basis to the radiolocation service. The radiolocation stations in these countries shall not cause harmful interference to, or claim protection from, stations of the fixed, mobile and mobile-satellite services operating in accordance with the Radio Regulations in the frequency band 2483.5-2500 MHz. (WRC-12)

5.399 Except for cases referred to in No. 5.401, stations of the radiodetermination-satellite service operating in the frequency band 2483.5-2500 MHz for which notification information is received by the Bureau after 17 February 2012, and the service area of which includes Armenia, Azerbaijan, Belarus, the Russian Federation, Kazakhstan, Uzbekistan, Kyrgyzstan, Tajikistan and Ukraine, shall not cause harmful interference to, and shall not claim protection from stations of the radiolocation service operating in these countries in accordance with No. 5.398A. (WRC-12)

5.401 In Angola, Australia, Bangladesh, Burundi, China, Eritrea, Ethiopia, India, Iran (Islamic Republic of), Lebanon, Liberia, Libya, Madagascar, Mali, Pakistan, Papua New Guinea, Syrian Arab Republic, Dem. Rep. of the Congo, Sudan, Swaziland, Togo and Zambia, the band 2483.5-2500 MHz was already allocated on a primary basis to the radiodetermination-satellite service before WRC-12, subject to agreement obtained under No. 9.21 from countries not listed in this provision. Systems in the radiodetermination-satellite service for which complete coordination information has been received by the Radiocommunication Bureau before 18 February 2012 will retain their regulatory status, as of the date of receipt of the coordination request information. (WRC-12)

5.402 The use of the band 2483.5-2500 MHz by the mobile-satellite and the radiodetermination-satellite services is subject to the coordination under No. 9.11A. Administrations are urged to take all practicable steps to prevent harmful interference to the radio astronomy service from emissions in the 2483.5-2500 MHz band, especially those caused by second-harmonic radiation that would fall into the 4990-5000 MHz band allocated to the radio astronomy service worldwide.

5.403 Subject to agreement obtained under No. 9.21, the band 2520-2535 MHz may also be used for the mobile-satellite (space-to-Earth), except aeronautical mobile-satellite, service for operation limited to within national boundaries. The provisions of No. 9.11A apply. (WRC-07)

5.404 *Additional allocation:* in India and Iran (Islamic Republic of), the band 2500-2516.5 MHz may also be used for the radiodetermination-satellite service (space-to-Earth) for operation limited to within national boundaries, subject to agreement obtained under No. 9.21.

5.407 In the band 2500-2520 MHz, the power flux-density at the surface of the Earth from space stations operating in the mobile-satellite (space-to-Earth) service shall not exceed –152 dB ($W/(m^2 \cdot 4$ kHz)) in Argentina, unless otherwise agreed by the administrations concerned.

5.410 The band 2500-2690 MHz may be used for tropospheric scatter systems in Region 1, subject to agreement obtained under No. 9.21. No. 9.21 does not apply to tropospheric scatter links situated entirely outside Region 1. Administrations shall make all practicable efforts to avoid developing new tropospheric scatter systems in this band. When planning new tropospheric scatter radio-relay links in this band, all possible measures shall be taken to avoid directing the antennas of these links towards the geostationary-satellite orbit. (WRC-12)

5.412 *Alternative allocation:* in Kyrgyzstan and Turkmenistan, the band 2500-2690 MHz is allocated to the fixed and mobile, except aeronautical mobile, services on a primary basis. (WRC-12)

5.413 In the design of systems in the broadcasting-satellite service in the bands between 2500 MHz and 2690 MHz, administrations are urged to take all necessary steps to protect the radio astronomy service in the band 2690-2700 MHz.

5.414 The allocation of the frequency band 2500-2520 MHz to the mobile-satellite service (space-to-Earth) is subject to coordination under No. 9.11A. (WRC-07)

5.414A In Japan and India, the use of the bands 2500-2520 MHz and 2520-2535 MHz, under No. 5.403, by a satellite network in the mobile-satellite service (space-to-Earth) is limited to operation within national boundaries and subject to the application of No. 9.11A. The following pfd values shall be used as a threshold for coordination under No. 9.11A, for all conditions and for all methods of modulation, in an area of 1000 km around the territory of the administration notifying the mobile-satellite service network:

-136 dB($W/(m^2 \cdot$ MHz)) for $0° \leq \theta \leq 5°$

$-136 + 0.55 (\theta - 5)$ dB($W/(m^2 \cdot$ MHz)) for $5° < \theta \leq 25°$

-125 dB($W/(m^2 \cdot$ MHz)) for $25° < \theta \leq 90°$

where θ is the angle of arrival of the incident wave above the horizontal plane, in degrees. Outside this area Table 21-4 of Article 21 shall apply. Furthermore, the coordination thresholds in Table 5-2 of Annex 1 to Appendix 5 of the Radio Regulations (Edition of 2004), in conjunction with the applicable provisions of Articles 9 and 11 associated with No. 9.11A, shall apply to systems for which complete notification information has been received by the Radicommunication Bureau by 14 November 2007 and that have been brought into use by that date. (WRC-07)

5.415 The use of the bands 2500-2690 MHz in Region 2 and 2500-2535 MHz and 2655-2690 MHz in Region 3 by the fixed-satellite service is limited to national and regional systems, subject to agreement obtained under No. 9.21, giving particular attention to the broadcasting-satellite service in Region 1. (WRC-07)

5.415A *Additional allocation:* in India and Japan, subject to agreement obtained under No. 9.21, the band 2515-2535 MHz may also be used for the aeronautical mobile-satellite service (space-to-Earth) for operation limited to within their national boundaries.

5.416 The use of the band 2520-2670 MHz by the broadcasting-satellite service is limited to national and regional systems for community reception, subject to agreement obtained under No. 9.21. The provisions of No. 9.19 shall be applied by administrations in this band in their bilateral and multilateral negotiations. (WRC-07)

5.417A In applying provision No. 5.418, in Korea (Rep. of) and Japan, *resolves* 3 of Resolution 528 (Rev. WRC-03) is relaxed to allow the broadcasting-satellite service (sound) and the complementary terrestrial broadcasting service to additionally operate on a primary basis in the band 2605-2630 MHz. This use is limited to systems intended for national coverage. An administration listed in this provision shall not have simultaneously two overlapping frequency assignments, one under this provision and the other under No. 5.416. The provisions of No. 5.416 and Table 21-4 of Article 21 do not apply. Use of non-geostationary-satellite systems in the broadcasting-satellite service (sound) in the band 2605-2630 MHz is subject to the provisions of Resolution 539 (Rev.WRC-03). The power flux-density at the Earth's surface produced by emissions from a geostationary broadcasting-satellite service (sound) space station operating in the band 2605-2630 MHz for which complete Appendix 4 coordination information, or notification information, has been received after 4 July 2003, for all conditions and for all methods of modulation, shall not exceed the following limits:

-130 dB(W/(m^2 · MHz)) for $0° \leq \theta \leq 5°$

$-130 + 0.4 (\theta - 5)$ dB(W/(m^2 · MHz)) for $5° < \theta \leq 25°$

-122 dB(W/(m^2 · MHz)) for $25° < \theta \leq 90°$

where θ is the angle of arrival of the incident wave above the horizontal plane, in degrees. These limits may be exceeded on the territory of any country whose administration has so agreed. In the case of the broadcasting-satellite service (sound) networks of Korea (Rep. of), as an exception to the limits above, the power flux-density value of -122 dB(W/(m^2 · MHz)) shall be used as a threshold for coordination under No. 9.11 in an area of 1000 km around the territory of the administration notifying the broadcasting-satellite service (sound) system, for angles of arrival greater than 35°.

5.417B In Korea (Rep. of) and Japan, use of the band 2605-2630 MHz by non-geostationary-satellite systems in the broadcasting-satellite service (sound), pursuant to No. 5.417A, for which complete Appendix 4 coordination information, or notification information, has been received after 4 July 2003, is subject to the application of the provisions of No. 9.12A, in respect of geostationary-satellite networks for which complete Appendix 4 coordination information, or notification information, is considered to have been received after 4 July 2003, and No. 22.2 does not apply. No. 22.2 shall continue to apply with respect to geostationary-satellite networks for which complete Appendix 4 coordination information, or notification information, is considered to have been received before 5 July 2003.

5.417C Use of the band 2605-2630 MHz by non-geostationary-satellite systems in the broadcasting-satellite service (sound), pursuant to No. 5.417A, for which complete Appendix 4 coordination information, or notification information, has been received after 4 July 2003, is subject to the application of the provisions of No. 9.12.

5.417D Use of the band 2605-2630 MHz by geostationary-satellite networks for which complete Appendix 4 coordination information, or notification information, has been received after 4 July 2003 is subject to the application of the provisions of No. 9.13 with respect to non-geostationary-satellite systems in the broadcasting-satellite service (sound), pursuant to No. 5.417A, and No. 22.2 does not apply.

5.418 *Additional allocation:* in Korea (Rep. of), India, Japan and Thailand, the band 2535-2655 MHz is also allocated to the broadcasting-satellite service (sound) and complementary terrestrial broadcasting service on a primary basis. Such use is limited to digital audio broadcasting and is subject to the provisions of

Resolution 528 (Rev.WRC-03). The provisions of No. 5.416 and Table 21-4 of Article 21, do not apply to this additional allocation. Use of non-geostationary-satellite systems in the broadcasting-satellite service (sound) is subject to Resolution 539 (Rev.WRC-03). Geostationary broadcasting-satellite service (sound) systems for which complete Appendix 4 coordination information has been received after 1 June 2005 are limited to systems intended for national coverage. The power flux-density at the Earth's surface produced by emissions from a geostationary broadcasting-satellite service (sound) space station operating in the band 2630-2655 MHz, and for which complete Appendix 4 coordination information has been received after 1 June 2005, shall not exceed the following limits, for all conditions and for all methods of modulation:

-130 dB(W/(m^2 · MHz)) for $0° \leq \theta \leq 5°$
$-130 + 0.4 (\theta - 5)$ dB(W/(m^2 · MHz)) for $5° < \theta \leq 25°$
-122 dB(W/(m^2 · MHz)) for $25° < \theta \leq 90°$

where θ is the angle of arrival of the incident wave above the horizontal plane, in degrees. These limits may be exceeded on the territory of any country whose administration has so agreed. As an exception to the limits above, the pfd value of –122 dB(W/(m^2 · MHz)) shall be used as a threshold for coordination under No. 9.11 in an area of 1500 km around the territory of the administration notifying the broadcasting-satellite service (sound) system.

In addition, an administration listed in this provision shall not have simultaneously two overlapping frequency assignments, one under this provision and the other under No. 5.416 for systems for which complete Appendix 4 coordination information has been received after 1 June 2005. (WRC-12)

5.418A In certain Region 3 countries listed in No. 5.418, use of the band 2630-2655 MHz by non-geostationary-satellite systems in the broadcasting-satellite service (sound) for which complete Appendix 4 coordination information, or notification information, has been received after 2 June 2000, is subject to the application of the provisions of No. 9.12A, in respect of geostationary-satellite networks for which complete Appendix 4 coordination information, or notification information, is considered to have been received after 2 June 2000, and No. 22.2 does not apply. No. 22.2 shall continue to apply with respect to geostationary-satellite networks for which complete Appendix 4 coordination information, or notification information, is considered to have been received before 3 June 2000.

5.418B Use of the band 2630-2655 MHz by non-geostationary-satellite systems in the broadcasting-satellite service (sound), pursuant to No. 5.418, for which complete Appendix 4 coordination information, or notification information, has been received after 2 June 2000, is subject to the application of the provisions of No. 9.12.

5.418C Use of the band 2630-2655 MHz by geostationary-satellite networks for which complete Appendix 4 coordination information, or notification information, has been received after 2 June 2000 is subject to the application of the provisions of No. 9.13 with respect to non-geostationary-satellite systems in the broadcasting-satellite service (sound), pursuant to No. 5.418 and No. 22.2 does not apply.

5.419 When introducing systems of the mobile-satellite service in the band 2670-2690 MHz, administrations shall take all necessary steps to protect the satellite systems operating in this band prior to 3 March 1992. The coordination of mobile-satellite systems in the band shall be in accordance with No. 9.11A. (WRC-07)

5.420 The band 2655-2670 MHz may also be used for the mobile-satellite (Earth-to-space), except aeronautical mobile-satellite, service for operation limited to within national boundaries, subject to agreement obtained under No. 9.21. The coordination under No. 9.11A applies. (WRC-07)

5.422 *Additional allocation:* in Saudi Arabia, Armenia, Azerbaijan, Bahrain, Belarus, Brunei Darussalam, Congo (Rep. of the), Côte d'Ivoire, Cuba, Djibouti, Egypt, the United Arab Emirates, Eritrea, Ethiopia, Gabon, Georgia, Guinea, Guinea-Bissau, Iran (Islamic Republic of), Iraq, Israel, Jordan, Kuwait, Lebanon, Mauritania, Mongolia, Montenegro, Nigeria, Oman, Pakistan, the Philippines, Qatar, Syrian Arab Republic, Kyrgyzstan, the Dem. Rep. of the Congo, Romania, Somalia, Tajikistan, Tunisia, Turkmenistan, Ukraine and Yemen, the band 2690-2700 MHz is also allocated to the fixed and mobile, except aeronautical mobile, services on a primary basis. Such use is limited to equipment in operation by 1 January 1985. (WRC-12)

5.423 In the band 2700-2900 MHz, ground-based radars used for meteorological purposes are authorized to operate on a basis of equality with stations of the aeronautical radionavigation service.

5.424 *Additional allocation:* in Canada, the band 2850-2900 MHz is also allocated to the maritime radionavigation service, on a primary basis, for use by shore-based radars.

5.424A In the band 2900-3100 MHz, stations in the radiolocation service shall not cause harmful interference to, nor claim protection from, radar systems in the radionavigation service.

5.425 In the band 2900-3100 MHz, the use of the shipborne interrogator-transponder (SIT) system shall be confined to the sub-band 2930-2950 MHz.

5.426 The use of the band 2900-3100 MHz by the aeronautical radionavigation service is limited to ground-based radars.

5.427 In the bands 2900-3100 MHz and 9300-9500 MHz, the response from radar transponders shall not be capable of being confused with the response from radar beacons (racons) and shall not cause interference to ship or aeronautical radars in the radionavigation service, having regard, however, to No. 4.9.

5.428 *Additional allocation:* in Azerbaijan, Mongolia, Kyrgyzstan and Turkmenistan, the band 3100-3300 MHz is also allocated to the radionavigation service on a primary basis. (WRC-12)

5.429 *Additional allocation:* in Saudi Arabia, Bahrain, Bangladesh, Brunei Darussalam, Cameroon, China, Congo (Rep. of the), Korea (Rep. of), Côte d'Ivoire, Egypt, the United Arab Emirates, India, Indonesia, Iran (Islamic Republic of), Iraq, Israel, Japan, Jordan, Kenya, Kuwait, Lebanon, Libya, Malaysia, Oman, Uganda, Pakistan, Qatar, the Syrian Arab Republic, the Dem. Rep. of the Congo, the Dem. People's Rep. of Korea and Yemen, the band 3300-3400 MHz is also allocated to the fixed and mobile services on a primary basis. The countries bordering the Mediterranean shall not claim protection for their fixed and mobile services from the radiolocation service. (WRC-12)

5.430 *Additional allocation:* in Azerbaijan, Mongolia, Kyrgyzstan and Turkmenistan, the band 3300-3400 MHz is also allocated to the radionavigation service on a primary basis. (WRC-12)

5.438 Use of the band 4200-4400 MHz by the aeronautical radionavigation service is reserved exclusively for radio altimeters installed on board aircraft and for the associated transponders on the ground. However, passive sensing in the Earth exploration-satellite and space research services may be authorized in this band on a secondary basis (no protection is provided by the radio altimeters).

5.439 *Additional allocation:* in Iran (Islamic Republic of), the band 4200-4400 MHz is also allocated to the fixed service on a secondary basis. (WRC-12)

5.440 The standard frequency and time signal-satellite service may be authorized to use the frequency 4202 MHz for space-to-Earth transmissions and the frequency 6427 MHz for Earth-to-space transmissions. Such transmissions shall be confined within the limits of ± 2 MHz of these frequencies, subject to agreement obtained under No. 9.21.

5.440A In Region 2 (except Brazil, Cuba, French overseas departments and communities, Guatemala, Paraguay, Uruguay and Venezuela), and in Australia, the band 4400-4940 MHz may be used for aeronautical mobile telemetry for flight testing by aircraft stations (see No. 1.83). Such use shall be in accordance with Resolution 416 (WRC-07) and shall not cause harmful interference to, nor claim protection from, the fixed-satellite and fixed services. Any such use does not preclude the use of this band by other mobile service applications or by other services to which this band is allocated on a co-primary basis and does not establish priority in the Radio Regulations. (WRC-07)

5.441 The use of the bands 4500-4800 MHz (space-to-Earth), 6725-7025 MHz (Earth-to-space) by the fixed-satellite service shall be in accordance with the provisions of Appendix 30B. The use of the bands 10.7-10.95 GHz (space-to-Earth), 11.2-11.45 GHz (space-to-Earth) and 12.75-13.25 GHz (Earth-to-space) by geostationary-satellite systems in the fixed-satellite service shall be in accordance with the provisions of Appendix 30B. The use of the bands 10.7-10.95 GHz (space-to-Earth), 11.2-11.45 GHz (space-to-Earth) and 12.75-13.25 GHz (Earth-to-space) by a non-geostationary-satellite system in the fixed-satellite service is subject to application of the provisions of No. 9.12 for coordination with other non-geostationary-satellite systems in the fixed-satellite service. Non-geostationary-satellite systems in the fixed-satellite service shall not claim protection from geostationary-satellite networks in the fixed-satellite service operating in accordance with the Radio Regulations, irrespective of the dates of receipt by the Bureau of the complete coordination or notification information, as appropriate, for the non-geostationary-satellite systems in the fixed-satellite service and of the complete coordination or notification information, as appropriate, for the geostationary-satellite networks, and No. 5.43A does not apply. Non-geostationary-satellite systems in the fixed-satellite service in the above bands shall be operated in such a way that any unacceptable interference that may occur during their operation shall be rapidly eliminated.

5.442 In the bands 4825-4835 MHz and 4950-4990 MHz, the allocation to the mobile service is restricted to the mobile, except aeronautical mobile, service. In Region 2 (except Brazil, Cuba, Guatemala, Paraguay, Uruguay and Venezuela), and in Australia, the band 4825-4835 MHz is also allocated to the aeronautical mobile service, limited to aeronautical mobile telemetry for flight testing by aircraft stations. Such use shall be in accordance with Resolution 416 (WRC-07) and shall not cause harmful interference to the fixed service. (WRC-07)

5.443 *Different category of service:* in Argentina, Australia and Canada, the allocation of the bands 4825-4835 MHz and 4950-4990 MHz to the radio astronomy service is on a primary basis (see No. 5.33).

5.443AA In the frequency bands 5000-5030 MHz and 5091-5150 MHz, the aeronautical mobile-satellite (R) service is subject to agreement obtained under No. 9.21. The use of these bands by the aeronautical mobile-satellite (R) service is limited to internationally standardized aeronautical systems. (WRC-12)

5.443B In order not to cause harmful interference to the microwave landing system operating above 5030 MHz, the aggregate power flux-density produced at the Earth's surface in the band 5030-5150 MHz by all the space stations within any radionavigation-satellite service system (space-to-Earth) operating in the band 5010-5030 MHz shall not exceed –124.5 dB(W/m^2) in a 150 kHz band. In order not to cause harmful interference to the radio astronomy service in the band 4990-5000 MHz, radionavigation-satellite service systems operating in the band 5010-5030 MHz shall comply with the limits in the band 4990-5000 MHz defined in Resolution 741 (Rev.WRC-12). (WRC-12)

5.443C The use of the frequency band 5030-5091 MHz by the aeronautical mobile (R) service is limited to internationally standardized aeronautical systems. Unwanted emissions from the aeronautical mobile (R) service in the frequency band 5030-5091 MHz shall be limited to protect RNSS system downlinks in the adjacent 5010-5030 MHz band. Until such time that an appropriate value is established in a relevant ITU-R Recommendation, the e.i.r.p. density limit of –75 dBW/MHz in the frequency band 5010-5030 MHz for any AM(R)S station unwanted emission should be used. (WRC-12)

5.443D In the frequency band 5030-5091 MHz, the aeronautical mobile-satellite (R) service is subject to coordination under No. 9.11A. The use of this frequency band by the aeronautical mobile-satellite (R) service is limited to internationally standardized aeronautical systems. (WRC-12)

5.444 The frequency band 5030-5150 MHz is to be used for the operation of the international standard system (microwave landing system) for precision approach and landing. In the frequency band 5030-5091 MHz, the requirements of this system shall have priority over other uses of this band. For the use of the frequency band 5091-5150 MHz, No. 5.444A and Resolution 114 (Rev.WRC-12) apply. (WRC-12)

5.444A *Additional allocation:* the band 5091-5150 MHz is also allocated to the fixed-satellite service (Earth-to-space) on a primary basis. This allocation is limited to feeder links of non-geostationary satellite systems in the mobile-satellite service and is subject to coordination under No. 9.11A.

In the band 5091-5150 MHz, the following conditions also apply:

—prior to 1 January 2018, the use of the band 5091-5150 MHz by feeder links of non-geostationary-satellite systems in the mobile-satellite service shall be made in accordance with Resolution 114 (Rev. WRC-12);

—after 1 January 2016, no new assignments shall be made to Earth stations providing feeder links of non-geostationary mobile-satellite systems;

—after 1 January 2018, the fixed-satellite service will become secondary to the aeronautical radionavigation service. (FCC)

5.444B The use of the frequency band 5091-5150 MHz by the aeronautical mobile service is limited to:

—systems operating in the aeronautical mobile (R) service and in accordance with international aeronautical standards, limited to surface applications at airports. Such use shall be in accordance with Resolution 748 (Rev.WRC-12);

—aeronautical telemetry transmissions from aircraft stations (see No. 1.83) in accordance with Resolution 418 (Rev.WRC-12). (WRC-12)

5.446 *Additional allocation:* in the countries listed in No. 5.369, the band 5150-5216 MHz is also allocated to the radiodetermination-satellite service (space-to-Earth) on a primary basis, subject to agreement obtained under No. 9.21. In Region 2, the band is also allocated to the radiodetermination-satellite service (space-to-Earth) on a primary basis. In Regions 1 and 3, except those countries listed in Nos. 5.369 and Bangladesh, the band is also allocated to the radiodetermination-satellite service (space-to-Earth) on a secondary basis. The use by the radiodetermination-satellite service is limited to feeder links in conjunction with the radiodetermination-satellite service operating in the bands 1610-1626.5 MHz and/or 2483.5-2500 MHz. The total power flux-density at the Earth's surface shall in no case exceed –159 dB (W/m^2) in any 4 kHz band for all angles of arrival. (WRC-12)

5.446A The use of the bands 5150-5350 MHz and 5470-5725 MHz by the stations in the mobile, except aeronautical mobile, service shall be in accordance with Resolution 229 (Rev.WRC-12). (WRC-12)

5.446B In the band 5150-5250 MHz, stations in the mobile service shall not claim protection from Earth stations in the fixed-satellite service. No. 5.43A does not apply to the mobile service with respect to fixed-satellite service Earth stations.

5.446C *Additional allocation:* in Region 1 (except in Algeria, Saudi Arabia, Bahrain, Egypt, United Arab Emirates, Jordan, Kuwait, Lebanon, Morocco, Oman, Qatar, Syrian Arab Republic, Sudan, South Sudan and Tunisia) and in Brazil, the band 5150-5250 MHz is also allocated to the aeronautical mobile service on a primary basis, limited to aeronautical telemetry transmissions from aircraft stations (see No. 1.83), in accordance with Resolution 418 (Rev.WRC-12). These stations shall not claim protection from other stations operating in accordance with Article 5. No. 5.43A does not apply. (WRC-12)

5.447 *Additional allocation:* in Côte d'Ivoire, Egypt, Israel, Lebanon, the Syrian Arab Republic and Tunisia, the band 5150-5250 MHz is also allocated to the mobile service, on a primary basis, subject to agreement obtained under No. 9.21. In this case, the provisions of Resolution 229 (Rev.WRC-12) do not apply. (WRC-12)

5.447A The allocation to the fixed-satellite service (Earth-to-space) in the band 5150-5250 MHz is limited to feeder links of non-geostationary-satellite systems in the mobile-satellite service and is subject to coordination under No. 9.11A.

5.447B *Additional allocation:* the band 5150-5216 MHz is also allocated to the fixed-satellite service (space-to-Earth) on a primary basis. This allocation is limited to feeder links of non-geostationary-satellite systems in the mobile-satellite service and is subject to provisions of No. 9.11A. The power flux-density at the Earth's surface produced by space stations of the fixed-satellite service operating in the space-to-Earth direction in the band 5150-5216 MHz shall in no case exceed –164 dB(W/m^2) in any 4 kHz band for all angles of arrival.

5.447C Administrations responsible for fixed-satellite service networks in the band 5150-5250 MHz operated under Nos. 5.447A and 5.447B shall coordinate on an equal basis in accordance with No. 9.11A with administrations responsible for non-geostationary-satellite networks operated under No. 5.446 and brought into use prior to 17 November 1995. Satellite networks operated under No. 5.446 brought into use after 17 November 1995 shall not claim protection from, and shall not cause harmful interference to, stations of the fixed-satellite service operated under Nos. 5.447A and 5.447B.

5.447D The allocation of the band 5250-5255 MHz to the space research service on a primary basis is limited to active spaceborne sensors. Other uses of the band by the space research service are on a secondary basis.

5.447E *Additional allocation:* The band 5250-5350 MHz is also allocated to the fixed service on a primary basis in the following countries in Region 3: Australia, Korea (Rep. of), India, Indonesia, Iran (Islamic Republic of), Japan, Malaysia, Papua New Guinea, the Philippines, Dem. People's Rep. of Korea, Sri Lanka, Thailand and Viet Nam. The use of this band by the fixed service is intended for the implementation of fixed wireless access systems and shall comply with Recommendation ITU-R F.1613. In addition, the fixed service shall not claim protection from the radiodetermination, Earth exploration-satellite (active) and space research (active) services, but the provisions of No. 5.43A do not apply to the fixed service with respect to the Earth exploration-satellite (active) and space research (active) services. After implementation of fixed wireless access systems in the fixed service with protection for the existing radiodetermination systems, no more stringent constraints should be imposed on the fixed wireless access systems by future radiodetermination implementations. (WRC-07)

5.447F In the band 5250-5350 MHz, stations in the mobile service shall not claim protection from the radiolocation service, the Earth exploration-satellite service (active) and the space research service (active). These services shall not impose on the mobile service more stringent protection criteria, based on system characteristics and interference criteria, than those stated in Recommendations ITU-R M.1638 and ITU-R RS.1632.

5.448 *Additional allocation:* in Azerbaijan, Kyrgyzstan, Romania and Turkmenistan, the band 5250-5350 MHz is also allocated to the radionavigation service on a primary basis. (WRC-12)

5.448A The Earth exploration-satellite (active) and space research (active) services in the frequency band 5250-5350 MHz shall not claim protection from the radiolocation service. No. 5.43A does not apply.

5.448B The Earth exploration-satellite service (active) operating in the band 5350-5570 MHz and space research service (active) operating in the band 5460-5570 MHz shall not cause harmful interference to the aeronautical radionavigation service in the band 5350-5460 MHz, the radionavigation service in the band 5460-5470 MHz and the maritime radionavigation service in the band 5470-5570 MHz.

5.448C The space research service (active) operating in the band 5350-5460 MHz shall not cause harmful interference to nor claim protection from other services to which this band is allocated.

5.448D In the frequency band 5350-5470 MHz, stations in the radiolocation service shall not cause harmful interference to, nor claim protection from, radar systems in the aeronautical radionavigation service operating in accordance with No. 5.449.

5.449 The use of the band 5350-5470 MHz by the aeronautical radionavigation service is limited to airborne radars and associated airborne beacons.

5.450 *Additional allocation:* in Austria, Azerbaijan, Iran (Islamic Republic of), Kyrgyzstan, Romania, Turkmenistan and Ukraine, the band 5470-5650 MHz is also allocated to the aeronautical radionavigation service on a primary basis. (WRC-12)

5.450A In the band 5470-5725 MHz, stations in the mobile service shall not claim protection from radiodetermination services. Radiodetermination services shall not impose on the mobile service more stringent protection criteria, based on system characteristics and interference criteria, than those stated in Recommendation ITU-R M.1638.

5.450B In the frequency band 5470-5650 MHz, stations in the radiolocation service, except ground-based radars used for meteorological purposes in the band 5600-5650 MHz, shall not cause harmful interference to, nor claim protection from, radar systems in the maritime radionavigation service.

5.451 *Additional allocation:* in the United Kingdom, the band 5470-5850 MHz is also allocated to the land mobile service on a secondary basis. The power limits specified in Nos. 21.2, 21.3, 21.4 and 21.5 shall apply in the band 5725-5850 MHz.

5.452 Between 5600 MHz and 5650 MHz, ground-based radars used for meteorological purposes are authorized to operate on a basis of equality with stations of the maritime radionavigation service.

5.453 *Additional allocation:* in Saudi Arabia, Bahrain, Bangladesh, Brunei Darussalam, Cameroon, China, Congo (Rep. of the), Korea (Rep. of), Côte d'Ivoire, Djibouti, Egypt, the United Arab Emirates, Gabon, Guinea, Equatorial Guinea, India, Indonesia, Iran (Islamic Republic of), Iraq, Israel, Japan, Jordan, Kenya, Kuwait, Lebanon, Libya, Madagascar, Malaysia, Niger, Nigeria, Oman, Uganda, Pakistan, the Philippines, Qatar, the Syrian Arab Republic, the Dem. People's Rep. of Korea, Singapore, Sri Lanka, Swaziland, Tanzania, Chad, Thailand, Togo, Viet Nam and Yemen, the band 5650-5850 MHz is also allocated to the fixed and mobile services on a primary basis. In this case, the provisions of Resolution 229 (Rev.WRC-12) do not apply. (WRC-12)

5.454 *Different category of service:* in Azerbaijan, the Russian Federation, Georgia, Kyrgyzstan, Tajikistan and Turkmenistan, the allocation of the band 5670-5725 MHz to the space research service is on a primary basis (see No. 5.33). (WRC-12)

5.455 *Additional allocation:* in Armenia, Azerbaijan, Belarus, Cuba, the Russian Federation, Georgia, Hungary, Kazakhstan, Moldova, Mongolia, Uzbekistan, Kyrgyzstan, Tajikistan, Turkmenistan and Ukraine, the band 5670-5850 MHz is also allocated to the fixed service on a primary basis. (WRC-07)

5.457 In Australia, Burkina Faso, Côte d'Ivoire, Mali and Nigeria, the allocation to the fixed service in the bands 6440-6520 MHz (HAPS-to-ground direction) and 6560-6640 MHz (ground-to-HAPS direction) may also be used by gateway links for high-altitude platform stations (HAPS) within the territory of these countries. Such use is limited to operation in HAPS gateway links and shall not cause harmful interference to, and shall not claim protection from, existing services, and shall be in compliance with Resolution 150 (WRC-12). Existing services shall not be constrained in future development by HAPS gateway links. The use of HAPS gateway links in these bands requires explicit agreement with other administrations whose territories are located within 1000 kilometres from the border of an administration intending to use the HAPS gateway links. (WRC-12)

5.457A In the bands 5925-6425 MHz and 14-14.5 GHz, Earth stations located on board vessels may communicate with space stations of the fixed-satellite service. Such use shall be in accordance with Resolution 902 (WRC-03).

5.457B In the bands 5925-6425 MHz and 14-14.5 GHz, Earth stations located on board vessels may operate with the characteristics and under the conditions contained in Resolution 902 (WRC-03) in Algeria, Saudi Arabia, Bahrain, Comoros, Djibouti, Egypt, United Arab Emirates, Jordan, Kuwait, Libya, Morocco, Mauritania, Oman, Qatar, the Syrian Arab Republic, Sudan, South Sudan, Tunisia and Yemen, in the maritime mobile-satellite service on a secondary basis. Such use shall be in accordance with Resolution 902 (WRC-03). (WRC-12)

5.457C In Region 2 (except Brazil, Cuba, French overseas departments and communities, Guatemala, Paraguay, Uruguay and Venezuela), the band 5925-6700 MHz may be used for aeronautical mobile telemetry for flight testing by aircraft stations (see No. 1.83). Such use shall be in accordance with Resolution 416 (WRC-07) and shall not cause harmful interference to, nor claim protection from, the fixed-satellite and fixed services. Any such use does not preclude the use of this band by other mobile service applications or by other services to which this band is allocated on a co-primary basis and does not establish priority in the Radio Regulations. (WRC-07)

5.458 In the band 6425-7075 MHz, passive microwave sensor measurements are carried out over the oceans. In the band 7075-7250 MHz, passive microwave sensor measurements are carried out. Administrations should bear in mind the needs of the Earth exploration-satellite (passive) and space research (passive) services in their future planning of the bands 6425-7025 MHz and 7075-7250 MHz.

5.458A In making assignments in the band 6700-7075 MHz to space stations of the fixed-satellite service, administrations are urged to take all practicable steps to protect spectral line observations of the radio astronomy service in the band 6650-6675.2 MHz from harmful interference from unwanted emissions.

5.458B The space-to-Earth allocation to the fixed-satellite service in the band 6700-7075 MHz is limited to feeder links for non-geostationary satellite systems of the mobile-satellite service and is subject to coordination under No. 9.11A. The use of the band 6700-7075 MHz (space-to-Earth) by feeder links for non-geostationary satellite systems in the mobile-satellite service is not subject to No. 22.2.

5.458C Administrations making submissions in the band 7025-7075 MHz (Earth-to-space) for geostationary-satellite systems in the fixed-satellite service after 17 November 1995 shall consult on the basis of relevant ITU-R Recommendations with the administrations that have notified and brought into use non-geostationary-satellite systems in this frequency band before 18 November 1995 upon request of the latter administrations. This consultation shall be with a view to facilitating shared operation of both geostationary-satellite systems in the fixed-satellite service and non-geostationary-satellite systems in this band.

5.459 *Additional allocation:* in the Russian Federation, the frequency bands 7100-7155 MHz and 7190-7235 MHz are also allocated to the space operation service (Earth-to-space) on a primary basis, subject to agreement obtained under No. 9.21.

5.460 The use of the band 7145-7190 MHz by the space research service (Earth-to-space) is restricted to deep space; no emissions to deep space shall be effected in the band 7190-7235 MHz. Geostationary satellites in the space research service operating in the band 7190-7235 MHz shall not claim protection from existing and future stations of the fixed and mobile services and No. 5.43A does not apply.

5.461A The use of the band 7450-7550 MHz by the meteorological-satellite service (space-to-Earth) is limited to geostationary-satellite systems. Non-geostationary meteorological-satellite systems in this band notified before 30 November 1997 may continue to operate on a primary basis until the end of their lifetime.

5.461B The use of the band 7750-7900 MHz by the meteorological-satellite service (space-to-Earth) is limited to non-geostationary satellite systems. (WRC-12)

5.462A In Regions 1 and 3 (except for Japan), in the band 8025-8400 MHz, the Earth exploration-satellite service using geostationary satellites shall not produce a power flux-density in excess of the following values for angles of arrival (θ), without the consent of the affected administration:

-135 dB(W/m^2) in a 1 MHz band for $0° \leq \theta < 5°$
$-135 + 0.5 (\theta - 5)$ dB(W/m^2) in a 1 MHz band for $5° \leq \theta < 25°$
-125 dB(W/m^2) in a 1 MHz band for $25° \leq \theta \leq 90°$ (WRC-12) (FCC)

5.463 Aircraft stations are not permitted to transmit in the band 8025-8400 MHz.

5.465 In the space research service, the use of the band 8400-8450 MHz is limited to deep space.

5.466 *Different category of service:* in Singapore and Sri Lanka, the allocation of the band 8400-8500 MHz to the space research service is on a secondary basis (see No. 5.32). (WRC-12)

5.468 *Additional allocation:* in Saudi Arabia, Bahrain, Bangladesh, Brunei Darussalam, Burundi, Cameroon, China, Congo (Rep. of the), Costa Rica, Djibouti, Egypt, the United Arab Emirates, Gabon, Guyana, Indonesia, Iran (Islamic Republic of), Iraq, Jamaica, Jordan, Kenya, Kuwait, Lebanon, Libya, Malaysia, Mali, Morocco, Mauritania, Nepal, Nigeria, Oman, Uganda, Pakistan, Qatar, Syrian Arab Republic, the Dem. People's Rep. of Korea, Senegal, Singapore, Somalia, Sudan, Swaziland, Tanzania, Chad, Togo, Tunisia and Yemen, the band 8500-8750 MHz is also allocated to the fixed and mobile services on a primary basis. (WRC-12)

5.469 *Additional allocation:* in Armenia, Azerbaijan, Belarus, the Russian Federation, Georgia, Hungary, Lithuania, Mongolia, Uzbekistan, Poland, Kyrgyzstan, the Czech Rep., Romania, Tajikistan, Turkmenistan and Ukraine, the band 8500-8750 MHz is also allocated to the land mobile and radionavigation services on a primary basis. (WRC-12)

5.469A In the band 8550-8650 MHz, stations in the Earth exploration-satellite service (active) and space research service (active) shall not cause harmful interference to, or constrain the use and development of, stations of the radiolocation service.

5.474 In the band 9200-9500 MHz, search and rescue transponders (SART) may be used, having due regard to the appropriate ITU-R Recommendation (see also Article 31).

5.475 The use of the band 9300-9500 MHz by the aeronautical radionavigation service is limited to airborne weather radars and ground-based radars. In addition, ground-based radar beacons in the aeronautical radionavigation service are permitted in the band 9300-9320 MHz on condition that harmful interference is not caused to the maritime radionavigation service. (WRC-07)

5.475A The use of the band 9300-9500 MHz by the Earth exploration-satellite service (active) and the space research service (active) is limited to systems requiring necessary bandwidth greater than 300 MHz that cannot be fully accommodated within the 9500-9800 MHz band. (WRC-07)

5.475B In the band 9300-9500 MHz, stations operating in the radiolocation service shall not cause harmful interference to, nor claim protection from, radars operating in the radionavigation service in conformity with the Radio Regulations. Ground-based radars used for meteorological purposes have priority over other radiolocation uses. (WRC-07)

5.476A In the band 9300-9800 MHz, stations in the Earth exploration-satellite service (active) and space research service (active) shall not cause harmful interference to, nor claim protection from, stations of the radionavigation and radiolocation services. (WRC-07)

5.477 *Different category of service:* in Algeria, Saudi Arabia, Bahrain, Bangladesh, Brunei Darussalam, Cameroon, Djibouti, Egypt, the United Arab Emirates, Eritrea, Ethiopia, Guyana, India, Indonesia, Iran (Islamic Republic of), Iraq, Jamaica, Japan, Jordan, Kuwait, Lebanon, Liberia, Malaysia, Nigeria, Oman, Pakistan, Qatar, Syrian Arab Republic, the Dem. People's Rep. of Korea, Singapore, Somalia, Sudan, South Sudan, Trinidad and Tobago, and Yemen, the allocation of the band 9800-10000 MHz to the fixed service is on a primary basis (see No. 5.33). (WRC-12)

5.478 *Additional allocation:* in Azerbaijan, Mongolia, Kyrgyzstan, Romania, Turkmenistan and Ukraine, the band 9800-10000 MHz is also allocated to the radionavigation service on a primary basis. (WRC-07)

5.478A The use of the band 9800-9900 MHz by the Earth exploration-satellite service (active) and the space research service (active) is limited to systems requiring necessary bandwidth greater than 500 MHz that cannot be fully accommodated within the 9300-9800 MHz band. (WRC-07)

5.478B In the band 9800-9900 MHz, stations in the Earth exploration-satellite service (active) and space research service (active) shall not cause harmful interference to, nor claim protection from stations of the fixed service to which this band is allocated on a secondary basis. (WRC-07)

5.479 The band 9975-10025 MHz is also allocated to the meteorological-satellite service on a secondary basis for use by weather radars.

5.480 *Additional allocation:* in Argentina, Brazil, Chile, Costa Rica, Cuba, El Salvador, Ecuador, Guatemala, Honduras, Mexico, Paraguay, the Netherlands Antilles, Peru and Uruguay, the band 10-10.45 GHz is also allocated to the fixed and mobile services on a primary basis. In Venezuela, the band 10-10.45 GHz is also allocated to the fixed service on a primary basis. (WRC-07)

5.482 In the band 10.6-10.68 GHz, the power delivered to the antenna of stations of the fixed and mobile, except aeronautical mobile, services shall not exceed −3 dBW. This limit may be exceeded, subject to agreement obtained under No. 9.21. However, in Algeria, Saudi Arabia, Armenia, Azerbaijan, Bahrain, Bangladesh, Belarus, Egypt, United Arab Emirates, Georgia, India, Indonesia, Iran (Islamic Republic of), Iraq, Jordan, Kazakhstan, Kuwait, Lebanon, Libya, Morocco, Mauritania, Moldova, Nigeria, Oman, Uzbekistan, Pakistan, Philippines, Qatar, Syrian Arab Republic, Kyrgyzstan, Singapore, Tajikistan, Tunisia, Turkmenistan and Viet Nam, this restriction on the fixed and mobile, except aeronautical mobile, services is not applicable. (WRC-07)

5.482A For sharing of the band 10.6-10.68 GHz between the Earth exploration-satellite (passive) service and the fixed and mobile, except aeronautical mobile, services, Resolution 751 (WRC-07) applies. (WRC-07)

5.483 *Additional allocation:* in Saudi Arabia, Armenia, Azerbaijan, Bahrain, Belarus, China, Colombia, Korea (Rep. of), Costa Rica, Egypt, the United Arab Emirates, Georgia, Iran (Islamic Republic of), Iraq, Israel, Jordan, Kazakhstan, Kuwait, Lebanon, Mongolia, Qatar, Kyrgyzstan, the Dem. People's Rep. of Korea, Tajikistan, Turkmenistan and Yemen, the band 10.68-10.7 GHz is also allocated to the fixed and mobile, except aeronautical mobile, services on a primary basis. Such use is limited to equipment in operation by 1 January 1985. (WRC-12)

5.484 In Region 1, the use of the band 10.7-11.7 GHz by the fixed-satellite service (Earth-to-space) is limited to feeder links for the broadcasting-satellite service.

5.484A The use of the bands 10.95-11.2 GHz (space-to-Earth), 11.45-11.7 GHz (space-to-Earth), 11.7-12.2 GHz (space-to-Earth) in Region 2, 12.2-12.75 GHz (space-to-Earth) in Region 3, 12.5-12.75 GHz (space-to-Earth) in Region 1, 13.75-14.5 GHz (Earth-to-space), 17.8-18.6 GHz (space-to-Earth), 19.7-20.2 GHz (space-to-Earth), 27.5-28.6 GHz (Earth-to-space), 29.5-30 GHz (Earth-to-space) by a non-geostationary-satellite system in the fixed-satellite service is subject to application of the provisions of No. 9.12 for co-ordination with other non-geostationary-satellite systems in the fixed-satellite service. Non-geostationary-satellite systems in the fixed-satellite service shall not claim protection from geostationary-satellite networks in the fixed-satellite service operating in accordance with the Radio Regulations, irrespective of the dates of receipt by the Bureau of the complete coordination or notification information, as appropriate, for the non-geostationary-satellite systems in the fixed-satellite service and of the complete coordination or notification information, as appropriate, for the geostationary-satellite networks, and No. 5.43A does not apply. Non-geostationary-satellite systems in the fixed-satellite service in the above bands shall be operated in such a way that any unacceptable interference that may occur during their operation shall be rapidly eliminated.

5.497 The use of the band 13.25-13.4 GHz by the aeronautical radionavigation service is limited to Doppler navigation aids.

5.498A The Earth exploration-satellite (active) and space research (active) services operating in the band 13.25-13.4 GHz shall not cause harmful interference to, or constrain the use and development of, the aeronautical radionavigation service.

5.499 *Additional allocation:* in Bangladesh and India, the band 13.25-14 GHz is also allocated to the fixed service on a primary basis. In Pakistan, the band 13.25-13.75 GHz is allocated to the fixed service on a primary basis. (WRC-12)

5.500 *Additional allocation:* in Algeria, Angola, Saudi Arabia, Bahrain, Brunei Darussalam, Cameroon, Egypt, the United Arab Emirates, Gabon, Indonesia, Iran (Islamic Republic of), Iraq, Israel, Jordan, Kuwait, Lebanon, Madagascar, Malaysia, Mali, Morocco, Mauritania, Niger, Nigeria, Oman, Qatar, the Syrian Arab Republic, Singapore, Sudan, South Sudan, Chad and Tunisia, the band 13.4-14 GHz is also allocated to the fixed and mobile services on a primary basis. In Pakistan, the band 13.4-13.75 GHz is also allocated to the fixed and mobile services on a primary basis. (WRC-12)

5.501 *Additional allocation:* in Azerbaijan, Hungary, Japan, Kyrgyzstan, Romania and Turkmenistan, the band 13.4-14 GHz is also allocated to the radionavigation service on a primary basis. (WRC-12)

5.501A The allocation of the band 13.4-13.75 GHz to the space research service on a primary basis is limited to active spaceborne sensors. Other uses of the band by the space research service are on a secondary basis.

5.501B In the band 13.4-13.75 GHz, the Earth exploration-satellite (active) and space research (active) services shall not cause harmful interference to, or constrain the use and development of, the radiolocation service.

5.502 In the band 13.75-14 GHz, an Earth station of a geostationary fixed-satellite service network shall have a minimum antenna diameter of 1.2 m and an Earth station of a non-geostationary fixed-satellite service system shall have a minimum antenna diameter of 4.5 m. In addition, the e.i.r.p., averaged over one second, radiated by a station in the radiolocation or radionavigation services shall not exceed 59 dBW for elevation angles above 2° and 65 dBW at lower angles. Before an administration brings into use an Earth station in a geostationary-satellite network in the fixed-satellite service in this band with an antenna diameter smaller than 4.5 m, it shall ensure that the power flux-density produced by this Earth station does not exceed:

— -115 dB(W/(m^2 · 10 MHz)) for more than 1% of the time produced at 36 m above sea level at the low water mark, as officially recognized by the coastal State;

— -115 dB(W/(m^2 · 10 MHz)) for more than 1% of the time produced 3 m above ground at the border of the territory of an administration deploying or planning to deploy land mobile radars in this band, unless prior agreement has been obtained.

For Earth stations within the fixed-satellite service having an antenna diameter greater than or equal to 4.5 m, the e.i.r.p. of any emission should be at least 68 dBW and should not exceed 85 dBW.

5.503 In the band 13.75-14 GHz, geostationary space stations in the space research service for which information for advance publication has been received by the Bureau prior to 31 January 1992 shall operate on an equal basis with stations in the fixed-satellite service; after that date, new geostationary space stations in the space research service will operate on a secondary basis. Until those geostationary space stations in the space research service for which information for advance publication has been received by the Bureau prior to 31 January 1992 cease to operate in this band:

—in the band 13.77-13.78 GHz, the e.i.r.p. density of emissions from any Earth station in the fixed-satellite service operating with a space station in geostationary-satellite orbit shall not exceed:

i) $4.7D + 28$ dB (W/40 kHz), where D is the fixed-satellite service Earth station antenna diameter (m) for antenna diameters equal to or greater than 1.2 m and less than 4.5 m;

ii) 49.2 + 20 log (D/4.5) dB(W/40 kHz), where D is the fixed-satellite service Earth station antenna diameter (m) for antenna diameters equal to or greater than 4.5 m and less than 31.9 m;
iii) 66.2 dB(W/40 kHz) for any fixed-satellite service Earth station for antenna diameters (m) equal to or greater than 31.9 m;
iv) 56.2 dB(W/4 kHz) for narrow-band (less than 40 kHz of necessary bandwidth) fixed-satellite service Earth station emissions from any fixed-satellite service Earth station having an antenna diameter of 4.5 m or greater;

—the e.i.r.p. density of emissions from any Earth station in the fixed-satellite service operating with a space station in non-geostationary-satellite orbit shall not exceed 51 dBW in the 6 MHz band from 13.772 to 13.778 GHz.

Automatic power control may be used to increase the e.i.r.p. density in these frequency ranges to compensate for rain attenuation, to the extent that the power flux-density at the fixed-satellite service space station does not exceed the value resulting from use by an Earth station of an e.i.r.p. meeting the above limits in clear-sky conditions.

5.504 The use of the band 14-14.3 GHz by the radionavigation service shall be such as to provide sufficient protection to space stations of the fixed-satellite service.

5.504A In the band 14-14.5 GHz, aircraft Earth stations in the secondary aeronautical mobile-satellite service may also communicate with space stations in the fixed-satellite service. The provisions of Nos. 5.29, 5.30 and 5.31 apply.

5.504B Aircraft Earth stations operating in the aeronautical mobile-satellite service in the band 14-14.5 GHz shall comply with the provisions of Annex 1, Part C of Recommendation ITU-R M.1643, with respect to any radio astronomy station performing observations in the 14.47-14.5 GHz band located on the territory of Spain, France, India, Italy, the United Kingdom and South Africa.

5.504C In the band 14-14.25 GHz, the power flux-density produced on the territory of the countries of Saudi Arabia, Botswana, Côte d'Ivoire, Egypt, Guinea, India, Iran (Islamic Republic of), Kuwait, Nigeria, Oman, the Syrian Arab Republic and Tunisia by any aircraft Earth station in the aeronautical mobile-satellite service shall not exceed the limits given in Annex 1, Part B of Recommendation ITU-R M.1643, unless otherwise specifically agreed by the affected administration(s). The provisions of this footnote in no way derogate the obligations of the aeronautical mobile-satellite service to operate as a secondary service in accordance with No. 5.29. (WRC-12)

5.505 *Additional allocation:* in Algeria, Angola, Saudi Arabia, Bahrain, Botswana, Brunei Darussalam, Cameroon, China, Congo (Rep. of the), Korea (Rep. of), Djibouti, Egypt, the United Arab Emirates, Gabon, Guinea, India, Indonesia, Iran (Islamic Republic of), Iraq, Israel, Japan, Jordan, Kuwait, Lebanon, Malaysia, Mali, Morocco, Mauritania, Oman, the Philippines, Qatar, the Syrian Arab Republic, the Dem. People's Rep. of Korea, Singapore, Somalia, Sudan, South Sudan, Swaziland, Tanzania, Chad, Viet Nam and Yemen, the band 14-14.3 GHz is also allocated to the fixed service on a primary basis. (WRC-12)

5.506 The band 14-14.5 GHz may be used, within the fixed-satellite service (Earth-to-space), for feeder links for the broadcasting-satellite service, subject to coordination with other networks in the fixed-satellite service. Such use of feeder links is reserved for countries outside Europe.

5.506A In the band 14-14.5 GHz, ship Earth stations with an e.i.r.p. greater than 21 dBW shall operate under the same conditions as Earth stations located on board vessels, as provided in Resolution 902 (WRC-03). This footnote shall not apply to ship Earth stations for which the complete Appendix 4 information has been received by the Bureau prior to 5 July 2003.

5.506B Earth stations located on board vessels communicating with space stations in the fixed-satellite service may operate in the frequency band 14-14.5 GHz without the need for prior agreement from Cyprus, Greece and Malta, within the minimum distance given in Resolution 902 (WRC-03) from these countries.

5.508 *Additional allocation:* in Germany, France, Italy, Libya, The Former Yugoslav Rep. of Macedonia and the United Kingdom, the band 14.25-14.3 GHz is also allocated to the fixed service on a primary basis. (WRC-12)

5.508A In the band 14.25-14.3 GHz, the power flux-density produced on the territory of the countries of Saudi Arabia, Botswana, China, Côte d'Ivoire, Egypt, France, Guinea, India, Iran (Islamic Republic of), Italy, Kuwait, Nigeria, Oman, the Syrian Arab Republic, the United Kingdom and Tunisia by any aircraft Earth station in the aeronautical mobile-satellite service shall not exceed the limits given in Annex 1, Part B of Recommendation ITU-R M.1643, unless otherwise specifically agreed by the affected administration(s). The provisions of this footnote in no way derogate the obligations of the aeronautical mobile-satellite service to operate as a secondary service in accordance with No. 5.29. (WRC-12)

5.509A In the band 14.3-14.5 GHz, the power flux-density produced on the territory of the countries of Saudi Arabia, Botswana, Cameroon, China, Côte d'Ivoire, Egypt, France, Gabon, Guinea, India, Iran (Islamic Republic of), Italy, Kuwait, Morocco, Nigeria, Oman, the Syrian Arab Republic, the United Kingdom, Sri Lanka, Tunisia and Viet Nam by any aircraft Earth station in the aeronautical mobile-satellite service shall not exceed the limits given in Annex 1, Part B of Recommendation ITU-R M.1643, unless otherwise specifically agreed by the affected administration(s). The provisions of this footnote in no way derogate the obligations of the aeronautical mobile-satellite service to operate as a secondary service in accordance with No. 5.29. (WRC-12)

5.510 The use of the band 14.5-14.8 GHz by the fixed-satellite service (Earth-to-space) is limited to feeder links for the broadcasting-satellite service. This use is reserved for countries outside Europe.

5.511 *Additional allocation:* in Saudi Arabia, Bahrain, Cameroon, Egypt, the United Arab Emirates, Guinea, Iran (Islamic Republic of), Iraq, Israel, Kuwait, Lebanon, Oman, Pakistan, Qatar, the Syrian Arab Republic and Somalia, the band 15.35-15.4 GHz is also allocated to the fixed and mobile services on a secondary basis. (WRC-12)

5.511A The band 15.43-15.63 GHz is also allocated to the fixed-satellite service (space-to-Earth) on a primary basis. Use of the band 15.43-15.63 GHz by the fixed-satellite service (space-to-Earth and Earth-to-space) is limited to feeder links of non-geostationary systems in the mobile-satellite service, subject to coordination under No. 9.11A. The use of the frequency band 15.43-15.63 GHz by the fixed-satellite service (space-to-Earth) is limited to feeder links of non-geostationary systems in the mobile-satellite service for which advance publication information has been received by the Bureau prior to 2 June 2000. In the space-to-Earth direction, the minimum Earth station elevation angle above and gain towards the local horizontal plane and the minimum coordination distances to protect an Earth station from harmful interference shall be in accordance with Recommendation ITU-R S.1341. In order to protect the radio astronomy service in the band 15.35-15.4 GHz, the aggregate power flux-density radiated in the 15.35-15.4 GHz band by all the space stations within any feeder-link of a non-geostationary system in the mobile-satellite service (space-to-Earth) operating in the 15.43-15.63 GHz band shall not exceed the level of -156 dB(W/m^2) in a 50 MHz bandwidth, into any radio astronomy observatory site for more than 2% of the time.

5.511C Stations operating in the aeronautical radionavigation service shall limit the effective e.i.r.p. in accordance with Recommendation ITU-R S.1340. The minimum coordination distance required to protect the aeronautical radionavigation stations (No. 4.10 applies) from harmful interference from feeder-link Earth stations and the maximum e.i.r.p. transmitted towards the local horizontal plane by a feeder-link Earth station shall be in accordance with Recommendation ITU-R S.1340.

5.511D Fixed-satellite service systems for which complete information for advance publication has been received by the Bureau by 21 November 1997 may operate in the bands 15.4-15.43 GHz and 15.63-15.7 GHz in the space-to-Earth direction and 15.63-15.65 GHz in the Earth-to-space direction. In the bands 15.4-15.43 GHz and 15.65-15.7 GHz, emissions from a non-geostationary space station shall not exceed the power flux-density limits at the Earth's surface of -146 dB(W/(m$^2 \cdot$ MHz)) for any angle of arrival. In the band 15.63-15.65 GHz, where an administration plans emissions from a non-geostationary space station that exceed -146 dB(W/(m$^2 \cdot$ MHz)) for any angle of arrival, it shall coordinate under No. 9.11A with the affected administrations. Stations in the fixed-satellite service operating in the band 15.63-15.65 GHz in the Earth-to-space direction shall not cause harmful interference to stations in the aeronautical radionavigation service (No. 4.10 applies).

5.511E In the frequency band 15.4-15.7 GHz, stations operating in the radiolocation service shall not cause harmful interference to, or claim protection from, stations operating in the aeronautical radionavigation service. (WRC-12)

5.511F In order to protect the radio astronomy service in the frequency band 15.35-15.4 GHz, radiolocation stations operating in the frequency band 15.4-15.7 GHz shall not exceed the power flux-density level of -156 dB(W/m^2) in a 50 MHz bandwidth in the frequency band 15.35-15.4 GHz, at any radio astronomy observatory site for more than 2 per cent of the time. (WRC-12)

5.512 *Additional allocation:* in Algeria, Angola, Saudi Arabia, Austria, Bahrain, Bangladesh, Brunei Darussalam, Cameroon, Congo (Rep. of the), Costa Rica, Egypt, El Salvador, the United Arab Emirates, Eritrea, Finland, Guatemala, India, Indonesia, Iran (Islamic Republic of), Jordan, Kenya, Kuwait, Lebanon, Libya, Malaysia, Mali, Morocco, Mauritania, Montenegro, Nepal, Nicaragua, Niger, Oman, Pakistan, Qatar, Syrian Arab Republic, the Dem. Rep. of the Congo, Serbia, Singapore, Somalia, Sudan, South Sudan, Tanzania, Chad, Togo and Yemen, the band 15.7-17.3 GHz is also allocated to the fixed and mobile services on a primary basis. (WRC-12)

5.513 *Additional allocation:* in Israel, the band 15.7-17.3 GHz is also allocated to the fixed and mobile services on a primary basis. These services shall not claim protection from or cause harmful interference to services operating in accordance with the Table in countries other than those included in No. 5.512.

5.513A Spaceborne active sensors operating in the band 17.2-17.3 GHz shall not cause harmful interference to, or constrain the development of, the radiolocation and other services allocated on a primary basis.

5.516 The use of the band 17.3-18.1 GHz by geostationary-satellite systems in the fixed-satellite service (Earth-to-space) is limited to feeder links for the broadcasting-satellite service. The use of the band 17.3-17.8 GHz in Region 2 by systems in the fixed-satellite service (Earth-to-space) is limited to geostationary satellites. For the use of the band 17.3-17.8 GHz in Region 2 by feeder links for the broadcasting-satellite service in the band 12.2-12.7 GHz, see Article 11. The use of the bands 17.3-18.1 GHz (Earth-to-space) in Regions 1 and 3 and 17.8-18.1 GHz (Earth-to-space) in Region 2 by non-geostationary-satellite systems in the fixed-satellite service is subject to application of the provisions of No. 9.12 for coordination with other non-geostationary-satellite systems in the fixed-satellite service. Non-geostationary-satellite systems in the fixed-satellite service shall not claim protection from geostationary-satellite networks in the fixed-satellite service operating in accordance with the Radio Regulations, irrespective of the dates of receipt by the Bureau of the complete coordination or notification information, as appropriate, for the non-geostationary-satellite systems in the fixed-satellite service and of the complete coordination or notification information, as appropriate, for the geostationary-satellite networks, and No. 5.43A does not apply. Non-geostationary-satellite systems in the fixed-satellite service in the above bands shall be operated in such a way that any unacceptable interference that may occur during their operation shall be rapidly eliminated.

5.516B The following bands are identified for use by high-density applications in the fixed-satellite service:

17.3-17.7 GHz (space-to-Earth) in Region 1,
18.3-19.3 GHz (space-to-Earth) in Region 2,
19.7-20.2 GHz (space-to-Earth) in all Regions,
39.5-40 GHz (space-to-Earth) in Region 1,
40-40.5 GHz (space-to-Earth) in all Regions,
40.5-42 GHz (space-to-Earth) in Region 2,
47.5-47.9 GHz (space-to-Earth) in Region 1,
48.2-48.54 GHz (space-to-Earth) in Region 1,
49.44-50.2 GHz (space-to-Earth) in Region 1, and
27.5-27.82 GHz (Earth-to-space) in Region 1,
28.35-28.45 GHz (Earth-to-space) in Region 2,
28.45-28.94 GHz (Earth-to-space) in all Regions,
28.94-29.1 GHz (Earth-to-space) in Region 2 and 3,
29.25-29.46 GHz (Earth-to-space) in Region 2,

29.46-30 GHz (Earth-to-space) in all Regions,

48.2-50.2 GHz (Earth-to-space) in Region 2.

This identification does not preclude the use of these bands by other fixed-satellite service applications or by other services to which these bands are allocated on a co-primary basis and does not establish priority in these Radio Regulations among users of the bands. Administrations should take this into account when considering regulatory provisions in relation to these bands. See Resolution 143 (Rev.WRC-07). (FCC)

5.519 *Additional allocation:* the bands 18-18.3 GHz in Region 2 and 18.1-18.4 GHz in Regions 1 and 3 are also allocated to the meteorological-satellite service (space-to-Earth) on a primary basis. Their use is limited to geostationary satellites. (WRC-07)

5.520 The use of the band 18.1-18.4 GHz by the fixed-satellite service (Earth-to-space) is limited to feeder links of geostationary-satellite systems in the broadcasting-satellite service.

5.521 *Alternative allocation:* in Germany, Denmark, the United Arab Emirates and Greece, the band 18.1-18.4 GHz is allocated to the fixed, fixed-satellite (space-to-Earth) and mobile services on a primary basis (see No. 5.33). The provisions of No. 5.519 also apply.

5.522A The emissions of the fixed service and the fixed-satellite service in the band 18.6-18.8 GHz are limited to the values given in Nos. 21.5A and 21.16.2, respectively.

5.522B The use of the band 18.6-18.8 GHz by the fixed-satellite service is limited to geostationary systems and systems with an orbit of apogee greater than 20000 km.

5.522C In the band 18.6-18.8 GHz, in Algeria, Saudi Arabia, Bahrain, Egypt, the United Arab Emirates, Jordan, Lebanon, Libya, Morocco, Oman, Qatar, the Syrian Arab Republic, Tunisia and Yemen, fixed-service systems in operation at the date of entry into force of the Final Acts of WRC-2000 are not subject to the limits of No. 21.5A.

5.523A The use of the bands 18.8-19.3 GHz (space-to-Earth) and 28.6-29.1 GHz (Earth-to-space) by geostationary and non-geostationary fixed-satellite service networks is subject to the application of the provisions of No. 9.11A and No. 22.2 does not apply. Administrations having geostationary-satellite networks under coordination prior to 18 November 1995 shall cooperate to the maximum extent possible to coordinate pursuant to No. 9.11A with non-geostationary-satellite networks for which notification information has been received by the Bureau prior to that date, with a view to reaching results acceptable to all the parties concerned. Non-geostationary-satellite networks shall not cause unacceptable interference to geostationary fixed-satellite service networks for which complete Appendix 4 notification information is considered as having been received by the Bureau prior to 18 November 1995.

5.523C No. 22.2 shall continue to apply in the bands 19.3-19.6 GHz and 29.1-29.4 GHz, between feeder links of non-geostationary mobile-satellite service networks and those fixed-satellite service networks for which complete Appendix 4 coordination information, or notification information, is considered as having been received by the Bureau prior to 18 November 1995.

5.523E No. 22.2 shall continue to apply in the bands 19.6-19.7 GHz and 29.4-29.5 GHz, between feeder links of non-geostationary mobile-satellite service networks and those fixed-satellite service networks for which complete Appendix 4 coordination information, or notification information, is considered as having been received by the Bureau by 21 November 1997.

5.524 *Additional allocation:* in Afghanistan, Algeria, Angola, Saudi Arabia, Bahrain, Brunei Darussalam, Cameroon, China, Congo (Rep. of the), Costa Rica, Egypt, the United Arab Emirates, Gabon, Guatemala, Guinea, India, Iran (Islamic Republic of), Iraq, Israel, Japan, Jordan, Kuwait, Lebanon, Malaysia, Mali, Morocco, Mauritania, Nepal, Nigeria, Oman, Pakistan, the Philippines, Qatar, the Syrian Arab Republic, the Dem. Rep. of the Congo, the Dem. People’s Rep. of Korea, Singapore, Somalia, Sudan, South Sudan, Tanzania, Chad, Togo and Tunisia, the band 19.7-21.2 GHz is also allocated to the fixed and mobile services on a primary basis. This additional use shall not impose any limitation on the power flux-density of space stations in the fixed-satellite service in the band 19.7-21.2 GHz and of space stations in the mobile-satellite service in the band 19.7-20.2 GHz where the allocation to the mobile-satellite service is on a primary basis in the latter band. (WRC-12)

5.525 In order to facilitate interregional coordination between networks in the mobile-satellite and fixed-satellite services, carriers in the mobile-satellite service that are most susceptible to interference shall, to the extent practicable, be located in the higher parts of the bands 19.7-20.2 GHz and 29.5-30 GHz.

5.526 In the bands 19.7-20.2 GHz and 29.5-30 GHz in Region 2, and in the bands 20.1-20.2 GHz and 29.9-30 GHz in Regions 1 and 3, networks which are both in the fixed-satellite service and in the mobile-satellite service may include links between Earth stations at specified or unspecified points or while in motion, through one or more satellites for point-to-point and point-to-multipoint communications.

5.527 In the bands 19.7-20.2 GHz and 29.5-30 GHz, the provisions of No. 4.10 do not apply with respect to the mobile-satellite service.

5.529 The use of the bands 19.7-20.1 GHz and 29.5-29.9 GHz by the mobile-satellite service in Region 2 is limited to satellite networks which are both in the fixed-satellite service and in the mobile-satellite service as described in No. 5.526.

5.530A Unless otherwise agreed between the administrations concerned, any station in the fixed or mobile services of an administration shall not produce a power flux-density in excess of -120.4 dB(W/(m$^2 \cdot$ MHz)) at 3 m above the ground of any point of the territory of any other administration in Regions 1 and 3 for more than 20% of the time. In conducting the calculations, administrations should use the most recent version of Recommendation ITU-R P.452 (see Recommendation ITU-R BO.1898). (WRC-12)

5.530B In the band 21.4-22 GHz, in order to facilitate the development of the broadcasting-satellite service, administrations in Regions 1 and 3 are encouraged not to deploy stations in the mobile service and are encouraged to limit the deployment of stations in the fixed service to point-to-point links. (WRC-12)

5.530C The use of the band 21.4-22 GHz is subject to the provisions of Resolution 755 (WRC-12). (WRC-12)

5.530D See Resolution 555 (WRC-12). (WRC-12)

5.531 *Additional allocation:* in Japan, the band 21.4-22 GHz is also allocated to the broadcasting service on a primary basis.

5.532 The use of the band 22.21-22.5 GHz by the Earth exploration-satellite (passive) and space research (passive) services shall not impose constraints upon the fixed and mobile, except aeronautical mobile, services.

5.532A The location of Earth stations in the space research service shall maintain a separation distance of at least 54 km from the respective border(s) of neighbouring countries to protect the existing and future deployment of fixed and mobile services unless a shorter distance is otherwise agreed between the corresponding administrations. Nos. 9.17 and 9.18 do not apply. (WRC-12)

5.535A The use of the band 29.1-29.5 GHz (Earth-to-space) by the fixed-satellite service is limited to geostationary-satellite systems and feeder links to non-geostationary-satellite systems in the mobile-satellite service. Such use is subject to the application of the provisions of No. 9.11A, but not subject to the provisions of No. 22.2, except as indicated in Nos. 5.523C and 5.523E where such use is not subject to the provisions of No. 9.11A and shall continue to be subject to Articles 9 (except No. 9.11A) and 11 procedures, and to the provisions of No. 22.2.

5.536 Use of the 25.25-27.5 GHz band by the inter-satellite service is limited to space research and Earth exploration-satellite applications, and also transmissions of data originating from industrial and medical activities in space.

5.536A Administrations operating Earth stations in the Earth exploration-satellite service or the space research service shall not claim protection from stations in the fixed and mobile services operated by other administrations. In addition, Earth stations in the Earth exploration-satellite service or in the space research service should be operated taking into account the most recent version of Recommendation ITU-R SA.1862. (WRC-12)

5.536B In Saudi Arabia, Austria, Belgium, Brazil, Bulgaria, China, Korea (Rep. of), Denmark, Egypt, United Arab Emirates, Estonia, Finland, Hungary, India, Iran (Islamic Republic of), Ireland, Israel, Italy, Jordan, Kenya, Kuwait, Lebanon, Libya, Liechtenstein, Lithuania, Moldova, Norway, Oman, Uganda, Pakistan, the Philippines, Poland, Portugal, the Syrian Arab Republic, Dem. People's Rep. of Korea, Slovakia, the Czech Rep., Romania, the United Kingdom, Singapore, Sweden, Switzerland, Tanzania, Turkey, Viet Nam and Zimbabwe, Earth stations operating in the Earth exploration-satellite service in the band 25.5-27 GHz shall not claim protection from, or constrain the use and deployment of, stations of the fixed and mobile services. (WRC-12)

5.536C In Algeria, Saudi Arabia, Bahrain, Botswana, Brazil, Cameroon, Comoros, Cuba, Djibouti, Egypt, United Arab Emirates, Estonia, Finland, Iran (Islamic Republic of), Israel, Jordan, Kenya, Kuwait, Lithuania, Malaysia, Morocco, Nigeria, Oman, Qatar, Syrian Arab Republic, Somalia, Sudan, South Sudan, Tanzania, Tunisia, Uruguay, Zambia and Zimbabwe, Earth stations operating in the space research service in the band 25.5-27 GHz shall not claim protection from, or constrain the use and deployment of, stations of the fixed and mobile services. (WRC-12)

5.537 Space services using non-geostationary satellites operating in the inter-satellite service in the band 27-27.5 GHz are exempt from the provisions of No. 22.2.

5.538 *Additional allocation:* the bands 27.500-27.501 GHz and 29.999-30.000 GHz are also allocated to the fixed-satellite service (space-to-Earth) on a primary basis for the beacon transmissions intended for up-link power control. Such space-to-Earth transmissions shall not exceed an equivalent isotropically radiated power (e.i.r.p.) of +10 dBW in the direction of adjacent satellites on the geostationary-satellite orbit. (WRC-07)

5.539 The band 27.5-30 GHz may be used by the fixed-satellite service (Earth-to-space) for the provision of feeder links for the broadcasting-satellite service.

5.540 *Additional allocation:* the band 27.501-29.999 GHz is also allocated to the fixed-satellite service (space-to-Earth) on a secondary basis for beacon transmissions intended for up-link power control.

5.541 In the band 28.5-30 GHz, the Earth exploration-satellite service is limited to the transfer of data between stations and not to the primary collection of information by means of active or passive sensors.

5.541A Feeder links of non-geostationary networks in the mobile-satellite service and geostationary networks in the fixed-satellite service operating in the band 29.1-29.5 GHz (Earth-to-space) shall employ uplink adaptive power control or other methods of fade compensation, such that the Earth station transmissions shall be conducted at the power level required to meet the desired link performance while reducing the level of mutual interference between both networks. These methods shall apply to networks for which Appendix 4 coordination information is considered as having been received by the Bureau after 17 May 1996 and until they are changed by a future competent world radiocommunication conference. Administrations submitting Appendix 4 information for coordination before this date are encouraged to utilize these techniques to the extent practicable.

5.542 *Additional allocation:* in Algeria, Saudi Arabia, Bahrain, Brunei Darussalam, Cameroon, China, Congo (Rep. of the), Egypt, the United Arab Emirates, Eritrea, Ethiopia, Guinea, India, Iran (Islamic Republic of), Iraq, Japan, Jordan, Kuwait, Lebanon, Malaysia, Mali, Morocco, Mauritania, Nepal, Oman, Pakistan, Philippines, Qatar, the Syrian Arab Republic, the Dem. People's Rep. of Korea, Somalia, Sudan, South Sudan, Sri Lanka and Chad, the band 29.5-31 GHz is also allocated to the fixed and mobile services on a secondary basis. The power limits specified in Nos. 21.3 and 21.5 shall apply. (WRC-12)

5.543 The band 29.95-30 GHz may be used for space-to-space links in the Earth exploration-satellite service for telemetry, tracking, and control purposes, on a secondary basis.

5.543A In Bhutan, Cameroon, Korea (Rep. of), the Russian Federation, India, Indonesia, Iran (Islamic Republic of), Iraq, Japan, Kazakhstan, Malaysia, Maldives, Mongolia, Myanmar, Uzbekistan, Pakistan, the Philippines, Kyrgyzstan, the Dem. People's Rep. of Korea, Sudan, Sri Lanka, Thailand and Viet Nam, the allocation to the fixed service in the band 31-31.3 GHz may also be used by systems using high altitude platform stations (HAPS) in the ground-to-HAPS direction. The use of the band 31-31.3 GHz by systems using HAPS is limited to the territory of the countries listed above and shall not cause harmful interference to, nor claim protection from, other types of fixed-service systems, systems in the mobile service and systems operated under No. 5.545. Furthermore, the development of these services shall not be constrained by HAPS. Systems using HAPS in the band 31-31.3 GHz shall not cause harmful interference to the radio astronomy service having a primary allocation in the band 31.3-31.8 GHz, taking into account the protection criterion as given in Recommendation ITU-R RA.769. In order to ensure the protection of satellite passive services, the level of unwanted power density into a HAPS ground station antenna in the band

31.3-31.8 GHz shall be limited to −106 dB(W/MHz) under clear-sky conditions, and may be increased up to −100 dB(W/MHz) under rainy conditions to mitigate fading due to rain, provided the effective impact on the passive satellite does not exceed the impact under clear-sky conditions. See Resolution 145 (Rev. WRC-12). (WRC-12)

5.544 In the band 31-31.3 GHz the power flux-density limits specified in Article 21, Table 21-4 shall apply to the space research service.

5.545 *Different category of service:* in Armenia, Georgia, Kyrgyzstan, Tajikistan and Turkmenistan, the allocation of the band 31-31.3 GHz to the space research service is on a primary basis (see No. 5.33). (WRC-12)

5.546 *Different category of service:* in Saudi Arabia, Armenia, Azerbaijan, Belarus, Egypt, the United Arab Emirates, Spain, Estonia, the Russian Federation, Georgia, Hungary, Iran (Islamic Republic of), Israel, Jordan, Lebanon, Moldova, Mongolia, Oman, Uzbekistan, Poland, the Syrian Arab Republic, Kyrgyzstan, Romania, the United Kingdom, South Africa, Tajikistan, Turkmenistan and Turkey, the allocation of the band 31.5-31.8 GHz to the fixed and mobile, except aeronautical mobile, services is on a primary basis (see No. 5.33). (WRC-12)

5.547 The bands 31.8-33.4 GHz, 37-40 GHz, 40.5-43.5 GHz, 51.4-52.6 GHz, 55.78-59 GHz and 64-66 GHz are available for high-density applications in the fixed service (see Resolution 75 (WRC-12)). Administrations should take this into account when considering regulatory provisions in relation to these bands. Because of the potential deployment of high-density applications in the fixed-satellite service in the bands 39.5-40 GHz and 40.5-42 GHz (see No. 5.516B), administrations should further take into account potential constraints to high-density applications in the fixed service, as appropriate. (FCC)

5.547A Administrations should take practical measures to minimize the potential interference between stations in the fixed service and airborne stations in the radionavigation service in the 31.8-33.4 GHz band, taking into account the operational needs of the airborne radar systems.

5.547B *Alternative allocation:* in the United States, the band 31.8-32 GHz is allocated to the radionavigation and space research (deep space) (space-to-Earth) services on a primary basis.

5.547C *Alternative allocation:* in the United States, the band 32-32.3 GHz is allocated to the radionavigation and space research (deep space) (space-to-Earth) services on a primary basis.

5.548 In designing systems for the inter-satellite service in the band 32.3-33 GHz, for the radionavigation service in the band 32-33 GHz, and for the space research service (deep space) in the band 31.8-32.3 GHz, administrations shall take all necessary measures to prevent harmful interference between these services, bearing in mind the safety aspects of the radionavigation service (see Recommendation 707).

5.549 *Additional allocation:* in Saudi Arabia, Bahrain, Bangladesh, Egypt, the United Arab Emirates, Gabon, Indonesia, Iran (Islamic Republic of), Iraq, Israel, Jordan, Kuwait, Lebanon, Libya, Malaysia, Mali, Morocco, Mauritania, Nepal, Nigeria, Oman, Pakistan, the Philippines, Qatar, the Syrian Arab Republic, the Dem. Rep. of the Congo, Singapore, Somalia, Sudan, South Sudan, Sri Lanka, Togo, Tunisia and Yemen, the band 33.4-36 GHz is also allocated to the fixed and mobile services on a primary basis. (WRC-12)

5.549A In the band 35.5-36.0 GHz, the mean power flux-density at the Earth's surface, generated by any spaceborne sensor in the Earth exploration-satellite service (active) or space research service (active), for any angle greater than 0.8° from the beam centre shall not exceed -73.3 dB(W/m^2) in this band.

5.550 *Different category of service:* in Armenia, Azerbaijan, Belarus, the Russian Federation, Georgia, Kyrgyzstan, Tajikistan and Turkmenistan, the allocation of the band 34.7-35.2 GHz to the space research service is on a primary basis (see No. 5.33). (WRC-12)

5.550A For sharing of the band 36-37 GHz between the Earth exploration-satellite (passive) service and the fixed and mobile services, Resolution 752 (WRC-07) shall apply. (WRC-07)

5.551F *Different category of service:* in Japan, the allocation of the band 41.5-42.5 GHz to the mobile service is on a primary basis (see No. 5.33).

5.551H The equivalent power flux-density (epfd) produced in the band 42.5-43.5 GHz by all space stations in any non-geostationary-satellite system in the fixed-satellite service (space-to-Earth), or in the broadcasting-satellite service operating in the 42-42.5 GHz band, shall not exceed the following values at the site of any radio astronomy station for more than 2% of the time:

–230 dB(W/m^2) in 1 GHz and –246 dB(W/m^2) in any 500 kHz of the 42.5-43.5 GHz band at the site of any radio astronomy station registered as a single-dish telescope; and

–209 dB(W/m^2) in any 500 kHz of the 42.5-43.5 GHz band at the site of any radio astronomy station registered as a very long baseline interferometry station.

These epfd values shall be evaluated using the methodology given in Recommendation ITU-R S.1586-1 and the reference antenna pattern and the maximum gain of an antenna in the radio astronomy service given in Recommendation ITU-R RA.1631 and shall apply over the whole sky and for elevation angles higher than the minimum operating angle θ_{min} of the radiotelescope (for which a default value of 5° should be adopted in the absence of notified information).

These values shall apply at any radio astronomy station that either:

—was in operation prior to 5 July 2003 and has been notified to the Bureau before 4 January 2004; or

—was notified before the date of receipt of the complete Appendix 4 information for coordination or notification, as appropriate, for the space station to which the limits apply.

Other radio astronomy stations notified after these dates may seek an agreement with administrations that have authorized the space stations. In Region 2, Resolution 743 (WRC-03) shall apply. The limits in this footnote may be exceeded at the site of a radio astronomy station of any country whose administration so agreed. (WRC-07)

5.551I The power flux-density in the band 42.5-43.5 GHz produced by any geostationary space station in the fixed-satellite service (space-to-Earth), or the broadcasting-satellite service operating in the 42-42.5 GHz band, shall not exceed the following values at the site of any radio astronomy station:

–137 dB(W/m^2) in 1 GHz and –153 dB(W/m^2) in any 500 kHz of the 42.5-43.5 GHz band at the site of any radio astronomy station registered as a single-dish telescope; and

–116 dB(W/m^2) in any 500 kHz of the 42.5-43.5 GHz band at the site of any radio astronomy station registered as a very long baseline interferometry station.

These values shall apply at the site of any radio astronomy station that either:

—was in operation prior to 5 July 2003 and has been notified to the Bureau before 4 January 2004; or

—was notified before the date of receipt of the complete Appendix 4 information for coordination or notification, as appropriate, for the space station to which the limits apply.

Other radio astronomy stations notified after these dates may seek an agreement with administrations that have authorized the space stations. In Region 2, Resolution 743 (WRC-03) shall apply. The limits in this footnote may be exceeded at the site of a radio astronomy station of any country whose administration so agreed.

5.552 The allocation of the spectrum for the fixed-satellite service in the bands 42.5-43.5 GHz and 47.2-50.2 GHz for Earth-to-space transmission is greater than that in the band 37.5-39.5 GHz for space-to-Earth transmission in order to accommodate feeder links to broadcasting satellites. Administrations are urged to take all practicable steps to reserve the band 47.2-49.2 GHz for feeder links for the broadcasting-satellite service operating in the band 40.5-42.5 GHz.

5.554 In the bands 43.5-47 GHz, 66-71 GHz, 95-100 GHz, 123-130 GHz, 191.8-200 GHz and 252-265 GHz, satellite links connecting land stations at specified fixed points are also authorized when used in conjunction with the mobile-satellite service or the radionavigation-satellite service.

5.554A The use of the bands 47.5-47.9 GHz, 48.2-48.54 GHz and 49.44-50.2 GHz by the fixed-satellite service (space-to-Earth) is limited to geostationary satellites.

5.555 *Additional allocation:* the band 48.94-49.04 GHz is also allocated to the radio astronomy service on a primary basis.

5.555B The power flux-density in the band 48.94-49.04 GHz produced by any geostationary space station in the fixed-satellite service (space-to-Earth) operating in the bands 48.2-48.54 GHz and 49.44-50.2 GHz shall not exceed –151.8 dB(W/m^2) in any 500 kHz band at the site of any radio astronomy station.

5.556 In the bands 51.4-54.25 GHz, 58.2-59 GHz and 64-65 GHz, radio astronomy observations may be carried out under national arrangements.

5.556A Use of the bands 54.25-56.9 GHz, 57-58.2 GHz and 59-59.3 GHz by the inter-satellite service is limited to satellites in the geostationary-satellite orbit. The single-entry power flux-density at all altitudes from 0 km to 1000 km above the Earth's surface produced by a station in the inter-satellite service, for all conditions and for all methods of modulation, shall not exceed –147 dB(W/(m^2 · 100 MHz)) for all angles of arrival.

5.556B *Additional allocation:* in Japan, the band 54.25-55.78 GHz is also allocated to the mobile service on a primary basis for low-density use.

5.557 *Additional allocation:* in Japan, the band 55.78-58.2 GHz is also allocated to the radiolocation service on a primary basis.

5.557A In the band 55.78-56.26 GHz, in order to protect stations in the Earth exploration-satellite service (passive), the maximum power density delivered by a transmitter to the antenna of a fixed service station is limited to –26 dB(W/MHz).

5.558 In the bands 55.78-58.2 GHz, 59-64 GHz, 66-71 GHz, 122.25-123 GHz, 130-134 GHz, 167-174.8 GHz and 191.8-200 GHz, stations in the aeronautical mobile service may be operated subject to not causing harmful interference to the inter-satellite service (see No. 5.43).

5.558A Use of the band 56.9-57 GHz by inter-satellite systems is limited to links between satellites in geostationary-satellite orbit and to transmissions from non-geostationary satellites in high-Earth orbit to those in low-Earth orbit. For links between satellites in the geostationary-satellite orbit, the single entry power flux-density at all altitudes from 0 km to 1000 km above the Earth's surface, for all conditions and for all methods of modulation, shall not exceed –147 dB(W/(m^2 · 100 MHz)) for all angles of arrival.

5.559 In the band 59-64 GHz, airborne radars in the radiolocation service may be operated subject to not causing harmful interference to the inter-satellite service (see No. 5.43).

5.560 In the band 78-79 GHz radars located on space stations may be operated on a primary basis in the Earth exploration-satellite service and in the space research service.

5.561 In the band 74-76 GHz, stations in the fixed, mobile and broadcasting services shall not cause harmful interference to stations of the fixed-satellite service or stations of the broadcasting-satellite service operating in accordance with the decisions of the appropriate frequency assignment planning conference for the broadcasting-satellite service.

5.561A The 81-81.5 GHz band is also allocated to the amateur and amateur-satellite services on a secondary basis.

5.561B In Japan, use of the band 84-86 GHz, by the fixed-satellite service (Earth-to-space) is limited to feeder links in the broadcasting-satellite service using the geostationary-satellite orbit.

5.562 The use of the band 94-94.1 GHz by the Earth exploration-satellite (active) and space research (active) services is limited to spaceborne cloud radars.

5.562A In the bands 94-94.1 GHz and 130-134 GHz, transmissions from space stations of the Earth exploration-satellite service (active) that are directed into the main beam of a radio astronomy antenna have the potential to damage some radio astronomy receivers. Space agencies operating the transmitters and the radio astronomy stations concerned should mutually plan their operations so as to avoid such occurrences to the maximum extent possible.

5.562B In the bands 105-109.5 GHz, 111.8-114.25 GHz, 155.5-158.5 GHz and 217-226 GHz, the use of this allocation is limited to space-based radio astronomy only.

5.562C Use of the band 116-122.25 GHz by the inter-satellite service is limited to satellites in the geostationary-satellite orbit. The single-entry power flux-density produced by a station in the inter-satellite service, for all conditions and for all methods of modulation, at all altitudes from 0 km to 1000 km above the Earth's surface and in the vicinity of all geostationary orbital positions occupied by passive sensors, shall not exceed –148 dB(W/(m^2 · MHz)) for all angles of arrival.

5.562D *Additional allocation:* In Korea (Rep. of), the bands 128-130 GHz, 171-171.6 GHz, 172.2-172.8 GHz and 173.3-174 GHz are also allocated to the radio astronomy service on a primary basis until 2015.

5.562E The allocation to the Earth exploration-satellite service (active) is limited to the band 133.5-134 GHz.

5.562F In the band 155.5-158.5 GHz, the allocation to the Earth exploration-satellite (passive) and space research (passive) services shall terminate on 1 January 2018.

5.562G The date of entry into force of the allocation to the fixed and mobile services in the band 155.5-158.5 GHz shall be 1 January 2018.

5.562H Use of the bands 174.8-182 GHz and 185-190 GHz by the inter-satellite service is limited to satellites in the geostationary-satellite orbit. The single-entry power flux-density produced by a station in the inter-satellite service, for all conditions and for all methods of modulation, at all altitudes from 0 to 1000 km above the Earth's surface and in the vicinity of all geostationary orbital positions occupied by passive sensors, shall not exceed -144 dB(W/(m^2 × MHz)) for all angles of arrival.

5.563A In the bands 200-209 GHz, 235-238 GHz, 250-252 GHz and 265-275 GHz, ground-based passive atmospheric sensing is carried out to monitor atmospheric constituents.

5.563B The band 237.9-238 GHz is also allocated to the Earth exploration-satellite service (active) and the space research service (active) for spaceborne cloud radars only.

5.565 The following frequency bands in the range 275-1000 GHz are identified for use by administrations for passive service applications:

—radio astronomy service: 275-323 GHz, 327-371 GHz, 388-424 GHz, 426-442 GHz, 453-510 GHz, 623-711 GHz, 795-909 GHz and 926-945 GHz;

—Earth exploration-satellite service (passive) and space research service (passive): 275-286 GHz, 296-306 GHz, 313-356 GHz, 361-365 GHz, 369-392 GHz, 397-399 GHz, 409-411 GHz, 416-434 GHz, 439-467 GHz, 477-502 GHz, 523-527 GHz, 538-581 GHz, 611-630 GHz, 634-654 GHz, 657-692 GHz, 713-718 GHz, 729-733 GHz, 750-754 GHz, 771-776 GHz, 823-846 GHz, 850-854 GHz, 857-862 GHz, 866-882 GHz, 905-928 GHz, 951-956 GHz, 968-973 GHz and 985-990 GHz.

The use of the range 275-1000 GHz by the passive services does not preclude use of this range by active services. Administrations wishing to make frequencies in the 275-1000 GHz range available for active service applications are urged to take all practicable steps to protect these passive services from harmful interference until the date when the Table of Frequency Allocations is established in the above-mentioned 275-1000 GHz frequency range.

All frequencies in the range 1000-3000 GHz may be used by both active and passive services. (WRC-12)

UNITED STATES (US) FOOTNOTES

These footnotes, each consisting of the letters "US" followed by one or more digits, denote stipulations applicable to both Federal and non-Federal operations and thus appear in both the Federal Table and the non-Federal Table.

US1 The bands 2501-2502 kHz, 5003-5005 kHz, 10003-10005 kHz, 15005-15010 kHz, 19990-19995 kHz, 20005-20010 kHz, and 25005-25010 kHz are also allocated to the space research service on a secondary basis for Federal use. In the event of interference to the reception of the standard frequency and time broadcasts, these space research transmissions are subject to immediate temporary or permanent shutdown.

US2 In the band 9-490 kHz, electric utilities operate Power Line Carrier (PLC) systems on power transmission lines for communications important to the reliability and security of electric service to the public. These PLC systems operate under the provisions of 47 CFR part 15, or Chapter 8 of the *NTIA Manual*, on an unprotected and non-interference basis with respect to authorized radio users. Notification of intent to place new or revised radio frequency assignments or PLC frequency uses in the band 9-490 kHz is to be made in accordance with the Rules and Regulations of the FCC and NTIA, and users are urged to minimize potential interference to the extent practicable. This footnote does not provide any allocation status to PLC radio frequency uses.

US8 The use of the frequencies 170.475, 171.425, 171.575, and 172.275 MHz east of the Mississippi River, and 170.425, 170.575, 171.475, 172.225 and 172.375 MHz west of the Mississippi River may be authorized to fixed, land and mobile stations operated by non-Federal forest firefighting agencies. In addition, land stations and mobile stations operated by non-Federal conservation agencies, for mobile relay operation only, may be authorized to use the frequency 172.275 MHz east of the Mississippi River and the frequency 171.475 MHz west of the Mississippi River. The use of any of the foregoing nine frequencies shall be on the condition that no harmful interference will be caused to Government stations.

US11 On the condition that harmful interference is not caused to present or future Federal stations in the band 162-174 MHz, the frequencies 166.25 MHz and 170.15 MHz may be authorized to non-Federal stations, as follows:

(a) Eligibles in the Public Safety Radio Pool may be authorized to operate in the fixed and land mobile services for locations within 150 miles (241.4 kilometers) of New York City; and

(b) Remote pickup broadcast stations may be authorized to operate in the land mobile service for locations within the conterminous United States, excluding locations within 150 miles of New York City and the Tennessee Valley Authority Area (TVA Area). The TVA Area is bounded on the west by the Mississippi River, on the north by the parallel of latitude 37° 30′ N, and on the east and south by that arc of the circle with center at Springfield, IL, and radius equal to the airline distance between Springfield, IL and Montgomery, AL, subtended between the foregoing west and north boundaries.

US13 The following center frequencies, each with a channel bandwidth not greater than 12.5 kHz, are available for assignment to non-Federal fixed stations for the specific purpose of transmitting hydrological and meteorological data in cooperation with Federal agencies, subject to the condition that harmful interference will not be caused to Federal stations:

Hydro Channels (MHz)			
169.4250	170.2625	171.1000	406.1250
169.4375	170.2750	171.1125	406.1750
169.4500	170.2875	171.1250	412.6625
169.4625	170.3000	171.8250	412.6750
169.4750	170.3125	171.8375	412.6875
169.4875	170.3250	171.8500	412.7125
169.5000	171.0250	171.8625	412.7250
169.5125	171.0375	171.8750	412.7375
169.5250	171.0500	171.8875	412.7625
170.2250	171.0625	171.9000	412.7750
170.2375	171.0750	171.9125	415.1250
170.2500	171.0875	171.9250	415.1750

New assignments on the frequencies 406.125 MHz and 406.175 MHz are to be primarily for paired operations with the frequencies 415.125 MHz and 415.175 MHz, respectively.

US18 In the bands 9-14 kHz, 90-110 kHz, 190-415 kHz, 510-535 kHz, and 2700-2900 MHz, navigation aids in the U.S. and its insular areas are normally operated by the Federal Government. However, authorizations may be made by the FCC for non-Federal operations in these bands subject to the conclusion of appropriate arrangements between the FCC and the Federal agencies concerned and upon special showing of need for service which the Federal Government is not yet prepared to render.

US41 In the band 2450-2500 MHz, the Federal radiolocation service is permitted on condition that harmful interference is not caused to non-Federal services.

US44 In the band 2900-3100 MHz, the non-Federal radiolocation service may be authorized on the condition that no harmful interference is caused to Federal services.

US49 In the band 5460-5470 MHz, the non-Federal radiolocation service may be authorized on the condition that it does not cause harmful interference to the aeronautical or maritime radionavigation services or to the Federal radiolocation service.

US50 In the band 5470-5650 MHz, the radiolocation service may be authorized for non-Federal use on the condition that harmful interference is not caused to the maritime radionavigation service or to the Federal radiolocation service.

US64 (a) In the band 401-406 MHz, the mobile, except aeronautical mobile, service is allocated on a secondary basis and is limited to, with the exception of military tactical mobile stations, Medical Device Radiocommunication Service (MedRadio) operations. MedRadio stations are authorized by rule on the condition that harmful interference is not caused to stations in the meteorological aids, meteorological-satellite, and Earth exploration-satellite services, and that MedRadio stations accept interference from stations in the meteorological aids, meteorological-satellite, and Earth exploration-satellite services.

(b) The bands 413-419 MHz, 426-432 MHz, 438-444 MHz, and 451-457 MHz are also allocated on a secondary basis to the mobile, except aeronautical mobile, service. The use of this allocation is limited to MedRadio operations. MedRadio stations are authorized by rule and operate in accordance with 47 CFR part 95.

US65 The use of the band 5460-5650 MHz by the maritime radionavigation service is limited to shipborne radars.

US67 The use of the band 9300-9500 MHz by the meteorological aids service is limited to ground-based radars. Radiolocation installations will be coordinated with the meteorological aids service and, insofar as practicable, will be adjusted to meet the requirements of the meteorological aids service.

US69 In the band 31.8-33.4 GHz, ground-based radionavigation aids are not permitted except where they operate in cooperation with airborne or shipborne radionavigation devices.

US70 The meteorological aids service allocation in the band 400.15-406.0 MHz does not preclude the operation therein of associated ground transmitters.

US71 In the band 9300-9320 MHz, low-powered maritime radionavigation stations shall be protected from harmful interference caused by the operation of land-based equipment.

US73 The frequencies 150.775, 150.79, 152.0075, and 163.25 MHz, and the bands 462.94-463.19675 and 467.94-468.19675 MHz shall be authorized for the purpose of delivering or rendering medical services to individuals (medical radiocommunication systems), and shall be authorized on a primary basis for Federal and non-Federal use. The frequency 152.0075 MHz may also be used for the purpose of conducting public safety radio communications that inclu1de, but are not limited to, the delivering or rendering of medical services to individuals.

(a) The use of the frequencies 150.775 and 150.79 MHz is restricted to mobile stations operating with a maximum e.r.p. of 100 watts. Airborne operations are prohibited.

(b) The use of the frequencies 152.0075 and 163.25 MHz is restricted to base stations that are authorized only for one-way paging communications to mobile receivers. Transmissions for the purpose of activating or controlling remote objects on these frequencies shall not be authorized.

(c) Non-Federal licensees in the Public Safety Radio Pool holding a valid authorization on May 27, 2005, to operate on the frequencies 150.7825 and 150.7975 MHz may, upon proper renewal application, continue to be authorized for such operation; provided that harmful interference is not caused to present or future Federal stations in the band 150.05-150.8 MHz and, should harmful interference result, that the interfering non-Federal operation shall immediately terminate.

US74 In the bands 25.55-25.67, 73-74.6, 406.1-410, 608-614, 1400-1427, 1660.5-1670, 2690-2700, and 4990-5000 MHz, and in the bands 10.68-10.7, 15.35-15.4, 23.6-24.0, 31.3-31.5, 86-92, 100-102, 109.5-111.8, 114.25-116, 148.5-151.5, 164-167, 200-209, and 250-252 GHz, the radio astronomy service shall be protected from unwanted emissions only to the extent that such radiation exceeds the level which would be present if the offending station were operating in compliance with the technical standards or criteria applicable to the service in which it operates. Radio astronomy observations in these bands are performed at the locations listed in US385.

US79 In the bands 1390-1400 MHz and 1427-1432 MHz, the following provisions shall apply:

(a) Airborne and space-to-Earth operations are prohibited.

(b) Federal operations (except for devices authorized by the FCC for the Wireless Medical Telemetry Service) are on a non-interference basis to non-Federal operations and shall not constrain implementation of non-Federal operations.

US81 The band 38-38.25 MHz is used by both Federal and non-Federal radio astronomy observatories. No new fixed or mobile assignments are to be made and Federal 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 Engineering and Technology, FCC, Washington, DC 20554.

US83 In the 1432-1435 MHz band, Federal stations in the fixed and mobile services may operate indefinitely on a primary basis at the 22 sites listed in the table below. The first 21 sites are in the United States and the last site is in Guam (GU). All other Federal stations in the fixed and mobile services shall operate in the band 1432-1435 MHz on a primary basis until reaccommodated in accordance with the National Defense Authorization Act of 1999.

State	Site	North	West	Radius
AK	Fort Greely	63° 47′	145° 52′	80
AL	Redstone Arsenal	34° 35′	086° 35′	80
AZ	Fort Huachuca	31° 33′	110° 18′	80
AZ	Yuma Proving Ground	32° 29′	114° 20′	160
CA	China Lake/Edwards AFB	35° 29′	117° 16′	100
CA	Lemoore	36° 20′	119° 57′	120
FL	Eglin AFB/Ft Rucker, AL	30° 28′	086° 31′	140
FL	NAS Cecil Field	30° 13′	081° 52′	160
MD	Patuxent River	38° 17′	076° 24′	70
ME	Naval Space Operations Center	44° 24′	068° 01′	80
MI	Alpene Range	44° 23′	083° 20′	80
MS	Camp Shelby	31° 20′	089° 18′	80
NC	MCAS Cherry Point	34° 54′	076° 53′	100
NM	White Sands Missile Range/Holloman AFB	32° 11′	106° 20′	160
NV	NAS Fallon	39° 30′	118° 46′	100
NV	Nevada Test and Training Range (NTTR)	37° 29′	114° 14′	130
SC	Beaufort MCAS	32° 26′	080° 40′	160
SC	Savannah River	33° 15′	081° 39′	3
UT	Utah Test and Training Range/Dugway Proving Ground, Hill AFB	40° 57′	113° 05′	160
VA	NAS Oceana	36° 49′	076° 01′	100
WA	NAS Whidbey Island	48° 21′	122° 39′	70
GU	NCTAMS	13° 35′	144° 51′	80

NOTE: The coordinates (North latitude and West longitude) are listed under the headings North and West. The Guam entry under the West heading is actually 144° 51′ East longitude. The operating radii in kilometers are listed under the heading Radius.

US85 Differential-Global-Positioning-System (DGPS) Stations, limited to ground-based transmitters, may be authorized on a primary basis in the band 1559-1610 MHz for the specific purpose of transmitting DGPS information intended for aircraft navigation.

US87 The band 449.75-450.25 MHz may be used by Federal and non-Federal stations for space telecommand (Earth-to-space) at specific locations, subject to such conditions as may be applied on a case-by-case basis. Operators shall take all practical steps to keep the carrier frequency close to 450 MHz.

US88 In the bands 1675-1695 MHz and 1695-1710 MHz, the following provisions shall apply:

(a) Non-Federal use of the band 1695-1710 MHz by the fixed and mobile except aeronautical mobile services is restricted to stations in the Advanced Wireless Service (AWS). Base stations that enable AWS mobile and portable stations to operate in the band 1695-1710 MHz must be successfully coordinated prior to operation as follows: (i) all base stations within the 27 protection zones listed in paragraph (b) that enable mobiles to operate at a maximum e.i.r.p. of 20 dBm, and (ii) nationwide for base stations that enable mobiles to operate with a maximum e.i.r.p. greater than 20 dBm, up to a maximum e.i.r.p. of 30 dBm, unless otherwise specified by Commission rule, order, or notice.

(b) Forty-seven Federal Earth stations located within the protection zones listed below operate on a co-equal, primary basis with AWS operations. All other Federal Earth stations operate on a secondary basis.

(1) Protection zones for Federal Earth stations receiving in the band 1695-1710 MHz:

State	Location	Latitude	Longitude	Radius (km)
AK	Barrow	71° 19′ 22″	156° 36′ 41″	35
AK	Elmendorf AFB	61° 14′ 08″	149° 55′ 31″	
AK	Fairbanks	64° 58′ 22″	147° 30′ 02″	20
AZ	Yuma	32° 39′ 24″	114° 36′ 22″	95
CA	Monterey	36° 35′ 34″	121° 51′ 20″	76
CA	Twenty-Nine Palms	34° 17′ 46″	116° 09′ 44″	80
FL	Miami	25° 44′ 05″	080° 09′ 45″	51
HI	Hickam AFB	21° 19′ 18″	157° 57′ 30″	28
MD	Suitland	38° 51′ 07″	076° 56′ 12″	98
MS	Stennis Space Center	30° 21′ 23″	089° 36′ 41″	57
SD	Sioux Falls	43° 44′ 09″	096° 37′ 33″	42
VA	Wallops Island	37° 56′ 45″	075° 27′ 45″	30
GU	Andersen AFB	13° 34′ 52″	144° 55′ 28″	42

(2) Protection zones for Federal Earth stations receiving in the band 1675-1695 MHz:

State	Location	Latitude	Longitude	Radius (km)
CA	Sacramento	38° 35′ 50″	121° 32′ 34″	55
CO	Boulder	39° 59′ 26″	105° 15′ 51″	02
ID	Boise	43° 35′ 42″	116° 13′ 49″	39
IL	Rock Island	41° 31′ 04″	090° 33′ 46″	19
MO	Kansas City	39° 16′ 40″	094° 39′ 44″	40
MO	St. Louis	38° 35′ 26″	090° 12′ 25″	34
MS	Columbus Lake	33° 32′ 04″	088° 30′ 06″	03
MS	Vicksburg	32° 20′ 47″	090° 50′ 10″	16
NE	Omaha	41° 20′ 56″	095° 57′ 34″	30
OH	Cincinnati	39° 06′ 10″	084° 30′ 35″	32
OK	Norman	35° 10′ 52″	097° 26′ 21″	03
TN	Knoxville	35° 57′ 58″	083° 55′ 13″	50
WV	Fairmont	39° 26′ 02″	080° 11′ 33″	04
PR	Guaynabo	18° 25′ 26″	066° 06′ 50″	48

NOTE: The coordinates are specified in the conventional manner (North latitude, West longitude), except that the Guam (GU) entry is specified in terms of East longitude.

US90 In the band 2025-2110 MHz, the power flux-density at the Earth's surface produced by emissions from a space station in the space operation, Earth exploration-satellite, or space research service that is transmitting in the space-to-space direction, for all conditions and all methods of modulation, shall not exceed the following values in any 4 kHz sub-band:

(a) –154 dBW/m^2 for angles of arrival above the horizontal plane (δ) of 0° to 5°,

(b) $-154 + 0.5(\delta - 5)$ dBW/m^2 for δ of 5° to 25°, and

(c) –144 dBW/m^2 for δ of 25° to 90°.

US91 In the band 1755-1780 MHz, the following provisions shall apply:

(a) Non-Federal use of the band 1755-1780 MHz by the fixed and mobile services is restricted to stations in the Advanced Wireless Service (AWS). Base stations that enable AWS mobile and portable stations to operate in the band 1755-1780 MHz must be successfully coordinated on a nationwide basis prior to operation, unless otherwise specified by Commission rule, order, or notice.

(b) In the band 1755-1780 MHz, the Federal systems listed below operate on a co-equal, primary basis with AWS stations. All other Federal stations in the fixed and mobile services identified in an approved Transition Plan will operate on a primary basis until reaccommodated in accordance with 47 CFR part 301.

(1) Joint Tactical Radio Systems (JTRS) may operate indefinitely at the following locations:

State	Training area	Latitude	Longitude
AZ	Yuma Proving Ground	33° 12′ 14″	114° 13′ 47″
CA	Fort Irwin	35° 23′ 19″	116° 37′ 43″
LA	Fort Polk	31° 08′ 38″	093° 06′ 52″
NC	Fort Bragg (including Camp MacKall	35° 09′ 04″	078° 59′ 13″
NM	White Sands Missile Range	32° 52′ 50″	106° 23′ 10″
TX	Fort Hood	31° 13′ 50″	097° 45′ 23″

(2) Air combat training system (ACTS) stations may operate on two frequencies within two geographic zones that are defined by the following coordinates:

Geographic Zone	Latitude	Longitude
Polygon 1	41° 52′ 00″	117° 49′ 00″
	42° 00′ 00″	115° 05′ 00″
	43° 31′ 13″	115° 47′ 18″
Polygon 2	47° 29′ 00″	111° 22′ 00″
	48° 13′ 00″	110° 00′ 00″
	47° 30′ 00″	107° 00′ 00″
	44° 11′ 00″	103° 06′ 00″

NOTE: ACTS transmitters may cause interference to AWS base stations between separation distances of 285 km (minimum) and 415 km (maximum).

(3) In the sub-band 1761-1780 MHz, Federal Earth stations in the space operation service (Earth-to-space) may transmit at the following 25 sites and non-Federal base stations must accept harmful interference caused by the operation of these Earth stations:

State	Site	Latitude	Longitude
AK	Fairbanks	64° 58′ 20″	147° 30′ 59″
CA	Camp Parks	37° 43′ 51″	121° 52′ 50″
CA	Huntington Beach	33° 44′ 50″	118° 02′ 04″
CA	Laguna Peak	34° 06′ 31″	119° 03′ 53″
CA	Monterey	36° 35′ 42″	121° 52′ 28″
CA	Sacramento	38° 39′ 59″	121° 23′ 33″
CA	Vandenberg AFB	34° 49′ 23″	120° 30′ 07″
CO	Buckley	39° 42′ 55″	104° 46′ 29″
CO	Schriever AFB	38° 48′ 22″	104° 31′ 41″
FL	Cape Canaveral AFS	28° 29′ 09″	080° 34′ 33″
FL	Cape GA, CCAFB	28° 29′ 03″	080° 34′ 21″
FL	JIATF-S Key West	24° 32′ 36″	081° 48′ 17″
HI	Kaena Point, Oahu	21° 33′ 43″	158° 14′ 31″
MD	Annapolis	38° 59′ 27″	076° 29′ 25″
MD	Blossom Point	38° 25′ 53″	077° 05′ 06″
MD	Patuxent River NAS	38° 16′ 28″	076° 24′ 45″
ME	Prospect Harbor	44° 24′ 16″	068° 00′ 46″
NC	Ft Bragg	35° 09′ 04″	078° 59′ 13″
NH	New Boston AFS	42° 56′ 46″	071° 37′ 44″
NM	Kirtland AFB	34° 59′ 06″	106° 30′ 28″
TX	Ft Hood	31° 08′ 57″	097° 46′ 12″
VA	Fort Belvoir	38° 44′ 04″	077° 09′ 12″
WA	Joint Base Lewis-McChord	47° 06′ 11″	122° 33′ 11″
GU	Andersen AFB	13° 36′ 54″	144° 51′ 22″
GU	NAVSOC Det. Charlie	13° 34′ 58″	144° 50′ 32″

NOTE: The coordinates are specified in the conventional manner (North latitude, West longitude), except that the Guam (GU) entries are specified in terms of East longitude. Use at Cape Canaveral AFS is restricted to launch support only. If required, successfully coordinated with all affected AWS licensees, and authorized by NTIA, reasonable modifications of these grandfathered Federal systems beyond their current authorizations or the addition of new Earth station locations may be permitted. The details of the coordination must be filed with NTIA and FCC.

(c) In the band 1755-1780 MHz, the military services may conduct Electronic Warfare (EW) operations on Federal ranges and within associated airspace on a non-interference basis with respect to non-Federal AWS operations and shall not constrain implementation of non-Federal AWS operations. This use is restricted to Research, Development, Test and Evaluation (RDT&E), training, and Large Force Exercise (LFE) operations.

US92 In the band 2025-2110 MHz, Federal use of the co-primary fixed and mobile services is restricted to the military services and the following provisions apply:

(a) Federal use shall not cause harmful interference to, nor constrain the deployment and use of the band by, the Television Broadcast Auxiliary Service, the Cable Television Relay Service, or the Local Television Transmission Service. To facilitate compatible operations, coordination is required in accordance with a Memorandum of Understanding between Federal and non-Federal fixed and mobile operations. Non-Federal licensees shall make all reasonable efforts to accommodate military mobile and fixed operations; however, the use of the band 2025-2110 MHz by the non-Federal fixed and mobile services has priority over military fixed and mobile operations.

(b) Military stations should, to the extent practicable, employ frequency agile technologies and techniques, including the capability to tune to other frequencies and the use of a modular retrofit capability, to facilitate sharing of this band with incumbent Federal and non-Federal operations.

US97 The following provisions shall apply in the band 2305-2320 MHz:

(a) In the sub-band 2305-2310 MHz, space-to-Earth operations are prohibited.

(b) Within 145 km of Goldstone, CA (35° 25′ 33″ N, 116° 53′ 23″ W), Wireless Communications Service (WCS) licensees operating base stations in the band 2305-2320 MHz shall, prior to operation of those base stations, achieve a mutually satisfactory coordination agreement with the National Aeronautics and Space Administration (NASA).

NOTE: NASA operates a deep space facility in Goldstone in the band 2290-2300 MHz.

US99 In the band 1668.4-1670 MHz, the meteorological aids service (radiosonde) will avoid operations to the maximum extent practicable. Whenever it is necessary to operate radiosondes in the band 1668.4-1670 MHz within the United States, notification of the operations shall be sent as far in advance as possible to the Electromagnetic Management Unit, Room 1030, National Science Foundation, 4201 Wilson Blvd., Arlington, VA 22230.

US100 The following provisions shall apply to the bands 2310-2320 MHz and 2345-2360 MHz:

(a) The bands 2310-2320 and 2345-2360 MHz are available for Federal aeronautical telemetering and associated telecommand operations for flight testing of manned or unmanned aircraft, missiles, or major components thereof, on a secondary basis to the Wireless Communications Service (WCS). The frequencies 2312.5 MHz and 2352.5 MHz are shared on a co-equal basis by Federal stations for telemetering and associated telecommand operations of expendable and reusable launch vehicles, irrespective of whether such operations involve flight testing. Other Federal mobile telemetering uses may be provided in the bands 2310-2320 and 2345-2360 MHz on a non-interference basis to all other uses authorized pursuant to this footnote.

(b) The band 2345-2360 MHz is available for non-Federal aeronautical telemetering and associated telecommand operations for flight testing of manned or unmanned aircraft, missiles, or major components thereof, on a secondary basis to the WCS until January 1, 2020. The use of this allocation is restricted to non-Federal licensees in the Aeronautical and Fixed Radio Service holding a valid authorization on April 23, 2015.

US108 In the bands 3300-3500 MHz and 10-10.5 GHz, survey operations, using transmitters with a peak power not to exceed five watts into the antenna, may be authorized for Federal and non-Federal use on a secondary basis to other Federal radiolocation operations.

US111 In the band 5091-5150 MHz, aeronautical mobile telemetry operations for flight testing are conducted at the following locations. Flight testing at additional locations may be authorized on a case-by-case basis.

Location	Test Sites	Lat. (N)	Long. (W)
Gulf Area Ranges Complex (GARC)	Eglin AFB, Tyndall AFB, FL; Gulfport ANG Range, MS; Ft. Rucker, Redstone, NASA Marshall Space Flight Center, AL	30° 28′	86° 31′
Utah Ranges Complex (URC)	Dugway PG; Utah Test & Training Range (Hill AFB), UT	40° 57′	113° 05′
Western Ranges Complex (WRC)	Pacific Missile Range; Vandenberg AFB, China Lake NAWS, Pt. Mugu NAWS, Edwards AFB, Thermal, Nellis AFB, Ft. Irwin, NASA Dryden Flight Research Center, Victorville, CA	35° 29′	117° 16′
Southwest Ranges Complex (SRC)	Ft. Huachuca, Tucson, Phoenix, Mesa, Yuma, AZ	31° 33′	110° 18′
Mid-Atlantic Ranges Complex (MARC)	Patuxent River, Aberdeen PG, NASA Langley Research Center, NASA Wallops Flight Facility, MD	38° 17′	76° 24′
New Mexico Ranges Complex (NMRC)	White Sands Missile Range, Holloman AFB, Albuquerque, Roswell, NM; Amarillo, TX	32° 11′	106° 20′
Colorado Ranges Complex (CoRC)	Alamosa, Leadville, CO	37° 26′	105° 52′
Texas Ranges Complex (TRC)	Dallas/Ft. Worth, Greenville, Waco, Johnson Space Flight Center/Ellington Field, TX	32° 53′	97° 02′
Cape Ranges Complex (CRC)	Cape Canaveral, Palm Beach-Dade, FL	28° 33′	80° 34′
Northwest Range Complex (NWRC)	Seattle, Everett, Spokane, Moses Lake, WA; Klamath Falls, Eugene, OR	47° 32′	122° 18′
St. Louis	St Louis, MO	38° 45′	90° 22′
Wichita	Wichita, KS	37° 40′	97° 26′
Marietta	Marietta, GA	33° 54′	84° 31′
Glasgow	Glasgow, MT	48° 25′	106° 32′
Wilmington/Ridley	Wilmington, DE/Ridley, PA	39° 49′	75° 26′
San Francisco Bay Area (SFBA)	NASA Ames Research Center, CA	37° 25′	122° 03′
Charleston	Charleston, SC	32° 52′	80° 02′

US113 Radio astronomy observations of the formaldehyde line frequencies 4825-4835 MHz and 14.47-14.5 GHz may be made at certain radio astronomy observatories as indicated below:

BANDS TO BE OBSERVED

4 GHz	14 GHz	Observatory
X	…..	National Astronomy and Ionosphere Center (NAIC), Arecibo, PR
X	X	National Radio Astronomy Observatory (NRAO), Green Bank, WV
X	X	NRAO, Socorro, NM
X	…..	Allen Telescope Array (ATA), Hat Creek, CA
X	X	Owens Valley Radio Observatory (OVRO), Big Pine, CA
X	X	NRAO's ten Very Long Baseline Array (VLBA) stations (see US131)
X	X	University of Michigan Radio Astronomy Observatory, Stinchfield Woods, MI
X	…..	Pisgah Astronomical Research Institute, Rosman, NC

Every practicable effort will be made to avoid the assignment of frequencies to stations in the fixed or mobile services in these bands. Should such assignments result in harmful interference to these observations, the situation will be remedied to the extent practicable.

US117 In the band 406.1-410 MHz, the following provisions shall apply:

(a) Stations in the fixed and mobile services are limited to a transmitter output power of 125 watts, and new authorizations for stations, other than mobile stations, are subject to prior coordination by the applicant in the following areas:

(1) Within Puerto Rico and the U.S. Virgin Islands, contact Spectrum Manager, Arecibo Observatory, HC3 Box 53995, Arecibo, PR 00612. Phone: 787-878-2612, Fax: 787-878-1861, E-mail: prcz@naic.edu.

(2) Within 350 km of the Very Large Array (34° 04′ 44″ N, 107° 37′ 06″ W), contact Spectrum Manager, National Radio Astronomy Observatory, P.O. Box O, 1003 Lopezville Road, Socorro, NM 87801. Phone: 505-835-7000, Fax: 505-835-7027, E-mail: nrao-rfi@nrao.edu.

(3) Within 10 km of the Table Mountain Observatory (40° 08′ 02″ N, 105° 14′ 40″ W) and for operations only within the sub-band 407-409 MHz, contact Radio Frequency Manager, Department of Commerce, 325 Broadway, Boulder, CO 80305. Phone: 303-497-4619, Fax: 303-497-6982, E-mail: frequencymanager@its.bldrdoc.gov.

(b) Non-Federal use is limited to the radio astronomy service and as provided by footnote US13.

US128 In the band 10-10.5 GHz, pulsed emissions are prohibited, except for weather radars on board meteorological satellites in the sub-band 10-10.025 GHz. The amateur service, the amateur-satellite service, and the non-Federal radiolocation service, which shall not cause harmful interference to the Federal radiolocation service, are the only non-Federal services permitted in this band. The non-Federal radiolocation service is limited to survey operations as specified in footnote US108.

US130 The band 10.6-10.68 GHz is also allocated on a primary basis to the radio astronomy service. However, the radio astronomy service shall not receive protection from stations in the fixed service which are licensed to operate in the one hundred most populous urbanized areas as defined by the 1990 U.S. Census. For the list of observatories operating in this band, see footnote US131.

US131 In the band 10.7-11.7 GHz, non-geostationary satellite orbit licensees in the fixed-satellite service (space-to-Earth), prior to commencing operations, shall coordinate with the following radio astronomy observatories to achieve a mutually acceptable agreement regarding the protection of the radio telescope facilities operating in the band 10.6-10.7 GHz:

Observatory	North latitude	West longitude	Elevation (in meters)
Arecibo Observatory, PR	18° 20′ 37″	66° 45′ 11″	497
Green Bank Telescope (GBT), WV	38° 25′ 59″	79° 50′ 23″	807
Very Large Array (VLA), Socorro, NM	34° 04′ 44″	107° 37′ 06″	2115
Very Long Baseline Array (VLBA) Stations:			
Brewster, WA	48° 07′ 52″	119° 41′ 00″	250
Fort Davis, TX	30° 38′ 06″	103° 56′ 41″	1606
Hancock, NH	42° 56′ 01″	71° 59′ 12″	296
Kitt Peak, AZ	31° 57′ 23″	111° 36′ 45″	1902
Los Alamos, NM	35° 46′ 30″	106° 14′ 44″	1962
Mauna Kea, HI	19° 48′ 05″	155° 27′ 20″	3763
North Liberty, IA	41° 46′ 17″	91° 34′ 27″	222
Owens Valley, CA	37° 13′ 54″	118° 16′ 37″	1196
Pie Town, NM	34° 18′ 04″	108° 07′ 09″	2365
St. Croix, VI	17° 45′ 24″	64° 35′ 01″	16

US133 In the bands 14-14.2 GHz and 14.47-14.5 GHz, the following provisions shall apply to the operations of Earth Stations Aboard Aircraft (ESAA):

(a) In the band 14-14.2 GHz, ESAA licensees proposing to operate within radio line-of-sight of the coordinates specified in 47 CFR 25.227(c) are subject to prior coordination with NTIA in order to minimize harmful interference to the ground terminals of NASA's Tracking and Data Relay Satellite System (TDRSS).

(b) In the band 14.47-14.5 GHz, operations within radio line-of-sight of the radio astronomy stations specified in 47 CFR 25.226(d)(2) are subject to coordination with the National Science Foundation in accordance with 47 CFR 25.227(d).

US139 Fixed stations authorized in the band 18.3-19.3 GHz under the provisions of 47 CFR 74.502(c), 74.602(g), 78.18(a)(4), and 101.147(r) may continue operations consistent with the provisions of those sections.

US145 The following unwanted emissions power limits for non-geostationary satellites operating in the inter-satellite service that transmit in the band 22.55-23.55 GHz shall apply in any 200 MHz of the passive band 23.6-24 GHz, based on the date that complete advance publication information is received by the ITU's Radiocommunication Bureau:

(a) For information received before January 1, 2020: –36 dBW/200 MHz.

(b) For information received on or after January 1, 2020: –46 dBW/200 MHz.

US156 In the bands 49.7-50.2 GHz and 50.4-50.9 GHz, for Earth stations in the fixed-satellite service (Earth-to-space), the unwanted emissions power in the band 50.2-50.4 GHz shall not exceed –20 dBW/ 200 MHz (measured at the input of the antenna), except that the maximum unwanted emissions power may be increased to –10 dBW/200 MHz for Earth stations having an antenna gain greater than or equal to 57 dBi. These limits apply under clear-sky conditions. During fading conditions, the limits may be exceeded by Earth stations when using uplink power control.

US157 In the band 51.4-52.6 GHz, for stations in the fixed service, the unwanted emissions power in the band 52.6-54.25 GHz shall not exceed –33 dBW/100 MHz (measured at the input of antenna).

US161 In the bands 81-86 GHz, 92-94 GHz, and 94.1-95 GHz and within the coordination distances indicated below, assignments to allocated services shall be coordinated with the following radio astronomy observatories. New observatories shall not receive protection from fixed stations that are licensed to operate in the one hundred most populous urbanized areas as defined by the U.S. Census Bureau for the year 2000.

(a) Within 25 km of the National Radio Astronomy Observatory's (NRAO's) Very Long Baseline Array (VLBA) Stations:

State	VLBA Station	Lat. (N)	Long. (W)
AZ	Kitt Peak	31° 57′ 23″	111° 36′ 45″
CA	Owens Valley	37° 13′ 54″	118° 16′ 37″
HI	Mauna Kea	19° 48′ 05″	155° 27′ 20″
IA	North Liberty	41° 46′ 17″	091° 34′ 27″
NH	Hancock	42° 56′ 01″	071° 59′ 12″
NM	Los Alamos	35° 46′ 30″	106° 14′ 44″
NM	Pie Town	34° 18′ 04″	108° 07′ 09″
TX	Fort Davis	30° 38′ 06″	103° 56′ 41″
VI	Saint Croix	17° 45′ 24″	064° 35′ 01″
WA	Brewster	48° 07′ 52″	119° 41′ 00″

(b) Within 150 km of the following observatories:

State	Telescope and site	Lat. (N)	Long. (W)
AZ	Heinrich Hertz Submillimeter Observatory, Mt. Graham	32° 42′ 06″	109° 53′ 28″
AZ	University of Arizona 12-m Telescope, Kitt Peak	31° 57′ 12″	111° 36′ 53″
CA	Caltech Telescope, Owens Valley	37° 13′ 54″	118° 17′ 36″
CA	Combined Array for Research in Millimeter-wave Astronomy (CARMA)	37° 16′ 43″	118° 08′ 32″
HI	James Clerk Maxwell Telescope, Mauna Kea	19° 49′ 33″	155° 28′ 47″
MA	Haystack Observatory, Westford	42° 37′ 24″	071° 29′ 18″
NM	NRAO's Very Large Array, Socorro	34° 04′ 44″	107° 37′ 06″
WV	NRAO's Robert C. Byrd Telescope, Green Bank	38° 25′ 59″	079° 50′ 23″

NOTE: Satisfactory completion of the coordination procedure utilizing the automated mechanism, see 47 CFR 101.1523, will be deemed to establish sufficient separation from radio astronomy observatories, regardless of whether the distances set forth above are met.

US205 Tropospheric scatter systems are prohibited in the band 2500-2690 MHz.

US208 Planning and use of the band 1559-1626.5 MHz necessitate the development of technical and/or operational sharing criteria to ensure the maximum degree of electromagnetic compatibility with existing and planned systems within the band.

US209 The use of frequencies 460.6625, 460.6875, 460.7125, 460.7375, 460.7625, 460.7875, 460.8125, 460.8375, 460.8625, 465.6625, 465.6875, 465.7125, 465.7375, 465.7625, 465.7875, 465.8125, 465.8375, and 465.8625 MHz may be authorized, with 100 mW or less output power, to Federal and non-Federal radio stations for one-way, non-voice bio-medical telemetry operations in hospitals, or medical or convalescent centers.

US210 In the bands 40.66-40.7 MHz and 216-220 MHz, frequencies may be authorized to Federal and non-Federal stations on a secondary basis for the tracking of, and telemetering of scientific data from, ocean buoys and wildlife. Operation in these bands is subject to the technical standards specified in: (a) Section 8.2.42 of the NTIA Manual for Federal use, or (b) 47 CFR 90.248 for non-Federal use. After January 1, 2002, no new assignments shall be authorized in the band 216-217 MHz.

US211 In the bands 1670-1690, 5000-5250 MHz and 10.7-11.7, 15.1365-15.35, 15.4-15.7, 22.5-22.55, 24-24.05, 31.0-31.3, 31.8-32.0, 40.5-42.5, 116-122.25, 123-130, 158.5-164, 167-168, 191.8-200, and 252-265 GHz, applicants for airborne or space station assignments are urged to take all practicable steps to protect radio astronomy observations in the adjacent bands from harmful interference; however, US74 applies.

US222 In the band 2025-2035 MHz, geostationary operational environmental satellite (GOES) Earth stations in the space research and Earth exploration-satellite services may be authorized on a coequal basis for Earth-to-space transmissions for tracking, telemetry, and telecommand at Honolulu, HI (21° 21′ 12″ N, 157° 52′ 36″ W); Seattle, WA (47° 34′ 15″ N, 122° 33′ 10″ W); and Wallops Island, VA (37° 56′ 44″ N, 75° 27′ 42″ W).

US241 The following provision shall apply to Federal operations in the band 216-220.035 MHz:

(a) Use of the fixed and land mobile services in the band 216-220 MHz and of the aeronautical mobile service in the sub-band 217-220 MHz is restricted to telemetry and associated telecommand operations. New stations in the fixed and land mobile services shall not be authorized in the sub-band 216-217 MHz.

(b) The sub-band 216.965-216.995 MHz is also allocated to the Federal radiolocation service on a primary basis and the use of this allocation is restricted to the Air Force Space Surveillance System (AFSSS) radar system. AFSSS stations transmit on the frequency 216.98 MHz and other operations may be affected within: 1) 250 km of Lake Kickapoo (Archer City), TX (33° 2′ 48″ N, 98° 45′ 46″ W); and 2) 150 km of Gila River (Phoenix), AZ (33° 6′ 32″ N, 112° 1′ 45″ W) and Jordan Lake (Wetumpka), AL (32° 39′ 33″ N, 86° 15′ 52″ W). AFSSS reception shall be protected from harmful interference within 50 km of: 1) Elephant Butte, NM (33° 26′ 35″ N, 106° 59′ 50″ W); 2) Fort Stewart, GA (31° 58′ 36″ N, 81° 30′ 34″ W); 3) Hawkinsville, GA (32° 17′ 20″ N, 83° 32′ 10″ W); 4) Red River, AR (33° 19′ 48″ N, 93° 33′ 1″ W); 5) San Diego, CA (32° 34′ 42″ N, 116° 58′ 11″ W); and 6) Silver Lake, MS (33° 8′ 42″ N, 91° 1′ 16″ W).

(c) The sub-band 219.965-220.035 MHz is also allocated to the Federal radiolocation service on a secondary basis and the use of this allocation is restricted to air-search radars onboard Coast Guard vessels.

US245 In the bands 3600-3650 MHz (space-to-Earth), 4500-4800 MHz (space-to-Earth), and 5850-5925 MHz (Earth-to-space), the use of the non-Federal fixed-satellite service is limited to international inter-continental systems and is subject to case-by-case electromagnetic compatibility analysis. The FCC's policy for these bands is codified at 47 CFR 2.108.

US246 No station shall be authorized to transmit in the following bands:

73-74.6 MHz,
608-614 MHz, except for medical telemetry equipment,[4]
1400-1427 MHz,

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[4] Medical telemetry equipment shall not cause harmful interference to radio astronomy operations in the band 608-614 MHz and shall be coordinated under the requirements found in 47 CFR 95.1119.

1660.5-1668.4 MHz,
2690-2700 MHz,
4990-5000 MHz,
10.68-10.7 GHz,
15.35-15.4 GHz,
23.6-24 GHz,
31.3-31.8 GHz,
50.2-50.4 GHz,
52.6-54.25 GHz,
86-92 GHz,
100-102 GHz,
109.5-111.8 GHz,
114.25-116 GHz,
148.5-151.5 GHz,
164-167 GHz,
182-185 GHz,
190-191.8 GHz,
200-209 GHz,
226-231.5 GHz,
250-252 GHz.

US251 The band 12.75-13.25 GHz is also allocated to the space research (deep space) (space-to-Earth) service for reception only at Goldstone, CA (35° 20′ N, 116° 53′ W).

US252 The band 2110-2120 MHz is also allocated to the space research service (deep space) (Earth-to-space) on a primary basis at Goldstone, CA (35° 20′ N, 116° 53′ W).

US254 In the band 18.6-18.8 GHz the fixed and mobile services shall be limited to a maximum equivalent isotropically radiated power of +35 dBW and the power delivered to the antenna shall not exceed –3 dBW.

US255 In addition to any other applicable limits, the power flux-density across the 200 MHz band 18.6-18.8 GHz produced at the surface of the Earth by emissions from a space station under assumed free-space propagation conditions shall not exceed –95 dB(W/m^2) for all angles of arrival. This limit may be exceeded by up to 3 dB for no more than 5% of the time.

US258 In the bands 8025-8400 MHz and 25.5-27 GHz, the Earth exploration-satellite service (space-to-Earth) is allocated on a primary basis for non-Federal use. Authorizations are subject to a case-by-case electromagnetic compatibility analysis.

US260 Aeronautical mobile communications which are an integral part of aeronautical radionavigation systems may be satisfied in the bands 1559-1626.5 MHz, 5000-5250 MHz and 15.4-15.7 GHz.

US261 The use of the band 4200-4400 MHz by the aeronautical radionavigation service is reserved exclusively for airborne radio altimeters. Experimental stations will not be authorized to develop equipment for operational use in this band other than equipment related to altimeter stations. However, passive sensing in the Earth-exploration satellite and space research services may be authorized in this band on a secondary basis (no protection is provided from the radio altimeters).

US262 The band 7145-7190 MHz is also allocated to the space research service (deep space) (Earth-to-space) on a secondary basis for non-Federal use. Federal and non-Federal use of the bands 7145-7190 MHz and 34.2-34.7 GHz by the space research service (deep space) (Earth-to-space) and of the band 31.8-32.3 GHz by the space research service (deep space) (space-to-Earth) is limited to Goldstone, CA (35° 20′ N, 116° 53′ W).

US264 In the band 48.94-49.04 GHz, airborne stations shall not be authorized.

US269 In the band 420-450 MHz, the following provisions shall apply to the non-Federal radiolocation service:

(a) Pulse-ranging radiolocation systems may be authorized for use along the shoreline of the conterminous United States and Alaska.

(b) In the sub-band 420-435 MHz, spread spectrum radiolocation systems may be authorized within the conterminous United States and Alaska.

(c) All stations operating in accordance with this provision shall be secondary to stations operating in accordance with the Table of Frequency Allocations.

(d) Authorizations shall be granted on a case-by-case basis; however, operations proposed to be located within the areas listed in paragraph (a) of US270 should not expect to be accommodated.

US270 In the band 420-450 MHz, the following provisions shall apply to the amateur service:

(a) The peak envelope power of an amateur station shall not exceed 50 watts in the following areas, unless expressly authorized by the FCC after mutual agreement, on a case-by-case basis, between the District Director of the applicable field office and the military area frequency coordinator at the applicable military base. For areas (5) through (7), the appropriate military coordinator is located at Peterson AFB, CO.

(1) Arizona, Florida and New Mexico.

(2) Within those portions of California and Nevada that are south of latitude 37° 10′ N.

(3) Within that portion of Texas that is west of longitude 104° W.

(4) Within 322 km of Eglin AFB, FL (30° 30′ N, 86° 30′ W); Patrick AFB, FL (28° 21′ N, 80° 43′ W); and the Pacific Missile Test Center, Point Mugu, CA (34° 09′ N, 119° 11′ W).

(5) Within 240 km of Beale AFB, CA (39° 08′ N, 121° 26′ W).

(6) Within 200 km of Goodfellow AFB, TX (31° 25′ N, 100° 24′ W) and Warner Robins AFB, GA (32° 38′ N, 83° 35′ W).

(7) Within 160 km of Clear AFS, AK (64° 17′ N, 149° 10′ W); Concrete, ND (48° 43′ N, 97° 54′ W); and Otis AFB, MA (41° 45′ N, 70° 32′ W).

(b) In the sub-band 420-430 MHz, the amateur service is not allocated north of Line A (def. § 2.1).

US273 In the bands 74.6-74.8 MHz and 75.2-75.4 MHz, stations in the fixed and mobile services are limited to a maximum power of 1 watt from the transmitter into the antenna transmission line.

US278 In the bands 22.55-23.55 GHz and 32.3-33 GHz, non-geostationary inter-satellite links may operate on a secondary basis to geostationary inter-satellite links.

US288 In the territorial waters of the United States, the preferred frequencies for use by on-board communication stations shall be 457.525 MHz, 457.550 MHz, 457.575 MHz and 457.600 MHz paired, respectively, with 467.750 MHz, 467.775 MHz, 467.800 MHz and 467.825 MHz. Where needed, equipment designed for 12.5 kHz channel spacing using also the additional frequencies 457.5375 MHz, 457.5625 MHz, 467.5375 MHz and 467.5625 MHz may be introduced for on-board communications. The characteristics of the equipment used shall conform to those specified in Recommendation ITU-R M.1174-2.

US289 In the bands 460-470 MHz and 1690-1695 MHz, the following provisions shall apply:

(a) In the band 460-470 MHz, space stations in the Earth exploration-satellite service (EESS) may be authorized for space-to-Earth transmissions on a secondary basis with respect to the fixed and mobile services. When operating in the meteorological-satellite service, such stations shall be protected from harmful interference from other EESS applications. The power flux density produced at the Earth's surface by any space station in this band shall not exceed –152 dBW/m^2/4 kHz.

(b) In the band 1690-1695 MHz, EESS applications, other than the meteorological-satellite service, may also be used for space-to-Earth transmissions subject to not causing harmful interference to stations operating in accordance with the Table of Frequency Allocations.

US297 The bands 47.2-49.2 GHz and 81-82.5 GHz are also available for feeder links for the broadcasting-satellite service.

US298 The assigned frequencies 27.555, 27.615, 27.635, 27.655, 27.765, and 27.860 MHz are available for use by forest product licensees on a secondary basis to Federal operations including experimental stations. Non-Federal operations on these frequencies will not exceed 150 watts output power and are limited to the states of Washington, Oregon, Maine, North Carolina, South Carolina, Tennessee, Georgia, Florida, Alabama, Mississippi, Louisiana, and Texas (eastern portion).

US300 The frequencies 169.445, 169.505, 170.245, 170.305, 171.045, 171.105, 171.845 and 171.905 MHz are available for wireless microphone operations on a secondary basis to Federal and non-Federal operations.

US303 In the band 2285-2290 MHz, non-Federal space stations in the space research, space operations and Earth exploration-satellite services may be authorized to transmit to the Tracking and Data Relay Satellite System subject to such conditions as may be applied on a case-by-case basis. Such transmissions shall not cause harmful interference to authorized Federal stations. The power flux-density at the Earth's surface from such non-Federal stations shall not exceed –144 to –154 dBW/m^2/4 kHz, depending on angle of arrival, in accordance with ITU Radio Regulation 21.16.

US307 The band 5150-5216 MHz is also allocated to the fixed-satellite service (space-to-Earth) for feeder links in conjunction with the radiodetermination-satellite service operating in the bands 1610-1626.5 MHz and 2483.5-2500 MHz. The total power flux-density at the Earth's surface shall in no case exceed –159 dBW/m^2 per 4 kHz for all angles of arrival.

US308 In the bands 1549.5-1558.5 MHz and 1651-1660 MHz, those requirements of the aeronautical mobile-satellite (R) service that cannot be accommodated in the bands 1545-1549.5 MHz, 1558.5-1559 MHz, 1646.5-1651 MHz and 1660-1660.5 MHz shall have priority access with real-time preemptive capability for communications in the mobile-satellite service. Systems not interoperable with the aeronautical mobile-satellite (R) service shall operate on a secondary basis. Account shall be taken of the priority of safety-related communications in the mobile-satellite service.

US309 In the bands 1545-1559 MHz, transmissions from terrestrial aeronautical stations directly to aircraft stations, or between aircraft stations, in the aeronautical mobile (R) service are also authorized when such transmissions are used to extend or supplement the satellite-to-aircraft links. In the band 1646.5-1660.5 MHz, transmissions from aircraft stations in the aeronautical mobile (R) service directly to terrestrial aeronautical stations, or between aircraft stations, are also authorized when such transmissions are used to extend or supplement the aircraft-to-satellite links.

US310 In the band 14.896-15.121 GHz, non-Federal space stations in the space research service may be authorized on a secondary basis to transmit to Tracking and Data Relay Satellites subject to such conditions as may be applied on a case-by-case basis. Such transmissions shall not cause harmful interference to authorized Federal stations. The power flux-density (pfd) produced by such non-Federal stations at the Earth's surface in any 1 MHz band for all conditions and methods of modulation shall not exceed:

-124 dB(W/m^2)	for $0° < \theta < 5°$
$-124 + (\theta-5)/2$ dB(W/m^2)	for $5° < \theta < 25°$
-114 dB(W/m^2)	for $25° < \theta < 90°$

where θ is the angle of arrival of the radio-frequency wave (degrees above the horizontal). These limits relate to the pfd and angles of arrival which would be obtained under free-space propagation conditions.

US312 The frequency 173.075 MHz may also be authorized on a primary basis to non-Federal stations in the Public Safety Radio Pool, limited to police licensees, for stolen vehicle recovery systems (SVRS). As of May 27, 2005, new SVRS licenses shall be issued for an authorized bandwidth not to exceed 12.5 kHz. Stations that operate as part of a stolen vehicle recovery system that was authorized and in operation prior to May 27, 2005 may operate with an authorized bandwidth not to exceed 20 kHz until May 27, 2019. After that date, all SVRS shall operate with an authorized bandwidth not to exceed 12.5 kHz.

US315 In the bands 1530-1544 MHz and 1626.5-1645.5 MHz, maritime mobile-satellite distress and safety communications, *e.g.*, GMDSS, shall have priority access with real-time preemptive capability in the mobile-satellite service. Communications of mobile-satellite system stations not participating in the GMDSS shall operate on a secondary basis to distress and safety communications of stations operating in the GMDSS. Account shall be taken of the priority of safety-related communications in the mobile-satellite service.

US316 The band 2900-3000 MHz is also allocated to the meteorological aids service on a primary basis for Federal use. Operations in this service are limited to Next Generation Weather Radar (NEXRAD) systems where accommodation in the band 2700-2900 MHz is not technically practical and are subject to coordination with existing authorized stations.

US319 In the bands 137-138 MHz, 148-149.9 MHz, 149.9-150.05 MHz, 399.9-400.05 MHz, 400.15-401 MHz, 1610-1626.5 MHz, and 2483.5-2500 MHz, Federal stations in the mobile-satellite service shall be limited to Earth stations operating with non-Federal space stations.

US320 The use of the bands 137-138 MHz, 148-150.05 MHz, 399.9-400.05 MHz, and 400.15-401 MHz by the mobile-satellite service is limited to non-voice, non-geostationary satellite systems and may include satellite links between land Earth stations at fixed locations.

US323 In the band 148-149.9 MHz, no individual mobile Earth station shall transmit on the same frequency being actively used by fixed and mobile stations and shall transmit no more than 1% of the time during any 15 minute period; except, individual mobile Earth stations in this band that do not avoid frequencies actively being used by the fixed and mobile services shall not exceed a power density of −16 dBW/4 kHz and shall transmit no more than 0.25% of the time during any 15 minute period. Any single transmission from any individual mobile Earth station operating in this band shall not exceed 450 ms in duration and consecutive transmissions from a single mobile Earth station on the same frequency shall be separated by at least 15 seconds. Land Earth stations in this band shall be subject to electromagnetic compatibility analysis and coordination with terrestrial fixed and mobile stations.

US324 In the band 400.15-401 MHz, Federal and non-Federal satellite systems shall be subject to electromagnetic compatibility analysis and coordination.

US325 In the band 148-149.9 MHz fixed and mobile stations shall not claim protection from land Earth stations in the mobile-satellite service that have been previously coordinated; Federal fixed and mobile stations exceeding 27 dBW EIRP, or an emission bandwidth greater than 38 kHz, will be coordinated with existing mobile-satellite service space stations.

US327 The band 2310-2360 MHz is allocated to the broadcasting-satellite service (sound) and complementary terrestrial broadcasting service on a primary basis. Such use is limited to digital audio broadcasting and is subject to the provisions of Resolution 528.

US334 In the bands between 17.7 GHz and 20.2 GHz, the following provisions shall apply:

(a) In the bands between 17.8 GHz and 20.2 GHz, Federal space stations in both geostationary (GSO) and non-geostationary satellite orbits (NGSO) and associated Earth stations in the fixed-satellite service (FSS) (space-to-Earth) may be authorized on a primary basis. For a Federal GSO FSS network to operate on a primary basis, the space station shall be located outside the arc, measured from east to west, 70-120° West longitude. Coordination between Federal FSS systems and non-Federal space and terrestrial systems operating in accordance with the United States Table of Frequency Allocations is required.

(b) In the bands between 17.8 GHz and 20.2 GHz, Federal Earth stations operating with Federal space stations shall be authorized on a primary basis only in the following areas: Denver, Colorado; Washington, DC; San Miguel, California; and Guam. Prior to the commencement of non-Federal terrestrial operations in these areas, the FCC shall coordinate with NTIA all applications for new stations and modifications to existing stations as specified in 47 CFR 1.924(f), 74.32, and 78.19(f). In the band 17.7-17.8 GHz, the FCC shall also coordinate with NTIA all applications for new stations and modifications to existing stations that support the operations of Multichannel Video Programming Distributors (MVPD) in these areas, as specified in the aforementioned regulations.

(c) In the bands between 17.8 GHz and 19.7 GHz, the power flux-density (pfd) at the surface of the Earth produced by emissions from a Federal GSO space station or from a Federal space station in a NGSO constellation of 50 or fewer satellites, for all conditions and for all methods of modulation, shall not exceed the following values in any 1 MHz band:

(1) -115 dB(W/m^2) for angles of arrival above the horizontal plane (δ) between 0° and 5°,
(2) $-115 + 0.5(\delta - 5)$ dB(W/m^2) for δ between 5° and 25°, and
(3) -105 dB(W/m^2) for δ between 25° and 90°.

(d) In the bands between 17.8 GHz and 19.3 GHz, the pfd at the surface of the Earth produced by emissions from a Federal space station in an NGSO constellation of 51 or more satellites, for all conditions and for all methods of modulation, shall not exceed the following values in any 1 MHz band:

(1) $-115 - X$ dB(W/m^2) for δ between 0° and 5°,

(2) $-115 - X + ((10 + X)/20)(\delta - 5)$ dB(W/m^2) for δ between 5° and 25°, and

(3) -105 dB(W/m^2) for δ between 25° and 90°; where X is defined as a function of the number of satellites, n, in an NGSO constellation as follows:

For $n \leq 288$, $X = (5/119)(n - 50)$ dB; and
For $n > 288$, $X = (1/69)(n + 402)$ dB.

US337 In the band 13.75-13.8 GHz, the FCC shall coordinate Earth stations in the fixed-satellite service with NTIA on a case-by-case basis in order to minimize harmful interference to the Tracking and Data Relay Satellite System's forward space-to-space link (TDRSS forward link-to-LEO).

US338A In the band 1435-1452 MHz, operators of aeronautical telemetry stations are encouraged to take all reasonable steps to ensure that the unwanted emissions power does not exceed -28 dBW/27 MHz in the band 1400-1427 MHz. Operators of aeronautical telemetry stations that do not meet this limit shall first attempt to operate in the band 1452-1525 MHz prior to operating in the band 1435-1452 MHz.

US340 The band 2-30 MHz is available on a non-interference basis to Federal and non-Federal maritime and aeronautical stations for the purposes of measuring the quality of reception on radio channels. See 47 CFR 87.149 for the list of protected frequencies and bands within this frequency range. Actual communications shall be limited to those frequencies specifically allocated to the maritime mobile and aeronautical mobile services.

US342 In making assignments to stations of other services to which the bands:

13360-13410 kHz
25550-25670 kHz
37.5-38.25 MHz
322-328.6 MHz*
1330-1400 MHz*
1610.6-1613.8 MHz*
1660-1660.5 MHz*
1668.4-1670 MHz*
3260-3267 MHz*
3332-3339 MHz*
3345.8-3352.5 MHz*
4825-4835 MHz*
4950-4990 MHz
6650-6675.2 MHz*
14.47-14.5 GHz*
22.01-22.21 GHz*
22.21-22.5 GHz
22.81-22.86 GHz*
23.07-23.12 GHz*
31.2-31.3 GHz
36.43-36.5 GHz*
42.5-43.5 GHz
42.77-42.87 GHz*
43.07-43.17 GHz*
43.37-43.47 GHz*
48.94-49.04 GHz*
76-86 GHz
92-94 GHz
94.1-100 GHz
102-109.5 GHz
111.8-114.25 GHz
128.33-128.59 GHz*
129.23-129.49 GHz*
130-134 GHz
136-148.5 GHz
151.5-158.5 GHz
168.59-168.93 GHz*
171.11-171.45 GHz*
172.31-172.65 GHz*
173.52-173.85 GHz*
195.75-196.15 GHz*
209-226 GHz
241-250 GHz
252-275 GHz

are allocated (*indicates radio astronomy use for spectral line observations), all practicable steps shall be taken to protect the radio astronomy service from harmful interference. Emissions from spaceborne or airborne stations can be particularly serious sources of interference to the radio astronomy service (*see* ITU *Radio Regulations* at Nos. 4.5 and 4.6 and Article 29).

US343 In the mobile service, the frequencies between 1435 and 1525 MHz will be assigned for aeronautical telemetry and associated telecommand operations for flight testing of manned or unmanned aircraft and missiles, or their major components. Permissible usage includes telemetry associated with launching and reentry into the Earth's atmosphere as well as any incidental orbiting prior to reentry of manned objects undergoing flight tests. The following frequencies are shared on a co-equal basis with flight telemetering mobile stations: 1444.5, 1453.5, 1501.5, 1515.5, and 1524.5 MHz.

US344 In the band 5091-5250 MHz, the FCC shall coordinate Earth stations in the fixed-satellite service (Earth-to-space) with NTIA (see Recommendation ITU-R S.1342). In order to better protect the operation of the international standard system (microwave landing system) in the band 5000-5091 MHz, non-Federal tracking and telecommand operations should be conducted in the band 5150-5250 MHz.

US346 Except as provided for below and by US222, Federal use of the band 2025-2110 MHz by the space operation service (Earth-to-space), Earth exploration-satellite service (Earth-to-space), and space research service (Earth-to-space) shall not constrain the deployment of the Television Broadcast Auxiliary Service, the Cable Television Relay Service, or the Local Television Transmission Service. To facilitate compatible operations between non-Federal terrestrial receiving stations at fixed sites and Federal Earth station transmitters, coordination is required. To facilitate compatible operations between non-Federal terrestrial transmitting stations and Federal spacecraft receivers, the terrestrial transmitters in the band 2025-2110 MHz shall not be high-density systems (see Recommendations ITU-R SA.1154 and ITU-R F.1247). Military satellite control stations at the following sites shall operate on a co-equal, primary basis with non-Federal operations:

Facility	Coordinates	
Naval Satellite Control Network, Prospect Harbor, ME	44° 24′ 16″ N	068° 00′ 46″ W
New Hampshire Tracking Station, New Boston AFS, NH	42° 56′ 52″ N	071° 37′ 36″ W
Eastern Vehicle Check-out Facility & GPS Ground Antenna & Monitoring Station, Cape Canaveral, FL	28° 29′ 09″ N	080° 34′ 33″ W
Buckley AFB, CO	39° 42′ 55″ N	104° 46′ 36″ W
Colorado Tracking Station, Schriever AFB, CO	38° 48′ 21″ N	104° 31′ 43″ W
Kirtland AFB, NM	34° 59′ 46″ N	106° 30′ 28″ W
Camp Parks Communications Annex, Pleasanton, CA	37° 43′ 51″ N	121° 52′ 50″ W
Naval Satellite Control Network, Laguna Peak, CA	34° 06′ 31″ N	119° 03′ 53″ W
Vandenberg Tracking Station, Vandenberg AFB, CA	34° 49′ 21″ N	120° 30′ 07″ W
Hawaii Tracking Station, Kaena Pt, Oahu, HI	21° 33′ 44″ N	158° 14′ 31″ W
Guam Tracking Stations, Anderson AFB, and Naval CTS, Guam	13° 36′ 54″ N	144° 51′ 18″ E

US347 In the band 2025-2110 MHz, non-Federal Earth-to-space and space-to-space transmissions may be authorized in the space research and Earth exploration-satellite services subject to such conditions as may be applied on a case-by-case basis. Such transmissions shall not cause harmful interference to Federal and non-Federal stations operating in accordance with the Table of Frequency Allocations.

US350 In the band 1427-1432 MHz, Federal use of the land mobile service and non-Federal use of the fixed and land mobile services is limited to telemetry and telecommand operations as described further:

(a) *Medical operations*. The use of the band 1427-1432 MHz for medical telemetry and telecommand operations (medical operations) shall be authorized for both Federal and non-Federal stations.

(1) Medical operations shall be authorized in the band 1427-1429.5 MHz in the United States and its insular areas, except in the following locations: Austin/Georgetown, Texas; Detroit and Battle Creek, Michigan; Pittsburgh, Pennsylvania; Richmond/Norfolk, Virginia; Spokane, Washington; and Washington DC metropolitan area (collectively, the “carved-out” locations). See Section 47 C.F.R. 90.259(b)(4) for a detailed description of these areas.

(2) In the carved-out locations, medical operations shall be authorized in the band 1429-1431.5 MHz.

(3) Medical operations may operate on frequencies in the band 1427-1432 MHz other than those described in paragraphs (a)(1) and (2) only if the operations were registered with a designated frequency coordinator prior to April 14, 2010.

(b) *Non-medical operations*. The use of the band 1427-1432 MHz for non-medical telemetry and telecommand operations (non-medical operations) shall be limited to non-Federal stations.

(1) Non-medical operations shall be authorized on a secondary basis to the Wireless Medical Telemetry Service (WMTS) in the band 1427-1429.5 MHz and on a primary basis in the band 1429.5-1432 MHz in the United States and its insular areas, except in the carved-out locations.

(2) In the carved-out locations, non-medical operations shall be authorized on a secondary basis in the band 1429-1431.5 MHz and on a primary basis in the bands 1427-1429 MHz and 1431.5-1432 MHz.

US353 In the bands 56.24-56.29 GHz, 58.422-58.472 GHz, 59.139-59.189 GHz, 59.566-59.616 GHz, 60.281-60.331 GHz, 60.41-60.46 GHz, and 62.461-62.511 GHz, space-based radio astronomy observations may be made on an unprotected basis.

US354 In the band 58.422-58.472 GHz, airborne stations and space stations in the space-to-Earth direction shall not be authorized.

US356 In the band 13.75-14 GHz, an Earth station in the fixed-satellite service shall have a minimum antenna diameter of 4.5 m and the e.i.r.p. of any emission should be at least 68 dBW and should not exceed 85 dBW. In addition the e.i.r.p., averaged over one second, radiated by a station in the radiolocation service shall not exceed 59 dBW. Receiving space stations in the fixed-satellite service shall not claim protection from radiolocation transmitting stations operating in accordance with the United States Table of Frequency Allocations. ITU Radio Regulation No. 5.43A does not apply.

US357 In the band 13.75-14 GHz, geostationary space stations in the space research service for which information for advance publication has been received by the ITU Radiocommunication Bureau (Bureau) prior to 31 January 1992 shall operate on an equal basis with stations in the fixed-satellite service; after that date, new geostationary space stations in the space research service will operate on a secondary basis. Until those geostationary space stations in the space research service for which information for advance publication has been received by the Bureau prior to 31 January 1992 cease to operate in this band:

a) the e.i.r.p. density of emissions from any Earth station in the fixed-satellite service operating with a space station in geostationary-satellite orbit shall not exceed 71 dBW in any 6 MHz band from 13.77 to 13.78 GHz;

b) the e.i.r.p. density of emissions from any Earth station in the fixed-satellite service operating with a space station in non-geostationary-satellite orbit shall not exceed 51 dBW in any 6 MHz band from 13.77 to 13.78 GHz.

Automatic power control may be used to increase the e.i.r.p. density in any 6 MHz band in these frequency ranges to compensate for rain attenuation, to the extent that the power flux-density at the fixed-satellite service space station does not exceed the value resulting from use by an Earth station of an e.i.r.p. of 71 dBW or 51 dBW, as appropriate, in any 6 MHz band in clear-sky conditions.

US359 In the band 15.43-15.63 GHz, use of the fixed-satellite service (Earth-to-space) is limited to non-Federal feeder links of non-geostationary systems in the mobile-satellite service. The FCC shall coordinate Earth stations in this band with NTIA (see Annex 3 of Recommendation ITU-R S.1340).

US360 The band 33-36 GHz is also allocated to the fixed-satellite service (space-to-Earth) on a primary basis for Federal use. Coordination between Federal fixed-satellite service systems and non-Federal systems operating in accordance with the United States Table of Frequency Allocations is required.

US362 The band 1670-1675 MHz is allocated to the meteorological-satellite service (space-to-Earth) on a primary basis for Federal use. Earth station use of this allocation is limited to Wallops Island, VA (37° 56′ 44″ N, 75° 27′ 37″ W), Fairbanks, AK (64° 58′ 22″ N, 147° 30′ 04″ W), and Greenbelt, MD (39° 00′ 02″ N, 76° 50′ 29″ W). Applicants for non-Federal stations within 100 kilometers of the Wallops Island or Fairbanks coordinates and within 65 kilometers of the Greenbelt coordinates shall notify NOAA in accordance with the procedures specified in 47 CFR 1.924.

US367 The band 5000-5150 MHz is also allocated to the aeronautical mobile-satellite (R) service on a primary basis, subject to agreement obtained under No. 9.21 of the ITU *Radio Regulations*.

US378 In the band 1710-1755 MHz, the following provisions apply:

(a) Federal fixed and tactical radio relay stations may operate indefinitely on a primary basis within 80 km of Cherry Point, NC (34° 58′ N, 76° 56′ W) and Yuma, AZ (32° 32′ N, 113° 58′ W).

(b) Federal fixed and tactical radio relay stations shall operate on a secondary basis to primary non-Federal operations at the 14 sites listed below:

State	Location	Coordinates
80 km radius of operation centered on:		
CA	China Lake	35° 41′ N 117° 41′ W
CA	Pacific Missile Test Range/Point Mugu	34° 07′ N 119° 30′ W
FL	Eglin AFB	30° 29′ N 086° 31′ W
MD	Patuxent River	38° 17′ N 076° 25′ W
NM	White Sands Missile Range	33° 00′ N 106° 30′ W
NV	Nellis AFB	36° 14′ N 115° 02′ W
UT	Hill AFB	41° 07′ N 111° 58′ W
50 km radius of operation centered on:		
AL	Fort Rucker	31° 13′ N 085° 49′ W
CA	Fort Irwin	35° 16′ N 116° 41′ W
GA	Fort Benning	32° 22′ N 084° 56′ W
GA	Fort Stewart	31° 52′ N 081° 37′ W
KY	Fort Campbell	36° 41′ N 087° 28′ W
NC	Fort Bragg	35° 09′ N 079° 01′ W
WA	Fort Lewis	47° 05′ N 122° 36′ W

(c) In the sub-band 1710-1720 MHz, precision guided munitions shall operate on a primary basis until inventory is exhausted or until December 31, 2008, whichever is earlier.

(d) All other Federal stations in the fixed and mobile services shall operate on a primary basis until reaccommodated in accordance with the Commercial Spectrum Enhancement Act.

US379 In the band 55.78-56.26 GHz, in order to protect stations in the Earth exploration-satellite service (passive), the maximum power density delivered by a transmitter to the antenna of a fixed service station is limited to –28.5 dB(W/MHz).

US380 In the bands 1525-1544 MHz, 1545-1559 MHz, 1610-1645.5 MHz, 1646.5-1660.5 MHz, and 2483.5-2500 MHz, a non-Federal licensee in the mobile-satellite service (MSS) may also operate an ancillary terrestrial component in conjunction with its MSS network, subject to the Commission's rules for ancillary terrestrial components and subject to all applicable conditions and provisions of its MSS authorization.

US382 In the band 39.5-40 GHz, Federal Earth stations in the mobile-satellite service (space-to-Earth) shall not claim protection from non-Federal stations in the fixed and mobile services. ITU Radio Regulation No. 5.43A does not apply.

US384 In the band 401-403 MHz, the non-Federal Earth exploration-satellite (Earth-to-space) and meteorological-satellite (Earth-to-space) services are limited to Earth stations transmitting to Federal space stations.

US385 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, and in the band 2655-2690 MHz on a secondary basis, at the following radio astronomy observatories:

Allen Telescope Array, Hat Creek, CA	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, CA	80 kilometers (50 mile) radius centered on 35° 20′ N, 116° 53′ W.	
National Astronomy and Ionosphere Center, Arecibo, PR	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, NM	Rectangle between latitudes 32° 30′ N and 35° 30′ N and between longitudes 106° 00′ W and 109° 00′ W.	
National Radio Astronomy Observatory, Green Bank, WV	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 kilometer radius centered on:	
	North latitude	West longitude
Brewster, WA	48° 08′	119° 41′
Fort Davis, TX	30° 38′	103° 57′
Hancock, NH	42° 56′	71° 59′
Kitt Peak, AZ	31° 57′	111° 37′
Los Alamos, NM	35° 47′	106° 15′
Mauna Kea, HI	19° 48′	155° 27′
North Liberty, IA	41° 46′	91° 34′
Owens Valley, CA	37° 14′	118° 17′
Pie Town, NM	34° 18′	108° 07′
Saint Croix, VI	17° 45′	64° 35′
Owens Valley Radio Observatory, Big Pine, CA	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.	

(a) 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.

(b) In the band 2655-2690 MHz, for radio astronomy observations performed at the locations listed above, licensees are urged to coordinate their systems through the Electromagnetic Spectrum Management Unit, Division of Astronomical Sciences, National Science Foundation, Room 1030, 4201 Wilson Blvd., Arlington, VA 22230.

US389 In the bands 71-76 GHz and 81-86 GHz, stations in the fixed, mobile, and broadcasting services shall not cause harmful interference to, nor claim protection from, Federal stations in the fixed-satellite service at any of the following 28 military installations:

Military Installation	State	Nearby city
Redstone Arsenal	AL	Huntsville
Fort Huachuca	AZ	Sierra Vista
Yuma Proving Ground	AZ	Yuma
Beale AFB	CA	Marysville
Camp Parks Reserve Forces Training Area	CA	Dublin
China Lake Naval Air Weapons Station	CA	Ridgecrest
Edwards AFB	CA	Rosamond
Fort Irwin	CA	Barstow
Marine Corps Air Ground Combat Center	CA	Twentynine Palms
Buckley AFB	CO	Aurora (Denver)
Schriever AFB	CO	Colorado Springs
Fort Gordon	GA	Augusta
Naval Satellite Operations Center	GU	Finegayan (Guam)
Naval Computer and Telecommunications Area Master Station, Pacific	HI	Wahiawa (Oahu Is.)
Fort Detrick	MD	Frederick
Nellis AFB	NV	Las Vegas
Nevada Test Site	NV	Amargosa Valley
Tonapah Test Range Airfield	NV	Tonapah
Cannon AFB	NM	Clovis
White Sands Missile Range	NM	White Sands
Dyess AFB	TX	Abilene
Fort Bliss	TX	El Paso
Fort Sam Houston	TX	San Antonio
Goodfellow AFB	TX	San Angelo
Kelly AFB	TX	San Antonio
Utah Test and Training Range	UT	…..
Fort Belvoir	VA	Alexandria
Naval Satellite Operations Center	VA	Chesapeake

US390 Federal stations in the space research service (active) operating in the band 5350-5460 MHz shall not cause harmful interference to, nor claim protection from, Federal and non-Federal stations in the aeronautical radionavigation service nor Federal stations in the radiolocation service.

US391 In the band 2495-2500 MHz, the mobile-satellite service (space-to-Earth) shall not receive protection from non-Federal stations in the fixed and mobile except aeronautical mobile services operating in that band.

US397 In the band 432-438 MHz, the Earth exploration-satellite service (active) is allocated on a secondary basis for Federal use. Stations in the Earth exploration-satellite service (active) shall not be operated within line-of-sight of the United States except for the purpose of short duration pre-operational testing. Operations under this allocation shall not cause harmful interference to, nor claim protection from, any other services allocated in the band 432-438 MHz in the United States, including secondary services and the amateur-satellite service.

US444 The frequency band 5030-5150 MHz is to be used for the operation of the international standard system (microwave landing system) for precision approach and landing. In the frequency band 5030-5091 MHz, the requirements of this system shall have priority over other uses of this band. For the use of the frequency band 5091-5150 MHz, US444A and Resolution 114 (Rev.WRC-12) of the ITU *Radio Regulations* apply.

US444A The band 5091-5150 MHz is also allocated to the fixed-satellite service (Earth-to-space) on a primary basis for non-Federal use. This allocation is limited to feeder links of non-geostationary satellite systems in the mobile-satellite service and is subject to coordination under No. 9.11A of the ITU *Radio Regulations*. In the band 5091-5150 MHz, the following conditions also apply:

(a) Prior to January 1, 2018, the use of the band 5091-5150 MHz by feeder links of non-geostationary-satellite systems in the mobile-satellite service shall be made in accordance with Resolution 114 (Rev. WRC-12);

(b) After January 1, 2016, no new assignments shall be made to Earth stations providing feeder links of non-geostationary mobile-satellite systems; and

(c) After January 1, 2018, the fixed-satellite service will become secondary to the aeronautical radionavigation service.

US444B In the band 5091-5150 MHz, the following provisions shall apply to the aeronautical mobile service:

(a) Use is restricted to: (1) Systems operating in the aeronautical mobile (R) service (AM(R)S) in accordance with international aeronautical standards, limited to surface applications at airports, and in accordance with Resolution 748 (Rev.WRC-12) (*i.e.*, AeroMACS); and (2) Aeronautical telemetry transmissions from aircraft stations (AMT) in accordance with Resolution 418 (Rev.WRC-12).

(b) Consistent with Radio Regulation No. 4.10, airport surface wireless systems operating in the AM(R)S have priority over AMT systems in the band.

(c) Operators of AM(R)S and AMT systems at the following airports are urged to cooperate with each other in the exchange of information about planned deployments of their respective systems so that the prospects for compatible sharing of the band are enhanced: 1) Boeing Field/King County Intl Airport, Seattle, WA; 2) Lambert-St. Louis Intl Airport, St. Louis, MO; 3) Charleston AFB/Intl Airport, Charleston, SC; 4) Wichita Dwight D. Eisenhower National Airport, Wichita, KS; 5) Roswell Intl Air Center Airport, Roswell, NM; and 6) William P. Gwinn Airport, Jupiter, FL. Other airports may be addressed on a case-by-case basis.

(d) Aeronautical fixed communications that are an integral part of the AeroMACS system authorized in paragraph (a)(1) are also authorized on a primary basis.

US475 The use of the band 9300-9500 MHz by the aeronautical radionavigation service is limited to airborne radars and associated airborne beacons. In addition, ground-based radar beacons in the aeronautical radionavigation service are permitted in the band 9300-9320 MHz on the condition that harmful interference is not caused to the maritime radionavigation service.

US476A In the band 9300-9500 MHz, Federal stations in the Earth exploration-satellite service (active) and space research service (active) shall not cause harmful interference to, nor claim protection from, stations of the radionavigation and Federal radiolocation services.

US482 In the band 10.6-10.68 GHz, the following provisions and urgings apply:

(a) Non-Federal use of the fixed service shall be restricted to point-to-point stations, with each station supplying not more than –3 dBW of transmitter power to the antenna, producing not more than 40 dBW of EIRP, and radiating at an antenna main beam elevation angle of 20° or less. Licensees holding a valid authorization on **[INSERT DATE 30 DAYS AFTER DATE OF PUBLICATION IN THE FEDERAL REGISTER]** to operate in this band may continue to operate as authorized, subject to proper license renewal.

(b) In order to minimize interference to the Earth exploration-satellite service (passive) receiving in this band, licensees of stations in the fixed service are urged to: (1) limit the maximum transmitter power supplied to the antenna to –15 dBW; and (2) employ automatic transmitter power control (ATPC). The maximum transmitter power supplied to the antenna of stations using ATPC may be increased by a value corresponding to the ATPC range, up to a maximum of –3 dBW.

US519 The band 18-18.3 GHz is also allocated to the meteorological-satellite service (space-to-Earth) on a primary basis. Its use is limited to geostationary satellites and shall be in accordance with the provisions of Article 21, Table 21-4 of the ITU *Radio Regulations*.

US532 In the bands 21.2-21.4 GHz, 22.21-22.5 GHz, and 56.26-58.2 GHz, the space research and Earth exploration-satellite services shall not receive protection from the fixed and mobile services operating in accordance with the Table of Frequency Allocations.

US550A In the band 36-37 GHz, the following provisions shall apply:

(a) For stations in the mobile service, the transmitter power supplied to the antenna shall not exceed –10 dBW, except that the maximum transmitter power may be increased to –3 dBW for stations used for public safety and disaster management.

(b) For stations in the fixed service, the elevation angle of the antenna main beam shall not exceed 20° and the transmitter power supplied to the antenna shall not exceed:

(1) –5 dBW for hub stations of point-to-multipoint systems; or

(2) –10 dBW for all other stations, except that the maximum transmitter power of stations using automatic transmitter power control (ATPC) may be increased by a value corresponding to the ATPC range, up to a maximum of –7 dBW.

US565 The frequency band 275-1000 GHz may be used by administrations for experimentation with, and development of, various active and passive services. In this band a need has been identified for the following spectral line measurements for passive services:

— radio astronomy service: 275-323 GHz, 327-371 GHz, 388-424 GHz, 426-442 GHz, 453-510 GHz, 623-711 GHz, 795-909 GHz and 926-945 GHz;

— Earth exploration-satellite service (passive) and space research service (passive): 275-277 GHz, 294-306 GHz, 316-334 GHz, 342-349 GHz, 363-365 GHz, 371-389 GHz, 416-434 GHz, 442-444 GHz, 496-506 GHz, 546-568 GHz, 624-629 GHz, 634-654 GHz, 659-661 GHz, 684-692 GHz, 730-732 GHz, 851-853 GHz and 951-956 GHz.

Future research in this largely unexplored spectral region may yield additional spectral lines and continuum bands of interest to the passive services. Administrations are urged to take all practicable steps to protect these passive services from harmful interference until the date when the allocation Table is established in the above-mentioned frequency band.

NON-FEDERAL GOVERNMENT (NG) FOOTNOTES

These footnotes, each consisting of the letters ''NG'' followed by one or more digits, denote stipulations applicable only to non-Federal operations and thus appear solely in the non-Federal Table.

NG3 Control stations in the domestic public mobile radio service may be authorized frequencies in the band 72-73 and 75.4-76 MHz on the condition that harmful interference will not be caused to operational fixed stations.

NG4 The use of the frequencies in the band 152.84-153.38 MHz may be authorized, in any area, to remote pickup broadcast base and mobile stations on the condition that harmful interference will not be caused to stations operating in accordance with the Table of Frequency Allocations.

NG5 In the band 535-1705 kHz, AM broadcast licensees and permittees may use their AM carrier on a secondary basis to transmit signals intended for both broadcast and non-broadcast purposes. In the band 88-108 MHz, FM broadcast licensees and permittees are permitted to use subcarriers on a secondary basis to transmit signals intended for both broadcast and non-broadcast purposes. In the bands 54-72, 76-88, 174-216, 470-608, and 614-698 MHz, TV broadcast licensees and permittees are permitted to use subcarriers on a secondary basis for both broadcast and non-broadcast purposes.

NG7 In the bands 2000-2065, 2107-2170, and 2194-2495 kHz, fixed stations associated with the maritime mobile service may be authorized, for purposes of communication with coast stations, to use frequencies assignable to ship stations in these bands on the condition that harmful interference will not be caused to services operating in accordance with the Table of Frequency Allocations. *See* 47 CFR 80.371(a) for the list of available carrier frequencies.

NG14 TV broadcast stations authorized to operate in the bands 54-72, 76-88, 174-216, 470-608, and 614-698 MHz may use a portion of the television vertical blanking interval for the transmission of telecommunications signals, on the condition that harmful interference will not be caused to the reception of primary services, and that such telecommunications services must accept any interference caused by primary services operating in these bands.

on a secondary basis to AWS.

NG49 The following frequencies may be authorized for mobile operations in the Manufacturers Radio Service subject to the condition that no interference is caused to the reception of television stations operating on channels 4 and 5 and that their use is limited to a manufacturing facility:

MHz				
72.02	72.10	72.18	72.26	72.34
72.04	72.12	72.20	72.28	72.36
72.06	72.14	72.22	72.30	72.38
72.08	72.16	72.24	72.32	72.40

Further, the following frequencies may be authorized for mobile operations in the Special Industrial Radio Service, Manufacturers Radio Service, Railroad Radio Service and Forest Products Radio Service subject to the condition that no interference is caused to the reception of television stations operating on channels 4 and 5; and that their use is limited to a railroad yard, manufacturing plant, logging site, mill, or similar industrial facility.

MHz				
72.44	72.52	72.60	75.48	75.56
72.48	72.56	75.44	75.52	75.60

NG50 In the band 10-10.5 GHz, non-Federal stations in the radiolocation service shall not cause harmful interference to the amateur service; and in the sub-band 10.45-10.5 GHz, these stations shall not cause harmful interference to the amateur-satellite service.

NG51 In Puerto Rico and the United States Virgin Islands, the use of band 150.8-151.49 MHz by the fixed and land mobile services is limited to stations in the Industrial/Business Pool.

NG52 Except as otherwise provided for herein, use of the bands 10.7-11.7 GHz (space-to-Earth) and 12.75-13.25 GHz (Earth-to-space) by geostationary satellites in the fixed-satellite service (FSS) shall be limited to international systems, *i.e.*, other than domestic systems. In the sub-bands 10.95-11.2 GHz and 11.45-11.7 GHz, Earth Stations on Vessels (ESV), Vehicle-Mounted Earth Stations (VMES), and Earth Stations Aboard Aircraft (ESAA) as regulated under 47 CFR part 25 may be authorized for the reception of FSS emissions from geostationary satellites, subject to the condition that these Earth stations shall not claim protection from transmissions of non-Federal stations in the fixed service.

NG53 In the band 13.15-13.25 GHz, the following provisions shall apply:

(a) The sub-band 13.15-13.2 GHz is reserved for television pickup (TVPU) and cable television relay service (CARS) pickup stations inside a 50 km radius of the 100 television markets delineated in 47 CFR 76.51; and outside these areas, TVPU stations, CARS stations and non-geostationary satellite orbit fixed-satellite service (NGSO FSS) gateway Earth stations shall operate on a co-primary basis.

(b) The sub-band 13.2-13.2125 GHz is reserved for TVPU stations on a primary basis and for CARS pickup stations on a secondary basis inside a 50 km radius of the 100 television markets delineated in 47 CFR 76.51; and outside these areas, TVPU stations and NGSO FSS gateway Earth stations shall operate on a co-primary basis and CARS stations shall operate on a secondary basis.

(c) In the band 13.15-13.25 GHz, fixed television auxiliary stations licensed pursuant to applications accepted for filing before September 1, 1979, may continue operation, subject to periodic license renewals.

(d) In the sub-band 13.15-13.2125 GHz, NGSO FSS gateway uplink transmissions shall be limited to a maximum e.i.r.p. of 3.2 dBW towards 0° on the radio horizon.

NOTE: The above provisions shall not apply to geostationary satellite orbit (GSO) FSS operations in the band 12.75-13.25 GHz.

NG55 In the bands 11.7-12.2 GHz (space-to-Earth) and 14.0-14.5 GHz (Earth-to-space), Earth Stations on Vessels (ESV), Vehicle-Mounted Earth Stations (VMES), and Earth Stations Aboard Aircraft (ESAA) as regulated under 47 CFR part 25 are applications of the fixed-satellite service and may be authorized to communicate with geostationary satellites in the fixed-satellite service on a primary basis.

NG56 In the bands 72-73 and 75.4-76 MHz, the use of mobile radio remote control of models is on a secondary basis to all other fixed and mobile operations. Such operations are subject to the condition that interference will not be caused to common carrier domestic public stations, to remote control of industrial equipment operating in the band 72-76 MHz, or to the reception of television signals on channels 4 (66-72 MHz) or 5 (76-82 MHz). Television interference shall be considered to occur whenever reception of regularly used television signals is impaired or destroyed, regardless of the strength of the television signal or the distance to the television station.

NG59 The frequencies 37.60 and 37.85 MHz may be authorized only for use by base, mobile, and operational fixed stations participating in an interconnected or coordinated power service utility system.

NG60 In the band 31-31.3 GHz, for stations in the fixed service authorized after **[INSERT DATE 30 DAYS AFTER DATE OF PUBLICATION IN THE FEDERAL REGISTER, PLUS 36 MONTHS**], the unwanted emissions power in any 100 MHz of the 31.3-31.5 GHz Earth exploration-satellite service (passive) band shall be limited to –38 dBW (–38 dBW/100 MHz), as measured at the input to the antenna.

NG112 The frequencies 25.04, 25.08, 150.980, 154.585, 158.445, 159.480, 454.000 and 459.000 MHz may be authorized to stations in the Industrial/Business Pool for use primarily in oil spill containment and cleanup operations and secondarily in regular land mobile communication.

NG115 In the bands 54-72 MHz, 76-88 MHz, 174-216 MHz, 470-608 MHz, and 614-698 MHz, wireless microphones and wireless assist video devices may be authorized on a non-interference basis, subject to the terms and conditions set forth in 47 CFR part 74, subpart H.

NG118 In the bands 2025-2110 MHz, 6875-7125 MHz, and 12.7-13.25 GHz, television translator relay stations may be authorized to use frequencies on a secondary basis to other stations in the Television Broadcast Auxiliary Service that are operating in accordance with the Table of Frequency Allocations.

NG124 In the bands 30.85-34, 37-38, 39-40, 42-47.41, 150.995-156.25, 158.715-159.465, 453.0125-453.9875, 458.0125-458.9875, 460.0125-465.6375, and 467.9375-467.9875 MHz, police licensees are authorized to operate low power transmitters on a secondary basis in accordance with the provisions of 47 CFR 2.803 and 90.20(e)(5).

NG147 In the band 2483.5-2500 MHz, non-Federal stations in the fixed and mobile services that are licensed under 47 CFR parts 74, 90, or 101, which were licensed as of July 25, 1985, and those whose initial applications were filed on or before July 25, 1985, may continue to operate on a primary basis with the mobile-satellite and radiodetermination-satellite services, and in the sub-band 2495-2500 MHz, these grandfathered stations may also continue to operate on a primary basis with stations in the fixed and mobile except aeronautical mobile services that are licensed under 47 CFR part 27.

NG149 The bands 54-72 MHz, 76-88 MHz, 174-216 MHz, 470-512 MHz, 512-608 MHz, and 614-698 MHz are also allocated to the fixed service to permit subscription television operations in accordance with 47 CFR part 73.

NG152 The use of the band 219-220 MHz by the amateur service is limited to stations participating, as forwarding stations, in point-to-point fixed digital message forwarding systems, including intercity packet backbone networks.

NG164 The use of the band 18.3-18.8 GHz by the fixed-satellite service (space-to-Earth) is limited to systems in the geostationary-satellite orbit.

NG171 In the band 6875-7125 MHz, the following two channels should be used for airborne TV pickup stations, wherever possible: 7075-7100 MHz and 7100-7125 MHz.

NG172 In the band 7025-7075 MHz, the fixed-satellite service (space-to-Earth) is allocated on a primary basis, but the use of this allocation shall be limited to two grandfathered satellite systems. Associated Earth stations located within 300 meters of the following locations shall be grandfathered: (a) In the band 7025-7075 MHz, Brewster, WA (48° 08′ 46.7″ N, 119° 42′ 8.0″ W); and (b) In the sub-band 7025-7055 MHz, Clifton, TX (31° 47′ 58.5″ N, 97° 36′ 46.7″ W) and Finca Pascual, PR (17° 58′ 41.8″ N, 67° 8′ 12.6″ W).

NG173 In the band 216-220 MHz, secondary telemetry operations are permitted subject to the requirements of 47 CFR 90.259. After January 1, 2002, no new assignments shall be authorized in the sub-band 216-217 MHz.

NG175 In the band 38.6-40 GHz, television pickup stations that were authorized on or before April 16, 2003, may continue to operate on a secondary basis to stations operating in accordance with the Table of Frequency Allocations.

NG338A In the bands 1390-1395 MHz and 1427-1435 MHz, licensees are encouraged to take all reasonable steps to ensure that unwanted emissions power does not exceed the following levels in the band 1400-1427 MHz:

(a) For stations of point-to-point systems in the fixed service: –45 dBW/27 MHz.

(b) For stations in the mobile service (except for devices authorized by the FCC for the Wireless Medical Telemetry Service): –60 dBW/27 MHz.

FEDERAL GOVERNMENT (G) FOOTNOTES

(These footnotes, each consisting of the letter ‘‘G’’ followed by one or more digits, denote stipulations applicable only to Federal operations and thus appear solely in the Federal Table.)

G2 In the bands 216.965-216.995 MHz, 420-450 MHz (except as provided for in G129), 890-902 MHz, 928-942 MHz, 1300-1390 MHz, 2310-2390 MHz, 2417-2450 MHz, 2700-2900 MHz, 3300-3500 MHz (except as provided for in US108), 5650-5925 MHz, and 9000-9200 MHz, use of the Federal radiolocation service is restricted to the military services.

G5 In the bands 162.0125-173.2, 173.4-174, 406.1-410 and 410-420 MHz, use by the military services is limited by the provisions specified in the channeling plans shown in Sections 4.3.7 and 4.3.9 of the NTIA Manual.

G6 Military tactical fixed and mobile operations may be conducted nationally on a secondary basis: (a) To the meteorological aids service in the band 403-406 MHz; and (b) 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.

G8 Low power Federal radio control operations are permitted in the band 420-450 MHz.

G15 Use of the band 2700-2900 MHz by the military fixed and shipborne air defense radiolocation installations will be fully coordinated with the meteorological aids and aeronautical radionavigation services. The military air defense installations will be moved from the band 2700-2900 MHz at the earliest practicable date. Until such time as military air defense installations can be accommodated satisfactorily elsewhere in the spectrum, such operations will, insofar as practicable, be adjusted to meet the requirements of the aeronautical radionavigation service.

G27 In the bands 225-328.6 MHz, 335.4-399.9 MHz, and 1350-1390 MHz, the fixed and mobile services are limited to the military services.

G30 In the bands 138-144 MHz, 148-149.9 MHz, and 150.05-150.8 MHz, the fixed and mobile services are limited primarily to operations by the military services.

G32 Except for weather radars on meteorological satellites in the band 9975-10025 MHz and for Federal survey operations (see footnote US108), Federal radiolocation in the band 10-10.5 GHz is limited to the military services.

G34 In the band 34.4-34.5 GHz, weather radars on board meteorological satellites for cloud detection are authorized to operate on the basis of equality with military radiolocation devices. All other non-military radiolocation in the band 33.4-36.0 GHz shall be secondary to the military services.

G42 The space operation service (Earth-to-space) is limited to the band 1761-1842 MHz, and is limited to space command, control, range and range rate systems.

G56 Federal radiolocation in the bands 1215-1300, 2900-3100, 5350-5650 and 9300-9500 MHz is primarily for the military services; however, limited secondary use is permitted by other Federal agencies in support of experimentation and research programs. In addition, limited secondary use is permitted for survey operations in the band 2900-3100 MHz.

G59 In the bands 902-928 MHz, 3100-3300 MHz, 3500-3650 MHz, 5250-5350 MHz, 8500-9000 MHz, 9200-9300 MHz, 13.4-14.0 GHz, 15.7-17.7 GHz and 24.05-24.25 GHz, all Federal non-military radiolocation shall be secondary to military radiolocation, except in the sub-band 15.7-16.2 GHz airport surface detection equipment (ASDE) is permitted on a co-equal basis subject to coordination with the military departments.

G100 The bands 235-322 MHz and 335.4-399.9 MHz are also allocated on a primary basis to the mobile-satellite service, limited to military operations.

G104 In the bands 7450-7550 and 8175-8215 MHz, it is agreed that although the military space radio communication systems, which include Earth stations near the proposed meteorological-satellite installations will precede the meteorological-satellite installations, engineering adjustments to either the military or the meteorological-satellite systems or both will be made as mutually required to assure compatible operations of the systems concerned.

G114 The band 1369.05-1390 MHz is also allocated to the fixed-satellite service (space-to-Earth) and to the mobile-satellite service (space-to-Earth) on a primary basis for the relay of nuclear burst data.

G115 In the band 13360-13410 kHz, the fixed service is allocated on a primary basis outside the conterminous United States. Within the conterminous United States, assignments in the fixed service are permitted, and will be protected for national defense purposes or, if they are to be used only in an emergency jeopardizing life, public safety, or important property under conditions calling for immediate communication where other means of communication do not exist.

G116 The band 7125-7155 MHz is also allocated for Earth-to-space transmissions in the Space Operations Service at a limited number of sites (not to exceed two), subject to established coordination procedures.

G117 In the bands 7.25-7.75 GHz, 7.9-8.4 GHz, 17.375-17.475 GHz, 17.6-21.2 GHz, 30-31 GHz, 33-36 GHz, 39.5-41 GHz, 43.5-45.5 GHz and 50.4-51.4 GHz, the Federal fixed-satellite and mobile-satellite services are limited to military systems.

G122 In the bands 2300-2310 MHz, 2395-2400 MHz, 2400-2417 MHz, and 4940-4990 MHz, Federal operations may be authorized on a non-interference basis to authorized non-Federal operations, and shall not constrain the implementation of any non-Federal operations.

G128 Use of the band 56.9-57 GHz by inter-satellite systems is limited to transmissions between satellites in geostationary orbit, to transmissions between satellites in geostationary satellite orbit and those in high-Earth orbit, to transmissions from satellites in geostationary satellite orbit to those in low-Earth orbit, and to transmissions from non-geostationary satellites in high-Earth orbit to those in low-Earth orbit. For links between satellites in the geostationary satellite orbit, the single entry power flux-density at all altitudes from 0 km to 1000 km above the Earth's surface, for all conditions and for all methods of modulation, shall not exceed –147 dB (W/m^2/100 MHz) for all angles of arrival.

G129 Federal wind profilers are authorized to operate on a primary basis in the radiolocation service in the frequency band 448-450 MHz with an authorized bandwidth of no more than 2 MHz centered on 449 MHz, subject to the following conditions: 1) wind profiler locations must be pre-coordinated with the military services to protect fixed military radars; and 2) wind profiler operations shall not cause harmful interference to, nor claim protection from, military mobile radiolocation stations that are engaged in critical national defense operations.

G130 Federal stations in the radiolocation service operating in the band 5350-5470 MHz, shall not cause harmful interference to, nor claim protection from, Federal stations in the aeronautical radionavigation service operating in accordance with ITU Radio Regulation No. 5.449.

G131 Federal stations in the radiolocation service operating in the band 5470-5650 MHz, with the exception of ground-based radars used for meteorological purposes operating in the band 5600-5650 MHz, shall not cause harmful interference to, nor claim protection from, Federal stations in the maritime radionavigation service.

G132 Use of the radionavigation-satellite service in the band 1215-1240 MHz shall be subject to the condition that no harmful interference is caused to, and no protection is claimed from, the radionavigation service authorized under ITU Radio Regulation No. 5.331. Furthermore, the use of the radionavigation-satellite service in the band 1215-1240 MHz shall be subject to the condition that no harmful interference is caused to the radiolocation service. ITU Radio Regulation No. 5.43 shall not apply in respect of the radiolocation service. ITU Resolution 608 (WRC-03) shall apply.

G133 In the band 7190-7235 MHz, emissions to deep space are prohibited. Geostationary satellites in the space research service operating in the band 7190-7235 MHz shall not claim protection from existing and future stations in the fixed service and ITU Radio Regulation No. 5.43A does not apply.

G134 In the band 7190-7235 MHz, Federal Earth stations operating in the meteorological-satellite service (Earth-to-space) may be authorized subject to the following conditions:

(a) Earth stations are limited to those communicating with the Department of Commerce Geostationary Operational Environmental Satellites (GOES).

(b) There shall not be more than five Earth stations authorized at one time.

(c) The GOES satellite receiver shall not claim protection from existing and future stations in the fixed service (ITU Radio Regulation No. 5.43A does not apply).

Appendixes

A

Definitions of Terms

The following National Telecommunications and Information Administration definitions are taken from the International Telecommunication Union (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 that 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, for example, type of modulation of the main carrier, modulating signal, type of information to be transmitted, and also if appropriate, any additional signal characteristics. (RR).

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[1] NOTE: The definitions in this appendix are reprinted from the National Telecommunications and Information Administration’s *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 June 17, 2015.

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

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 halfwave dipole in a given direction. (RR)

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 that endangers the functioning of a radio-navigation service or of other safety services or seriously degrades, obstructs, or repeatedly interrupts a radiocommunication 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 radiocommunication system, manifested by any performance degradation, misinterpretation, or loss of information that 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 that 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 $\beta/2$ 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 $\beta/2$ should be taken as 0.5%. (RR)

Out-of-band Emission: Emission on a frequency or frequencies immediately outside the necessary bandwidth that 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 that 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);
- 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 that 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: A combination of both spurious 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.

B

IEEE Standard Letter Designations for Radar Bands

The remote sensing community regularly uses letter designations for frequency bands whose origins can be traced back to the U.S. military during World War II. These designations were used to keep the frequencies of radar operations a secret throughout the war and afterward. This secrecy ended and some degree of global standardization was achieved during the International Telecommunication Union (ITU) meeting of 1959 in Geneva. The Institute of Electrical and Electronics Engineers (IEEE) has been maintaining the Standard Letter Designations for radar-frequency bands since 1976, which were revised most recently in 2002 (see Table B.1). The letter designations are assigned to frequency bands that are spaced at intervals of about an octave within the frequency range from 3 MHz to 300 GHz. Table B.1 also provides the comparison of the IEEE Letter Designations with the ITU bands and their nomenclature.

TABLE B.1 IEEE Standard Letter Designations for Radar Bands Used by the EESS Community and Their Comparison to the ITU Allocations

<table>
<tr><th colspan="5">International Table</th></tr>
<tr><th rowspan="2">Band Designation</th><th rowspan="2">Nominal Frequency Range</th><th colspan="3">Specific Frequency Ranges for Radar Based on ITU Assignments (see Notes 1, 2)</th></tr>
<tr><th>Region 1</th><th>Region 2</th><th>Region 3</th></tr>
<tr><td>HF</td><td>3-30 MHz</td><td colspan="3">(Note 3)</td></tr>
<tr><td>VHF</td><td>30-300 MHz</td><td>None</td><td>138-144 MHz
216-225 MHz
(See Note 4)</td><td>223-230 MHz</td></tr>
<tr><td>UHF</td><td>300-1000 MHz
(Note 5)</td><td colspan="3">420-450 MHz (Note 4)
890-942 MHz (Note 6)</td></tr>
<tr><td>L</td><td>1-2 GHz</td><td colspan="3">1215-1400 MHz</td></tr>
<tr><td rowspan="2">S</td><td rowspan="2">2-4 GHz</td><td colspan="3">2300-2500 MHz</td></tr>
<tr><td>2700-3600 MHz</td><td colspan="2">2700-3700 MHz</td></tr>
<tr><td rowspan="2">C</td><td rowspan="2">4-8 GHz</td><td colspan="3">4200-4400 MHz (Note 7)</td></tr>
<tr><td>5250-5850 MHz</td><td colspan="2">5250-5925 MHz</td></tr>
<tr><td>X</td><td>8-12 GHz</td><td colspan="3">8.5-10.68 GHz</td></tr>
<tr><td rowspan="2">Ku</td><td rowspan="2">12-18 GHz</td><td colspan="3">13.4-14 GHz</td></tr>
<tr><td colspan="3">15.7-17.7 GHz</td></tr>
<tr><td>K</td><td>18-27 GHz</td><td>24.05-24.25 GHz</td><td>24.05-24.25 GHz
24.65-24.75 GHz
(Note 8)</td><td>24.05-24.25 GHz</td></tr>
<tr><td>Ka</td><td>27-40 GHz</td><td colspan="3">33.4-36 GHz</td></tr>
<tr><td>V</td><td>40-75 GHz</td><td colspan="3">59-64 GHz</td></tr>
<tr><td rowspan="2">W</td><td rowspan="2">75-110 GHz</td><td colspan="3">76-81 GHz</td></tr>
<tr><td colspan="3">92-100 GHz</td></tr>
<tr><td rowspan="3">mm
(Note 9)</td><td rowspan="3">110-300 GHz</td><td colspan="3">126-142 GHz</td></tr>
<tr><td colspan="3">144-149 GHz</td></tr>
<tr><td colspan="3">231-235 GHz
238-248 GHz
(Note 10)</td></tr>
</table>

NOTES:

1. These International Telecommunication Union (ITU) frequency allocations are from the table contained in Article S5 of the ITU Radio Regulations, 2002 edition, reaffirmed in 2009 (see https://standards.ieee.org/findstds/standard/521-2002.html). The ITU defines no specific service for radar, and the frequency assignments listed are derived from those radio services that use radiolocation. The frequency allocations listed include those for both primary and secondary service. The listings of frequency assignments are included for reference only and are subject to change.
2. The specific frequency ranges for radiolocation are listed in the National Telecommunications and Information Administration (NTIA) *Manual of Regulations & Procedures for Federal Radio Frequency Management*, Chapter 4. The NTIA manual (known as the Redbook) can be downloaded from http://www.ntia.doc.gov/osmhome/redbook/redbook.html.
3. There are no official ITU radiolocation bands at HF. So-called HF radars might operate anywhere from just above the broadcast band (1.605 MHz) to 40 MHz or higher.
4. Frequencies from 216-450 MHz were sometimes called P-band.
5. The official ITU designation for the ultra high frequency band extends to 3000 MHz. In radar practice, however, the upper limit is usually taken as 1000 MHz, L- and S-bands being used to describe the higher UHF region.

6. Sometimes included in L-band.
7. Designated for aeronautical navigation, this band is reserved (with few exceptions) exclusively for airborne radar altimeters.
8. The frequency range of 24.65-24.75 GHz includes satellite radiolocation (Earth to space only).
9. The designation mm is derived from millimeter wave radar and is also used to refer to V- and W-bands, and part of Ka-band, when general information relating to the region above 30 GHz is to be conveyed.
10. No ITU allocations are listed for frequencies above 275 GHz.

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) reviews carefully 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 (IUCAF) 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 suggested minimum band limits are Doppler-shifted frequencies corresponding to radial velocities of ±300 km/s, consistent with line radiation occurring in our Milky Way galaxy. Spectral lines with primary (P), secondary (S), or footnote (F) protection status are noted in Table C.1.

TABLE C.1 The Most Important Spectral Lines Below 300 GHz

Species	Formula	Frequency (GHz)	Suggested Minimum Band (GHz)	Band Allocation Status	Notes (1)
Deuterium	DI	0.327384	0.327-0.3277	P	
Hydrogen	HI	1.420406	1.370-1.427	S 1.33-1.40 P 1.40-1.427	2, 3
Hydroxyl radical	OH	1.612231 1.665402 1.667359	1.6068-1.6138 1.6598-1.6671 1.6618-1.6690	P 1.6106-1.6138 P 1.66-1.67	4 4 4
Hydroxyl radical	OH	1.720530	1.7148-1.7222	S 1.7188-1.7222	3, 4
Methyladyne	CH	3.263794 3.335481 3.349193	3.2424-3.2671 3.3244-3.3388 3.3380-3.3525	S 3.260-3.267 S 3.332-3.339 S 3.3458-3.3525	3, 4 3, 4 3, 4
Formaldehyde	H_2CO	4.829660	4.8136-4.8345	S 4.8-4.9	3, 4
Methanol	CH_3OH	6.668518	6.6618-6.6752	S 6.650-6.6752	3
Helium	$^3He^+$	8.665650	8.6570-8.6743		3, 6
Methanol	CH_3OH	12.178	12.17-12.19		3, 6
Formaldehyde	H_2CO	14.488	14.44-14.50	S 14.47-14.50	3, 4
Cyclopropenylidene	C_3H_2	18.343	18.28-18.36		3, 4, 6
Water vapor	H_2O	22.235	22.16-22.26	F 22.01-22.21 P 22.21-22.50	3, 4
Ammonia	NH_3	23.694 23.723 23.870	23.61-23.71 23.64-23.74 23.79-23.89	P 23.60-24.00	4 4 4
Sulphur monoxide	SO	30.002	29.97-30.03		6
Methanol	CH_3OH	36.169	36.13-36.21	P 36-37	6
Silicon monoxide	SiO	42.519 42.821 43.122 43.424	42.47-42.57 42.78-42.86 43.08-43.17 43.38-43.47	F 42.77-42.87 F 43.07-43.17 F 43.37-43.47	6, 8
Dicarbon monosulphide	CCS	45.379	45.33-45.42		6
Carbon monosulphide	CS	48.991	48.94-49.04	P 48.94-49.04	
Oxygen	O_2	61.1	56.21-63.06	P 58.2-59.0	5, 6, 7
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	87.21-87.39	P	5
Hydrogen cyanide	HCN	88.632	88.34-88.72	P	4
Formylium	HCO^{++}	89.189	88.89-89.28	P	4
Hydrogen isocyanide	HNC	90.664	90.57-90.75	P	

continued

TABLE C.1 Continued

Species	Formula	Frequency (GHz)	Suggested Minimum Band (GHz)	Band Allocation Status	Notes (1)
Diazenylium	N_2H^+	93.174	93.08-93.27		
Carbon monosulphide	CS	97.981	97.65-98.08		4
Sulfur monoxide	SO	99.300	99.20-99.40		
Methyl acetylene	CH_3CCH	102.5	102.39-102.60		5
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	110.83-110.31	P	4
Carbon monoxide	$C^{17}O$	112.359	112.25-112.47	P	6
Cyano radical	CN	113.500	113.39-113.61	P	5
Carbon monoxide	CO	115.271	114.88-115.39	P	4
Oxygen	O_2	118.750	118.63-118.87	P 116-126	7
Formaldehyde	$H_2{}^{13}CO$	137.450	137.31-137.59		6
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	5
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	219.67-220.62	P	4
Cyano radical	CN	226.600	226.37-226.83	P	5
Cyano radical	CN	226.800	226.57-227.03	P	5
Carbon monoxide	CO	230.538	229.77-230.77	P	4
Carbon monosulphide	CS	244.953	244.14-245.20		6
Nitric oxide	NO	250.6	250.35-250.85	P	5
Ethynyl radical	C_2H	262.000	261.74-262.26		5
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		
Diazenylium	N_2H^+	279.511	279.23-279.79		
Carbon monosulphide	CS	293.912	292.93-294.21		

NOTES:

1. If Notes 2 or 4 are not listed, then the band limits are the Doppler-shifted frequencies corresponding to radial velocities of ± 300 km/s (consistent with line radiation occurring in our Milky Way galaxy).
2. An extension to lower frequency of the allocation of 1 400-1 427 MHz is required to allow for the higher Doppler shifts for HI observed in distant galaxies.
3. The current international allocation is not primary and/or does not meet bandwidth requirements. See the Radio Regulations (RR) for more detailed information.

4. Because these line frequencies are also being used for observing other galaxies, the listed bandwidths include Doppler shifts corresponding to radial velocities of up to 1,000 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%.
5. There are several closely spaced lines associated with these molecules. The listed bands are wide enough to permit observations of all lines.
6. This line frequency is not mentioned in RR Article 5.
7. These lines are observable only outside the atmosphere.
8. A portion of the "suggested minimum band" for this line extends outside the band allocated to the radio astronomy service. Protection for observations conducted in this portion of the band may not be practicable.

SOURCE: Data and further information can be found in the International Telecommunication Union, *RA 314 Series: Preferred Frequency Bands for Radio Astronomical Measurements*, June 2003, http://www.itu.int/dms_pubrec/itu-r/rec/ra/R-REC-RA.314-10-200306-I!!PDF-E.pdf.

D

International Astronomical Union Spectral Lines of Most Importance Between 300 and 1000 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 (IUCAF) 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 between 300-1000 GHz are listed in Table D.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 our Milky Way galaxy. Although no formal frequency allocations are established above 275 GHz, the International Telecommunication Union (ITU) Radio Regulation 5.565 urges administrations to take all practicable steps to protect passive services from harmful interference in the frequency range of 275-1000 GHz. Of particular note are the following frequency bands, which are identified for passive use by the Radio Astronomy Service: 275-323 GHz, 327-371 GHz, 388-424 GHz, 426-442 GHz, 453510 GHz, 623-711 GHz, 795-909 GHz, and 926-945 GHz. These frequency bands correspond to atmospheric “windows” (see Figure 2.6) that permit ground-based observations of cosmic sources from high, dry sites.

TABLE D.1 The Most Important Spectral Lines Between 300 and 1000 GHz

Species	Formula	Frequency (GHz)	Suggested Minimum Band (GHz)	Notes[1]
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	2
Water vapor	H_2O	380.197	379.82-380.58	2
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	
Deuterated water	HDO	464.925	464.46-465.39	
Carbon	CI	492.162	490.52-492.65	
Deuterated water	HDO	509.292	508.78-509.80	
Hydrogen cyanide	HCN	531.716	529.94-532.25	2
Carbon monosulphide	CS	538.689	536.89-539.23	2
Water vapor	$H_2{}^{18}O$	547.676	547.13-548.22	2
Carbon monoxide	^{13}CO	550.926	549.09-551.48	2
Water vapor	H_2O	556.936	556.38-557.49	2
Ammonia	$^{15}NH_3$	572.113	571.54-572.69	2
Ammonia	NH_3	572.498	571.93-573.07	2
Carbon monoxide	CO	576.268	574.35-576.84	2
Carbon monosulphide	CS	587.616	587.03-588.20	2
Deuterated water	HDO	599.927	599.33-600.53	2
Water vapor	H_2O	620.700	620.08-621.32	2
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	

continued

TABLE D.1 Continued

Species	Formula	Frequency (GHz)	Suggested Minimum Band (GHz)	Notes[1]
Oxygen	O_2	715.393	714.68-716.11	2
Carbon monosulphide	CS	734.324	733.59-735.06	2
Water vapor	H_2O	752.033	751.28-752.79	2
Oxygen	O_2	773.840	773.07-774.61	2
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	2
Carbon monoxide	CO	921.800	918.72-922.72	2
Carbon monosulphide	CS	929.723	926.62-930.65	
Water vapor	H_2O	970.315	969.34-971.29	2
Carbon monosulphide	CS	978.529	977.55-979.51	2
Water vapor	H_2O	987.927	986.94-988.92	2

NOTES:
1. The band limits are the Doppler-shifted frequencies corresponding to radial velocities of ±300 km/s (consistent with line radiation occurring in our Milky Way galaxy).
2. These lines are observable only outside the atmosphere.
SOURCE: Data and further information can be found in International Telecommunication Union, *RA 314 Series: Preferred Frequency Bands for Radio Astronomical Measurements*, June 2003, http://www.itu.int/dms_pubrec/itu-r/rec/ra/R-REC-RA.314-10-200306-I!!PDF-E.pdf.

E

International Astronomical Union Spectral Lines of Most Importance Above 1 THz

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. Spectral lines above 1 THz are listed in Table E.1. The suggested minimum bandwidths are Doppler-shifted frequencies corresponding to radial velocities of ±300 km/s, consistent with line radiation occurring in our Milky Way galaxy. Because of severe atmospheric attenuation (see Figure 2.6), most observations in this spectral region can only be conducted from space. Table E.1 notes those spectral transitions that fall within atmospheric "windows" that could be observed from the ground at a high, dry site. Following World Radiocommunication Conference (WRC) 2012, International Telecommunication Union (ITU) Radio Regulation 5.565 states that "all frequencies in the range 1000-3000 GHz may be used by both active and passive services."

TABLE E.1 The Most Important Spectral Lines Above 1 THz

Species	Rest Frequency (GHz)	Suggested Minimum Band (GHz)	Consolidated Minimum Band (GHz)	Notes
Water vapor ($H_2{}^{18}O$)	1 003.278	1 002.274 – 1 004.281	1 002.274 – 1 004.281	G
Heavy water (HDO)	1 009.945	1 008.935 – 1 010.955	1 008.935 – 1 010.955	G
Azanylidenium (NH^+)	1 012.524	1 011.511 – 1 013.537	1 011.511 – 1 013.537	G
Carbon monosulphide (CS)	1 027.314	1 026.287 – 1 028.341	1 026.287 – 1 028.341	G
Hydroxylium (OH^+)	1 033.119	1 032.085 – 1 034.152	1 032.085 – 1 034.152	G
Carbon monoxide (CO)	1 036.912	1 035.875 – 1 037.949	1 035.875 – 1 037.949	G
Hydrogen cyanide (HCN)	1 062.983	1 061.920 – 1 064.046	1 061.920 – 1 064.046	
Formylium (HCO^+)	1 069.694	1 068.624 – 1 070.764	1 068.624 – 1 070.764	
Carbon monosulphide (CS)	1 076.078	1 075.002 – 1 077.154	1 075.002 – 1 077.154	
Sulfhydrylium (SH^+)	1 082.909	1 081.826 – 1 083.993	1 081.826 – 1 083.993	
Water vapor ($H_2{}^{18}O$)	1 095.627	1 094.532 – 1 096.723	1 094.532 – 1 098.462	
Carbon monoxide ($C^{18}O$)	1 097.163	1 096.066 – 1 098.260		
Water vapor (H_2O)	1 097.365	1 096.267 – 1 098.462		
Carbon monoxide (^{13}CO)	1 101.350	1 100.248 – 1 102.451	1 100.248 – 1 102.800	
Water vapor ($H_2{}^{18}O$)	1 101.698	1 100.597 – 1 102.800		
Water vapor (H_2O)	1 113.343	1 112.230 – 1 114.456	1 112.230 – 1 116.175	
Water cation (H_2O^+)	1 115.059	1 113.943 – 1 116.175		
Carbon monosulphide (CS)	1 124.820	1 123.696 – 1 125.945	1 123.696 – 1 125.945	
Water vapor ($H_2{}^{18}O$)	1 136.704	1 135.567 – 1 137.840	1 135.567 – 1 137.840	
Hydrogen cyanide (HCN)	1 151.452	1 150.301 – 1 152.603	1 150.301 – 1 154.280	
Carbon monoxide (CO)	1 151.985	1 150.833 – 1 153.137		
Water vapor (H_2O)	1 153.127	1 151.974 – 1 154.280		
Water vapor (H_2O)	1 158.324	1 157.165 – 1 159.482	1 157.165 – 1 159.886	
Formylium (HCO^+)	1 158.727	1 157.568 – 1 159.886		
Heavy water (HDO)	1 161.953	1 160.791 – 1 163.115	1 160.791 – 1 165.935	
Water vapor (H_2O)	1 162.912	1 161.749 – 1 164.075		
Heavy water (HDO)	1 164.770	1 163.605 – 1 165.935		
Ammonia (NH_3)	1 168.452	1 167.283 – 1 169.620	1 167.283 – 1 169.620	
Carbon monosulphide (CS)	1 173.539	1 172.366 – 1 174.713	1 172.366 – 1 174.713	
Heavy water (HDO)	1 180.324	1 179.143 – 1 181.504	1 179.143 – 1 182.575	
Water vapor ($H_2{}^{18}O$)	1 181.394	1 180.213 – 1 182.575		
Water vapor ($H_2{}^{18}O$)	1 188.863	1 187.674 – 1 190.052	1 187.674 – 1 190.052	
Water vapor ($H_2{}^{18}O$)	1 199.006	1 197.807 – 1 200.205	1 197.807 – 1 200.205	
Carbon monoxide ($C^{18}O$)	1 206.725	1 205.519 – 1 207.932	1 205.519 – 1 208.846	
Water vapor (H_2O)	1 207.639	1 206.431 – 1 208.846		
Carbon monoxide (^{13}CO)	1 211.330	1 210.118 – 1 212.541	1 210.118 – 1 212.541	

TABLE E.1 Continued

Species	Rest Frequency (GHz)	Suggested Minimum Band (GHz)	Consolidated Minimum Band (GHz)	Notes
Ammonia (NH_3)	1 214.859	1 213.644 – 1 216.073	1 213.644 – 1 218.476	
Ammonia (NH_3)	1 215.245	1 214.030 – 1 216.460		
Water vapor ($H_2{}^{18}O$)	1 216.850	1 215.634 – 1 218.067		
Heavy water (HDO)	1 217.258	1 216.041 – 1 218.476		
Carbon monosulphide (CS)	1 222.234	1 221.012 – 1 223.456	1 221.012 – 1 223.456	
Water vapor (H_2O)	1 228.789	1 227.560 – 1 230.018	1 227.560 – 1 231.633	
Heavy water (HDO)	1 230.403	1 229.173 – 1 231.633		
Hydrogen cyanide (HCN)	1 239.895	1 238.655 – 1 241.134	1 238.655 – 1 241.134	
Formylium (HCO^+)	1 247.735	1 246.487 – 1 248.982	1 246.487 – 1 248.982	
Heavy water (HDO)	1 259.072	1 257.813 – 1 260.331	1 257.813 – 1 262.731	G
Heavy water (HDO)	1 261.469	1 260.208 – 1 262.731		
Carbon monoxide (CO)	1 267.014	1 265.747 – 1 268.282	1 265.747 – 1 268.310	G
Heavy water (HDO)	1 267.043	1 265.776 – 1 268.310		
Carbon monosulphide (CS)	1 270.903	1 269.632 – 1 272.174	1 269.632 – 1 272.174	G
Heavy water (HDO)	1 277.676	1 276.398 – 1 278.954	1 276.398 – 1 278.954	G
Heavy water (HDO)	1 291.642	1 290.351 – 1 292.934	1 290.351 – 1 294.666	G
Heavy water (HDO)	1 293.372	1 292.079 – 1 294.666		
Heavy water (HDO)	1 297.805	1 296.507 – 1 299.103	1 296.507 – 1 299.103	G
Carbon monoxide ($C^{18}O$)	1 316.244	1 314.928 – 1 317.560	1 314.928 – 1 317.560	G
Carbon monosulphide (CS)	1 319.545	1 318.226 – 1 320.865	1 318.226 – 1 323.387	
Carbon monoxide (^{13}CO)	1 321.266	1 319.944 – 1 322.587		
Water vapor (H_2O)	1 322.065	1 320.743 – 1 323.387		
Hydrogen cyanide (HCN)	1 328.308	1 326.980 – 1 329.637	1 326.980 – 1 329.637	G
Formylium (HCO^+)	1 336.714	1 335.378 – 1 338.051	1 335.378 – 1 338.051	G
Water vapor ($H_2{}^{18}O$)	1 340.739	1 339.398 – 1 342.080	1 339.398 – 1 342.080	G
Heavy water (HDO)	1 353.777	1 352.423 – 1 355.130	1 352.423 – 1 355.130	G
Carbon monosulphide (CS)	1 368.160	1 366.792 – 1 369.528	1 366.792 – 1 371.455	G
Trihydrogen (H_2D^+)	1 370.085	1 368.715 – 1 371.455		
Carbon monoxide (CO)	1 381.995	1 380.613 – 1 383.377	1 380.613 – 1 383.377	G
Heavy water (HDO)	1 385.216	1 383.831 – 1 386.601	1 383.831 – 1 386.601	
Heavy water (HDO)	1 392.919	1 391.526 – 1 394.312	1 391.526 – 1 394.312	
Water vapor ($H_2{}^{18}O$)	1 402.966	1 401.563 – 1 404.369	1 401.563 – 1 404.369	
Water vapor (H_2O)	1 410.618	1 409.207 – 1 412.029	1 409.207 – 1 412.029	
Hydrogen cyanide (HCN)	1 416.691	1 415.275 – 1 418.108	1 415.275 – 1 418.162	
Carbon monosulphide (CS)	1 416.745	1 415.329 – 1 418.162		
Formylium (HCO^+)	1 425.664	1 424.238 – 1 427.090	1 424.238 – 1 427.141	
Carbon monoxide ($C^{18}O$)	1 425.715	1 424.289 – 1 427.141		

TABLE E.1 Continued

Species	Rest Frequency (GHz)	Suggested Minimum Band (GHz)	Consolidated Minimum Band (GHz)	Notes
Carbon monoxide (^{13}CO)	1 431.153	1 429.722 – 1 432.584	1 429.722 – 1 434.310	
Heavy water (HDO)	1 432.877	1 431.444 – 1 434.310		
Water vapor ($H_2^{18}O$)	1 438.649	1 437.210 – 1 440.087	1 437.210 – 1 442.222	
Water vapor (H_2O)	1 440.782	1 439.341 – 1 442.222		
Heavy water (HDO)	1 444.829	1 443.384 – 1 446.274	1 443.384 – 1 448.460	G
Sulfhydryl (SH)	1 447.012	1 445.564 – 1 448.460		
Nitrogen ion (N II)	1 461.130	1 459.669 – 1 462.591	1 459.669 – 1 462.591	G
Trihydrogen (D_2H^+)	1 476.606	1 475.128 – 1 478.083	1 475.128 – 1 478.083	G
Heavy water (HDO)	1 491.927	1 490.435 – 1 493.419	1 490.435 – 1 493.419	G
Carbon monoxide (CO)	1 496.923	1 495.426 – 1 498.420	1 495.426 – 1 498.420	G
Heavy water (HDO)	1 500.990	1 499.489 – 1 502.491	1 499.489 – 1 502.491	G
Hydrogen cyanide (HCN)	1 505.042	1 503.537 – 1 506.547	1 503.537 – 1 508.768	G
Heavy water (HDO)	1 507.261	1 505.754 – 1 508.768		
Formylium (HCO^+)	1 514.582	1 513.067 – 1 516.096	1 513.067 – 1 516.096	G
Heavy water (HDO)	1 522.926	1 521.403 – 1 524.449	1 521.403 – 1 524.449	G
Carbon monoxide ($C^{18}O$)	1 535.134	1 533.599 – 1 536.669	1 533.599 – 1 536.669	G
Carbon monoxide (^{13}CO)	1 540.989	1 539.448 – 1 542.530	1 539.448 – 1 543.509	
Water vapor (H_2O)	1 541.967	1 540.425 – 1 543.509		
Heavy water (HDO)	1 577.178	1 575.600 – 1 578.755	1 575.600 – 1 578.755	
Hydrogen cyanide (HCN)	1 593.357	1 591.764 – 1 594.951	1 591.764 – 1 594.951	
Water vapor (H_2O)	1 602.219	1 600.617 – 1 603.821	1 600.617 – 1 607.568	
Formylium (HCO^+)	1 603.466	1 601.862 – 1 605.069		
Water vapor ($H_2^{18}O$)	1 605.962	1 604.356 – 1 607.568		
Carbon monoxide (CO)	1 611.794	1 610.182 – 1 613.405	1 610.182 – 1 617.242	
Heavy water (HDO)	1 614.294	1 612.679 – 1 615.908		
Heavy water (HDO)	1 615.626	1 614.010 – 1 617.242		
Water vapor ($H_2^{18}O$)	1 620.852	1 619.231 – 1 622.472	1 619.231 – 1 622.472	
Heavy water (HDO)	1 625.408	1 623.783 – 1 627.033	1 623.783 – 1 627.033	
Sulfhydrylium (SH^+)	1 632.518	1 630.884 – 1 634.151	1 630.884 – 1 636.274	
Water vapor ($H_2^{18}O$)	1 633.484	1 631.850 – 1 635.117		
Heavy water (HDO)	1 634.639	1 633.005 – 1 636.274		
Carbon monoxide ($C^{18}O$)	1 644.497	1 642.852 – 1 646.141	1 642.852 – 1 646.141	
Heavy water (HDO)	1 648.801	1 647.153 – 1 650.450	1 647.153 – 1 652.418	
Carbon monoxide (^{13}CO)	1 650.768	1 649.117 – 1 652.418		

continued

TABLE E.1 Continued

Species	Rest Frequency (GHz)	Suggested Minimum Band (GHz)	Consolidated Minimum Band (GHz)	Notes
Oxonium (H_3O^+)	1 655.813	1 654.158 – 1 657.469	1 654.158 – 1 657.858	
Water vapor ($H_2{}^{18}O$)	1 655.868	1 654.212 – 1 657.523		
Water vapor ($H_2{}^{18}O$)	1 656.202	1 654.546 – 1 657.858		
Water vapor (H_2O)	1 661.008	1 659.347 – 1 662.669	1 659.347 – 1 665.247	
Oxonium (H_3O^+)	1 663.584	1 661.920 – 1 665.247		
Methylidynium (CH^+)	1 669.170	1 667.499 – 1 670.840	1 667.499 – 1 673.021	
Water vapor (H_2O)	1 669.905	1 668.235 – 1 671.575		
Water vapor ($H_2{}^{18}O$)	1 671.350	1 669.679 – 1 673.021		
Heavy water (HDO)	1 678.578	1 676.899 – 1 680.256	1 676.899 – 1 686.290	
Hydrogen cyanide (HCN)	1 681.636	1 679.955 – 1 683.318		
Heavy water (HDO)	1 684.606	1 682.921 – 1 686.290		
Formylium (HCO^+)	1 692.313	1 690.621 – 1 694.006	1 690.621 – 1 694.006	
Water vapor (H_2O)	1 713.883	1 712.169 – 1 715.597	1 712.169 – 1 721.701	
Water vapor (H_2O)	1 716.770	1 715.053 – 1 718.486		
Water vapor (H_2O)	1 716.957	1 715.240 – 1 718.674		
Water vapor ($H_2{}^{18}O$)	1 719.250	1 717.531 – 1 720.969		
Water vapor ($H_2{}^{18}O$)	1 719.981	1 718.261 – 1 721.701		
Carbon monoxide (CO)	1 726.603	1 724.876 – 1 728.329	1 724.876 – 1 728.329	
Carbon monoxide ($C^{18}O$)	1 753.800	1 752.046 – 1 755.554	1 752.046 – 1 755.554	
Heavy water (HDO)	1 759.978	1 758.218 – 1 761.738	1 758.218 – 1 765.585	
Carbon monoxide (^{13}CO)	1 760.486	1 758.726 – 1 762.247		
Water vapor (H_2O)	1 762.043	1 760.281 – 1 763.805		
Ammonia (NH_3)	1 763.525	1 761.762 – 1 765.289		
Heavy water (HDO)	1 763.558	1 761.795 – 1 765.322		
Ammonia (NH_3)	1 763.602	1 761.838 – 1 765.365		
Ammonia (NH_3)	1 763.821	1 762.058 – 1 765.585		
Hydrogen cyanide (HCN)	1 769.877	1 768.107 – 1 771.647	1 768.107 – 1 771.647	
Formylium (HCO^+)	1 781.123	1 779.342 – 1 782.904	1 779.342 – 1 782.904	
Water vapor (H_2O)	1 794.789	1 792.994 – 1 796.584	1 792.994 – 1 796.584	
Water vapor ($H_2{}^{18}O$)	1 800.475	1 798.674 – 1 802.275	1 798.674 – 1 802.275	
Ammonia (NH_3)	1 808.936	1 807.127 – 1 810.744	1 807.127 – 1 812.188	
Ammonia (NH_3)	1 810.378	1 808.567 – 1 812.188		
Water vapor ($H_2{}^{18}O$)	1 815.853	1 814.038 – 1 817.669	1 814.038 – 1 820.348	
Heavy water (HDO)	1 818.530	1 816.711 – 1 820.348		
Water vapor ($H_2{}^{18}O$)	1 824.554	1 822.729 – 1 826.378	1 822.729 – 1 826.378	

TABLE E.1 Continued

Species	Rest Frequency (GHz)	Suggested Minimum Band (GHz)	Consolidated Minimum Band (GHz)	Notes
Hydroxyl (OH)	1 834.745	1 832.911 – 1 836.580	1 832.911 – 1 843.187	
Hydroxyl (OH)	1 837.741	1 835.903 – 1 839.578		
Hydroxyl (OH)	1 837.812	1 835.974 – 1 839.649		
Carbon monoxide (CO)	1 841.346	1 839.504 – 1 843.187		
Water vapor ($H_2{}^{18}O$)	1 846.872	1 845.025 – 1 848.719	1 845.025 – 1 850.154	
Heavy water (HDO)	1 848.306	1 846.458 – 1 850.154		
Heavy water (HDO)	1 853.873	1 852.019 – 1 855.727	1 852.019 – 1 855.727	
Hydrogen cyanide (HCN)	1 858.077	1 856.219 – 1 859.935	1 856.219 – 1 859.935	
Carbon monoxide ($C^{18}O$)	1 863.039	1 861.176 – 1 864.902	1 861.176 – 1 864.902	
Water vapor (H_2O)	1 867.749	1 865.881 – 1 869.616	1 865.881 – 1 874.481	
Water vapor (H_2O)	1 867.819	1 865.951 – 1 869.687		
Formylium (HCO^+)	1 869.893	1 868.023 – 1 871.763		
Carbon monoxide (^{13}CO)	1 870.141	1 868.271 – 1 872.011		
Heavy water (HDO)	1 872.609	1 870.736 – 1 874.481		
Heavy water (HDO)	1 877.487	1 875.609 – 1 879.364	1 875.609 – 1 883.172	
Water vapor (H_2O)	1 880.753	1 878.872 – 1 882.634		
Heavy water (HDO)	1 881.291	1 879.410 – 1 883.172		
Heavy water (HDO)	1 890.757	1 888.866 – 1 892.647	1 888.866 – 1 896.218	
Water vapor (H_2O)	1 893.687	1 891.793 – 1 895.580		
Water vapor ($H_2{}^{18}O$)	1 894.324	1 892.429 – 1 896.218		
Water vapor ($H_2{}^{18}O$)	1 899.604	1 897.705 – 1 901.504	1 897.705 – 1 902.438	
Carbon ion (C II)	1 900.537	1 898.637 – 1 902.438		
Heavy water (HDO)	1 909.602	1 907.693 – 1 911.512	1 907.693 – 1 911.512	
Water vapor (H_2O)	1 918.475	1 916.557 – 1 920.394	1 916.557 – 1 922.353	
Water vapor (H_2O)	1 918.485	1 916.567 – 1 920.404		
Water vapor (H_2O)	1 919.360	1 917.440 – 1 921.279		
Water vapor (H_2O)	1 919.360	1 917.440 – 1 921.279		
Heavy water (HDO)	1 920.433	1 918.513 – 1 922.353		
Heavy water (HDO)	1 929.255	1 927.326 – 1 931.184	1 927.326 – 1 932.259	
Heavy water (HDO)	1 930.329	1 928.398 – 1 932.259		
Heavy water (HDO)	1 941.797	1 939.855 – 1 943.739	1 939.855 – 1 943.739	
Hydrogen cyanide (HCN)	1 946.235	1 944.288 – 1 948.181	1 944.288 – 1 948.181	
Heavy water (HDO)	1 950.155	1 948.204 – 1 952.105	1 948.204 – 1 952.159	
Heavy water (HDO)	1 950.209	1 948.259 – 1 952.159		

continued

TABLE E.1 Continued

Species	Rest Frequency (GHz)	Suggested Minimum Band (GHz)	Consolidated Minimum Band (GHz)	Notes
Azanylidene (NH)	1 955.027	1 953.072 – 1 956.982	1 953.072 – 1 960.579	
Carbon monoxide (CO)	1 956.018	1 954.062 – 1 957.974		
Azanylidene (NH)	1 958.198	1 956.240 – 1 960.156		
Formylium (HCO^+)	1 958.621	1 956.662 – 1 960.579		
Heavy water (HDO)	1 965.554	1 963.588 – 1 967.519	1 963.588 – 1 967.519	
Carbon monoxide ($C^{18}O$)	1 972.211	1 970.239 – 1 974.183	1 970.239 – 1 987.905	G
Water vapor ($H_2{}^{18}O$)	1 974.636	1 972.661 – 1 976.611		
Azanylidene (NH)	1 978.464	1 976.485 – 1 980.442		
Carbon monoxide (^{13}CO)	1 979.727	1 977.747 – 1 981.707		
Heavy water (HDO)	1 982.064	1 980.082 – 1 984.046		
Water vapor ($H_2{}^{18}O$)	1 985.919	1 983.933 – 1 987.905		
Heavy water (HDO)	1 994.285	1 992.291 – 1 996.280	1 992.291 – 1 996.280	G
Heavy water (HDO)	2 003.495	2 001.491 – 2 005.498	2 001.491 – 2 008.785	
Heavy water (HDO)	2 005.180	2 003.175 – 2 007.186		
Methylidyne (CH)	2 006.779	2 004.772 – 2 008.785		
Methylidyne (CH)	2 010.799	2 008.788 – 2 012.810	2 008.788 – 2 016.880	
Heavy water (HDO)	2 014.370	2 012.355 – 2 016.384		
Water vapor (H_2O)	2 014.865	2 012.850 – 2 016.880		
Heavy water (HDO)	2 019.134	2 017.115 – 2 021.154	2 017.115 – 2 021.154	
Heavy water (HDO)	2 031.743	2 029.711 – 2 033.774	2 029.711 – 2 033.774	
Water vapor (H_2O)	2 040.477	2 038.436 – 2 042.517	2 038.436 – 2 042.517	
Oxygen (O I)	2 060.070	2 058.010 – 2 062.130	2 058.010 – 2 062.130	
Heavy water (HDO)	2 064.690	2 062.625 – 2 066.755	2 062.625 – 2 066.755	
Heavy water (HDO)	1 929.255	1 927.326 – 1 931.184	1 927.326 – 1 932.259	
Heavy water (HDO)	1 930.329	1 928.398 – 1 932.259		
Heavy water (HDO)	1 941.797	1 939.855 – 1 943.739	1 939.855 – 1 943.739	
Hydrogen cyanide (HCN)	1 946.235	1 944.288 – 1 948.181	1 944.288 – 1 948.181	
Heavy water (HDO)	1 950.155	1 948.204 – 1 952.105	1 948.204 – 1 952.159	
Heavy water (HDO)	1 950.209	1 948.259 – 1 952.159		
Azanylidene (NH)	1 955.027	1 953.072 – 1 956.982	1 953.072 – 1 960.579	
Carbon monoxide (CO)	1 956.018	1 954.062 – 1 957.974		
Azanylidene (NH)	1 958.198	1 956.240 – 1 960.156		
Formylium (HCO^+)	1 958.621	1 956.662 – 1 960.579		
Heavy water (HDO)	1 965.554	1 963.588 – 1 967.519	1 963.588 – 1 967.519	

TABLE E.1 Continued

Species	Rest Frequency (GHz)	Suggested Minimum Band (GHz)	Consolidated Minimum Band (GHz)	Notes
Carbon monoxide ($C^{18}O$)	1 972.211	1 970.239 – 1 974.183	1 970.239 – 1 987.905	G
Water vapor ($H_2^{18}O$)	1 974.636	1 972.661 – 1 976.611		
Azanylidene (NH)	1 978.464	1 976.485 – 1 980.442		
Carbon monoxide (^{13}CO)	1 979.727	1 977.747 – 1 981.707		
Heavy water (HDO)	1 982.064	1 980.082 – 1 984.046		
Water vapor ($H_2^{18}O$)	1 985.919	1 983.933 – 1 987.905		
Heavy water (HDO)	1 994.285	1 992.291 – 1 996.280	1 992.291 – 1 996.280	G
Heavy water (HDO)	2 003.495	2 001.491 – 2 005.498	2 001.491 – 2 008.785	
Heavy water (HDO)	2 005.180	2 003.175 – 2 007.186		
Methylidyne (CH)	2 006.779	2 004.772 – 2 008.785		
Methylidyne (CH)	2 010.799	2 008.788 – 2 012.810	2 008.788 – 2 016.880	
Heavy water (HDO)	2 014.370	2 012.355 – 2 016.384		
Water vapor (H_2O)	2 014.865	2 012.850 – 2 016.880		
Heavy water (HDO)	2 019.134	2 017.115 – 2 021.154	2 017.115 – 2 021.154	
Heavy water (HDO)	2 031.743	2 029.711 – 2 033.774	2 029.711 – 2 033.774	
Water vapor (H_2O)	2 040.477	2 038.436 – 2 042.517	2 038.436 – 2 042.517	
Oxygen (O I)	2 060.070	2 058.010 – 2 062.130	2 058.010 – 2 062.130	
Heavy water (HDO)	2 064.690	2 062.625 – 2 066.755	2 062.625 – 2 066.755	
Carbon monoxide (CO)	2 070.616	2 068.545 – 2 072.687	2 068.545 – 2 076.519	
Water vapor (H_2O)	2 074.432	2 072.358 – 2 076.507		
Water vapor (H_2O)	2 074.444	2 072.370 – 2 076.519		
Carbon monoxide ($C^{18}O$)	2 081.311	2 079.229 – 2 083.392	2 079.229 – 2 085.118	
Heavy water (HDO)	2 082.718	2 080.635 – 2 084.801		
Heavy water (HDO)	2 083.035	2 080.952 – 2 085.118		
Heavy water (HDO)	2 087.226	2 085.139 – 2 089.313	2 085.139 – 2 091.330	
Carbon monoxide (^{13}CO)	2 089.241	2 087.151 – 2 091.330		
Water vapor ($H_2^{18}O$)	2 099.963	2 097.863 – 2 102.063	2 097.863 – 2 102.063	
Heavy water (HDO)	2 110.993	2 108.882 – 2 113.104	2 108.882 – 2 113.104	
Heavy water (HDO)	2 121.216	2 119.095 – 2 123.338	2 119.095 – 2 123.338	
Water vapor ($H_2^{18}O$)	2 143.752	2 141.608 – 2 145.895	2 141.608 – 2 154.357	
Water vapor ($H_2^{18}O$)	2 147.733	2 145.585 – 2 149.880		
Heavy water (HDO)	2 149.224	2 147.075 – 2 151.373		
Heavy water (HDO)	2 152.205	2 150.052 – 2 154.357		
Water vapor (H_2O)	2 164.132	2 161.968 – 2 166.296	2 161.968 – 2 166.296	
Carbon monoxide (CO)	2 185.135	2 182.950 – 2 187.320	2 182.950 – 2 187.320	

continued

TABLE E.1 Continued

Species	Rest Frequency (GHz)	Suggested Minimum Band (GHz)	Consolidated Minimum Band (GHz)	Notes
Water vapor (H_2O)	2 196.346	2 194.149 – 2 198.542	2 194.149 – 2 201.998	
Heavy water (HDO)	2 199.798	2 197.599 – 2 201.998		
Heavy water (HDO)	2 204.707	2 202.503 – 2 206.912	2 202.503 – 2 206.912	
Heavy water (HDO)	2 213.707	2 211.493 – 2 215.921	2 211.493 – 2 215.921	
Water vapor (H_2O)	2 221.751	2 219.529 – 2 223.972	2 219.529 – 2 223.972	
Water vapor ($H_2{}^{18}O$)	2 227.872	2 225.644 – 2 230.100	2 225.644 – 2 230.100	
Water vapor ($H_2{}^{18}O$)	2 242.198	2 239.956 – 2 244.440	2 239.956 – 2 244.440	
Water vapor (H_2O)	2 264.150	2 261.886 – 2 266.414	2 261.886 – 2 266.414	
Heavy water (HDO)	2 269.686	2 267.416 – 2 271.956	2 267.416 – 2 271.956	
Heavy water (HDO)	2 278.017	2 275.739 – 2 280.295	2 275.739 – 2 280.295	
Heavy water (HDO)	2 283.942	2 281.658 – 2 286.226	2 281.658 – 2 288.499	
Heavy water (HDO)	2 286.213	2 283.926 – 2 288.499		
Heavy water (HDO)	2 291.309	2 289.018 – 2 293.601	2 289.018 – 2 293.601	
Heavy water (HDO)	2 296.248	2 293.952 – 2 298.544	2 293.952 – 2 302.002	
Heavy water (HDO)	2 297.652	2 295.355 – 2 299.950		
Carbon monoxide (CO)	2 299.569	2 297.269 – 2 301.868		
Heavy water (HDO)	2 299.702	2 297.402 – 2 302.002		
Carbon monoxide (^{13}CO)	2 308.031	2 305.723 – 2 310.339	2 305.723 – 2 310.339	
Water vapour ($H_2{}^{18}O$)	2 318.554	2 316.236 – 2 320.873	2 316.236 – 2 320.873	
Heavy water (HDO)	2 327.429	2 325.101 – 2 329.756	2 325.101 – 2 329.756	
Heavy water (HDO)	2 335.788	2 333.452 – 2 338.123	2 333.452 – 2 338.556	
Heavy water (HDO)	2 336.220	2 333.883 – 2 338.556		
Heavy water (HDO)	2 343.735	2 341.392 – 2 346.079	2 341.392 – 2 368.266	
Water vapour (H_2O)	2 344.290	2 341.945 – 2 346.634		
Methylene (CH_2)	2 344.726	2 342.381 – 2 347.071		
Methylene (CH_2)	2 348.622	2 346.274 – 2 350.971		
Heavy water (HDO)	2 351.731	2 349.380 – 2 354.083		
Heavy water (HDO)	2 355.192	2 352.837 – 2 357.548		
Ammonia (NH_3)	2 357.210	2 354.853 – 2 359.568		
Ammonia (NH_3)	2 357.727	2 355.369 – 2 360.084		
Ammonia (NH_3)	2 358.563	2 356.205 – 2 360.922		
Heavy water (HDO)	2 360.340	2 357.980 – 2 362.700		
Trihydrogen (H_2D^+)	2 363.306	2 360.943 – 2 365.669		
Amino (NH_2)	2 364.268	2 361.903 – 2 366.632		
Water vapor (H_2O)	2 365.900	2 363.534 – 2 368.266		
Heavy water (HDO)	2 382.166	2 379.784 – 2 384.548	2 379.784 – 2 384.548	

TABLE E.1 Continued

Species	Rest Frequency (GHz)	Suggested Minimum Band (GHz)	Consolidated Minimum Band (GHz)	Notes
Water vapor ($H_2^{18}O$)	2 388.325	2 385.936 – 2 390.713	2 385.936 – 2 393.964	
Water vapor (H_2O)	2 391.573	2 389.181 – 2 393.964		
Heavy water (HDO)	2 399.218	2 396.819 – 2 401.618	2 396.819 – 2 407.526	
Ammonia (NH_3)	2 400.018	2 397.618 – 2 402.418		
Ammonia (NH_3)	2 400.578	2 398.178 – 2 402.979		
Ammonia (NH_3)	2 402.265	2 399.863 – 2 404.667		
Ammonia (NH_3)	2 405.121	2 402.716 – 2 407.526		
Heavy water (HDO)	2 411.827	2 409.415 – 2 414.239	2 409.415 – 2 420.888	
Carbon monoxide (CO)	2 413.924	2 411.510 – 2 416.338		
Water vapor ($H_2^{18}O$)	2 418.469	2 416.051 – 2 420.888		
Nitrogen ion (N II)	2 459.379	2 456.920 – 2 461.839	2 456.920 – 2 468.338	
Water vapor (H_2O)	2 462.933	2 460.470 – 2 465.396		
Heavy water (HDO)	2 463.054	2 460.591 – 2 465.517		
Hydrogen fluoride (HF)	2463.427	2 460.964 – 2 465.891		
Heavy water (HDO)	2 465.872	2 463.406 – 2 468.338		
Heavy water (HDO)	2 477.453	2 474.976 – 2 479.931	2 474.976 – 2 486.788	
Heavy water (HDO)	2 480.807	2 478.326 – 2 483.287		
Heavy water (HDO)	2 484.303	2 481.819 – 2 486.788		
Hydroxyl (^{18}OH)	2 494.674	2 492.179 – 2 497.169	2 492.179 – 2 516.847	
Hydroxyl (^{18}OH)	2 498.970	2 496.471 – 2 501.469		
Hydroxyl (^{17}OH)	2 501.856	2 499.355 – 2 504.358		
Heavy water (HDO)	2 502.167	2 499.665 – 2 504.669		
Hydroxyl (^{17}OH)	2 506.186	2 503.680 – 2 508.692		
Hydroxyl (OH)	2 509.965	2 507.455 – 2 512.475		
Hydroxyl (OH)	2 514.333	2 511.819 – 2 516.847		
Water vapor ($H_2^{18}O$)	2 526.741	2 524.214 – 2 529.268	2 524.214 – 2 531.838	
Carbon monoxide (CO)	2 528.166	2 525.638 – 2 530.694		
Heavy water (HDO)	2 529.308	2 526.779 – 2 531.838		
Heavy water (HDO)	2 541.065	2 538.524 – 2 543.606	2 538.524 – 2 547.650	
Amino (NH_2)	2 545.105	2 542.560 – 2 547.650		
Amino (NH_2)	2 553.966	2 551.412 – 2 556.520	2 551.412 – 2 563.471	
Heavy water (HDO)	2 558.905	2 556.346 – 2 561.464		
Amino (NH_2)	2 560.910	2 558.349 – 2 563.471		
Heavy water (HDO)	2 577.667	2 575.089 – 2 580.244	2 575.089 – 2 582.211	
Heavy water (HDO)	2 579.631	2 577.052 – 2 582.211		

continued

TABLE E.1 Continued

Species	Rest Frequency (GHz)	Suggested Minimum Band (GHz)	Consolidated Minimum Band (GHz)	Notes
Water vapor ($H_2^{18}O$)	2 591.047	2 588.456 – 2 593.638	2 588.456 – 2 595.117	
Heavy water (HDO)	2 592.524	2 589.932 – 2 595.117		
Heavy water (HDO)	2 598.288	2 595.690 – 2 600.886	2 595.690 – 2 606.031	
Hydroxyl (OH)	2 603.427	2 600.824 – 2 606.031		
Heavy water (HDO)	2 616.165	2 613.549 – 2 618.781	2 613.549 – 2 618.781	
Water vapor ($H_2^{18}O$)	2 622.939	2 620.316 – 2 625.562	2 620.316 – 2 625.562	
Water vapor (H_2O)	2 630.960	2 628.329 – 2 633.590	2 628.329 – 2 633.682	
Water vapor (H_2O)	2 631.051	2 628.420 – 2 633.682		
Water vapor (H_2O)	2 640.474	2 637.833 – 2 643.114	2 637.833 – 2 644.963	
Carbon monoxide (CO)	2 642.321	2 639.679 – 2 644.963		
Water vapor (H_2O)	2 657.666	2 655.008 – 2 660.323	2 655.008 – 2 660.323	
Water vapor (H_2O)	2 664.561	2 661.897 – 2 667.226	2 661.897 – 2 677.662	
Water vapor ($H_2^{18}O$)	2 666.732	2 664.065 – 2 669.398		
Heavy water (HDO)	2 669.415	2 666.745 – 2 672.084		
Heavy water (HDO)	2 674.283	2 671.609 – 2 676.957		
Deuterated hydrogen (HD)	2 674.987	2 672.312 – 2 677.662		
Water vapor (H_2O)	2 685.639	2 682.953 – 2 688.325	2 682.953 – 2 688.325	
Heavy water (HDO)	2 735.277	2 732.541 – 2 738.012	2 732.541 – 2 738.012	
Water vapor ($H_2^{18}O$)	2 741.675	2 738.933 – 2 744.416	2 738.933 – 2 744.416	
Heavy water (HDO)	2 748.312	2 745.564 – 2 751.060	2 745.564 – 2 751.060	
Carbon monoxide (CO)	2 756.383	2 753.626 – 2 759.139	2 753.626 – 2 759.139	
Water vapor (H_2O)	2 773.977	2 771.203 – 2 776.751	2 771.203 – 2 776.751	
Methylene (CH_2)	2 783.064	2 780.281 – 2 785.847	2 780.281 – 2 785.847	
Heavy water (HDO)	2 794.002	2 791.208 – 2 796.796	2 791.208 – 2 796.829	
Heavy water (HDO)	2 794.035	2 791.241 – 2 796.829		
Water vapor ($H_2^{18}O$)	2 805.384	2 802.579 – 2 808.190	2 802.579 – 2 816.325	
Heavy water (HDO)	2 807.498	2 804.691 – 2 810.306		
Heavy water (HDO)	2 809.406	2 806.597 – 2 812.216		
Heavy water (HDO)	2 810.880	2 808.069 – 2 813.691		
Heavy water (HDO)	2 813.511	2 810.698 – 2 816.325		
Heavy water (HDO)	2 834.411	2 831.577 – 2 837.245	2 831.577 – 2 837.245	
Water vapor ($H_2^{18}O$)	2 845.980	2 843.134 – 2 848.826	2 843.134 – 2 848.826	
Heavy water (HDO)	2 855.631	2 852.776 – 2 858.487	2 852.776 – 2 861.891	
Heavy water (HDO)	2 859.032	2 856.173 – 2 861.891		
Carbon monoxide (CO)	2 870.338	2 867.468 – 2 873.208	2 867.468 – 2 875.782	
Heavy water (HDO)	2 872.909	2 870.036 – 2 875.782		

TABLE E.1 Continued

Species	Rest Frequency (GHz)	Suggested Minimum Band (GHz)	Consolidated Minimum Band (GHz)	Notes
Water vapor (H_2O)	2 880.025	2 877.145 – 2 882.905	2 877.145 – 2 890.914	
Water vapor (H_2O)	2 884.279	2 881.395 – 2 887.163		
Water vapor (H_2O)	2 884.312	2 881.427 – 2 887.196		
Water vapor (H_2O)	2 884.941	2 882.056 – 2 887.826		
Water vapor (H_2O)	2 884.950	2 882.065 – 2 887.835		
Water vapor ($H_2{}^{18}O$)	2 888.026	2 885.138 – 2 890.914		
Heavy water (HDO)	2 900.172	2 897.272 – 2 903.072	2 897.272 – 2 906.294	
Heavy water (HDO)	2 903.391	2 900.487 – 2 906.294		
Heavy water (HDO)	2 916.109	2 913.193 – 2 919.025	2 913.193 – 2 923.819	
Heavy water (HDO)	2 920.898	2 917.977 – 2 923.819		
Water vapor ($H_2{}^{18}O$)	2 938.998	2 936.059 – 2 941.937	2 936.059 – 2 944.831	
Water vapor ($H_2{}^{18}O$)	2 939.000	2 936.061 – 2 941.939		
Heavy water (HDO)	2 941.889	2 938.947 – 2 944.831		
Water vapor (H_2O)	2 773.977	2 771.203 – 2 776.751	2 771.203 – 2 776.751	
Methylene (CH_2)	2 783.064	2 780.281 – 2 785.847	2 780.281 – 2 785.847	
Heavy water (HDO)	2 794.002	2 791.208 – 2 796.796	2 791.208 – 2 796.829	
Heavy water (HDO)	2 794.035	2 791.241 – 2 796.829		
Water vapor ($H_2{}^{18}O$)	2 805.384	2 802.579 – 2 808.190	2 802.579 – 2 816.325	
Heavy water (HDO)	2 807.498	2 804.691 – 2 810.306		
Heavy water (HDO)	2 809.406	2 806.597 – 2 812.216		
Heavy water (HDO)	2 810.880	2 808.069 – 2 813.691		
Heavy water (HDO)	2 813.511	2 810.698 – 2 816.325		
Heavy water (HDO)	2 834.411	2 831.577 – 2 837.245	2 831.577 – 2 837.245	
Water vapor ($H_2{}^{18}O$)	2 845.980	2 843.134 – 2 848.826	2 843.134 – 2 848.826	
Heavy water (HDO)	2 855.631	2 852.776 – 2 858.487	2 852.776 – 2 861.891	
Heavy water (HDO)	2 859.032	2 856.173 – 2 861.891		
Carbon monoxide (CO)	2 870.338	2 867.468 – 2 873.208	2 867.468 – 2 875.782	
Heavy water (HDO)	2 872.909	2 870.036 – 2 875.782		
Water vapor (H_2O)	2 880.025	2 877.145 – 2 882.905	2 877.145 – 2 890.914	
Water vapor (H_2O)	2 884.279	2 881.395 – 2 887.163		
Water vapor (H_2O)	2 884.312	2 881.427 – 2 887.196		
Water vapor (H_2O)	2 884.941	2 882.056 – 2 887.826		
Water vapor (H_2O)	2 884.950	2 882.065 – 2 887.835		
Water vapor ($H_2{}^{18}O$)	2 888.026	2 885.138 – 2 890.914		
Heavy water (HDO)	2 900.172	2 897.272 – 2 903.072	2 897.272 – 2 906.294	
Heavy water (HDO)	2 903.391	2 900.487 – 2 906.294		

continued

TABLE E.1 Continued

Species	Rest Frequency (GHz)	Suggested Minimum Band (GHz)	Consolidated Minimum Band (GHz)	Notes
Heavy water (HDO)	2 916.109	2 913.193 – 2 919.025	2 913.193 – 2 923.819	
Heavy water (HDO)	2 920.898	2 917.977 – 2 923.819		
Water vapor ($H_2{}^{18}O$)	2 938.998	2 936.059 – 2 941.937	2 936.059 – 2 944.831	
Water vapor ($H_2{}^{18}O$)	2 939.000	2 936.061 – 2 941.939		
Heavy water (HDO)	2 941.889	2 938.947 – 2 944.831		
Heavy water (HDO)	2 948.042	2 945.094 – 2 950.990	2 945.094 – 2 955.592	
Ammonia (NH_3)	2 948.411	2 945.462 – 2 951.359		
Ammonia (NH_3)	2 948.669	2 945.721 – 2 951.618		
Ammonia (NH_3)	2 949.480	2 946.531 – 2 952.430		
Ammonia (NH_3)	2 950.815	2 947.864 – 2 953.765		
Ammonia (NH_3)	2 952.640	2 949.687 – 2 955.592		
Water vapor (H_2O)	2 962.111	2 959.149 – 2 965.073	2 959.149 – 2 975.081	
Heavy water (HDO)	2 966.081	2 963.115 – 2 969.047		
Water vapor (H_2O)	2 968.749	2 965.780 – 2 971.717		
Water vapor ($H_2{}^{18}O$)	2 969.868	2 966.899 – 2 972.838		
Water vapor (H_2O)	2 970.800	2 967.829 – 2 973.771		
Water vapor (H_2O)	2 970.801	2 967.830 – 2 973.772		
Oxonium (H_3O^+)	2 972.109	2 969.137 – 2 975.081		
Oxonium (H_3O^+)	2 980.735	2 977.754 – 2 983.715	2 977.754 – 3 002.430	
Carbon monoxide (CO)	2 984.168	2 981.183 – 2 987.152		
Heavy water (HDO)	2 984.559	2 981.575 – 2 987.544		
Ammonia (NH_3)	2 989.643	2 986.653 – 2 992.632		
Water vapor ($H_2{}^{18}O$)	2 990.139	2 987.149 – 2 993.129		
Ammonia (NH_3)	2 991.555	2 988.564 – 2 994.547		
Ammonia (NH_3)	2 994.786	2 991.792 – 2 997.781		
Heavy water (HDO)	2 997.115	2 994.118 – 3 000.112		
Ammonia (NH_3)	2 999.430	2 996.431 – 3 002.430	2 977.754 – 3 002.430	

NOTE: Suggested minimum bands correspond to Doppler-shifted frequencies for ± 300 km/s (consistent with line radiation occurring in our Milky Way galaxy). Consolidated minimum bands reflect spectral regions where multiple molecular transitions result in overlapping recommend bandwidths; the minimum and maximum ranges reflect those of the lowest and highest frequencies for these spectral lines, respectively. G in the "Notes" column indicates that the line is observable from the ground under very good atmospheric condition.

SOURCE: Available at http://www.itu.int/dms_pubrec/itu-r/rec/ra/R-REC-RA.1860-0-201001-I!!PDF-E.pdf; IAU Resolution A.2 (1991, Buenos Aires; revised 2009, Rio de Janeiro); JPL Molecular Spectroscopy Database (http://spec.jpl.nasa.gov/); The Cologne Database for Molecular Spectroscopy (http://www.astro.uni-koeln.de/cdms/).

F

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 20° 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.

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

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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 F.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%

sidelobe gain as a function of boresight angle Φ is equal to (32-25 log Φ) dBi for $1° < \Phi < 48°$, and is a constant value of –10 dBi for $\Phi > 48°$. With this model the 0 dBi sidelobe level occurs at a boresight angle of $\Phi_0 = 19°$. 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 F.1. The solid angle of the antenna response for which the gain exceeds 0 dBi is $\Omega = 2\pi (1 - \cos \Phi_0)$ ster. 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.

G

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 https://www.fcc.gov/encyclopedia/rules-regulations-title-47. Table G.1 presents a selected list of FCC rules particularly relevant to the Radio Astronomy Service and the Earth Exploration Satellite Service.

TABLE G.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)

H

Selected Acronyms and Abbreviations

For the reader's convenience, following is an alphabetical list of selected acronyms and abbreviations used in this handbook.

AGN	active galactic nuclei
ALMA	Atacama Large Millimeter Array
AMSU	Advanced Microwave Sounding Unit
AMT	aeronautical mobile telemetry
ATMS	Advanced Technology Microwave Sounder
BAO	baryonic acoustic oscillation
CCIR	International Radio Consultative Committee (antecedent of the ITU-R)
CIWP	cloud ice water path
CMB	cosmic microwave background radiation
COBE	Cosmic Background Explorer
CORF	Committee on Radio Frequencies
COSPAR	Committee on Space Research
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CyGNSS	Cyclone GNSS
DMSP	Defense Meteorological Satellite Program
DOD	Department of Defense
EESS	Earth Exploration-Satellite Service
EoR	Epoch of Reionization
EOS	Earth Observing System
ERS	Earth Remote Sensing Satellite

ESA	European Space Agency
FARS	Frequency Allocations in Remote Sensing
FCC	Federal Communications Commission
FS	Fixed Service (point-to-point transmissions, such as radio relay towers)
GBT	Green Bank Telescope
GEO	geostationary orbit (satellite)
GEOSS	Global Earth Observation System of Systems
GLONASS	Global Navigation Satellite System
GMI	GPM Microwave Imager
GNSS	Global Navigation Satellite System
GOES	Geostationary Operational Environmental Satellites
GPM	Global Precipitation Mission
GPS	Global Positioning System
GSO	geostationary orbit
GWR	gravitational wave radiation
IAU	International Astronomical Union
ICSU	International Council of Scientific Unions
IGS	International Global Navigation Satellite System (GNSS)
InSAR	interferometric synthetic aperture radar
IRAC	Inter-department Radio Advisory Committee
ISM	industrial, scientific, and medical (bands in which radio-frequency-noisy systems can be operated)
ITAC	International Telecommunication Advisory Committee
ITU	International Telecommunication Union
ITU-R	ITU Radiocommunication Sector
IUCAF	Scientific Committee on Frequency Allocations for Radio Astronomy and Space Science
JPSS	Joint Polar Satellite System
LEO	low Earth orbit
LWA	Long Wavelength Array
MetAids	Meteorological Aids Service (radiosondes, etc.)
MetSat	Meteorological Satellite Service
MF	medium frequency
MLS	Microwave Limb Sounder
MLT	Mesosphere/Lower Thermosphere
MR	meteor radar
MS	Mobile Service
MSU	Microwave Sounding Unit
NAIC	National Astronomy and Ionosphere Center
NASA	National Aeronautics and Space Administration

NOAA	National Oceanic and Atmospheric Administration
NRAO	National Radio Astronomy Observatory
NSF	National Science Foundation
NTIA	National Telecommunications and Information Administration
OH	hydroxyl
OOBE	out-of-band emissions
OSTM	Ocean Surface Topography Mission
pfd	power flux density (usually measured in W m^{-2})
RAS	Radio Astronomy Service
RF	radio frequency
RFI	radio frequency interference
RLS	Radiolocation Service (radars)
RSS	radio star scintillation
SAR	synthetic aperture radar
SED	spectral energy distribution
SETI	search for extraterrestrial intelligence
SG	study group
SM	soil moisture
SMAP	Soil Moisture Active/Passive
SMBH	supermassive black hole
SMOS	Soil Moisture and Ocean Salinity
SOS	Space Operations Service
spfd	spectral power flux density (measured in W m^{-2} Hz^{-1})
SRS	Space Research Service
SRT	Small Radio Telescope
SRTM	Shuttle Radar Topographic Mapper
SSM/I	Special Sensor Microwave/Imager (of the Defense Meteorological Satellite Program)
SSM/T	Special Sensor Microwave/Temperature (of the Defense Meteorological Satellite Program)
SZ	Sunyaev-Zel'dovich
TDRSS	Tracking and Data Relay Satellite System
TEC	total electron content
TPW	total precipitable water
TRMM	Tropical Rainfall Measurement Mission
UNESCO	United Nations Educational, Scientific, and Cultural Organization
URSI	International Union of Radio Science
VLA	Very Large Array
VLBA	Very Long Baseline Array
VLBI	very long baseline interferometry

WARC	World Administrative Radio Conference (antecedent of WRC)
WMAP	Wilkinson Microwave Anisotropy Probe
WRC	World Radiocommunication Conference