Views of the U.S. National Academies of Sciences, Engineering, and Medicine on Agenda Items of Interest to the Science Services at the World Radiocommunication Conference 2019

DETAILS

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WORLD RADIOCOMMUNICATION CONFERENCE 2019

Committee on the Views on the
World Radiocommunication Conference 2019

Board on Physics and Astronomy

Division on Engineering and Physical Sciences

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Acknowledgment of Reviewers

This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

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David DeBoer, University of California, Berkeley,
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Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report, nor did they see the final draft before its release. The review of this report was overseen by Frank D. Drake, SETI Institute. He was responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

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APPENDIXES

1

Introduction

The radio frequency (RF) spectrum is a limited resource with ever-increasing demand from an expansive range of applications—all the way from commercial, such as mobile phones, to scientific, such as hurricane monitoring from space. The RF spectrum is conventionally defined as the part of the electromagnetic spectrum from 3 kHz up to 3000 GHz,[1] but recent uses extend to frequencies approaching the edge of the infrared part of the spectrum. The selection of a frequency band for a particular use depends on many factors, including propagation characteristics, atmospheric attenuation, technological advances, sensitivity to physical parameters of interest, and cost. Changing the band of operation is not always viable, particularly for scientists, who in many cases must observe at specific frequency bands, which can be dictated in remote sensing by the electromagnetic properties of Earth parameters, such as sea surface temperature, sea salinity, surface winds, and soil moisture; or, in the case of radio astronomers, the transition frequencies of atoms and molecules, which are established by the laws of physics and chemistry.

NOTE: Portions of this text are taken from National Research Council, *Views of the NAS and NAE on Agenda Items at the World Radiocommunication Conference 2015*, The National Academies Press, Washington, D.C., 2013.

[1] International Telecommunications Union (ITU) Radio Regulations, Article 2, Section I, 2016.

Since radio waves do not stop at national borders, international regulation is necessary to ensure effective use of the radio spectrum for all parties. The International Telecommunication Union (ITU) has as its mission to facilitate the efficient and interference-free use of the radio spectrum. One of the most important functions of the ITU is to maintain the International Table of Frequency Allocations. Every country is sovereign to allocate uses of the RF spectrum within its borders, but most choose to follow the International Table of Frequency Allocations out of convenience and to avoid potential interference to their neighbors.

In the radio regulations (RR), radio spectrum users are divided into different categories, which are usually referred to as radiocommunication services. Some examples are signal broadcasting, radionavigation, meteorology, space research, mobile, mobile-satellite, and the Earth Exploration-Satellite Service (EESS). In the regulations, the Radio Astronomy Service (RAS) is classified as a radio service but not a radiocommunication service; it is the only service so distinguished. Services can be active or passive, depending on whether they transmit and receive or receive only. Passive services use receivers to measure natural radio frequency emissions from ocean, land, and atmosphere phenomena such as hurricanes or, in the case of radio astronomy, cosmic sources such as solar system objects, stars, and the medium between stars, galaxies, and other celestial bodies. RAS, as defined in the radio regulations, is always a passive service. Active services, on the other hand, use both a transmitter, which radiates an electromagnetic signal within a given band of frequencies, and a receiver, which receives and detects a transmitted signal or, in some cases, receives a signal that is reflected back from a target, such as Earth's surface. The EESS may be active or passive, and these two uses are distinguished in the regulations. While RAS is only a passive service, astronomers also use powerful radar to study the surface and other properties of asteroids, the planets, and their satellites (including radar observations to detect near Earth objects); radar astronomy is considered part of the Radiolocation Services and follows its rules and regulations.

There are several major differences between RAS and EESS. RAS facilities are typically ground based, looking upward (to celestial objects), whereas most EESS sensors are on board satellites, usually looking downward to study Earth's radio emission from atmosphere, land, and ocean. Active sensors that are airborne are potential radio frequency interference (RFI) sources for passive observations both on the ground and on satellites, depending on their power level, antenna radiation pattern, polarization, distance, and other parameters.

Radio telescopes and passive sensors operated by EESS measure the natural, noise-like emissions from targets under study. Passive RAS facilities with spectral power flux density (*spfd*) sensitivity on the order of –250 dBW/m^2/Hz are common at gigahertz frequencies, and radio astronomers work to detect emissions even four to six orders of magnitude fainter in that frequency range. This high sensitivity makes them vulnerable to interference from in-band emissions, from spurious and out-of-band emissions from licensed and unlicensed users of neighboring bands, and from emissions that produce harmonic signals in the RAS bands.[2] Weak signals that are unintended by-products of human activity can obstruct the scientific use of the spectrum. Remote sensing scientists observe the extremely weak natural emission from Earth's surface and atmosphere. Their observations are similarly very vulnerable to interference from unintended human-made transmissions. Recommendations ITU-R RA.769 and ITU-R RS.2017 contain the threshold levels of interference that are deemed detrimental to the use of the radio spectrum by the passive scientific services.

Scientific users understand the need to share the spectrum between active and passive users, but it is important to note that some sharing techniques that work for active services do not necessarily work for passive uses. For example, dynamic spectrum management (DSM), where RF monitoring is used to identify "unused" parts of the spectrum, may not be appropriate to share the spectrum with the passive services that have no detectable radio signature within the sensitivities and integration times of the DSM systems. On the other hand, in specific cases, either geographic or time separation may be used to share the spectrum effectively between active and passive services.

A factor that needs to be considered in some cases is the "aggregate interference," especially when dealing with spectrum users such as low-power RF transmitting (active) devices that do not require individual licenses and are designed to be used by thousands or even millions of transmitters at a given moment. For example, wireless mobile handsets and radars mounted on vehicles are two increasingly numerous potential sources of radio frequency interference. The aggregate factor takes into account the power (*spfd*) at the passive "victim" facility. Whereas one such transmitter might

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[2] Allocations and protection for scientific use is discussed in National Academies of Sciences, Engineering, and Medicine, *Handbook of Frequency Allocations and Spectrum Protection for Scientific Uses: Second Edition*, The National Academies Press, Washington, D.C., 2015.

comply with threshold levels of interference for a radio astronomy receiver, the sum of many such transmitters may not.

Every 3 to 6 years, the ITU convenes a World Radiocommunication Conference (WRC) to review and revise the international RR. Changes to the RR are formulated through proposals to the conference according to the agenda items, which are agreed on at the previous WRC. Governments or Member States (referred to within the ITU as "Administrations") and academic, industrial, and scientific organizations (referred to within the ITU as members, with lower case "m") can participate in the WRC, but only the more than 190 Member States (Administrations) of the ITU are entitled to formulate proposals and to vote.

In the period between two WRCs, Administrations work internally and with their regional counterparts to develop a consensus position on each agenda item, to the extent possible, given varying national priorities and interests. The national delegations then submit proposals to the WRC and negotiate with other delegations before adoption of each proposal. Much of this negotiation takes place between regional groups—for example, the European Post and Telecommunications Conference (CEPT), with more than 40 members, or the Inter-American Telecommunications Commission (CITEL), which has more than 30 members. The outcome of a WRC, a revision of the RR, is an international treaty.

Agenda items are typically very specific and propose substantial changes to the use of the spectrum that can have a significant impact on services. Because more than 95 percent of spectrum allocations below 3 GHz are for active uses of the spectrum, it is critical for vulnerable passive services to participate in the process and express their concerns about potential adverse effects on their operations.[3]

To ensure their continued ability to access the radio spectrum for scientific purposes, scientists must participate in the discussions leading up to WRC-19, scheduled to be held in November 2019 in Geneva, Switzerland. By request of the National Science Foundation (NSF) and the National Aeronautics and Space Administration (NASA), a committee was convened by the National Academies of Sciences, Engineering, and Medicine to provide guidance to U.S. spectrum managers and policy makers as they prepare for

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[3] In the United States, the Radio Astronomy Service (RAS) and the Earth Exploration-Satellite Service (EESS) are allocated 2.07 percent of the spectrum on a primary basis and 4.08 percent of the spectrum on a secondary basis below 3 GHz. Allocations for RAS and EESS are comparable in the ITU's international allocation tables. From National Research Council, *Spectrum Management for Science in the 21st Century*, The National Academies Press, Washington, D.C., 2010, pp.137-138.

the WRC-19, to protect the scientific exploration of Earth and the universe using the radio spectrum (see Appendix A for the committee's statement of task). While the resulting document is targeted primarily at U.S. agencies dealing with radio spectrum issues, other Administrations and foreign scientific users may find its recommendations useful in their own WRC planning.

This report identifies the WRC-19 agenda items of relevance to, and with potential impact on, U.S. radio astronomers and Earth remote sensing researchers. The agenda items are discussed in numerical order to facilitate locating a specific one. The committee has determined that some outcomes of the agenda items shown in Table 1.1 may impact RAS and EESS operations and provides the reasons for its view as well as the passive application of the bands that may be impacted. Agenda items not discussed in this report are not expected to have an impact on RAS or EESS operations. It is noted that potential impact is assessed based on criteria related to in-band, out-of-band, and spurious emissions, as appropriate.

To provide context for the potential scientific impact of these agenda items, a brief overview of some of the scientific results derived from the passive use of the radio spectrum by EESS and RAS is described below. A more complete view of both the scientific uses and the frequency allocations can be found in the *Handbook of Frequency Allocations and Spectrum Protection for Scientific Uses: Second Edition*.[4]

EARTH EXPLORATION-SATELLITE SERVICE

Satellite remote sensing is a uniquely valuable resource for monitoring the global atmosphere, land, and oceans. Microwave remote sensing from space presents a global view, vital for obtaining atmospheric and surface data for the entire planet. Instruments operating in the EESS bands provide data that are important to human welfare and security and include support for scientific research, commercial endeavor, and military operations in areas such as meteorology, atmospheric chemistry, climate studies, and oceanography. For example, measurements of ocean temperature and salinity are needed to understand ocean circulation and the associated global distribution of heat and hurricane genesis. Measurements of soil moisture are needed for agriculture and drought assessment, for weather

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[4] National Academies of Sciences, Engineering, and Medicine, *Handbook of Frequency Allocations and Spectrum Protection for Scientific Uses: Second Edition*, The National Academies Press, Washington, D.C., 2015.

TABLE 1.1 World Radiocommunication Conference (WRC)-19 and WRC-23 Agenda Items of Relevance to and Potential Impact on the Radio Astronomy Service and the Earth Exploration-Satellite Service

WRC-19	
1	On the basis of proposals from administrations, taking account of the results of WRC-15 and the Report of the Conference Preparatory Meeting, and with due regard to the requirements of existing and future services in the frequency bands under consideration, to consider and take appropriate action in respect of the following items:
1.2	To consider in-band power limits for Earth stations operating in the mobile-satellite service, meteorological-satellite service, and Earth exploration-satellite service in the frequency bands 401-403 MHz and 399.9-400.05 MHz, in accordance with Resolution 765 (WRC-15)
1.5	To consider the use of the frequency bands 17.7-19.7 GHz (space-to-Earth) and 27.5-29.5 GHz (Earth-to-space) by Earth stations in motion communicating with geostationary space stations in the fixed-satellite service and take appropriate action, in accordance with Resolution 158 (WRC-15)
1.6	To consider the development of a regulatory framework for non-GSO FSS satellite systems that may operate in the frequency bands 37.5-39.5 GHz (space-to-Earth), 39.5-42.5 GHz (space-to-Earth), 47.2-50.2 GHz (Earth-to-space), and 50.4-51.4 GHz (Earth-to-space), in accordance with Resolution 159 (WRC-15)
1.7	To study the spectrum needs for telemetry, tracking, and command in the space operation service for non-GSO satellites with short-duration missions, to assess the suitability of existing allocations to the space operation service, and, if necessary, to consider new allocations, in accordance with Resolution 659 (WRC-15)
1.8	To consider possible regulatory actions to support Global Maritime Distress Safety Systems (GMDSS) modernization and to support the introduction of additional satellite systems into the GMDSS, in accordance with Resolution 359 (Rev. WRC-15)
1.9	To consider, based on the results of ITU-R studies:
1.9.1	regulatory actions within the frequency band 156-162.05 MHz for autonomous maritime radio devices to protect the GMDSS and automatic identification systems (AIS), in accordance with Resolution 362 (WRC-15)

TABLE 1.1 Continued

1.9.2	modifications of the Radio Regulations, including new spectrum allocations to the maritime mobile-satellite service (Earth-to-space and space-to-Earth), preferably within the frequency bands 156.0125-157.4375 MHz and 160.6125-162.0375 MHz, to enable a new VHF data exchange system (VDES) satellite component, while ensuring that this component will not degrade the current terrestrial VDES components, applications specific messages (ASM) and Automatic identification systems (AIS) operations and not impose any additional constraints on existing services in these and adjacent frequency bands as stated in *recognizing d)* and *e)* of Resolution 360 (Rev. WRC-15)
1.13	To consider identification of frequency bands for the future development of International Mobile Telecommunications (IMT), including possible additional allocations to the mobile service on a primary basis, in accordance with Resolution 238 (WRC-15)
1.14	To consider, on the basis of ITU-R studies in accordance with Resolution 160 (WRC-15), appropriate regulatory actions for high-altitude platform stations (HAPS), within existing fixed-service allocations.
1.15	To consider identification of frequency bands for use by administrations for the land-mobile and fixed services applications operating in the frequency range 275-450 GHz, in accordance with Resolution 767 (WRC-15)
1.16	To consider issues related to wireless access systems, including radio local area networks (WAS/RLAN), in the frequency bands between 5150 MHz and 5925 MHz, and take the appropriate regulatory actions, including additional spectrum allocations to the mobile service, in accordance with Resolution 239 (WRC-15)
WRC-23	
2	On the basis of proposals from administrations and the Report of the Conference Preparatory Meeting, and taking account of the results of WRC-19, to consider and take appropriate action in respect of the following items:
2.2	To conduct, and complete in time for WRC-23, studies for a possible new allocation to the Earth Exploration-Satellite Service (active) for spaceborne radar sounders with the range of frequencies around 45 MHz, taking into account the protection of incumbent services, in accordance with Resolution 656 (WRC-15)

NOTE: Acronyms defined in Appendix B.

prediction (heat exchange with the atmosphere), and for defense (planning military deployment). Passive sensors also provide temperature and humidity profiles of the atmosphere, information to monitor changes in the polar ice cover, and information needed in assessing hazards such as hurricanes, wildfires, and drought. For many applications, satellite-based RF remote sensing represents the only available method of obtaining atmospheric and surface data for the entire planet. Major U.S. governmental users of EESS data include the National Oceanic and Atmospheric Administration (NOAA), the National Science Foundation, NASA, the Department of Defense (DoD), the Department of Agriculture, the U.S. Geological Survey, the Agency for International Development, the Federal Emergency Management Agency (FEMA), and the U.S. Forest Service. Much of these data are also available free to anyone anywhere in the world.

However, passive instruments in space are particularly vulnerable to anthropogenic emissions because they rely on very faint signals emitted naturally from Earth's surface and atmosphere. This is especially a concern for EESS because sensors view large swaths of the surface at one time. Measurement accuracy is already limited by the available bandwidth, and some of these valuable measurements are being blocked by RFI, even within protected bands. For instance, it is now impossible to retrieve soil moisture by the Advanced Microwave Scanning Radiometer 2 (AMSR2) at 10.7 GHz in some areas of the globe due to RFI. Similarly, the Soil Moisture Active Passive (SMAP) and Soil Moisture and Ocean Salinity (SMOS) missions, which operate at 1.413 GHz, are adversely impacted by RFI even though they operate in a band protected for passive use only. Figure 1.1 shows the impact of RFI as observed by the SMAP radiometer. In addition to the RFI effects on passive instruments, recent measurements from active instruments are also found to be affected by RFI, as is the case for the L-band scatterometer on board the Aquarius/SAC-D satellite.

RADIO ASTRONOMY SERVICE

Radio astronomy is a vital tool to study our universe. Radio astronomy provides valuable data for the benefit of society such as the monitoring of solar flares and sunspots. Such monitoring allows for 1- to 4-day forecasts of geomagnetic disturbances that can affect the operation of satellite communications, Global Positioning System (GPS) navigation systems, and terrestrial power grids. The first planets outside the solar system, circling a distant pulsar, were

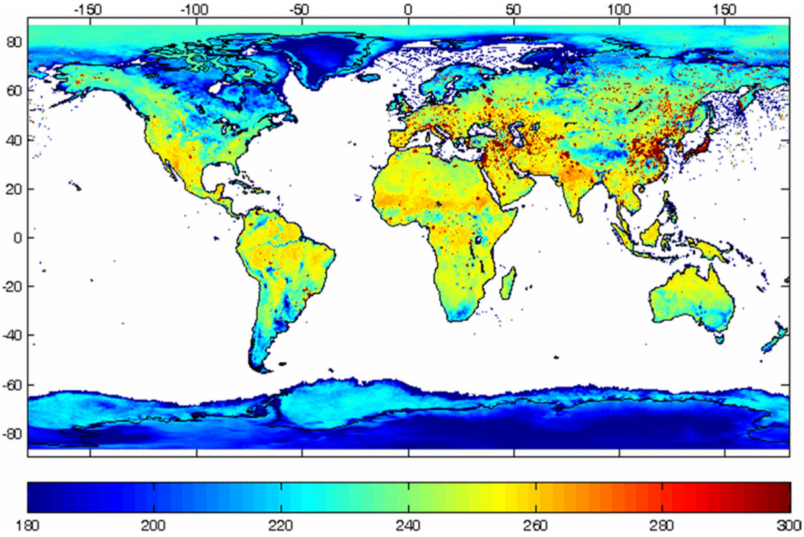

FIGURE 1.1 Peak hold L-band data of Soil Moisture Active Passive H-pol in Kelvins during the period June 3-9, 2015. Radio frequency interference (RFI) appears as red dots over land (see P.N. Mohammed, M. Aksoy, and J.R. Piepmeier, SMAP L-Band Microwave Radiometer: RFI mitigation prelaunch analysis and first year on-orbit observations, *IEEE Transactions on Geoscience and Remote Sensing* 54(10):6035-6047, 2016). Particularly strong RFI events occur over Europe, the Middle East, and Asia. Some regions are inaccessible due to RFI events corrupting the whole footprint.

discovered through the use of radio astronomy. Pulsars are stars rotating so precisely that their electromagnetic (primarily radio) pulses can be tracked with precision rivaling atomic clocks on Earth. Subsequent observations of pulsars have revolutionized our understanding of the physics of neutron stars and general relativity and resulted in the first experimental evidence for gravitational radiation.

Radio astronomy has also enabled the discovery of organic matter and prebiotic molecules outside our solar system, leading to new insights into the potential existence of life elsewhere in our Milky Way galaxy. Measurements of radio spectral line emission have identified and characterized the birth sites of stars in the Milky Way, the processes by which stars slowly die, and the complex distribution and evolution of galaxies in the universe.

Radio astronomy measurements discovered the cosmic microwave background (CMB), the radiation left over from the original

Big Bang. Later observations discovered the weak fluctuations in the CMB of only one-thousandth of a percent, generated in the early universe, which later formed the stars and galaxies we know today. Radio observations uncovered the first evidence for the existence of a black hole in our galactic center, a phenomenon that may be crucial to the creation of many other galaxies. Observations of supernovas have allowed astronomers to witness the distribution of heavy elements essential to the formation of planets like Earth, and of life itself.

In addition, since radio astronomy poses extra challenges due to the extreme sensitivity required for observing very faint signals, engineers have to come up with solutions to these challenges to enable cosmic radio astronomy observations. Many of these solutions have proven to be extremely useful to other applications. These include the following: optical mapping technology adapted for laser eye surgery; wireless networking technology; sensitive microwave receiving systems, including high-gain antennas and low-noise receivers; cancer therapy using knowledge obtained from observing black hole environments; time calibration for GPS; and wireless technology, including fast Fourier transform chips, solid-state oscillators, frequency multipliers, and cryogenics. Other examples include data correlation and recording technology and image restoration techniques, among many others.

For context, it is important to understand the exceedingly weak nature of the typical signals detected by radio telescopes. They can be a million times smaller than the internal receiver noise, and their measurement, or even just their detection, can require bandwidths of many gigahertz and integration times of a day or more. This requirement puts a premium on operating in a very low noise environment. It should be emphasized that serious interference can result from weak transmitters even when they are situated in the sidelobes of a radio astronomy antenna. In addition, radio telescopes are particularly vulnerable to interference from airborne and satellite transmitters, since terrain shielding cannot block the signal from high-altitude emitters.

As mentioned above, radio spectroscopic observations require measurements at frequencies determined by the physical and chemical properties of individual atoms and molecules. In particular, knowledge of the chemical makeup of the universe comes through measurement of spectral lines arising from quantum mechanical transitions, so it is important to protect the frequencies characteristic of the most important atomic and molecular cosmic constituents. However, the necessary parameters are not yet known for all species of interest. In addition, due to the expansion of the universe, even known spectral lines may be Doppler-shifted by up to an order of magnitude for distant objects. Therefore, detection of molecules in distant sources may require observations at frequencies well below the characteristic frequency measured in the laboratory. Thus, observations at spectral frequencies well outside the bands allocated to RAS on a primary or secondary basis are often conducted in order to search for new molecular species and to detect Doppler-shifted spectroscopic lines from both nearby and distant sources, including the very early universe.

The situation with continuum observations of radio emission from cosmic thermal and nonthermal sources, however, is different from that of spectral lines. There are no preferred frequencies, but observations at multiple frequencies and potentially wide bandwidths are required to define the properties of stars, galaxies, quasars, pulsars, and other cosmic radio sources. Historically, narrow bands spaced throughout the spectrum have been given various levels of protection to enable these important *continuum spectral* studies. However, improvements in antenna and receiver design now permit instantaneous fractional bandwidths of 50 percent or more to be used in the latest generation of radio telescopes. This results in an improvement in sensitivity over earlier narrowband systems by up to an order of magnitude; furthermore, broad bandwidths are also used to study many spectral lines simultaneously. Unfortunately, receivers can become nonlinear as a result of RFI at neighboring frequencies, and intrinsically weak emissions can be easily overwhelmed by RFI. Thus, the advent of routine observations over broad bandwidths by radio telescopes requires even more vigilance in RFI mitigation to enable further advances in radio astronomy. In particular, while improved RFI mitigation and excision techniques have expanded the scientific return of many facilities, they are an inferior option relative to a clean, interference-free spectrum. Indeed, it is clear that all users, both passive and active, benefit from a clean spectrum. Thus, while radio astronomy facilities rely in part on geographic shielding and local designations of radio quiet zones to reduce sources of RFI, it is the shared responsibility of all users to assure effective use of the radio spectrum and to enable both active and passive services to coexist.

2

Views of the U.S. National Academies of Sciences, Engineering, and Medicine on Selected WRC-19 and WRC-23 Agenda Items

The following pages provide a discussion of the committee's consensus opinions on the potential impact and relevance of certain agenda items at issue at the upcoming World Radiocommunication Conference (WRC) in 2019 and preliminary agenda items for WRC-23.

AGENDA ITEM 1.2: POWER LIMITS FOR EARTH STATIONS

Agenda Item 1.2 considers "in-band power limits for Earth stations operating in the mobile-satellite service, meteorological-satellite service and Earth exploration-satellite service in the frequency bands 401-403 MHz and 399.9-400.05 MHz, in accordance with Resolution 765 (WRC-15)."

This agenda item invites the consideration of in-band power limits for Earth stations for the Earth Exploration-Satellite Service (EESS) (Earth-to-space) and meteorological-satellite service (MetSat) (Earth-to-space) services.

Radio Astronomy Service

There is a nearby primary allocation from 406.1-410 MHz to the Radio Astronomy Service (RAS). Care should be taken that out-of-band emission (OOBE) levels conform to the listed detrimental power levels in RA.769, even with the establishment of maximum allowed power levels in this neighboring frequency range. The committee notes that several major RAS facilities in the United States operate in or near this frequency range, including the Robert C. Byrd Green Bank Telescope (GBT), the Karl G. Jansky Very Large Array (VLA), the Very Long Baseline Array (an instrument with 10 discrete receiving stations spread over North America), the Owens Valley Radio Observatory, the Sagamore Hill Solar Observatory, and the Arecibo Observatory. Globally, facilities include the Giant Metrewave Radio Telescope in India, the Parkes 64-m in Australia, the Dominion Radio Astrophysical Observatory Synthesis Telescope in Canada, the Radio Telescope Effelsberg in Germany, the Nancay RadioHeliograph in France, and future facilities such as the Square Kilometer Array (SKA) Molongolo Prototype (SKAMP) in Australia and the Five-hundred-meter Aperture Spherical Radio Telescope (FAST) in China. Of particular scientific interest in this band are studies of the Sun, the interstellar medium, pulsars, steep spectrum sources, and active galaxies.

Earth Exploration-Satellite Service

Radio frequencies below 1 GHz 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, and environmental remote sensing. 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. Near 400 MHz, 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. One beacon currently on-orbit operates at 400.032 MHz; and an on-ground beacon operates at 401.25 MHz. Both active transmissions from such satellite beacons and passive observations of radio source scintillation (RSS), related to ionospheric structure, are routinely conducted at these frequencies.[1]

> **Conclusion: The committee concurs with the placement of carefully considered power limits for Earth stations operating in these bands.**

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[1] Portions of this text are taken from National Academies of Sciences, Engineering, and Medicine, *Handbook of Frequency Allocations and Spectrum Protection for Scientific Uses: Second Edition,* The National Academies Press, Washington, D.C., 2015.

AGENDA ITEM 1.5: EARTH STATIONS IN MOTION

Agenda Item 1.5 considers "the use of the frequency bands 17.7-19.7 GHz (space-to-Earth) and 27.5-29.5 GHz (Earth-to-space) by Earth stations in motion communicating with geostationary space stations in the fixed-satellite service and [to] take appropriate action, in accordance with Resolution 158 (WRC-15)."

Of primary concern to the scientific services is the 18.6-18.8 GHz band that has a co-primary allocation for EESS (passive) along with Fixed, FSS (s-E) and Mobile, except for aeronautical mobile services, and Space Research (passive). The Space Research allocation is secondary in Regions 2 and 3. The emission limits and other transmission specifications in the band are regulated by radio regulations (RR) 5.522A and 5.522C. In the United States, power flux density limits in this frequency range are specified in Footnotes US254, US255, and US334.

Earth Exploration-Satellite Service

Frequency bands within the 17.7-19.7 GHz range are used extensively in many operational environments for EESS (see Table 2.1) to provide critical measurements for weather forecasting and studies of climate and environmental impacts. These measurements enable studies of clouds, precipitation, the freeze-thaw transition, snow, and ice. In addition, these measurements enable water vapor profiling and include measurements of sea surface temperatures, winds, and topography. There is significant concern that EESS observations may be contaminated by in-band and out-of-band interference from backscattered space-Earth transmissions if this frequency range is allocated to ESIM.

Specifically, a very important atmospheric water vapor absorption line is located at 22.235 GHz, where K band[2] is centered. This spectral line is highly sensitive to small changes in atmospheric water vapor concentrations, and it is pressure broadened, with some contributions from spectral continuum, which must be measured in the adjacent Ku and Ka bands. These continuum observations are at risk with the proposed frequency allocations to ESIM. Measurements of continuum emission at frequencies both below and

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[2] Nominal frequency ranges for Ku, K, and Ka bands are 12-18, 18-27, and 27-40 GHz, respectively.

TABLE 2.1 Passive EESS Sensors in the 17.7-19.7 GHz Band Under Consideration

Sensor	Satellite	Center Frequency (GHz)	Bandwidth (MHz)
AMSR2	GCOM-W1	18.7	200
GMI	GPM	18.7	200
PMR	WindSat	18.7	750
AMR-2	Jason-2 & 3	18.7	200
MWI	MetOp-SG	18.7	200
MADRAS	Megha-Tropiques	18.7	200
MTVZA-GY	Meteor-M	18.7	200
MWRI	FY-3	18.7	200
MWRI′	HY-2A	18.7	250
SSM/I	DMSP-F15	19.35	250
SSMIS	DMSP-F16, -F17, -F18, -F19	19.35	357

NOTE: Acronyms are defined in Appendix B.

above are critical to understand the shape of this line and to therefore derive a more precise indication of the water vapor concentration. This water vapor measurement is vital for many applications. It has a strong influence on Earth's atmospheric radiation budget and, consequently, influencing climate, formation of clouds, and precipitation—making its precise measurement vital.[3] Lack of water vapor measurements will have a detrimental impact on accurate weather forecasting, including hurricane tracking and landfall prediction, and precise projection for extreme weather events such as hail storms, thunderstorms, tornadoes, and sheer winds.[4] Without such measurements, scientists would not be able to monitor and forecast El Niño Southern Oscillations, affecting prediction of expected storms during hurricane season and of drought, forest fires, flooding, and landslides. Water vapor measurements are indispensable for agricultural and food security, disease dissemination,

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[3] R. Müller, A. Kunz, D.F. Hurst, C. Rolf, M. Krämer, and M. Riese, The need for accurate long-term measurements of water vapor in the upper troposphere and lower stratosphere with global coverage, *Earth's Future* 4:25-32, doi:10.1002/2015EF000321, 2016.

[4] R.M. Rabin, S.F. Corfidi, J.C. Brunner, and C.E. Hane, Detecting winds aloft from water vapour satellite imagery in the vicinity of storms, *Weather* 59:251-257, doi:10.1256/wea.182.03, 2004.

and the economy, among others. Water vapor measurements are also used to correct the path delay caused by water vapor molecules to calibrate altimeter data used for ocean geoid estimation, sea surface topography, and other remote sensing Earth variables.

Despite existing protections in the radio regulations, WindSat, the Advanced Microwave Scanning Radiometer 2, and the Global Precipitation Measurement Microwave Imager have reported radio frequence interference (RFI) over the continental United States at K band (18.7) GHz. In addition, RFI that is reflected from the ocean surface also impedes measurement of ocean surface wind speed. As an example of the increased RFI detected at 18.7 GHz, McKague et al. (2010)[5] reported RFI measurements derived using the difference between observations at 23.8 and 18.7 GHz from WindSat. The data indicate an increase in RFI from 2005 to 2008 and a seasonal dependence. The data also indicate that signals from satellite downlinks, reflected from Earth's surface, are contributing to the RFI detected in the EESS passive sensors. Further degradation of this band will severely limit the validity of these water vapor measurements.

Radio Astronomy Service

While there are no allocations to RAS within these frequency ranges, many radio telescopes, such as the VLA and the GBT in the United States, have receivers that operate at these frequencies. The 17.7-19.7 GHz band is used for measurements of rare chemical species that trace the origins of stars, planets, and life (e.g., cyclopropenylidene). The 27.5-29.5 GHz band is used for broadband continuum observations of distant galaxies and quasars and studies of red-shifted lines of species such as carbon monoxide from distant galaxies and the early universe.

> **Recommendation: Any new Earth Stations in Motion uses should strictly preserve the extensive existing scientific use of the 18.6-18.8 GHz band. New uses of these bands should take due account of** *considering g)* **of Resolution 158 (WRC-15).**

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[5] D. McKague, J. Puckett, and C. Ruf, Characterization of K-band radio frequency interference from AMSR-E, WindSat and SSM/I, pp. 2492-2494 in *2010 IEEE International Geoscience Remote Sensing Symposium*, July 25, 2010, http://ieeexplore.ieee.org/xpl/mostRecentIssue.jsp?punumber=5639672.

AGENDA ITEM 1.6: NON-GSO FSS SATELLITE SYSTEMS AT 37-50 GHZ

Agenda Item 1.6 considers "the development of a regulatory framework for non-GSO FSS satellite systems that may operate in the frequency bands 37.5-39.5 GHz (space-to-Earth), 39.5-42.5 GHz (space-to-Earth), 47.2-50.2 GHz (Earth-to-space) and 50.4-51.4 GHz (Earth-to-space), in accordance with Resolution 159 (WRC-15)."

This agenda item calls for studies of technical, operational, and regulatory provisions for operations in the above bands, including protection of EESS (passive) in the bands 36-37 GHz and 50.2-50.4 GHz and protection of the radio astronomy service in the bands 42.5-43.5 GHz, 48.94-49.04 GHz, and 51.4-54.25 GHz.

Radio Astronomy Service

Of significant concern for RAS is the potential for out-of-band emission (OOBE) from the adjacent frequency allocations to non-GSO FSS systems. As noted in Footnote US342, radio astronomy is particularly vulnerable to space-borne radio interference because terrain shielding cannot be utilized to block transmissions originating at high altitude. Internationally, the following telescopes have receivers that operate in these frequency bands: Very Large Array (U.S.), Very Long Baseline Array (U.S.), Green Bank Telescope (U.S.), Haystack Radio Telescope (U.S.), Australia Telescope Compact Array (Australia), Mopra Radio Telescope (Australia), Parkes Radio Telescope (Australia), and Radio Telescope Effelsberg (Germany).

Administrations are urged to take all practicable steps to protect the radio astronomy band at 42.5-43.5 GHz from harmful interference (RR 5.149) and further regulations regarding acceptable power levels are designated in RR 5.551I and RR 5.551H. This band is used for observations of silicon monoxide (SiO) masers that have rest-frame emission lines at 42.519, 42.821, 43.122, and 43.424 GHz. Measurement of SiO masers from stars and star-forming regions in our Milky Way galaxy yield important information on stellar temperature, density, wind velocities, and other parameters. Polarization observations are also used to trace the magnetic field distribution around the stars. The 42.5-43.5 GHz band is also one of the preferred RAS bands for continuum observations. Its location in the spectrum at approximately twice the frequency of the 23.6-24 GHz continuum band, and its 1 GHz bandwidth, makes it an effective point for sampling the continuum emission at octave or better frequency intervals. Because the sensitivity of continuum observations increases with the bandwidth of the observation, and because this band is the only RAS band below 75 GHz that is a full gigahertz wide, the band is extremely valuable scientifically. Continuum observations in this band provide critical information on the physical state of the interstellar medium associated with star-forming regions, and observations at this frequency have been used to measure the cosmic microwave background emission that reveals details of the early universe. The detrimental levels for continuum and spectral line radio astronomy observations are –227 dBW/m^2/Hz and –210 dBW/m^2/Hz for the average across the full 1 GHz band and the peak level in any single 500 kHz channel (ITU-R RA.769, Tables 1 and 2, respectively).

The narrow RAS frequency allocation at 48.94-49.04 GHz is used to observe carbon monosulfide (CS) in our galaxy. CS observations probe the dense interstellar medium that is the site of star-forming regions, including the formation of solar systems like our own. In addition, based on the observed isotope ratios of $C^{32}S$, $C^{33}S$, and $C^{34}S$, radio astronomers are investigating theories of nucleosynthesis and the star formation history of the Milky Way galaxy. In this band, administrations are urged to take all practicable steps to protect the RAS from harmful interference (RR 5.149), and all airborne emissions are prohibited (RR 5.340). Furthermore, additional protections are stated in RR 5.555B: "the power flux density in the band 48.94-49.04 GHz produced by any geostationary space station in the FSS (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." However, given the geographic shielding of many of the radio astronomy stations, the proposed use of 47.2-50.2 GHz for Earth-to-space transmission by non-GSO satellites is not in conflict automatically. Shared use of this frequency range must consider the existing regulations and potential impact on radio astronomy applications.

Also of concern, as noted in WRC-15 Resolution 159, is the frequency range 51.4-54.25 GHz, which is used by RAS in some nations (RR 5.556).

Earth Exploration-Satellite Service

Of critical importance for EESS is the protection of OOBE of the passive microwave observations in the 36-37 GHz band, with a co-primary allocation. This band is important for observations of weather and climate. In particular, measurements in this band are used to maintain long, time-series records of atmospheric water vapor, clouds, ocean winds, sea ice extent/concentration/type, snow depth, melt/freeze of seasonal snow, and glacier surfaces. In addition, in conjunction with observations at other bands, these measurements provide critical values for regular operations such as weather forecasts. Secondary applications include sea surface temperature and topography. Sensors operating at 37-50 GHz are listed in Table 2.2.

While the 36-37 GHz band is co-primary with Fixed and Mobile services as well as Space Research passive services, effective EESS compatibility has been due to limited use of this band by other services. That said, increased use in the 37.5-39.5 GHz band must allow for a sufficient guard band to protect these and follow-on EESS instruments from widespread transmission from services in adjacent bands.

There is also a primary allocation for EESS (passive) at 50.2-50.4 GHz, with additional protection (transmissions prohibited) under RR 5.340. Observations in this band are used to retrieve atmospheric temperature profiles. It should be noted that the combined proposed services at 47.2-50.2 GHz and at 50.4-51.1 GHz would completely surround the EESS (passive) allocation.

Of special concern is the potential for uplinks to non-GSO satellites operating near 50 GHz to interfere with downward-looking passive EESS. A simple static calculation using the ITU-R Resolution. 750-prescribed levels for FSS Earth stations in adjacent bands shows that a main-beam-to-main-beam coupling between the FSS Earth station uplink into the EESS (passive) receiver will exceed the ITU-R RS.2017 protection levels by at least 71 dB.

TABLE 2.2 EESS Sensors Operating at 37-50 GHz

Sensor	Center Frequency (GHz)	Bandwidth (MHz)
Windsat	37	2000
SSM/I	37	1000
SSMIS	37, 50.3	1500, 400
GMI	36.5	1000
AMSR2	36.5	1000
AMSUA	50.3	180
ATMS	50.3, 51.76	180, 400

NOTE: In addition to providing critical scientific observations, building and deploying these sensors represents a multibillion dollar U.S. investment. Acronyms are defined in Appendix B.

Recommendation: Given the scientific importance of the 42.5-43.5 GHz and 48.94-49.04 GHz Radio Astronomy Service (RAS) frequency allocations, any Fixed-Satellite Service allocations to non-geostationary orbit satellite systems should consider the impact of aggregate emissions, both out-of-band and in-band, on the neighboring and coexisting RAS allocations. Similarly, continued protection of the Earth Exploration-Satellite Service (EESS) (passive) bands at 36-37 GHz and 50.2-50.4 GHz is critical for global weather forecasting and climate research. Emission limits, as specified in radio regulations 5.555B and ITU-R RA.769-2, should be respected, and guard bands should be implemented to protect frequency allocations to passive scientific services from out-of-band emissions. A static analysis should be included to make sure that Earth stations near the equator radiating toward zenith do not exceed the protection levels stipulated by Recommendation ITU-R RS.2017 into the downward-looking EESS (passive) receivers. This is particularly important given that the EESS sensors operating at 50.2-50.4 GHz are nadir-pointing.

AGENDA ITEM 1.7: SPECTRUM NEEDS FOR NON-GSO SATELLITES

Agenda Item 1.7 considers "spectrum needs for telemetry, tracking and command in the space operation service for non-GSO satellites with short duration missions, to assess the suitability of existing allocations to the space operation service, and, if necessary, to consider new allocations, in accordance with Resolution 659 (WRC-15)."

The frequency ranges under consideration are 150-174 MHz and 400.15-420 MHz. Of key import for this agenda item is that propagation is largely unimpeded by the atmosphere at these low frequencies so that geographic shielding is largely ineffective.

Radio Astronomy Service

There are primary allocations from 150.05-153 MHz and 406.1-410 MHz to RAS within the bands being considered. ITU RR 5.149 urges administrators to take all practicable steps to protect the RAS from harmful interference in the 150.05-153 MHz frequency range (Region 1) and the 406.1-410 MHz frequency range (global). The detrimental interference levels for these bands are -259 dBW/m^2/Hz and -255 dBW/m^2/Hz, respectively (ITU-R RA.769, Table 1). A proposed allocation within this range could have a severe impact on RAS, making it difficult or impossible to conduct scientific research in these bands. In particular, radio telescopes can be greatly impacted by space-to-Earth transmissions because emissions from satellites often come from high-elevation angles directly into the main beam of radio telescopes. Significantly, at these low frequencies, radio telescopes have a correspondingly larger primary beam. The typical antennas used at these frequencies have significant receptivity in all directions, and strong interference places difficult demands on the dynamic range of the signal processing systems. In these circumstances, the presence of strong interference anywhere in the sky may corrupt the observations or require excessive computational resources to mitigate the interference in post-processing analysis. Thus, at these frequencies, RAS observations are particularly vulnerable to interference from satellite operations.

The committee notes that several major RAS facilities operate in the 406-410 MHz frequency range, including the GBT, the VLA, the Very Long Baseline Array (an instrument with 10 discrete receiving stations spread over North America), the Owens Valley Radio Observatory, the Sagamore Hill Solar Observatory, and the Arecibo Observatory, all in the United States. Globally, facilities include the Giant Metrewave Radio Telescope in India, the Parkes 64-m in Australia, the Dominion Radio Astrophysical Observatory Synthesis Telescope in Canada, the Radio Telescope Effelsberg in Germany, the Nancay RadioHeliograph in France, and future facilities such as SKAMP in Australia and FAST in China. Of particular scientific interest in this band are studies of the Sun, interstellar medium, pulsars, steep spectrum sources, and active galaxies.

There are several existing and planned facilities operating in the 150-153 MHz frequency range that conduct observations for the above scientific topics and also for studies of the epoch of reionization (EoR), when the first luminous sources emerged in the universe. Existing facilities in the United States include the Hydrogen EoR Array (HERA), which is being tested at Green Bank and the University of California, Berkeley, and will be built in South Africa. International facilities working in this frequency range include the Low Frequency Array (LOFAR) in the Netherlands (and stations across Europe), the Murchison Widefield Array (MWA) in Australia, the Mauritius Radio Telescope, and the Giant Metrewave Radio Telescope in India. Future facilities that will eventually operate in this frequency range include FAST in China and the low-frequency component of the Square Kilometer Array (SKA-Low), being planned for Australia.

Earth Exploration-Satellite Service

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. Near 150 MHz, satellite and ground-based phase coherent radio beacons measure TEC and the amplitude and phase fluctuations in the trans-ionospheric signals (i.e., scintillations) related to the irregularities along the propagation path. One beacon currently on-orbit operates at 150.012 MHz. Both active transmissions from satellites and observation of RSS are routinely conducted. A relatively new field of ionospheric and plasmaspheric remote sensing has recently opened using ground-based interferometers operating at meter wavelengths. For example, the P-band system on the VLA (~236-492 MHz) measures tiny fluctuations in TEC (or delta-TEC). These fluctuations can be caused by a variety of disturbances, including natural (e.g., from space weather) and human-made (e.g., from underground explosions). Measurements are made by utilizing natural cosmic sources as background beacons against which ionized atmospheric turbulence and waves can be characterized and tracked. Ionospheric remote sensing measurements are also conducted from the MWA in Australia (80-300 MHz) and LOFAR in Europe (10-90 MHz, 110-250 MHz).[6]

> **Recommendation: Any spectrum allocation should be done in such a way so as to preserve access of the Radio Astronomy Service and Earth Exploration-Satellite Service to the bands allocated to them, including appropriate frequency separations conforming to the interference criteria provided in ITU-R RA.769 and ITU-R RS.2017. This is particularly important since, in many cases, at these frequencies, satellite transmissions will be made directly into the main beam of the individual elements of the radio telescope array. Further, if new allocations are made, Radio Regulations 5.208A and 5.208B and Resolution 739 should be updated to reflect the importance of protecting radio astronomy services in these bands.**

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[6] Portions of this text are taken from National Academies of Sciences, Engineering, and Medicine, *Handbook of Frequency Allocations and Spectrum Protection for Scientific Uses: Second Edition*, The National Academies Press, Washington, D.C., 2015.

AGENDA ITEM 1.8: GLOBAL MARITIME DISTRESS SAFETY SYSTEMS

Agenda Item 1.8 considers "possible regulatory actions to support Global Maritime Distress Safety Systems (GMDSS) modernization and to support the introduction of additional satellite systems into the GMDSS, in accordance with Resolution 359 (Rev. WRC-15)."

This agenda item proposes to use the Mobile Satellite (Earth-to-space) and Aeronautical Radio Navigation bands between 1616-1626.5 MHz, or parts thereof, to add an additional satellite system into the GMDSS. Resolution 359 specifically calls for protection for allocations in neighboring bands, which include a radio astronomy band at 1610.6-1613.8 MHz.

Radio Astronomy Service

The 1610.6-1613.8 MHz band is used for spectral line observations of the hydroxyl radical (OH). The OH transition at rest frequency 1612 MHz is one of the most important spectral lines for RAS and is listed as such in Recommendation ITU-R RA.314. OH was the first cosmic radical to be detected at radio frequencies and continues to be a powerful research tool. In its ground state, the OH molecule produces four spectral lines at frequencies of approximately 1612, 1665, 1667, and 1720 MHz, all of which have been observed in emission and in absorption in our Milky Way galaxy, as well as in external galaxies. The study of OH lines provides information on a wide range of astronomical phenomena—for example, the formation of protostars and the evolution of stars. To interpret most observations made of the OH molecule, it is necessary to measure the relative strength of several of these lines. The loss of the ability to observe any one of these lines will prevent the study of these classes of physical phenomena.

Spectral line observations are made using spectrometers that can simultaneously integrate the power in each of a large number of frequency channels distributed across the frequency band used. The width and number of channels has to be large enough to accurately reproduce the spectral shape of the emission or absorption received by the radio telescope. Instantaneous channel bandwidths of typically ~1 kHz are used, depending on the scientific program.[7]

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[7] From ECC Report 171, "Impact of Unwanted Emissions of Iridium Satellites on Radioastronomy Operations in the Band 1610.6-1613.8 MHz," Electronic Communications Committee of the European Conference of Postal and Telecommunications Administrations, Tallinn, Estonia, October 2011.

One challenge for coordinated spectral sharing of this frequency range is that observations in the 1612 MHz band are sometimes conducted on targets of opportunity (e.g., particularly on objects such as comets, which have been observed to produce transient emissions in this line). Observations in the 1612 MHz band are carried out at a number of radio astronomy sites in numerous countries worldwide. In the United States, these include the VLA, the GBT, the Arecibo Observatory, the Allen Telescope Array, and the 10 stations of the Very Long Baseline Array. Internationally, current facilities include the Nancay RadioHeliograph Telescope (France), Jodrell Bank (United Kingdom), MERLIN (United Kingdom), the 100-m Radio Telescope Effelsberg (Germany), the Westerbork Synthesis Radio Telescope (Netherlands), the stations of the European VLBI Network, the Medicina Radio Observatory (Italy), the 64m Parkes Observatory (Australia), the Australia Telescope Compact Array (Australia), the Australian Square Kilometre Array Pathfinder (Australia), the stations of the Australian Long Baseline Array (Australia), MeerKAT (South Africa), FAST (China), the Russian VLBI network (Russia), the RATAN-600 (Russia), the ROT-54/2.6 (Armenia), and the Brazilian Decimetric Array (Brazil).

Recommendation: The committee supports modernization of the Global Maritime Distress Safety Systems as long as radio astronomy operations are protected. There is special concern for new satellite operations because one communication satellite operator in this band has had a history of producing interference (e.g., ECC Report 171: "Impact of Unwanted Emissions of Iridium Satellites on Radioastronomy Operations in the Band 1610.6-1613.8 MHz"). At this time, the satellite operator is replacing the present generation of satellites with new ones that may address this issue. Tests with the new system are expected to be completed before WRC-19. Given the concerns raised, the results of these tests should be taken into consideration before radio regulations relative to this band are adopted.

AGENDA ITEM 1.9.1: AUTONOMOUS MARITIME RADIO DEVICES

Agenda Item 1.9.1 considers "regulatory actions within the frequency band 156-162.05 MHz for autonomous maritime radio devices to protect the Global Maritime Distress Safety Systems (GMDSS) and automatic identification systems (AIS), in accordance with Resolution 362 (WRC-15)."

The frequency ranges under consideration are 156-162.05 MHz. The devices used for AIS are likely to be low cost, numerous, and primarily deployed in oceans and lakes. Any unlicensed device is a potential interferer if deployed near a radio telescope.

Radio Astronomy Service

There is a primary allocation to RAS from 150.05-153.0 MHz. There are several existing and planned radio astronomy facilities that operate in the 150-153 MHz frequency range. These facilities are used for studies of the Sun, interstellar medium, pulsars, steep spectrum sources, and active galaxies, as well as the EoR, when the first luminous sources emerged in the universe. Facilities in the United States include HERA, being tested at Green Bank and Berkeley and to be built in South Africa. International facilities working in this frequency range include the LOFAR in the Netherlands (with international stations across Europe), the MWA in Australia, the Mauritius Radio Telescope, and the Giant Metrewave Radio Telescope in India. Future facilities that will eventually operate in this frequency range include FAST in China and the low-frequency component of SKA-Low, being planned for Australia. While the geographic locations of most radio facilities should help mitigate the possibility of RFI from GMDSS, if deployed only in maritime environments, care should be taken that aggregate out-of-band emission (OOBE) levels from these devices still conform to the provisions established by ITU-R RA.769, which sets the detrimental interference level as -259 dBW/m^2/Hz in this band.

Earth Exploration-Satellite Service

Active techniques in this band are 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. The Irkutsk incoherent scatter radar currently operates at these frequencies.[8]

> **Recommendation: Any spectrum allocation should be done in such a way so as to preserve access of the Radio Astronomy Service and the Earth Exploration-Satellite Service to the bands allocated to them, including appropriate frequency separations that conform to ITU-R RA.769 and ITU-R RS.2017.**

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[8] Portions of this text are taken from National Academies of Sciences, Engineering, and Medicine, *Handbook of Frequency Allocations and Spectrum Protection for Scientific Uses: Second Edition*, The National Academies Press, Washington, D.C., 2015.

AGENDA ITEM 1.9.2: MARITIME MOBILE-SATELLITE ALLOCATIONS

Agenda Item 1.9.2 considers "modifications of the Radio Regulations, including new spectrum allocations to the maritime mobile-satellite service (Earth-to-space and space-to-Earth), preferably within the frequency bands 156.0125-157.4375 MHz and 160.6125-162.0375 MHz, to enable a new VHF data exchange system (VDES) satellite component, while ensuring that this component will not degrade the current terrestrial VDES components, applications specific messages (ASM) and automatic identification systems (AIS) operations and not impose any additional constraints on existing services in these and adjacent frequency bands as stated in *recognizing d)* and *e)* of Resolution 360 (Rev. WRC-15)."

The frequency ranges under consideration are 156.0125-157.4375 MHz and 160.6125-162.0375 MHz. The committee notes that propagation is largely unimpeded by the atmosphere at these low frequencies. Thus, geographic shielding is less effective in mitigating RFI in these bands.

Radio Astronomy Service

There is a primary allocation to RAS from 150.05-153.0 MHz. Care should be taken that out-of-band emission (OOBE) levels still conform to the provisions established by ITU-R RA.769, which sets the detrimental interference level at -259 dBW/m^2/Hz in this band. In particular, at these low frequencies, telescopes have a correspondingly larger primary beam and can be greatly impacted by space-to-Earth transmissions. The typical antennas used at these frequencies have significant receptivity in all directions, and strong interference places difficult demands on the dynamic range of the signal processing systems. Thus, there is significant concern that emissions from satellites will come from high-elevation angles directly into the main beam or sidelobes of radio telescopes.

There are several existing and planned facilities operating in the 150-153 MHz frequency range that conduct observations of the Sun, the interstellar medium, pulsars, steep spectrum sources, and active galaxies, as well as the EoR, when the first luminous sources emerged in the universe. Facilities in the United States include HERA, which is being tested at Green Bank and Berkeley and will be built in South Africa. International facilities working in this frequency range include the LOFAR in the Netherlands (with international stations across Europe), the MWA in Australia, the Mauritius

Radio Telescope, and the Giant Metrewave Radio Telescope in India. Future facilities that will eventually operate in this frequency range include FAST in China and the low-frequency component of the SKA-Low, being planned for Australia.

Earth Exploration-Satellite Service

Active techniques in this frequency range are 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. The Irkutsk incoherent scatter radar currently operates at these frequencies.[9]

> **Recommendation: Any spectrum allocation should be done in such a way so as to preserve access of the Radio Astronomy Service and the Earth Exploration-Satellite Service to the bands allocated to them, including appropriate spectral separations that conform to interference criteria provided by ITU-R RA.769 and ITU-R RS.2017. This is particularly important since in many cases, at these frequencies, satellite transmissions will be made directly into the main beam of the individual elements of the radio telescope array. Further, if new allocations are made, RR 5.208A and 5.208B and Resolution 739 should be updated to reflect the importance of protecting radio astronomy services in these bands.**

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[9] Portions of this text are taken from National Academies of Sciences, Engineering, and Medicine, *Handbook of Frequency Allocations and Spectrum Protection for Scientific Uses: Second Edition*, The National Academies Press, Washington, D.C., 2015.

AGENDA ITEM 1.13: FUTURE DEVELOPMENT OF INTERNATIONAL MOBILE TELECOMMUNICATIONS

Agenda Item 1.13 considers "identification of frequency bands for the future development of International Mobile Telecommunications (IMT), including possible additional allocations to the mobile service on a primary basis, in accordance with Resolution 238 (WRC-15)."

The frequency bands proposed in Resolution 238 (WRC-15) for future development of IMT applications include 24.25-27.5 GHz, 31.8-33.4 GHz, 37.0-40.5 GHz, 40.5-42.5 GHz, 42.5-43.5 GHz, 45.5-47 GHz, 47-47.2 GHz, 47.2-50.2 GHz, 50.4-52.6 GHz, 66-76 GHz, and 81-86 GHz. As a general technical note applicable to all proposed new frequency allocations, care must be taken in assessment of the impact on incumbent RAS and EESS bands. Absence of detectable emissions does not imply that the frequencies are not in use by the passive service. While RAS bands can be protected regionally by limiting emissions within a certain radius of a facility, this is not the case with EESS observations, which are typically satellite based and global in nature. Almost all of the frequency ranges under consideration here are adjacent to, or congruent with, EESS and RAS passive allocations. Of particular concern for RAS and EESS are possible new primary allocations to IMT at 31.8-33.4 GHz and 40.5-42.5 GHz, which are adjacent to primary allocations to the passive services.

The discussion below includes text from comments filed by the Committee on Radio Frequencies in response to the Federal Communications Commission (FCC) Notice of Inquiry (October 2014),[10] Notice of Proposed Rulemaking (October 2015),[11] and Further Notice of Proposed Rulemaking (July 2016)[12] on a similar topic. For simplicity in the headers, the broad frequency ranges are referred to as "24 GHz Band": 24.25-27.5 GHz; "31 GHz Band": 31.8-33.4 GHz; "37/42 GHz Bands": 37.0-40.5 GHz, 40.5-42.5 GHz, and 42.5-43.5 GHz; "47/50 GHz Bands": 45.5-47 GHz, 47-47.2 GHz, 47.2-50.2 GHz, and 50.4-52.6 GHz; and "70/80 GHz Bands": 66-76 GHz and 81-86 GHz.

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[10] FCC Docket RM-11713.

[11] FCC Dockets GN 14-177, IB 15-256, RM-11664, WT 10-112, and IB 97-95.

[12] FCC Dockets GN 14-177, IB 15-256, RM-11664, WT 10-112, and IB 97-95.

Radio Astronomy Service

In general, radio observatories that operate above 24 GHz are located in remote, high, and dry sites, where signal attenuation is due only to the inverse square law with little atmospheric attenuation, even at high frequencies. Thus, consideration of RFI to RAS must include analysis appropriate to the geographic location of the observatory. In the United States, these observatories include the VLA (New Mexico), the GBT (West Virginia), the Haystack Observatory (Massachusetts), Owens Valley (California), the 10 sites included in the Very Long Baseline Array, and the 12m ALMA prototype antenna located at Kitt Peak (Arizona). Internationally, these include the Large Millimeter Telescope (Mexico); the Mopra and the Australian Telescope Compact Array in Australia; the Nobeyama 45m Telescope and Nobeyama Millimeter Array in Japan; the 100-m Radio Telescope Effelsberg in Germany; the IRAM 30m in Spain; the ALMA prototype antenna recently deployed to Greenland; the Atacama Large Millimeter Array (ALMA) in Chile; the Plateau de Bure Interferometer (and the planned expansion of PdBI to NOEMA) in France; the Onsala 20m telescope in Sweden; the 10 stations of the European VLBI Network (EVN), including Medicina, Noto, and Sardinia in Italy, Metsahovi in Finland, and Yebes in Spain; the Korean VLBI Network (KVN) in Korea; DASI at the South Pole; the Delingha Observation Station and the planned Qitai Radio Telescope in China; the RATAN-600, Galenki RT-70, and Suffa RT-70 radio telescopes in Russia; and the Yevpatoria RT-70 radio telescope in Crimea. In addition, radio astronomy observatories are particularly vulnerable to out-of-band emission (OOBE), including the harmonics of mobile devices. Full consideration of the impact of new allocations must include the possibility of OOBE and the sum of aggregate emissions from multiple devices.

24 GHz Band

The frequency range 23.6-24.0 GHz is protected by RR 5.340 (no transmissions are permitted) and is 250 MHz from the lower edge of the frequency range under consideration. The protected band includes spectral line transitions associated with ammonia at 23.694, 23.723, and 23.870 GHz, which is observed in molecular clouds in the Milky Way. Any use of the lower frequencies in the range allocated for IMT (i.e., those just above 24.0 GHz) must include measures to protect the 23.6-24.0 GHz RAS band from OOBE.

31 GHz Band

For RAS, the primary allocation at 31.3-31.5 GHz (and also 31.5-31.8 GHz in Region 2) is vitally important for continuum measurements because it lies near the minimum in atmospheric absorption in this part of the spectrum. Combined with measurements in other bands at approximately octave intervals, such measurements provide information on the broad spectrum of astronomical radio sources, such as supernovae, pulsars, radio galaxies, and quasars. The detrimental interference level for this band is -228 dBW/m^2/Hz, averaged across the full 500 MHz width of the band (ITU-R RA.769, Table 1), and as such, careful filtering will be required for the proposed adjacent IMT allocation at 31.8-33.4 GHz.

37/42 GHz Bands

Of primary concern for RAS is that there is a primary allocation at 42.5-43.5 GHz that is congruent with, and adjacent to, several of the frequency ranges under consideration for IMT (e.g., the proposed new primary allocation of 40.5-42.5 GHz and the existing co-primary allocation at 42.5-43.5 GHz). This frequency band is protected such that administrations should take all practicable steps to protect RAS from harmful interference (ITU RR 5.149). Spectral line emission of SiO at 42.519, 42.821, 43.122, and 43.424 GHz are among those of greatest importance to radio astronomy.[13] This frequency band is important for detection of strong SiO maser emissions from stars and star-forming regions. Measurements of these masers yield important information on stellar temperature, density, wind velocities, and other parameters. The 42.5-43.5 GHz band is also one of the preferred RAS bands for continuum observations.[14] The detrimental levels for continuum and spectral line radio astronomy observations are -227 dBW/m^2/Hz and -210 dBW/m^2/Hz for the average across the full 1 GHz band and the peak level in any single 500 kHz channel (ITU-R RA.769, Tables 1 and 2, respectively). Careful studies will be required to determine whether mobile and/or fixed point-to-point services in the 42 GHz band can be consistent with protection of the RAS in the 42.5-43.5 GHz band.[15]

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[13] See International Telecommunication Union (ITU) Radiocommunications Bureau, *Handbook on Radio Astronomy*, Third Edition, http://www.itu.int/pub/R-HDB-22, 2013, p. 37, Table 3.2.

[14] Ibid., p. 35, Table 3.1.

[15] From CORF Comments to the FCC in GN Docket No. 14-177; IB Docket No. 15-256; RM-116640; WT Docket No. 10-112; and IB Docket No. 97-95; filed March 16, 2016.

Furthermore, pursuant to ITU RR 5.149, radio observatories are protected from interference in the frequency range 36.43-36.5 GHz, which is used to observe spectral line emission from methanol (36.169 GHz) located in molecular clouds in the Milky Way. This frequency range falls within the EESS passive band window at 36-37 GHz. Thus, OOBE from IMT allocations at 37.0-40.5 GHz are of concern for RAS as well.

47/50 GHz Bands

A very narrow spectral window is allocated to RAS within the frequency ranges of interest. Specifically, pursuant to ITU RR 5.149, radio astronomy observatories are protected from interference in the frequency range 48.94-49.04 GHz. Furthermore, to protect radio astronomy, all airborne emissions are prohibited in this frequency range (ITU RR 5.340), which is used to observe spectral line emission from carbon monosulfide in molecular clouds. Since this RAS allocation falls within the IMT allocation of 47.2-50.2 GHz, care must be taken to retain the protections for RAS, including the restrictions on airborne use of the narrow RAS frequency allocation.

In addition, due to the potential for OOBE arising from harmonics, there are also significant concerns about this and other IMT allocations between 45.5 and 52.6 GHz (45.5-47 GHz, 47-47.2 GHz, and 50.4-52.6 GHz). Specifically, all emissions are prohibited in the frequency ranges of 86-92 GHz and 100-102 GHz (ITU RR 5.340), which correspond to frequencies associated with the first harmonic of these IMT allocations. Furthermore, radio astronomy has primary allocations, and radio observatories are to be protected from harmful interference (ITU RR 5.149), in the frequency ranges of 92-94 GHz, 94.1-95 GHz, and 95-100 GHz. Thus, consideration of IMT applications at this frequency band should take into account the feasibility of dampening the harmonics from mobile devices to meet the low emission levels required to protect RAS.

70/80 GHz Bands

The IMT allocations at 66-76 GHz and 81-86 GHz are located near protected frequency bands for RAS. Radio astronomy observatories are to be protected from harmful interference in the frequency range 76-86 GHz (ITU RR 5.149), and all emissions are prohibited from 86-92 GHz (ITU RR 5.340). For the latter, the detrimental levels for continuum and spectral line radio astronomy observations are -228 dBW/m^2/Hz and -208 dBW/m^2/Hz for the average across the full 6 GHz band and the peak level in any single 1 MHz channel (ITU-R RA.769, Tables 1 and 2, respectively). Radio astronomy observatories that operate at these high frequencies are usually located at high, dry sites so that little, if any, terrain shielding is in effect. Thus, the signal attenuation with distance is due only to the inverse square law, with some small atmospheric attenuation.

Indeed, because there is relatively little absorption from atmospheric O_2 and H_2O at these frequencies, these bands constitute some of the most important high-frequency ranges for both continuum and line observations of celestial objects.[16] The growing understanding of star formation and stellar evolution is critically dependent on millimeter wave observations. In addition, highly red-shifted galaxies can be detected over the full range of the RAS allocations. Furthermore, a new scientific field, astrochemistry, has arisen from the discovery of a very wide range of complex molecules in space. It is essential that the protection presently available to radio astronomy observatories remain in place.

Earth Exploration-Satellite Service

ITU-R-RS.2017 defines interference criteria for all EESS passive satellites. For the bands in question, consideration of OOBE is particularly important for the mobile communication bands that are proposed adjacent to passive Earth remote sensing bands. Specifically, it is imperative that any proposed IMT bands include spectral separation (guard bands) to protect the incumbent users of the passive bands, who have designed and developed EESS missions without the expectation of mobile communications in such close spectral proximity. These incumbent EESS missions represent billions of dollars in development and deployment of instruments and satellites. Most incumbent passive EESS users at 24, 31.5, and 37 GHz operate in a direct detection (homodyne) mode with limited protection against OOBE. In direct detection, band definition is achieved with filters that are limited by the properties of the materials used in the filter itself. For a given material, the bandwidth of a filter is proportional to the central frequency, so the width of the necessary guard bands to suppress emissions to a desired level also increases in proportion to the frequency. In other words, proportionally larger guard bandwidths are needed as the frequency increases. Furthermore, for the same reasons, it is likely that mobile devices with limited size and cost will not be able to adequately filter their OOBE

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[16] See ITU, *Handbook on Radio Astronomy*, supra note 3, Tables 3.1 and 3.2.

to meet the stringent requirements of the adjacent passive bands. Creating guard bands proportional to the operating frequency is the only way to protect the incumbent EESS applications that are vital for global weather forecasting and climate research. Passive satellite missions operating in the bands in question are enumerated in Table 2.3.

24 GHz Band

The frequency range 23.6-24.0 GHz is protected by ITU RR 5.340 (no transmissions are permitted) and is 250 MHz from the lower edge of the frequencies under consideration. The protected band is intended to cover a water vapor absorption line that is unique in the atmosphere in that it is not opaque at sea level. This band is extremely important for forecasting the weather and is used oper-

TABLE 2.3 EESS (Passive) Satellite Missions Relevant to Agenda Item 1.13

Sensor	Satellite	Center Frequency (GHz)	Bandwidth (MHz)
AMSR2	GCOM-W1	23.8, 36.5, 89	400, 1000, 3000
AMSU-A, ATMS	NOAA-15, NOAA-18, NOAA-19, MetOp-A, MetOp-B, Suomi NPP	23.8, 31.4, 50.3, 51.76, 52.8, 89.5	270, 180, 180, 400, 400, 5000
GMI	GPM	23.8, 36.5, 89	400, 1000, 6000
PMR	WindSat	23.8, 37[a]	500, 2000
AMR-2	Jason-2 and Jason-3	23.8	
MWI	MetOp-SG	23.8, 31.4, 50.3, 52.61, 89	400, 200, 400, 400, 4000
MADRAS	Megha-Tropiques	23.8, 36.5, 89	200, 500, 1350
MTVZA-GY	Meteor-M	23.8, 31.5, 36.7, 42, 48, 52.8	400, 400, 400, 400, 400, 400
MWRI	FY-3	23.8, 36.5, 89	400, 1000, 6000
MWRI′	HY-2A	23.8, 37	400, 1000
SSM/I, SSMIS	DMSP-F15, -F16, -F17, -F18, -F19	22.2, 37[a], 50.3[b], 52.8[b], 85.5	401, 1600, 380, 389, 1500

NOTE: Acronyms are defined in Appendix B.

[a] Department of Defense satellites operate outside the passive protected band and into a shared government use band.

[b] Not every instrument in the list has every channel. SSMIS has the full channel suite.

ationally by many nations. Any use of the lower frequencies in the proposed range for IMT (i.e., those just above 24.0 GHz) must include measures to protect the 23.6-24.0 GHz EESS band.

31 GHz Band

The two primary EESS (passive) allocations of concern in this frequency range are (1) 31.3-31.5 GHz, in which all emissions are prohibited, and (2) 31.5-31.8 GHz, in which all emissions are prohibited in Region 2 (ITU RR 5.340). The protected 31.3-31.8 GHz frequency band is used by a variety of satellites for weather forecasting, notably the ATMS instrument on the National Oceanic and Atmospheric Administration (NOAA)/NASA Suomi National Polar-orbiting Partnership (NPP) satellite and the AMSU-A instruments on NOAA 15, 18, and 19 satellites as well as the European MetOp A and B satellites. Data products obtained from this frequency band include cloud liquid water and integrated water vapor, both of which are key to initializing global weather forecast models.

There is significant concern regarding OOBE from the proposed adjacent IMT band at 31.8-33.4 GHz because the instrument filter rejection levels for typical EESS sensors are limited. Indeed, the typical 3 dB band edge for Earth remote sensing instruments is only 10 MHz from the proposed IMT band. Thus, guard band protection is required to preserve the incumbent use by EESS. For example, a single 1 W isotropic radiator at 31.3 GHz results in an equivalent thermal signal of 30 K and will need to be rejected at >20 dB to not be seen by NASA/NOAA's ATMS.[17] Similarly, for mobile applications, 1,000 devices operating in that band will need to be rejected by >50 dB.

37/40 GHz Bands

There is an important primary EESS allocation at 36-37 GHz that is used by many agencies and is adjacent to the 37.0-40.5 GHz band under discussion for IMT applications. This band offers the largest

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[17] The ATMS instrument is the next-generation cross-track microwave sounder providing atmospheric temperature and moisture measurements for operational weather and climate applications. ATMS is a key instrument that collects microwave radiation measurements from Earth's atmosphere and surface all day and all night, even through clouds. ATMS currently flies on the Suomi NPP satellite mission and will fly on the JPSS-1 and JPSS-2 satellite missions. See National Oceanic and Atmospheric Administration, Joint Polar Satellite System, "Advanced Technology Microwave Sounder (ATMS)," http://www.jpss.noaa.gov/atms.html.

contiguous bandwidth between the 23 GHz water line and the 60 GHz oxygen line complex. Because this bandwidth affords unmatched radiometric sensitivity, scientific applications are found in a range of environmental conditions, including atmospheric water vapor, precipitation, cloud properties, freeze/thaw conditions, snow, sea ice, sea-surface temperature, ocean vector winds, and ocean topography (tracing conditions such as El Niño).[18] The data obtained by satellite observations are assimilated into global circulation models and affect directly the quality of weather forecasting.

Earth remote sensing observations are conducted with instruments on satellites such as the NASA Global Precipitation Measurement Mission's Microwave Imager, the Department of Defense (DOD) Special Sensor Microwave/Imager and WindSat instruments, and the Japan Aerospace Exploration Agency Global Change Observation Mission-Water 1's Advanced Microwave Scanning Radiometer 2. As described above, many of these sensors operate in direct detection mode, and their ability to reject OOBEs is limited by basic physics. Of particular concern is that the proposed IMT bands will offer no protection for these EESS instruments because the band definitions line up precisely with the allocated passive bands. Furthermore, with lower orbits and larger receiver antennas, these EESS passive sensors are far more susceptible to terrestrial interference than the ATMS described above. With multiple interfering sources, assuming the sources are incoherent, the interfering powers received at the satellite add directly; with, say, 1,000 interfering mobile sources, the interference level will be increased by 30 dB. OOBE rejection levels need to be increased by 16 dB over the ATMS levels specified above to >36 dB and >66 dB rejection for a single mobile device and 1,000 mobile devices, respectively. It would therefore be prudent to include spectral separation (guard bands) designed to match the incumbent users' filter response in order to preserve these expensive and important assets. Alternatively, dynamic allocation of frequencies could be mandated to avoid interfering with the satellite receptors when the footprint of the satellite crosses terrain, as determined by ephemerides and instrument beam.

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[18] See NASA, "Global Precipitation Mission," last updated August 3, 2017, http://www.nasa.gov/mission_pages/GPM/spacecraft/; NASA, "TMI," http://pmm.nasa.gov/node/161; Jet Propulsion Laboratory, "SSM/I," http://podaac.jpl.nasa.gov/SSMI; and NOAA, "Sensors—WindSat Overview," https://www.star.nesdis.noaa.gov/mirs/windsat.php.

47/50 GHz Bands

The IMT allocation at 50.4-52.6 GHz band is placed directly between two passive bands used for microwave temperature sounding. Specifically, all emissions are prohibited for 50.2-50.4 GHz and 52.6-54.25 GHz (ITU RR 5.340). In addition, with the IMT allocation at 47.2-50.2 GHz, the lower of these two bands will be completely surrounded by active users (see also Agenda Item 1.6). These EESS allocations are used by an international suite of weather satellites (see Table 2.3). The instruments aboard these satellites operate on the edge of the 58-59 GHz oxygen line complex and are used to measure temperature as a function of altitude. The data obtained from these instruments are used to initialize global and regional weather forecast models and therefore have a large impact on the ability to forecast weather events, including life-threatening and costly extreme weather events. Because this band is far from the center of the oxygen line complex, observations penetrate deep into the atmosphere with little atmospheric attenuation. This makes these bands susceptible to RFI, and care must be taken to protect them. As with several of the other instruments described above, guard bands must be provided, accounting for technological limitations of both the incumbent receivers and the proposed transmitters to adequately protect weather forecast ability. It should be noted that when combined with proposed services at 47.2-50.2 GHz, the EESS (passive) allocation at 50.2-50.4 GHz would be completely surrounded by active users.

70/80 GHz Bands

The IMT allocation at 81-86 GHz is immediately adjacent to a protected EESS (passive) band at 86-92 GHz, for which all emissions are prohibited (RR 5.340). This band is used by satellite-based instruments such as the NOAA AMSU-A, AMSU-B, and ATMS; NASA's Global Precipitation Measurement Mission's Microwave Imager (GMI); the DOD's SSMI and SSMI/S; and the AMSR2 instruments. The primary data product from these observations is a measurement of precipitation (from cloud ice scattering), which is widely used to provide real-time imagery for weather forecasting (such as NOAA's NexRad system).[19] The frequency range used tends to be quite broad in order to reduce the effect of the higher receiver noise at these frequencies. As such, this band is also highly susceptible to OOBE

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[19] See NOAA, "NWS Southern Region Headquarters," http://www.weather.gov/srh/sod/radar/radinfo/radinfo.html.

and, being at a higher frequency and having a large bandwidth, will require an even larger spectral allocation for guard banding to preserve the incumbent EESS applications.

> **Recommendation: While the committee recognizes the need to share spectral frequencies, care should be taken in the assessment of the impact on incumbent Radio Astronomy Service (RAS) and Earth Exploration-Satellite Service (EESS) bands, particularly with regard to spectral separation. In all cases, it is critical that the limits of out-of-band emissions into the RAS and EESS bands must comply with ITU-R RA.769 (Tables 1, 2, and 3) and ITU-R RS.2017 (Table 1), respectively. In addition to an exclusion zone around each RAS facility, likely growth of the International Mobile Telecommunications service and the impact of future aggregate interference must be taken into account.**

AGENDA ITEM 1.14: HIGH-ALTITUDE PLATFORM STATIONS

Agenda Item 1.14 considers "on the basis of ITU-R studies in accordance with Resolution 160 (WRC-15), appropriate regulatory actions for high-altitude platform stations (HAPS), within existing Fixed-Service allocations."

As summarized in Resolution 160, current allocations to HAPS include the following: 1885-1980 MHz (global), 2010-2025 MHz (Regions 1 and 3), 2110-2170 MHz (Regions 1 and 3), 2110-2160 MHz (Region 2), 6440-6520 MHz (HAPS-to-ground; five countries, RR 5.457), 6560-6640 MHz (ground-to-HAPS; five countries, RR 5.547), 27.9-28.2 GHz (fixed downlink; Regions 1 and 3), 31.0-31.3 GHz (fixed uplink; Regions 1 and 3), 47.2-47.5 GHz (global), and 47.9-48.2 GHz (global). Resolution 160 proposes harmonizing these frequency allocations at the global or regional level and also considers the use of 38-39.5 GHz (global), 21.4-22 GHz (Region 2), and 24.25-27.5 GHz (Region 2) for HAPS. While there are no RAS or EESS science applications directly in the bands given in Resolution 160, several of the bands are either adjacent to bands allocated to the passive services or may have harmonics that fall within bands for which administrations are also urged to take all practical steps to protect the passive services from harmful interference (RR 5.149) or for which all emissions are prohibited (RR 5.340). Furthermore, for 23 countries, RR 5.543A specifies additional emission level limits for HAPS systems using the 31.0-31.3 GHz band in order to protect the adjacent passive services band (31.3-31.8 GHz) from harmful interference.

Radio Astronomy Service

Of significant concern for RAS is that radio astronomy is particularly vulnerable to high-altitude emissions (such as airborne or space-borne transmitters) because terrain shielding cannot block emissions originating at high altitude. Thus, suppression of out-of-band emission (OOBE) in the adjacent or harmonic frequencies is a critical concern for compatibility of HAPS with existing services because they may be in direct line of sight to a radio observatory. Of further concern is that HAPS are likely to serve rural and remote regions—precisely the geographic considerations that are favorable for sites of radio astronomy observatories. In the United States, radio astronomy facilities that observe at these frequencies include the GBT, the VLA, and the 10 stations of the Very Long Baseline Array.

Of the existing HAPS allocations summarized in Resolution 160, the 31.0-31.3 GHz (fixed uplink, Regions 1 and 3) is of concern to RAS due to the possibility of in-band emissions at 31.2-31.3 GHz (ITU RR 5.149) and OOBE, particularly in the adjacent frequency allocation of 31.3-31.5 GHz, for which all emissions are prohibited (RR 5.340). This frequency range is used by radio astronomers for the detection of complex molecules and for continuum observations of radio sources (see also Agenda Item 1.13). In addition, the first harmonic of the 47.2-47.5 GHz (global) and 47.9-48.2 GHz (global) allocations fall within a spectral band (94.1-100 GHz) for which administrations are urged to take all practicable steps to protect the RAS from harmful interference (RR 5.149). This frequency range is used by radio astronomers for observations of complex molecules that provide information on protoplanetary systems, star formation, and the origins of life. In addition, this frequency range is used for broadband continuum observations of a variety of radio sources.

Of the proposed new HAPS allocations summarized in Resolution 160, both the 38-39.5 GHz (global) and 21.4-22 GHz (Region 2) allocations are of particular concern to RAS due to the possibility of OOBE in the first harmonic, which fall in spectral bands (76-86 GHz and 42.5-43.5 GHz, respectively) for which administrations are urged to take all practicable steps to protect RAS from harmful interference (RR 5.149). The 21.4-22 GHz region is also adjacent to 22.01-22.5 GHz, for which administrations are urged to take all practicable steps to protect RAS from harmful interference (RR 5.149). These spectral windows correspond to regions rich with molecular transitions and are also preferred regions for continuum observations of radio sources (see also Agenda Item 1.13).

Earth Exploration-Satellite Service

Of the existing HAPS allocations summarized in Resolution 160, the 31.0-31.3 GHz (fixed uplink in Regions 1 and 3) is of particular concern to EESS due to the possibility of OOBE in the adjacent frequency allocation of 31.3-31.5 GHz, for which all emissions are prohibited (RR 5.340). This frequency range is used by a variety of weather satellites for weather forecasting (see also Agenda Item 1.13). In addition, the 27.9-28.2 GHz allocation (fixed downlink; Regions 1 and 3) is of concern because the first harmonics fall within the EESS band at 55.78-56.26 GHz within which, to protect the EESS passive service in this band, the maximum power density delivered by a transmitter to the antenna of a fixed-service station is limited to

–26 dB W/MHz (RR 5.557). This frequency range is used to measure the atmospheric temperature profile.

Of the proposed new allocations, the 21.4-22 GHz region is of concern because it is adjacent to an EESS allocation that is used to measure precipitable water and to study the freeze/thaw transition. In addition, the proposed allocation of 24.25-27.5 GHz is only 250 MHz from the edge of the EESS band at 23.6-24.0 GHz, for which all emissions are prohibited (RR 5.340). This protected band is intended to cover a water vapor absorption line (see also Agenda Item 1.13). In addition, the first harmonic of this frequency allocation falls within the EESS band at 50.2-50.4 GHz (see also Agenda Item 1.13).

Recommendation: Compatibility studies should be made to ensure the protection of the Radio Astronomy Service and the Earth Exploration-Satellite Service from unwanted emissions of high-altitude platform stations links. The limits defined by ITU-R RA.769 should be met under all conditions. In addition, if allocations are extended to other administrations not currently listed in RR 5.543A, they should be included in it.

AGENDA ITEM 1.15:
275-450 GHZ

Agenda Item 1.15 considers "identification of frequency bands for use by administrations for the land-mobile and fixed services applications operating in the frequency range 275-450 GHz, in accordance with Resolution 767 (WRC-15)."

As noted in Resolution 767 (WRC-15), the current Table of Frequency Allocations does not allocate bands above 275 GHz, but a number of bands have been identified for use by passive services within this frequency range. Specifically, RR 5.565 identifies spectral regions for both RAS and EESS (passive) but does not preclude use of these bands by active services. Rather, administrations are urged to take all practicable steps to protect the passive services in these identified bands.

Use of the frequency range 275-3000 GHz was discussed previously as Agenda Item 1.6 of the WRC-12. It is important to note that in the intervening years since this spectral range was discussed at the WRC, the importance of receive-only scientific use of this frequency range has become even more evident, particularly with the new discoveries enabled by the world's most powerful millimeter/submillimeter telescope—ALMA in Chile. As many of the scientific concerns remain the same, the discussion below includes text from the *Views of the National Academies on the World Radiocommunication Conference 2012*.[20]

Radio Astronomy Service

Protection of the atmospheric windows for passive use in the 275-450 GHz frequency range is highly desirable because the submillimeter range of the radio spectrum is a prime region for molecular spectroscopy and for studying continuum emission from dust (see Table 2.4).[21] In particular, with the increased sensitivity afforded by ALMA, the exploration of the universe using this part of the

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[20] National Research Council, *Views of the National Academy of Sciences and the National Academy of Engineering on Agenda Items at Issue at the World Radiocommunication Conference 2012*, The National Academies Press, Washington, D.C., 2013.

[21] The theory of quantum mechanics dictates that the rotational motion of molecules is characterized by discrete energy levels. When a molecule changes energy levels, it makes a transition, either emitting or absorbing a photon at a frequency proportional to the energy difference between the two levels. The emission at these specific frequencies therefore allows scientists to study their concentration in the region under study.

TABLE 2.4 Selected Spectral Lines between 275 and 450 GHz[a]

Spectral Line	Transition	Frequency (GHz)	Significance
CO	3-2	345	Important tracer of galactic and extragalactic structure
	4-3	461	Probe of star-forming regions and protoplanetary disks
HCO^+	4-3	356	Probe of high-density regions, protostellar cores
	5-4	446	
HCN	4-3	354	Probe of high-density regions, protostellar cores,
	5-4	443	Inner shells of evolved stars
CS	6-5	293	Dense protostellar cores, evolved stars, planetary nebulae
	7-6	342	
	8-7	392	
	9-8	440	
H_3O^+	1(1)-2(1)	307	Oxygen chemistry, leading to H_2O, OH, O_2
	2(1)-3(1)	388	
HDO	6(2,5)-5(3,2)	314	Probe of D/H isotope ratio
H_2D^+	1(1,0)-1(1,1)	372	Probe of D/H isotope ratio, chemical fractionation
O_2	(3,2-1,2)	425	Interstellar coolant, origins of life
Metal hydrides (SiH, LiH, MgH, NaH, AlH)	1-0	Various	Interstellar coolants
	2-1		Building blocks of interstellar chemistry
	3-2		
	Etc.		

[a] To observe the listed transitions, fractional bandwidths of 1 percent are required for observations of the Milky Way galaxy. Larger bandwidths are needed for extragalactic measurements on the low-frequency side because of the Doppler shift caused by the recessional velocities of distant objects in the universe—for example, a 10 percent bandwidth is required to cover the nearby clusters of galaxies of which our Milky Way galaxy is a member.

radio spectrum has expanded greatly in recent years. In addition to ALMA and the Atacama Pathfinder Experiment (APEX), both located in Chile, radio astronomy observations at these frequencies are also obtained with the James Clark Maxwell Telescope (JCMT) and the Submillimeter Array (SMA), both located in Hawaii; the Submillimeter Telescope (SMT) of the Arizona Radio Observatory; the Large Millimeter Telescope in Mexico; the IRAM 30m in Spain; the Solar Submillimeter Telescope and the planned Large Latin American Millimeter Array (LLAMA) in Argentina; the Suffa RT-70 radio telescope in Russia; the NOEMA array in France; and the South Pole Telescope (SPT).

In many situations, band protection for radio astronomy can be accomplished with geographic isolation of observatories. As discussed in ITU-R RA.2189, this is particularly relevant at high frequencies due to the reduced atmospheric transmission above 275 GHz (see Figure 2.1). However, by necessity, radio astronomy facilities observing at these high frequencies are located at sites with typically low atmospheric attenuation (i.e., dry sites at high altitudes) and usually with very little geographic shielding. Each observatory site experiences a variety of physical conditions that affect propagation models, including a range of humidity and temperature. Thus,

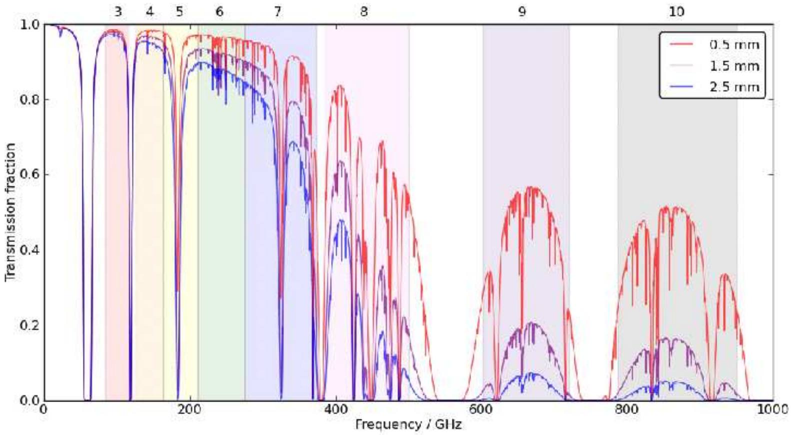

FIGURE 2.1 Atmospheric transmission fraction at the Atacama Large Millimeter Array (ALMA) site as a function of frequency for three different column densities of precipitable water vapor. The vertical colored banding indicates the frequency ranges of the ALMA bands, which are labeled at the top (3 through 10). The frequency ranges under consideration here correspond to ALMA bands 7 and 8. SOURCE: ALMA Observation Support Tool (OST) Help Documentation, http://almaost.jb.man.ac.uk/help/.

multiple propagation models must be developed to inform the appropriate separation and power limitations on spectrum uses at these frequencies for each site. Furthermore, because of the frequencies involved at every stage of signal processing, damaging interference from lower-frequency spectrum uses can also be amplified and introduced into high-frequency detectors. Thus, protection from RFI across the spectrum at these geographically isolated sites is critical.

The 275-450 GHz region encompasses several spectral windows that are used for ground-based astronomy: 275-323 GHz, 327-371 GHz, 388-424 GHz, and 426-442 GHz (see Figure 2.1). In this frequency range, many of the common interstellar molecules such as CO, HCN, HCO^+, and CS have their higher-energy rotational transitions (see Table 2.4). Because these spectral lines trace relatively hot ($T > 200$ K) and dense ($n > 10^7$ cm^{-3}) gas, they are important probes of the interstellar medium, where stars form. These transitions also trace circumstellar gas close to the stellar photosphere and can be used to elucidate the physical processes associated with evolved stars, including mass loss and photospheric shocks. In addition, these molecules are also of great significance for the investigation of the roles of organic molecules in the origin of solar systems, planets, and life.[22]

Due to the expansion of the universe, observations of higher-frequency molecular transitions can be shifted into these frequency bands. Thus, observations in these spectral windows provide insight into the formation and assembly of galaxies in the early universe, the evolution of large-scale structure in the universe, and the evolution of the powerful active nuclei in the centers of galaxies as a function of cosmic time.

One clear indication of the scientific importance of these high-frequency spectral windows is that almost 50 percent of the scientific observations with ALMA are conducted in the 275-450 GHz range. These include studies of the reionization era, otherwise known as the cosmic dawn. In particular, ALMA's line sensitivity and spatial resolution have allowed it to image emission from distant [C II], [N II], and [O III] in galaxies forming in the early universe. Indeed, at the time of this writing, the most distant detection of oxygen in the universe comes from observations of the 88 micron line of [O III] redshifted ($z = 7.212$) to 414 GHz.[23] For context, this oxygen line was

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[22] National Research Council, *Views of the National Academy of Sciences and National Academy of Engineering on Agenda Items at Issue at the World Radiocommunication Conference 2012*, The National Academies Press, Washington, D.C., 2013.

[23] A.K. Inoue, Y. Tamura, H. Matsuo, K. Mawatari, I. Shimizu, T. Shibuya, K. Ota, et al., Detection of an oxygen emission line from a high-redshift galaxy in the reionization epoch, *Science* 352:1559-1562, 2016.

emitted from a galaxy at an epoch of only about 700 million years after the Big Bang and therefore provides insight into the physical properties and elemental abundances of the interstellar medium in the early universe.

The stable atmosphere in this spectral range also makes it possible to obtain extremely high-spatial-resolution images with ALMA. For example, with ALMA's long baseline configuration, observations of a strongly gravitationally lensed submillimeter galaxy were obtained with an angular resolution of 23 milliarcsecond (mas) at 290 GHz, an order of magnitude improvement over previous observations.[24] With the additional magnification provided by the gravitational lens, this angular resolution corresponds to a linear spatial scale of only a few tens of parsecs for this galaxy at a redshift of 3.042. High-spatial-resolution continuum and line observations of such gravitationally lensed sources reveal the physical conditions and distributions of dust and gas in these star-forming galaxies and, therefore, provide significant insight into the evolution of galaxies as a function of cosmic time.

The most highly cited ALMA results are on protoplanetary and transition disks. In the 275-450 GHz frequency range, observations of the CO 4-3 line at 308 GHz can image the "snow line" in many disks, a critical transition region beyond which volatile molecules such as water, ammonia, and carbon monoxide condense into solid ice grains. These grains then accrete to form planetesimals and, eventually, planets. Information about the dust emission in these protoplanetary disks comes from submillimeter continuum observations. For example, 350 GHz continuum observations of TW Hydrae traced millimeter-sized particles on spatial scales as small as 1 astronomical unit.[25] The series of concentric ring-shaped substructures in this system suggests interactions between the disk and young planets. Understanding the physical conditions of these protoplanetary disks and their evolution are critical to studies of the formation of planets and life in the universe.

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[24] ALMA Consortium, The 2014 ALMA Long Baseline Campaign: Observations of the strongly lensed submillimeter galaxy HATLAS J090311.6+003906 at $z = 3.042$, *The Astrophysical Journal Letters* 808(1):L4, 2015.

[25] S.M. Andrews, D.J. Wilner, Z. Zhu, T. Birnstiel, J.M. Carpenter, L.M. Pérez, X.-N. Bai, K.I. Öberg, A.M. Hughes, A. Isella, and L. Ricci, Ringed substructure and a gap at 1 au in the nearest protoplanetary disk, *The Astrophysical Journal Letters* 820(2):L40, 2016.

Earth Exploration-Satellite Service

The 275-450 GHz band is used by EESS (passive) primarily for atmospheric measurements at frequencies within the atmospheric windows (see Figure 2.2 and Table 2.5), where opacity, and therefore atmospheric propagation, is minimum. Hence, the “protection” from atmospheric propagation is minimal at these frequencies and potential risk of data contamination from RFI is larger. Unlike RAS measurements, where geographic exclusion zones may be sufficient, EESS measurements are global and require protection in all ITU-R Regions.

Significant applications in this band include determination of columnar water vapor, temperature, and molecular species that play critical roles in atmospheric science, ozone, and carbon cycle monitoring. For example, three-dimensional (3D) mapping of ozone in the stratosphere, polar stratospheric clouds, and chlorine sources is used to understand ozone distribution and mechanisms for its

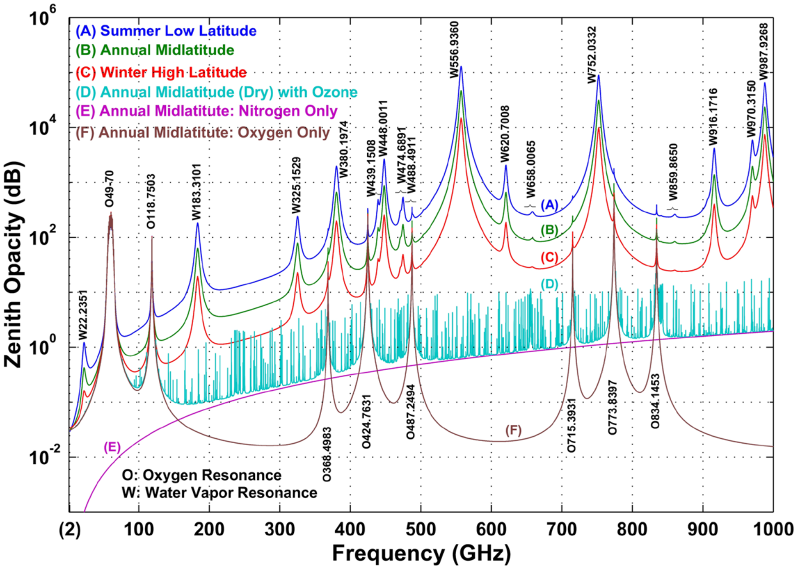

FIGURE 2.2 Atmospheric zenith opacity in the radio spectrum commonly used for the Earth Exploration-Satellite Service. The frequency ranges under consideration here include both atmospheric absorption bands and transparent windows. SOURCE: A.J. Gasiewski and M. Klein, The sensitivity of millimeter and submillimeter frequencies to atmospheric temperature and water vapor variations, *Journal of Geophysical Research Atmospheres* 13:178481-178511, 2000, copyright 2001 by the American Geophysical Union.

TABLE 2.5 Representative Passive Sensing Bands and Their Associated Measurements in 275-450 GHz[a]

Frequency (GHz)	Bandwidth (MHz)	Spectral Line(s) (GHz)	Measurement (GHz)	Existing or Planned Instrument(s)
275-285.4	10 400	276.33 (N_2O), 278.6 (ClO)	Window (276.4-285.4) for N_2O, ClO, NO	
296-306	10 000	Window for 325.1, 298.5 (HNO_3), 300.22 (HOCl), 301.44 (N_2O), 303.57 (O_3), 305.2 (HNO_3), 304.5 ($O^{17}O$)	Wing channel for temperature sounding Window (296-306) for N_2O, O_3 , $O^{17}O$, HNO_3, HOCl	MASTER
313.5-355.6	42 100	{318.8, 345.8, 344.5} (HNO_3), 313.8 (HDO), {321.15, 325.15} (H_2O), {321, 345.5, 352.3, 352.6, 352.8} (O_3), {322.8, 343.4} (HOCl), 345.8 (CO), {345.0, 345.4} (CH_3Cl), 345.0 ($O^{18}O$), 354.5 (HCN), 349.4 (CH_3CN), {315.8, 346.9, 344.5, 352.9} (ClO), 351.67 (N_2O), 346 (BrO)	Water vapor sounding, cloud ice, wing channel for temperature sounding Window (339.5-348.5) for H_2O, CH_3Cl, HDO, ClO, O_3, HNO_3, HOCl, CO, $O^{18}O$, HCN, CH_3CN, N_2O, BrO	TWICE, ICI, STEAM-R, CIWSIR, MASTER, MWI, GOMAS, GEM, CAMLS
361-365	4 000	364.32 (O_3)	Wing channel for water vapor sounding for O_3	GOMAS
369.2-391.2	22 000	380.2 (H_2O)	Water vapor sounding	TWICE, GEM, GOMAS
397-399	2000		Water vapor sounding	GOMAS
409-411	2000		Temperature sounding	

416-433.46	17 460	424.7 (O_2)	Temperature sounding	GEM, GOMAS
439.1-466.3	27 200	{443.1, 448} (H_2O), 443.2 (O_3), 442 (HNO_3)	Water vapor profiling, cloud ice	ICI, MWI, CIWSIR
			Window (458.5-466.3) for O_3, HNO_3, N_2O, CO	

NOTE: Acronyms are defined in Appendix B.

[a] Adapted from Table 2 in ITU-R RS.515-5.

SOURCE: National Research Council, *Views of the National Academy of Sciences and National Academy of Engineering on Agenda Items at Issue at the World Radiocommunication Conference 2012*, The National Academies Press, Washington, D.C., 2013, Table 1.6-3.

depletion. Cloud ice and frozen precipitation are key variables in understanding Earth's energy budget, water cycle, and the effect of cloud feedback on climate. The upper troposphere and stratospheric water vapor are key aspects of the water cycle and are important for determining climate feedback effects on radiative forcing in the presence of increasing greenhouse gases. The stratosphere temperature measurements provide 3D mapping of the temperature for understanding atmosphere dynamics. Research on chemical composition in the upper troposphere is used for understanding the distribution and transport of pollutants. In addition, observations of trace gases provide a 3D mapping of key atmospheric constituents (e.g., CO, HCl, BrO, N_2O) tied to the carbon cycle, global climate, pollution, and atmospheric transport.[26] This is vital for potential tracking of chemical or biological weapons of mass destruction in the atmosphere.[27] Table 2.5 provides a list of frequency bands that are associated with these applications.

> **Recommendation: The committee urges administrations to protect the passive services from harmful interference, particularly those bands in use by the Atacama Large Millimeter/Submillimeter Array (275-375 GHz, 385-500 GHz, 602-720 GHz, and 787-950 GHz) and the Earth Exploration-Satellite Service (EESS) (passive) applications. Atmospheric propagation models should include the physical conditions for radio observatories located in high, dry sites to appropriately assist in assessing the impact of spectrum allocations on passive scientific uses. No changes should be made to the ITU Radio Regulations unless acceptable sharing and compatibility criteria are developed to ensure the protection of the Radio Astronomy Service and EESS (passive) from future services and applications above 275 GHz.**

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[26] National Research Council, *Views of the National Academy of Sciences and National Academy of Engineering on Agenda Items at Issue at the World Radiocommunication Conference 2012*, The National Academies Press, Washington, D.C., 2013.

[27] Nuclear Threat Initiative, Counterproliferation of Weapons of Mass Destruction, Chapter XII in *Joint Warfighting Science and Technology Plan*, http://www.nti.org/media/pdfs/35_8.pdf?_=1318280270, and D. Imbro, A national strategy against terrorism using weapons of mass destruction, *Science and Technology Review*, January/February 1998, https://str.llnl.gov/str/Imbro.html.

AGENDA ITEM 1.16: WIRELESS ACCESS BETWEEN 5150 AND 5925 MHZ

Agenda Item 1.16 will "consider issues related to wireless access systems, including radio local area networks (WAS/RLAN), in the frequency bands between 5150 MHz and 5925 MHz, and take the appropriate regulatory actions, including additional spectrum allocations to the mobile service, in accordance with Resolution 239 (WRC-15)."

Resolution 239 specifically mentions that EESS missions (current and planned) in this band are used for reliable and up-to-date information on how Earth and its climate are changing and recognizes that sharing 5350-5470 MHz between EESS (active) and WAS/RLAN is not feasible.

Resolution 239 recommends studies to facilitate sharing with incumbent systems in the frequency bands 5150-5350 MHz, 5350-5470 MHz, 5725-5850 MHz, and 5850-5925 MHz, with a specific mention to determine whether any additional mitigation techniques in the frequency band 5350-5470 MHz beyond those analyzed previously could provide coexistence between WAS/RLAN systems and EESS (active) and Space Research Service (active) systems.

Earth Exploration-Satellite Service

The frequency range under consideration includes the co-primary EESS (active) allocation between 5250 and 5570 MHz that is used for satellite and airborne active remote sensing of surface deformation (e.g., volcanoes, earthquakes, and glacier movements) as well as the monitoring of agricultural crops, forest disturbances, and ocean vector winds. The frequency allocation for these applications in these bands is important because of the dimensional connection between the scattering mechanisms of the targets being observed.

Mobile services that include WAS/RLAN share this band from 5250-5350 MHz and 5470-5570 MHz. In addition, for selected countries in Region 3, there is also a fixed wireless access (FWA) allocation on a co-primary basis from 5250-5350 MHz that is governed by Recommendation ITU-R F.1613. There is no current mobile service allocation in the 120 MHz region extending from 5350-5470 MHz. Providing mobile access to this new band has the potential for increasing aggregate interference over large geographic regions. Satellite sensors that use this band are listed in Table 2.6. It is important to note that these sensors have a variety of applications and use different measurement principles (e.g., synthetic-aperture radar,

TABLE 2.6 Satellite Sensors at 5300 to 5500 MHz

Sensor	Center Frequency (MHz)	Bandwidth (MHz)
Sentinel 1A	5405	100
Envisat (ASAR)	5331	16
RISAT-1	5350	18.75-75
Radarsat-2	5405	11.6, 17.3, 30, 50, and 100
Radarsat-3 (RCM)	5405	14-100
Radarsat Next Generation	5405	13-300
Jason-2/3 SSALT, POSEIDON-3/3B	5300	100, 320
Sentinel-3	5410	320
HY-2A	5250	160
Sentinel-6, POSEIDON-4	5410	320
MetOp-A, B, C (ASCAT)	5255, 5355	0.5, 2
MetOp-SG (SCA)	5355	2

NOTE: Acronyms are defined in Appendix B.

scatterometry, radar altimetry, etc.), so any planned compatibility studies must include a full range of cases.

> **Recommendation: The committee agrees with the resolution that compatibility studies are critical to ensure the protection of the Earth Exploration-Satellite Service (EESS) (active) in the 5350-5470 MHz band from unwanted emissions from planned radio local area networks (WAS/RLAN) units. Such studies should also assess the impact of ITU-R F.1613 on the data collected by current satellites. Future protection of the EESS (active) allocation could be achieved through coordination with published satellite ephemerides. However, no changes should be made to the Radio Regulations unless acceptable technical and operational restrictions can be specified to facilitate non-interference with existing or planned EESS active systems.**

WRC-23 AGENDA ITEM 2.2: RADAR SOUNDERS AT 45 MHZ

WRC-23 Agenda Item 2.2 will "conduct, and complete in time for WRC-23, studies for a possible new allocation to the Earth exploration-satellite service (active) service for spaceborne radar sounders with the range of frequencies around 45 MHz, taking into account the protection of incumbent services, in accordance with Resolution 656 (WRC-15)."

Radio Astronomy Service

It is important that the studies consider the impact of the orbiting radar on existing radio telescopes operating at similar frequencies or near the harmonics. These facilities include the Long Wavelength Array stations in New Mexico and California, LOFAR in the Netherlands (with international stations across Europe), and SKA prototype antennas in Australia. These facilities are part of a renaissance in low-frequency radio astronomy now under way, with a promise of new and important discoveries. A recent example in this frequency range includes a new natural phenomenon: intrinsic radio emission from fireballs (large meteors), recently discovered by the Long Wavelength Array. Astronomers around the world are now conducting follow-up observations. Also, careful measurements of the sky background temperature in this frequency range are important for calibration of sensitive cosmology measurements (e.g., cosmic dawn) at higher frequencies (100-200 MHz). The impact of the radar could be significant in view of the likely large footprint on the ground of transmissions from the satellite at these relatively low frequencies. Note that the individual dipole elements see the entire sky, and the individual elements have limited sidelobe rejection, placing difficult demands on the dynamic range of the signal-processing systems in the presence of strong interference anywhere in the sky. Further, the best times for operation of the radar, with stable ionospheric conditions, coincide with the best times for radio astronomical observations for the same reason.

> **Recommendation: The committee urges administrations to protect current and future radio astronomy facilities from harmful interference in the frequency range near and around 45 MHz. Coordination between the use of a satellite-based radar system and both passive and active radio astronomy and**

remote sensing observations should be explored. The committee endorses the importance of the pending characterization of the new radar system in time for WRC-23.

Appendixes

A

Statement of Task

The National Academies of Sciences, Engineering, and Medicine will convene a committee to prepare a short report which will articulate the views of the U.S. science community on specific agenda items at issue at the 2019 World Radiocommunication Conference (WRC) with potential impact on scientific observations, particularly future radio astronomy and Earth remote sensing observations. The committee will:

- Identify the agenda items at issue at the 2019 WRC that are potentially relevant to the scientific use of the radio and microwave spectrum, namely for, but not limited to, radio astronomy and Earth remote sensing;
- Assess each of the identified agenda items for their potential impact—positive, negative, or none—on radio frequency science applications;
- Provide the scientific justification for protecting radio astronomy and Earth remote sensing observations in agenda items with potential impact on those observations, where appropriate;
- Solicit and consider input from the broad international science community relevant to the committee's task; and
- Establish a position, where needed and within the scope of the identified agenda items, to ensure that radio astronomy and Earth remote sensing and other related radio frequency

science applications will continue to be able to make needed observations.

In preparing its report, the committee will take into account the anticipated future spectrum requirements of the scientific communities and will ensure that the needs of multiple communities are appropriately considered. The report will not consider impacts on the transmission of scientific data.

B

Acronyms

3D	three dimensional
AIS	automatic identification system
ALMA	Atacama Large Millimeter/Submillimeter Array
AMR-2	Advanced Microwave Radiometer-2
AMSR2	Advanced Microwave Scanning Radiometer 2
AMSU-A	Advanced Microwave Sounding Unit-A
APEX	Atacama Pathfinder Experiment
ARO	Arizona Radio Observatory
ASAR	Advanced Synthetic Aperture Radar
ASCAT	Advanced Scatterometer
ASM	Applications Specific Message
ATMS	Advanced Technology Microwave Sounder (JPSS)
CAMLS	Compact Adaptable Microwave Limb Sounder
CEPT	European Post and Telecommunications Conference
CITEL	Inter-American Telecommunications Commission
CIWSIR	Cloud Ice Water Sub-millimetre Imaging Radiometer
CMB	cosmic microwave background
CS	carbon monosulfide
DMSP	Defense Meteorological Satellite Program
DOD	Department of Defense
DSM	dynamic spectrum management

EESS	Earth Exploration-Satellite Service
EoR	epoch of reionization
ESIM	Earth Stations in Motion
FAST	Five-hundred-meter Aperture Spherical Radio Telescope
FCC	Federal Communications Commission
FEMA	Federal Emergency Management Agency
FSS	Fixed-Satellite Service
FWA	fixed wireless access
FY-3	Fēngyún satellite series (China)
GBT	Green Bank Telescope
GCOM-W1	Global Change Observation Mission 1st-Water
GEM	Geosynchronous Microwave Sounder/Imager
GMDSS	Global Maritime Distress Safety Systems
GMI	GPM Microwave Imager
GOMAS	Geostationary Observatory for Microwave Atmospheric Sounding
GPM	Global Precipitation Measurement (NASA)
GPS	Global Positioning System
GSO	geostationary orbit
HAPS	High Altitude Platform Stations
HERA	Hydrogen Epoch of Reionization Array
HY-2A	Second-generation ocean observation/monitoring satellite series (China)
ICI	Ice Cloud Imager
IMT	International Mobile Telecommunications
ITU	International Telecommunication Union
JAXA	Japan Aerospace Exploration Agency
JCMT	James Clark Maxwell Telescope
JPSS	Joint Polar Satellite System
LLAMA	Large Latin American Millimeter Array
LOFAR	Low Frequency Array
MADRAS	Microwave Analysis and Detection of Rain and Atmospheric Structures
MASTER	Millimetre-wave Acquisitions for Stratosphere/Troposphere Exchange Research

MetOp-SG	Meteorological Operations—Second Generation
MTVZA-GY	Imaging/Sounding Microwave Radiometer-Improved (Russia)
MWA	Murchison Widefield Array
MWI	Microwave Imager
MWRI	Microwave Radiation Imager
MWRI′	Microwave Radiometer Imager
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NPP	National Polar-orbiting Partnership
NSF	National Science Foundation
OH	hydroxyl radical
OOBE	out-of-band emission
PMR	passive microwave radiometry
RAS	Radio Astronomy Service
RCM	Radarsat Constellation Mission
RF	radio frequency
RFI	radio frequency interference
RISAT	Radar Imaging Satellite
RLAN	Radio Local Area Networks
RR	radio regulations
RSS	radio source scintillation
SiO	silicon monoxide
SKA	Square Kilometer Array
SKAMP	SKA Molongolo Prototype
SMA	Submillimeter Array
SMAP	Soil Moisture Active Passive
SMOS	Soil Moisture and Ocean Salinity
SMT	Submillimeter Telescope (ARO)
SPT	South Pole Telescope
SSM/I	Special Sensor Microwave Imager
SSMIS	Special Sensor Microwave Imager/Sounder
STEAM-R	Stratosphere-Troposphere Exchange and Climate Monitor-Radiometer
TEC	total electron content
TWICE	Tropospheric Water Vapor and Cloud ICE

VDES	VHF Data Exchange System
VLA	Very Large Array
WAS	wireless access system
WRC	World Radiocommunication Conference