Before the
FEDERAL COMMUNICATIONS COMMISSION
Washington, D.C. 20554

In the Matter of	)	
Spectrum Horizons	)	ET Docket No. 18-21
Battelle Memorial Institute Petition for Rulemaking to Adopt Fixed Service Rules in the 102-109.5 GHz Band	)	RM-11713 (Terminated)
Request for Waiver of ZenFi Networks, Inc. and Geneva Communications LLC	)	WT Docket No. 15-245 (Terminated)
James Edwin Whedbee Petition for Rulemaking to Allow Unlicensed Operation in the 95-1,000 GHz Band	)	RM-11795

COMMENTS OF THE
NATIONAL ACADEMY OF SCIENCES'
COMMITTEE ON RADIO FREQUENCIES

The National Academy of Sciences, through its Committee on Radio Frequencies (hereinafter, CORF[1]), hereby submits its comments in response to the Commission's February 28, 2018, *Notice of Proposed Rulemaking* ("NPRM") in the above-captioned dockets. CORF appreciates that the NPRM was drafted with detailed attention to the need to protect important scientific observations in bands above 95 GHz, while opening up opportunities for innovative commercial uses above 95 GHz. In these comments, CORF responds to questions regarding protections for passive scientific use of these bands.

I. Introduction: The Role of Radio Astronomy and Earth Remote Sensing, and the Unique Vulnerability of Passive Services to Interference.

CORF has a substantial interest in this proceeding, as it represents the interests

[1] See the Appendix for the membership of the Committee on Radio Frequencies.

of the scientific users of the radio spectrum, including users of the Radio Astronomy Service (RAS) and Earth Exploration-Satellite Service (EESS) bands. These users perform extremely important, yet vulnerable, research.

As the Commission has also long recognized, radio astronomy is a vitally important tool used by scientists to study our universe. It was through the use of radio astronomy that scientists discovered the first planets outside the solar system, circling a distant pulsar. The discovery of pulsars by radio astronomers has led to the recognition of a widespread galactic population of rapidly spinning neutron stars with gravitational fields at their surface up to 100 billion times stronger than on Earth's surface. Subsequent radio observations of pulsars have revolutionized understanding of the physics of neutron stars and have resulted in the first experimental evidence for gravitational radiation. Within our own solar system, radio astronomy observations of the Sun have been used for more than half a century to aid in the prediction of terrestrial high-frequency radio propagation. 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 galaxy, the Milky Way. Radio spectroscopy and broadband continuum observations 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. The enormous energies contained in the enigmatic quasars and radio galaxies discovered by radio astronomers have led to the recognition that most galaxies, including our own, contain supermassive black holes at their centers, a phenomenon that appears to be crucial to the creation and evolution of galaxies. Synchronized observations using widely spaced radio telescopes around the world give extraordinarily high angular resolution, far superior to that which can be obtained using the largest optical telescopes on the ground or in space.

Radio astronomy measurements led to the discovery of the cosmic microwave background (CMB), the radiation left over from the original Big Bang that has now cooled to only 2.7 K above absolute zero. Later observations revealed the weak temperature fluctuations in the CMB of only one-thousandth of a percent – signatures of tiny density fluctuations in the early universe that were the seeds of the stars and galaxies we know today. The CMB is a unique probe for the ongoing search for gravity waves in the inflationary period of growth after the Big Bang, a particularly active topic in modern astrophysics.

At millimeter wavelengths, radio astronomy applications include observations of rotational and vibrational transitions of interstellar molecules and thermal emission from dust particles. Recent results highlight the wealth of astronomical knowledge that can be gained by observations in these high frequency bands. In particular, observations of proto-planetary disks in both molecular transitions and thermal dust emission provide insight into the physical conditions, which are critical to studies of the formation of planets and life in the universe. In addition, due to the expansion of the universe, higher frequency molecular transitions can be shifted to these frequency bands and allow observations of the gas (and dust, from continuum observations) in the early universe. Specific molecular bands of interest to radio astronomers in the millimeter wavelength range are listed in Appendices C, D, and E of the *Handbook of Frequency Allocations* *and Spectrum Protection for Scientific Uses: Second Edition*.[2] In sum, radio astronomers anticipate significant growth in observation at these frequencies during the next decade, which is likely to yield foundational knowledge about the formation of the first structures in the universe.

CORF notes that these observations cannot be obtained in any other portion of the electromagnetic spectrum. This critical science undertaken by RAS observers, however, cannot be performed without access to interference-free bands. Notably, the emissions that radio astronomers receive are extremely weak—a radio telescope receives less than 1 percent of one-billionth of one-billionth of a watt (10^{-20} W) from a typical cosmic object. Because radio astronomy receivers are designed to pick up such remarkably weak signals, radio observatories are particularly vulnerable to interference from in-band emissions, spurious and out-of-band emissions from licensed and unlicensed users of neighboring bands, and emissions that produce harmonic signals in the RAS bands, even if those human-made emissions are weak and distant.

The Commission has also long recognized that satellite-based Earth remote sensing, including sensing by users of the EESS bands, is a critical and uniquely valuable resource for monitoring Earth and our environment. Satellite-based microwave remote sensing presents a global perspective and, in many cases, is the only practical method of obtaining atmospheric and surface data for the entire planet. Instruments operating in the EESS bands provide data that is important to human welfare and security, and includes support for scientific research, commercial endeavor, and

[2] 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, https://doi.org/10.17226/21774. *See also* ITU-R Recommendations RA.314-10 and RA.1860.

government operations in areas such as meteorology, atmospheric chemistry, climatology, and oceanography. Examples are measurements of parameters needed to understand ocean circulation and the associated global distribution of heat—such as ocean surface temperature, wind velocity, salinity, and precipitation rate over the ocean. They also include monitoring soil moisture, a parameter needed for agriculture and drought assessment, and for weather prediction (heat exchange with the atmosphere) and even for defense (planning military deployment). Passive sensors 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. Users of this data include the National Oceanic and Atmospheric Administration, the National Science Foundation, the National Aeronautics and Space Administration, the Department of Defense, the Department of Agriculture, the U.S. Geological Survey, the Agency for International Development, the Federal Emergency Management Agency, and the U.S. Forest Service. Much of this data is also available free to anyone anywhere in the world.

Earth remote sensing research that employs observations from 95 GHz to 3 THz is growing rapidly, as technological developments further push the frontiers of measurement capabilities. In particular, temperature and water vapor bands, near 118 and 183 GHz especially, continue to be critically important for severe weather forecasting and also to enable study of key aspects of the water cycle. These bands are at the forefront of research both for all-sky numerical weather prediction and for low-noise instrumentation. Other bands near these absorption lines and in the surrounding continuum also are extremely valuable to scientific endeavors and must be protected from harmful radio frequency interference to enable scientific discovery and scientific applications, such as study of the transport of pollutants in Earth's atmosphere.

Passive instruments in space are particularly vulnerable to human-made 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 in space monitor globally and view large swaths of the surface at one time. In this sense, the issue for EESS differs from that of RAS, which generally involves receivers at fixed locations that often can be protected with regionally specific restrictions.

In sum, the important science performed by radio astronomers and Earth remote sensing scientists cannot be performed without access to interference-free bands. Loss of such access constitutes a loss for the scientific and cultural heritage of all people, as well as a loss of the practical applications enabled by this access, which can include financial loss arising from impaired weather forecasting and climate monitoring. CORF generally supports the sharing of frequency allocations where practical, but protection of passive scientific observations, as discussed herein, must be addressed.

II. Attenuation in the Millimeter Wave Bands.

In Paragraph 22, the NPRM notes that the technologies to be used above 95 GHz depend on the propagation properties of the spectrum in which those technologies will operate:

> The propagation of millimeter wave radio signals is limited when compared to that associated with lower-frequency radio signals. Signals in millimeter wave bands are significantly affected by the presence of oxygen and water vapor within the atmosphere, although the amount of signal attenuation due to oxygen and water vapor varies with frequency and other factors. Attenuation caused by oxygen is significant throughout the millimeter wave spectrum, but increases

dramatically around 60 GHz, 120 GHz, and 183 GHz.[3]

CORF agrees that the use of these bands for active services, and the utility of the bands for passive scientific observation, is greatly impacted by the level of atmospheric attenuation at various frequencies and that the atmospheric absorption is in general higher at millimeter wavelengths than at lower frequencies. However, it is also important to note that the strength of the atmospheric oxygen bands at 60 GHz and 120 GHz, and the water line at 183 GHz, are all critical parameters for weather prediction and calibration of scientific data. Thus, although these spectral features provide significant attenuation, these spectral lines must be protected from human-made interference under all atmospheric conditions, including times of high transparency.

Specifically, the NPRM includes a graph (Figure 1) showing the attenuation of radio waves per kilometer (km) traveled caused by atmospheric absorption as a function of frequency, "during typical conditions." However, atmospheric absorption is highly variable and depends on many factors, as the NPRM recognizes in footnote 66: "[w]hile the graph in Figure 1 is intended to represent standard atmosphere (which includes oxygen and water vapor), it does not include the effects of rain, snow, and fog, which can all also affect the range of millimeter wave transmissions." In the context of considering spectrum allocations and radio regulations, CORF notes that it is also important to recognize that atmospheric transmission can be *better than* that shown in Figure 1 of the NPRM. For example, as illustrated in ITU-R RA.2189, not only do levels of *humidity* impact the standard model for attenuation, but *altitude* does as well. Examples of zenith atmospheric attenuation at Mauna Kea, Hawaii, in three different

3 CORF notes that the attenuation at 183 GHz arises from water vapor, not from oxygen.

atmospheric conditions are illustrated in Figure 1 (below). In general, the atmospheric conditions favorable to radio astronomy observations of distant, faint, celestial sources are much better (more transparent) than the standard atmosphere presented in Figure 1 of the NPRM or that adopted in ITU-R RA.2189.

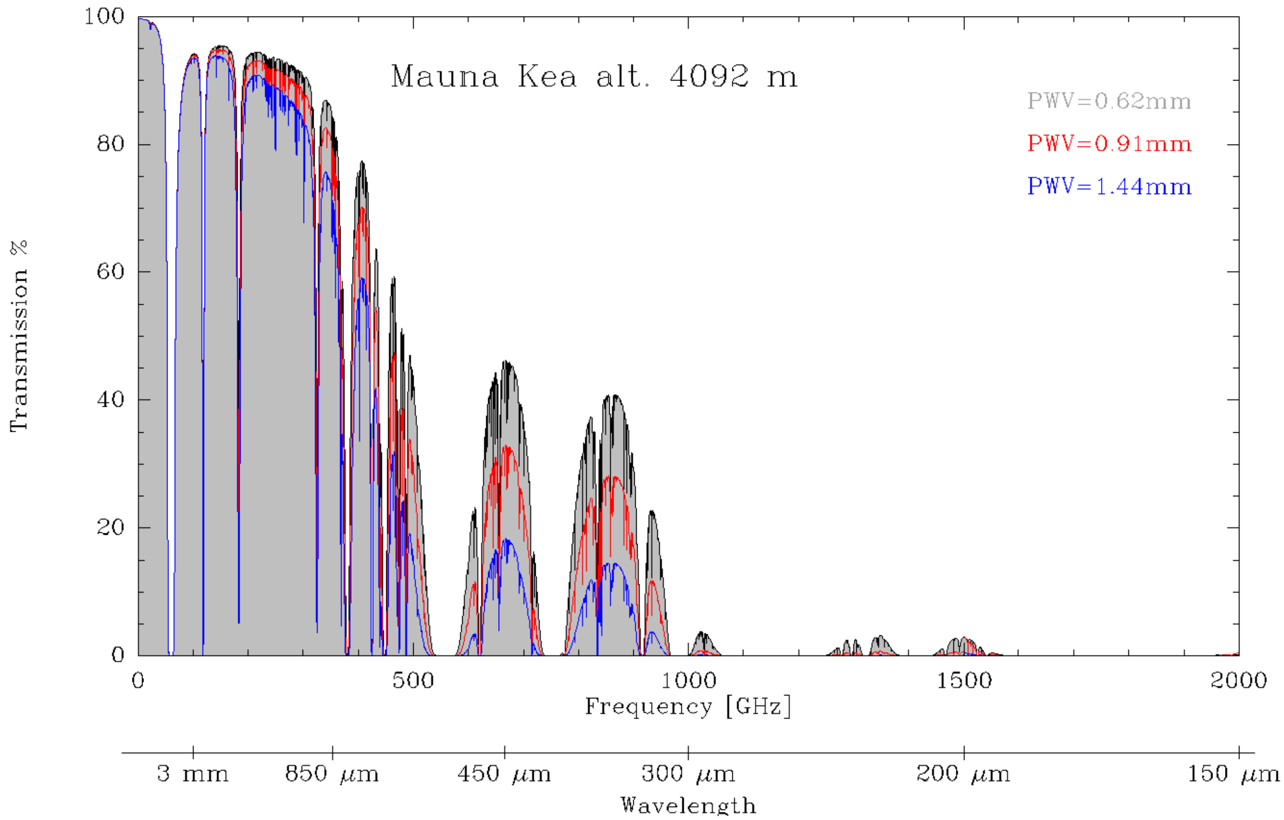

Figure 1: Radio Astronomy Service (RAS) frequency allocations correspond to atmospheric windows with relatively high transmission. As an example, the atmospheric transmission on Mauna Kea is illustrated for three values of precipitable water vapor (0.62 mm, 0.91 mm, and 1.44 mm), corresponding to the best 10% (black), 25% (red), and 50% (blue) conditions on the site. SOURCE: P. Tremblin, N. Schneider, V. Minier, G.Al. Durand, and J. Urban. *Astronomy & Astrophysics* 548:A65, 2012.

For example, while the “standard atmosphere” illustrated in Figure 1 of the NPRM indicates atmospheric attenuation of approximately 0.35 dB/km at 80 GHz, a direct measurement of the atmospheric attenuation at Kitt Peak, Arizona, in 2011 found 0.15 dB/km (National Radio Astronomy Observatory, Electronics Division Technical Note No. 219). Using the formulation presented in ITU-R P.676-11, Figure 2 illustrates the atmospheric attenuation for three different assumptions: (1) the standard model shown in Figure 1 of the NPRM; (2) atmospheric parameters at the Kitt Peak 12 m on the night of March 4-5, 2018; and (3) atmospheric parameters at the James Clerk Maxwell Telescope on Mauna Kea, Hawaii, on the night of March 4-5, 2018. Changes in assumptions regarding the atmospheric conditions can decrease the atmospheric attenuation by very significant factors between sea level and a high, dry site, such as the summit of Mauna Kea. As a further example, Figure 2 of ITU-R P.676-11 illustrates the difference between attenuation at sea level (0.4 dB/km) and mountain elevations (5 km) (0.1 dB/km) at the edge of the 60 GHz oxygen band. It is precisely due to these optimal atmospheric conditions that radio astronomy observatories are built on high, dry sites; these favorable conditions must be considered when determining appropriate exclusion or coordination zones for high frequency transmitters.

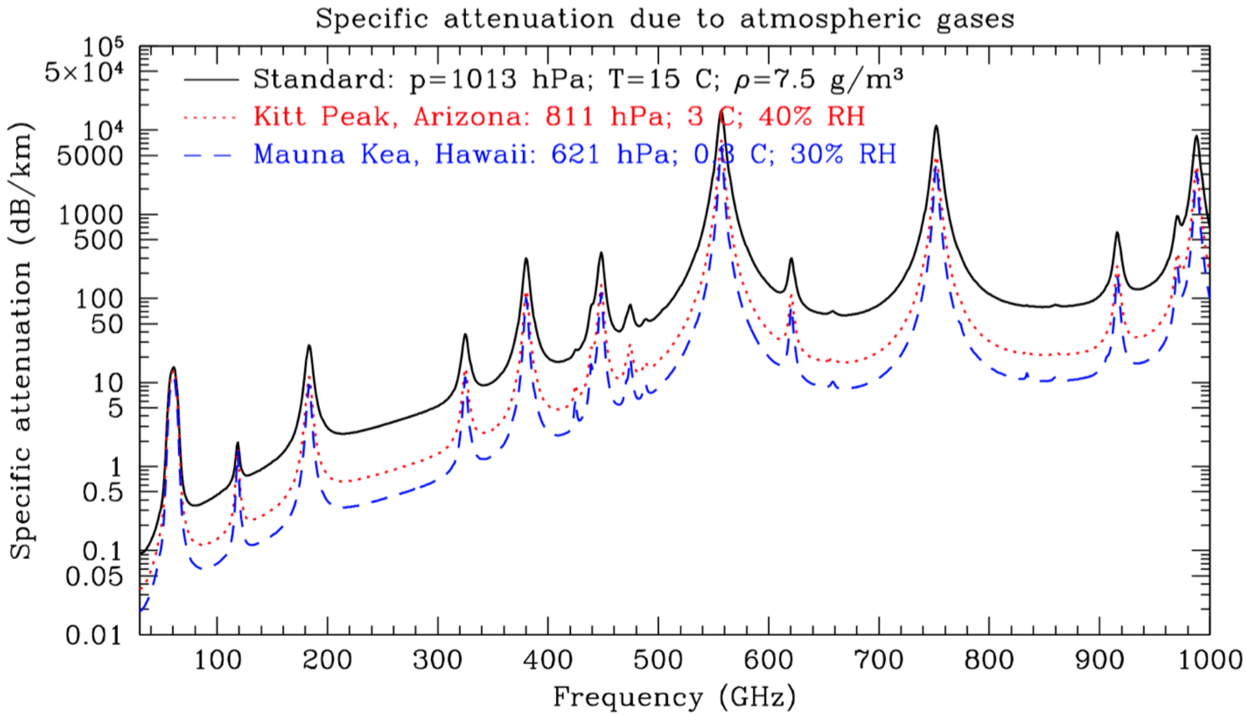

Figure 2: Specific attenuation for three different atmospheric conditions illustrating that the standard atmosphere model underestimates the typical transparency at the high, dry sites selected for millimeter-wave radio observatories. The atmospheric parameters for these models are based on measurements at the Kitt Peak 12-meter dish site and the Mauna Kea James Clerk Maxwell Telescope site at local midnight of UT date 2018 March 5. These models should be considered indicative only, as they are a random sampling of the site conditions and do not represent the best atmospheric conditions possible at these high, dry sites. All calculations are based on the formulation presented in ITU-R P.676-11.

In paragraph 36 of the NPRM, the question is raised as to whether the EIRP (equivalent isotropically radiated power) limit should be increased to compensate for the atmospheric attenuation at these higher frequencies. CORF understands that commercial use applications may be impacted by adverse weather conditions. However, protection of radio astronomy applications requires consideration of signal propagation under the *best* conditions. Thus, higher EIRP limits would require larger coordination or exclusion zones and therefore limit the possible geographical distribution of such commercial applications. However, a higher EIRP limit under adverse weather conditions (when radio telescopes are unlikely to be operating) could be considered should there be an automatic reduction in power associated with improving atmospheric conditions. Such automatically regulated emissions would be beneficial to both commercial and passive service applications, as it would limit interference and reduce the cost of operating such devices.

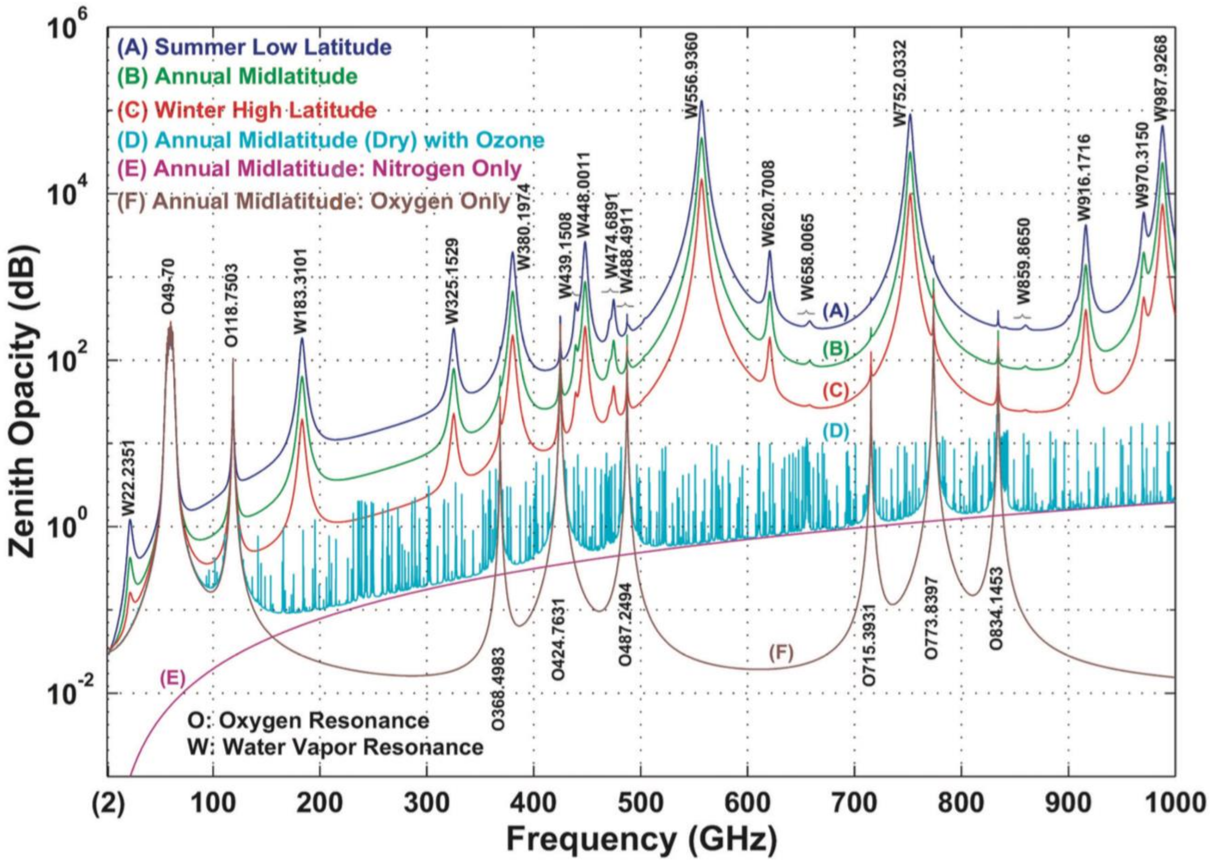

Figure 3: Atmospheric zenith opacity in the radio spectrum commonly used for the Earth Exploration-Satellite Service. SOURCE: A.J. Gasiewski and M. Klein, The sensitivity of millimeter and sub-millimeter frequencies to atmospheric temperature and water vapor variations, *Journal of Geophysical Research-Atmospheres* 13:178481-17511, 2000.

Variations in atmospheric attenuation are also of concern for EESS observations. As illustrated in Figure 3 above, the zenith opacity at millimeter wavelengths depends on temperature and water vapor content. Measurement of the 60 GHz and 118 GHz oxygen bands and the 183 GHz water line provide critical parameters for weather prediction models. These lines can vary by up to factors of five, depending on the atmospheric conditions. In particular, in cold, dry conditions, the attenuation near the peak of the 183.31 GHz water vapor line can be *less than* that of the peak of the 60 GHz oxygen bands by at least a factor of three (e.g., models (A) and (C) in Figure 3).

The overarching point here is that when creating rules to protect important passive scientific observation in these bands, attention must be paid not just to the impact of frequency on attenuation, but also to the altitude of the observatory for RAS, and to the impact of atmospheric water vapor in the *best* of conditions (most transparent) for both EESS and RAS. In particular, the standard atmosphere model indicated in Figure 1 of the NPRM vastly overestimates the atmospheric attenuation to be found in cold, dry locations generally, and at the high, dry sites of millimeter-wave radio observatories, specifically.

III. Protection of Radio Astronomy

The NPRM seeks comment on whether to adopt rules for fixed point-to-point operations in the 95-100 GHz, 102-109.5 GHz, 111.8-114.25 GHz, 122.25-123 GHz, 130-134 GHz, 141-148.5 GHz, 151.5-158.5 GHz, 174.5-174.8 GHz, 231.5-232 GHz, and 240-241 GHz bands based on the rules currently in place for the 70/80/90 GHz band. The NPRM also seeks comment on applying these rules to several other frequency bands above 95 GHz that may be suitable for licensed fixed operations, including 158.5-164 GHz, 167-174.5 GHz, 191.8-200 GHz, 209-226 GHz, 232-235 GHz, 238-240 GHz, and 252-275 GHz. Nine of these 17 bands are allocated to the RAS or are protected by footnote US342, where all practicable steps should be taken to protect the radio astronomy service from harmful interference:

95-100 GHz
102-109.5 GHz
111.8-114.25 GHz
130-134 GHz
141-148.5 GHz
151.5-158.5 GHz
168.59-168.93 GHz; 171.11-171.45 GHz; 172.31-172.65 GHz; 173.52-173.85 GHz
209-226 GHz
252-275 GHz

Observations in these bands are important to radio astronomy. For example, spectral emission lines at 97.981, 99.300, 102.5, 107.014, 112.359, 113.5, 146.969, 156.602, 262.0, 265.886, 267.557, and 271.981 GHz determine critically important frequencies for RAS studies of the cosmos. *See*, ITU Handbook on Radio Astronomy, (ITU Radiocommunications Bureau, 2013) at Table 3.2.[4] In addition, Table 3.1 of the ITU Handbook includes 76-116, 123-158.5, 200-231.5, and 250-275 GHz in its list of frequency bands preferred for continuum observations.[5]

The following radio astronomy observatories are located in the United States and currently observe, or are projected to observe, in these bands. However, CORF notes that the millimeter wavebands listed below only reflect current and planned capabilities at the present time. New receivers may expand these capabilities over the space of just a few years, depending on the mandates of science.[6]

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[4] *See also* Recommendation ITU-R RA.314-10, Table 1.

[5] *See also* Recommendation ITU-R RA.314-10, Table 3.

[6] The Commission should also be mindful that its actions in this proceeding will impact the development of technology and the provision of radio-based services not just in the United States, but throughout the world. Radio astronomy observatories that are funded by the U.S. and observe in these bands but are located in other countries will be impacted by this proceeding. For example, the Atacama Large Millimeter Array (ALMA) in Chile is funded in part by the National Science Foundation, and includes the NRAO as an operating partner. *See* www.almaobservatory.org. The Large Millimeter Telescope (LMT) in

1. The Smithsonian Astrophysical Observatory Submillimeter Array (SMA) is located atop Mauna Kea in Hawaii at an elevation of 4,080 meters and currently has receivers capable of observing at frequencies from 180 GHz to 418 GHz.[7]

2. The James Clerk Maxwell Telescope (JCMT), also located at Mauna Kea at an elevation of 4,092 meters, is the largest astronomical telescope in the world designed to operate in the submillimeter wavelength region of the spectrum. Owned by the University of Hawaii and operated by the East Asian Observatory (a non-profit Hawaii corporation), it is capable of continuum observation from 100 to 800 GHz, with specific receivers to observe at 211.5-276.5 GHz, 330-335 GHz, 340-375 GHz, and 620-710 GHz.[8]

3. The Owens Valley Radio Observatory (OVRO) is located near Bishop, California, at an elevation of 1,222 meters, and is operated by the California Institute of Technology.[9] There are several telescopes located at OVRO with capabilities to observe throughout the radio spectrum. Current receivers relevant to this NPRM include those that operate at 85-115 GHz and 215-265 GHz.

4. The Arizona Radio Observatory (ARO) is operated by the University of Arizona and consists of two separate telescopes in Arizona.[10] The 12 Meter Alma Prototype Telescope at an elevation of 1,895 meters on Kitt Peak (KP12m), can observe from 83-116 GHz and has a new receiver under development that will be capable of observations from 75-250 GHz. The Submillimeter Telescope (SMT) located on Mt. Graham near Safford, Arizona, and at an elevation of 3,186 meters, currently has receivers that can observe selected frequency bands between 205-720 GHz.

5. The Haystack Radio Telescope is located near Westford, Massachusetts, at an elevation of 122 meters and is operated by the Massachusetts Institute of Technology. It currently has receivers that can observe at 85-115 GHz.[11]

6. The Green Bank Observatory is located in Green Bank, West Virginia. The Green Bank Telescope (GBT), at an elevation of 807 meters, currently has receivers capable of observing throughout the radio spectrum, including two that observe at 75-105 GHz and 80-115.3 GHz.[12]

7. The Next Generation Very Large Array (ngVLA) is currently being developed by the National Radio Astronomy Observatory (NRAO).[13] This new facility will be

Mexico is a joint project of the Instituto Nacional de Astrofísica, Óptica y Electrónica and the University of Massachusetts. www.lmtgtm.org.

[7] *See* http://sma1.sma.hawaii.edu/.

[8] *See* http://www.eaobservatory.org/jcmt/instrumentation/.

[9] *See* https://www.ovro.caltech.edu/.

[10] *See* http://aro.as.arizona.edu/.

[11] *See* https://www.haystack.mit.edu/obs/haystack/index.html.

[12] *See* http://greenbankobservatory.org.

[13] *See* http://ngvla.nrao.edu/page/about.

able to observe at up to 116 GHz. The current ngVLA design is centered at the location of the current VLA on the Plains of San Agustin, New Mexico, and includes more than200 dishes to be located in New Mexico, Texas, and Mexico**.**

In addition to the above, the Stratospheric Observatory for Infrared Astronomy (SOFIA)[14] is an airborne astronomical observatory that is designed to climb above the majority of the atmospheric absorption to enable observations in the far infrared and submillimeter wavelength range. Current instrumentation includes both science and calibration instruments that could be impacted by this NPRM. On the calibration side, SOFIA's water vapor monitor (WVM) operates at 183 GHz. These 183 GHz measurements are critical for the analysis of all of its science observations. On the science side, three of the current instruments operate at frequency ranges of interest to this NPRM: HAWC+ (1.25-6 THz), FIFI-LS (1.5-6 THz), and GREAT (0.49-4.747 THz). SOFIA is particularly vulnerable to satellite transmissions at these frequency ranges, as the atmospheric attenuation is exceedingly low at its typical operating altitude (37,000-45,000 feet).

With the exception of SOFIA, which is not at a fixed geographical location, all of these sites are currently listed in footnote US161,[15] with a coordination zone of 150 km. Smaller coordination zones may be appropriate at higher frequencies (above 275 GHz). However, it is important to note that radio astronomy observations will only be conducted at these high frequencies under the best atmospheric conditions, and thus

[14] *See* https://www.sofia.usra.edu/science.

[15] The NPRM requests an update of the observatories listed in footnote US161. At the present time, the Combined Array for Research in Millimeter-wave Astronomy (CARMA) has been decommissioned, but the telescopes have been relocated to Owens Valley Radio Observatory. The coordination zone for the James Clerk Maxwell Telescope on Mauna Kea is also appropriate for the Submillimeter Array (SMA), also located atop Mauna Kea. Nonetheless, any listing of facilities that operate receivers in the 100 GHz – 1 THz regime should also list the SMA explicitly.

coordination zones should be based on propagation models at the relevant altitude of the radio telescope and for extremely low humidity, rather than the standard (sea level) atmosphere illustrated in Figure 1 of the NPRM.

Nevertheless, CORF does not oppose fixed terrestrial use of the proposed bands, subject to implementation and use of effective frequency coordination. There are a limited number of major RAS facilities that observe in these bands in the United States, and those facilities can be identified with relative ease.[16] While CORF does not have direct experience with the existing coordination system for the 70/80/90 GHz bands, it is logical that a similar system of geographic coordination through the National Telecommunications and Information Administration (NTIA) be applied to these bands. It is CORF's understanding that the criteria used by NTIA for coordination of 70/80/90 GHz links with RAS facilities are taken from ITU-R Recommendation RA.769-2. That is appropriate, and criteria for coordination of the proposed higher frequency bands should do so as well. At a minimum, coordination of fixed links should occur where such links are in line-of-sight to RAS facilities that observe in these bands.

In order to mitigate the absorption of Earth's atmosphere, especially water vapor, millimeter-wave observatories are usually located at high, dry sites. This means that the line-of-sight distances to roads and centers of population may be quite high, with very little terrain shielding. For example, the Kitt Peak radio observatory is located at about 1,900 meters above sea level, and much of the surrounding terrain is at less than 900 meters. Thus, using the well-known formula:

Radio horizon (km) = 4.12*sqrt(h) with h in meters,

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[16] Procedures should also be adopted for notification to NTIA when additional RAS observatories commence observing in these bands.

the line-of-sight from the Kitt Peak 12-m radio telescope to a transmitter at ground level can be as much as about 130 km. Due to the excellent atmospheric transmission properties at these high, dry sites, the curvature of Earth may be the limiting factor in reducing distant interference, even at these high frequencies. However, one mitigating effect at some of the radio astronomy facilities located within the United States is that they may be geographically sheltered such that, in some directions, the line-of-sight distances may be less than the avoidance distance calculated below. If precise avoidance distances are required (e.g., as a function of azimuthal angle), propagation models specific to the geography and the best (most transparent) atmospheric conditions may be required for each radio astronomy site to enable effective sharing of the radio spectrum.

Given the low atmospheric attenuation at radio astronomy sites, the exclusion/coordination zones already established in footnote US161 (for the bands 81-86 GHz, 92-94 GHz, and 94.1-95 GHz) are quite large. Similar large exclusion zones will be required for above 95 GHz as well. For example, to achieve the RA.769 protection criteria for a single 25 dBW/MHz transmitter (maximum EIRP density proposed for fixed services in paragraph 34 of the NPRM) with atmospheric conditions appropriate for the locations of radio astronomy facilities, exclusion zones can be as large as hundreds of kilometers (see Table 1 below). These calculations include atmospheric attenuation, inverse square law propagation effects, and isotropic radiation. Note, in particular, that the RA.769 protection criteria assume that any interference received at the radio telescope enters via its isotropic sidelobes, not by its narrow main beam. Thus, in contrast to the statement in paragraph 25 of the NPRM, no protection for

RAS is assumed from having a narrow telescope beam. Similarly, in calculating interference levels from, for example, fixed emitters, interference is usually assumed to result from sidelobe-to-sidelobe coupling from the transmitting antenna into the radio telescope antenna. The isotropic sidelobes of both transmitting and receiving antenna cover the entire hemisphere. Thus, no additional protection is derived from the low probability of main antenna beam coupling when considering spectrum sharing with RAS.

Table 1: Indicative Avoidance Zones for RAS bands assuming representative atmospheric conditions for radio telescope facilities during astronomical observations

Frequency (GHz)	RA.769 threshold for spectral line observations (dB(W/(m^2 Hz)))	Atmospheric Attenuation Kitt Peak, Arizona (dB/km)	Avoidance Distance Kitt Peak, Arizona (km)	Atmospheric Attenuation Mauna Kea, Hawaii (dB/km)	Avoidance Distance Mauna Kea, Hawaii (km)
98	-208	0.16	130	0.07	270
105	-208	0.18	130	0.08	270
113	-208	0.28	130	0.13	270
123	-208	0.38	130	0.17	267
132	-204	0.28	130	0.12	270
145	-204	0.33	130	0.15	270
155	-201	0.42	123	0.19	237
174.7	-202	1.54	41	0.71	79
217	-199	0.81	69	0.36	137
231.8	-199	0.87	65	0.39	128
240.5	-198	0.92	61	0.41	121

263	-197	1.14	50	0.50	101

Table note: The calculated avoidance distances are truncated at the radio horizon, taking into account the height of the observatory and the curvature of the Earth. The avoidance distances calculated here should be considered as indicative only, as they are not calculated for the best possible atmospheric conditions at these sites and are based on the less stringent spectral line threshold interference levels. However, it should also be noted that these calculations consider only horizontal propagation models, whereas a slant path calculation may be appropriate for some terrestrial emitters, depending on the surrounding topography. Nonetheless, to an extent, the additional attenuation expected for a full propagation path model to a terrestrial emitter will be offset by consideration of the more stringent continuum thresholds for detrimental levels of interference listed in ITU-R RA.769-2 and the reduced attenuation experienced during the best possible atmospheric conditions at these high, dry sites.

CORF notes that Table 1 refers to calculations for a single transmitter, with an EIRP of 25 dBW/MHz into an isotropic antenna. Without knowledge of the expected power or the number of mobile devices, it is not possible to create a similar table of avoidance or exclusion zones for mobile services. It is reasonable to estimate that slightly smaller exclusion zones are likely to be appropriate, assuming lower individual power limits for multiple mobile devices. However, such zones should also consider the likelihood of a large number of devices per square kilometer, resulting in higher aggregate emission received at the radio telescope.

At paragraphs 54-56, the NPRM seeks comments on allowing unlicensed devices to operate at 116-122 GHz, 122-123 GHz, 174.8-182 GHz, 185-190 GHz, and 244-246 GHz.[17] CORF appreciates that none of these bands are allocated to the RAS,

[17] CORF recognizes that Mr. James Whedbee has filed a rulemaking petition requesting the adoption of rules to permit unlicensed device operation in the entire 95-1000 GHz range. While CORF agrees that limiting unlicensed operations to indoors only would significantly reduce the risk of interference to passive observations, the proposal that transmitters not be deliberately pointed at windows while transmitting in passive bands is impossible to enforce. CORF shares the Commission's concern regarding opening the entire 95-1000 GHz band to unlicensed use, as the risks of interference would increase significantly, and

except for 244-246 GHz, which is used for observations of rotational transitions of carbon monosulfide (CS) and is included in footnote RR 5.149 and US342. Unauthorized transmissions by unlicensed devices into protected RAS bands can be particularly harmful because, due to their mobility and lack of licensing records, it is very difficult to identify the operator of such devices and to remedy the interference. In regards to protection of radio astronomy observations from unlicensed devices operating at 244-246 GHz, the Commission should look to existing rules protecting radio astronomy observatories from unlicensed devices. Specifically, the Commission should consider limiting operation of 244-246 GHz devices to the indoors, as is the case in Section 15.257 of the Commission's rules for 92-95 GHz devices. In addition, the Commission should consider the use of guard bands in all of these bands, to protect against spurious and out-of-band emissions into passive bands.

CORF notes that aeronautical use of unlicensed devices in the RAS bands should be prohibited since radio astronomy facilities are located at sites with favorable transmission properties and the telescopes are pointed toward the sky. Thus, high-altitude sources do not benefit from geographic shielding, nor from the substantial atmospheric attenuation that can mitigate the effects of terrestrial transmitters. Specifically, the proposed allocation of the 244-246 GHz band for unlicensed devices is of potential concern for RAS, as administrations are urged to take all practicable steps to protect RAS observations in the 241-250 GHz frequency range (footnote RR 5.149).

Paragraph 44 of the NPRM notes that footnote US246 prohibits all transmissions in a number of bands above 95 GHz to protect RAS and EESS, while footnote US74

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the Commission's proposals would already provide considerable opportunities for unlicensed devices above 95 GHz.

specifies that radio astronomy observatories operating in most of the frequency bands listed in US246 will be protected from unwanted emissions from other stations only to the extent the emissions exceed what would be permitted under the technical standards or criteria applicable to the service in which the station operates. As the NPRM points out, US74 omits the 182-185 GHz and 226-231.5 GHz bands, even though they are included in US246 and have RAS allocations, and seeks comment on whether these two bands should be added to US74. In response, CORF urges the Commission not to include these two bands in footnote US74. The 182-185 GHz band is critical for *calibration* of both RAS and EESS instruments, because it provides a measure of the atmospheric absorption that attenuates the signal from the naturally occurring radio emission (both from astronomical sources and from the Earth's atmosphere).[18] For example, concurrent measurement of the atmospheric transparency, obtained through observations of the 183 GHz water line, enables astronomers using science instruments on SOFIA to correct their flux measurements for the (highly variable) atmospheric losses during their observations. The 226-231.5 GHz band is also important for radio astronomy as it includes the low order rotational transitions of the cyano radical (CN) at 226.600 and 226.800 GHz and carbon monoxide (CO) at 230.538 GHz. Observations of the rotational transitions of carbon monoxide are the foundational basis for our understanding of the distribution and kinematics of molecular gas in galaxies, including the Milky Way, because CO is one of the most abundant molecules in the universe. Dense molecular clouds are the birth sites of stars, and studies of their complex chemistry, structure, and dynamics through observations of molecular emission lines

[18] In addition, as explained below, important EESS observations also occur at 183 GHz.

such as CO and CN, provides fundamental knowledge regarding the formation of solar system-like objects and the potential for evolution of life in the universe. Notably, ITU Handbook on Radio Astronomy, at Table 3.2, lists 226.6, 226.8, and 230.538 GHz among the radio frequency lines of greatest importance.[19] In addition, Table 3.1 of the ITU Handbook includes 200-231.5 GHz in its list of frequency bands preferred for continuum observations.[20] In sum, it was well justified that the 182-185 GHz and 226-231.5 GHz bands were omitted from US74, and CORF urges the Commission not to change that status.

IV. Protection of Remote Sensing/EESS

CORF appreciates the detailed information regarding EESS and remote sensing missions provided in the NPRM. In response to questions regarding protecting EESS, CORF notes the following.

A. Background – Use of 95-275 GHz for Remote Sensing/EESS

EESS observations at frequencies above 95 GHz are used extensively for atmospheric profiling, precipitation mapping, and analysis of atmospheric chemistry. Appendix B in the NPRM provides a long list of current and future missions that will observe in the sub-millimeter wave and terahertz bands. For example, measurements of atmospheric temperature are obtained using passive radiometric observations on or near the 118.75 GHz O_2 line (by the Microwave Limb Sounder), and measurements of atmospheric moisture are obtained using passive radiometric observations on or near

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19 *See also* Recommendation ITU-R RA.314-10, Table 1.

20 *See also* Recommendation ITU-R RA.314-10, Table 3.

the 183.31 GHz H_2O line (by the Advanced Microwave Sounding Unit-B, Advanced Technology Microwave Sounder, Global Precipitation Measurement Microwave Imager, and Microwave Humidity Sounder). Observations near the 183 GHz line are particularly important, because recent work to assimilate these measurements into numerical weather prediction models has shown profound improvements in forecast accuracy in cloud- and rain-impacted atmospheres.[21] In addition to these profiling bands, critically important observations are also obtained in the troughs of the absorption lines. These window bands are used to assess continuum absorption and to detect and characterize cirrus clouds for more effective numerical weather prediction. Some currently operational systems observe near 150 GHz (the Advanced Microwave Sounding Unit-B),[22] 157 GHz (the Microwave Humidity Sounder),[23] and 166 GHz (the Advanced Technology Microwave Sounder and GPM Microwave Imager),[24] and future systems now funded for development will observe near 196 and 206 GHz (MicroMAS and TROPICS)[25] to derive information on precipitation intensity and structure and water vapor continuum absorption for weather prediction and climate change research. Additionally, measurements obtained at frequencies near 118, 183, 190, and 205 GHz are used to measure O_3, SO_2, and HNO_3 for studies of atmospheric chemistry with a variety of applications spanning many facets of atmospheric and climate study.

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21 *See, e.g.,* A.J. Geer *et al.*, "All-Sky Satellite Data Assimilation at Operational Weather Forecasting Centres," *Q.J.R. Meteorol. Soc.*, Nov. 14, 2017, doi:10.1002/qj.3202*.*

22 *See, e.g.*, https://nwpsaf.eu/deliverables/aapp/amsu_b.html and http://mirs.nesdis.noaa.gov/amsub.php.

23 *See, e.g.*, http://mirs.nesdis.noaa.gov/mhs.php.

24 *See, e.g.*, http://www.jpss.noaa.gov/atms.html.

25 *See, e.g.*, https://tropics.ll.mit.edu/CMS/tropics/The-MicroMAS-2-Cubesat.

Furthermore, the NASA IceCube (currently operating),[26] TWICE,[27] and CAMLS[28] missions will observe in the submillimeter-wave bands.

B. Appropriate Harmful Interference Levels

ITU-R RS.2017 establishes a maximum level of interference on Earth sensing instruments for specific frequencies,[29] and ITU-R RS.1858 addresses aggregate interference into EESS bands. For example, at 236 GHz, ITU-R RS.2017 sets the maximum level of interference as -194 dBW; at 664 GHz, this level is -155 dBW for nadir or conical scanning modes and -194 dBW for microwave limb sounding applications. These levels are appropriate for current sensors, but future instruments will benefit from rapidly advancing technology in low-noise receiver front ends and new ultra-compact closed-cycle coolers that can maintain amplifiers at cryogenic temperatures for improved performance. New detector technologies, for example, Kinetic Inductance Detectors (KIDs), will further drive down the noise floor and could require tighter restrictions on radio frequency interference into EESS (passive) sensors.[30]

C. Propagation Modeling

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[26] *See* Wu, D., Esper, J., Ehsan, N., Johnson, T., Mast, W., Piepmeier, J. R., and Racette, P. E., "IceCube: CubeSat 883-GHz Radiometry for Future Ice Cloud Remote Sensing," NASA Technical Report GSFC-E-DAA-TN25376, 2015.

[27] *See* S.C. Reising *et al*., "Tropospheric Water and Cloud ICE (TWICE) Millimeter and Submillimeter-Wave Radiometer Instrument for 6U-Class Nanosatellites," pp. 1-2 in *2016 41st International Conference on Infrared, Millimeter, and Terahertz waves (IRMMW-THz)*, Copenhagen, 2016, doi:10.1109/IRMMW-THz.2016.7758396.

[28] *See* N.J. Livesey *et al.*, "New Technologies for Spaceborne Measurements of the Upper Troposphere and Lower Stratosphere: The Compact Adaptable Microwave Limb Sounder (CAMLS) Project," AMS Seventh Conference on Transition of Research to Operations, Jan. 2017.

[29] It is CORF's understanding that revisions to ITU-R RS.2017 are currently under discussion by ITU WP7C.

[30] *See, e.g.,* A.R. Nehrir *et al.*, "Emerging Technologies and Synergies for Airborne and Space-Based Measurements of Water Vapor Profiles," *Surv. Geophys.* 38: 1445, 2017, https://doi.org/10.1007.

In paragraph 45, the NPRM requests information regarding ways of predicting atmospheric attenuation. Atmospheric attenuation along the line-of-sight is a critically important element required to calculate the level of interference at a remote sensor due an extraneous radiating source; for example, as noted in the NPRM, models for attenuation by atmospheric gases up to 1 THz are presented in ITU-R P676-11. One example of a more complete environmental propagation model is the Atmospheric Radiative Transfer Simulator (ARTS),[31] an open source radiative transfer model. ARTS has been developed to enable analysis of measurements from passive microwave instruments, including the Microwave Limb Sounder (MLS) and the Odin-Submillimeterwave Radiometer. ARTS employs state of the art absorption models, including transmission and scattering from clouds and rain,[32] and can provide simulations with arbitrary frequency resolution from the microwave to the thermal infrared. The line-by-line calculations are based on molecular line catalogs, such as HITRAN,[33] and various models for the continuum. Spherical geometries and polarization are considered, and all sensor viewing geometries can be accommodated (up, limb, nadir, from inside or outside the atmosphere). Use of radiative transfer simulators, such as ARTS, is critically important when evaluating the feasibility of sharing spectrum between passive and active services under a variety of atmospheric conditions.

For example, unlike oxygen, which is generally well-mixed and constant throughout the atmosphere, water vapor is highly variable and depends strongly on

[31] *See* P. Eriksson *et al.*, "ARTS, The Atmospheric Radiative Transfer Simulator, Version 2," *Journal of Quantitative Spectroscopy and Radiative Transfer* 112: 1551-1558, 2011, doi:10.1016/j.jqsrt.2011.03.001.
[32] *See, e.g.,* H.J. Liebe, "MPM—An Atmospheric Millimeter-Wave Propagation Model," *International Journal of Infrared and Millimeter Waves* 10: 631-650, 1989.
[33] *See* L.S. Rothman *et al.*, "The HITRAN2012 Molecular Spectroscopic Database," *Journal of Quantitative Spectroscopy and Radiative Transfer* 130: 4-50, 2012, doi:10.1016/j.jqsrt.2013.07.002.

temperature. Therefore, modeling of interference on sensors viewing near the water vapor absorption bands, and in the continuum, must consider cold, dry air when computing atmospheric attenuation, not just the standard model illustrated in Figure 1 of the NPRM. For example, the path loss for a sensor with 0.05 m^2 effective antenna aperture viewing at a 53-degree Earth incidence angle from a low Earth orbit is approximately 2 dB at 243 GHz, and 30 dB at 664 GHz for an atmosphere with 1.25 g/m^3 water vapor density at the surface. Using the Friis transmission equation to calculate the radiance of 1,000 1 W dipole transmitters within the footprint of a spaceborne sensor measuring at these frequencies yields approximately -110 dBW at 243 GHz and -140 dBW at 664 GHz at the spacecraft. These levels are well above the -194 dBW level mandated by ITU-R RS.2017, and there will likely be many more than 1,000 transmitters within a typical 200 km^2 sensor footprint. Thus, when considering shared use of the radio spectrum above 95 GHz, upward-pointing transmitters and airborne use should be avoided in order to prevent interference to EESS (passive). In addition, in any configuration, a full link analysis under appropriate atmospheric conditions should be conducted to verify that there will be no interference to EESS (passive) bands. Estimated aggregate power levels should also be kept well below the maximum interference levels specified in ITU-R RS.2017.

Paragraph 45 of the NPRM seeks comments on whether additional environmental characteristics, such as clutter models, should be considered. CORF is not familiar with statistically based clutter models at the high frequencies covered in this proceeding, outside of those that can be derived through ray-tracing. At low frequencies, an empirical model derived from observations by Okumara[34] and Hata,[35] is known as the Okumura-Hata model, but would not apply in such a facet-driven high-frequency-scattering environment. Rather, the specular interactions of these signals with large, reflective flat surfaces that exist in urban areas could create the potential for nominally horizontally propagating fields to be reflected towards zenith, and hence act as false signals for nadir-looking EESS satellites making atmospheric observations. Accordingly, CORF suggests that the Commission encourage the development of such models.

D. Consideration of Shared Use: Oxygen and Water Bands

The NPRM considers additional shared use of the 116-122 GHz band for inter-satellite service (ISS) communication links with non-geostationary orbit (NGSO) satellites (paragraph 49) and unlicensed devices (paragraph 57). At the present time, this frequency range is allocated to EESS (passive), Space Research (passive) and Inter-Satellite (ISS), with restriction of ISS to geostationary-satellite orbits only (footnote RR 5.562C).[36] This frequency band is ideal for EESS observations of molecular oxygen in the atmosphere and Space Research Service (SRS) observations of oxygen emission lines from astronomical sources. As mentioned above, the 118 GHz oxygen line provides a measure of the atmospheric temperature profile, which is an important parameter for weather forecasting and other applications. Given the importance of this

[34] *See* Y. Okumura *et al.*, "Field Strength and Its Variability in the VHF and UHF Land Mobile Radio Service," *Rev. Elec. Commun. Lab.* 16(9/10): 825-73. 1968.

[35] See, M. Hata, "Empirical Formula for Propagation Loss in Land Mobile Radio Services," *IEEE Transactions on Vehicular Technology* 29(3): 317-325, 1980.

[36] Footnote RR 5.562C states that "Use of the band 116-122.25 GHz by the inter-satellite service is limited to satellites in the geostationary-satellite orbit. The single-entry power flux-density produced by a station in the inter-satellite service, for all conditions and for all methods of modulation, at all altitudes from 0 km to 1,000 km above Earth's surface and in the vicinity of all geostationary orbital positions occupied by passive sensors, shall not exceed –148 dB(W/(m^2 · MHz)) for all angles of arrival."

spectral line, and the anticipated number of NGSO satellites to be launched in the near future, which could result in significant aggregate interference, CORF does not recommend extending ISS use to NGSO satellites in this band. In addition, for the reasons identified in paragraph 57 of the NPRM, CORF does not recommend allocation of 116-122 GHz for unlicensed devices, due to the possibility of interference with both EESS (passive) and RAS if these devices are numerous or airborne.

In paragraph 55 of the NPRM, there is a proposal to allow unlicensed devices in frequency ranges that correspond to the wings of 183 GHz water line: 174.8-182 GHz and 185-190 GHz. At the present time, these frequency ranges are allocated to EESS (passive), Space Research (passive) and Inter-Satellite (ISS). CORF notes that despite the strong atmospheric absorption, operation of low-power unlicensed devices in these bands may produce unacceptable levels of interference into these critical bands for EESS (passive) if the devices are numerous or airborne. If ground-based use of unlicensed devices is to be permitted, power levels must be limited such that aggregate emissions fall below that recommended in ITU-R RS.2017 (-163 dBW for nadir or conical scanning modes; -189 dBW for microwave limb sounding applications) under the *best* (most transparent) atmospheric conditions. Specifically, as noted above, in cold, dry conditions, the 183 GHz water line can be weaker than the 60 GHz oxygen band by a factor of three, so extrapolation of power levels set for unlicensed devices at 60 GHz may underestimate the possibility of interference that could corrupt EESS observations at 183 GHz, and higher power levels are even more likely to cause interference in the aggregate. Furthermore, given the importance of the 183 GHz water line for measurement of water vapor content in both EESS and RAS applications, and for weather prediction, airborne use of unlicensed devices in these frequency ranges should be prohibited.

CORF notes that many of the proposed unlicensed bands are adjacent to passive use-only allocations. Out-of-band emissions (OOBE) and spurious emissions are of increased concern, especially when there are no guard bands provided between passive and active allocations. Accordingly, CORF recommends that guard bands be included in allocations and rules for these bands. Nonetheless, CORF also recognizes that implementation of OOBE limits can enable effective sharing between services (both active and passive) and therefore acknowledges the importance of the OOBE/spurious emission limits included in the proposed new text for Section 15.258.

V. Spectrum Horizons Experimental Licenses

Radio astronomy and remote sensing Earth scientists have always been on the forefront of developing and using innovative telecommunications technologies. CORF thus supports the experimental development of new technologies, and the use of shared spectrum to do so, when protection of passive observations is practicable. CORF appreciates the acknowledgement in paragraph 77 of the NPRM that passive services are vulnerable to interference with the proposal to open all of 95 GHz to 3 THz to experimental licenses,[37] and thus endorses the recommendation that "applicants must ensure that the significant number of passive services that use spectrum above 95

[37] CORF notes that Agenda Item 1.15 of World Radiocommunications Conference 2019 (WRC-19) may result in international radio regulations for spectrum use between 275-450 GHz. CORF urges the Commission not to preempt the WRC-19 decision on AI 1.15, by adopting an action that may prove contradictory to the future international radio regulations above 275 GHz. In addition, CORF notes that footnote US565 identifies frequency bands in the range of 275-1000 GHz that are also of interest and use to the RAS and the EESS.

GHz are protected from harmful interference and, if proposing to use spectrum that is exclusively allocated for passive use(s), they must explain why nearby bands that have non-passive allocations are not adequate for the experiment."[38] A limitation on that proposal, however, is footnote US246, which prohibits transmissions in certain bands,[39] including primary allocations for passive services at 100-102 GHz, 109.5-111.8 GHz, 114.25-116 GHz, 148.5-151.5 GHz, 164-167 GHz, 182-185 GHz, 190-191.8 GHz, 200-209 GHz, 226-231.5 GHz, and 250-252 GHz. Thus, to avoid confusion from these otherwise conflicting regulations, and to properly protect passive observations, the Commission should specifically exclude the bands listed in US246 from the spectrum range available for Experimental Radio Service (ERS) licenses.

VI. Conclusion.

CORF appreciates that the NPRM was drafted with detailed attention to the need to protect important scientific observations in bands above 95 GHz. Such protections serve the public interest. CORF generally supports the sharing of frequency allocations, where practical, but protection of passive scientific observations, as discussed herein, must be addressed.

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[38] The Commission should require that any such explanations be substantive and compelling. For example, minor differences in the cost of performing the experiment should not justify use of otherwise-prohibited bands allocated to passive services.

[39] An identical list of frequency bands is set aside for exclusive use of passive services by international RR 5.340.

Respectfully submitted,

NATIONAL ACADEMY OF SCIENCES'
COMMITTEE ON RADIO FREQUENCIES

By: ______________________________
Marcia McNutt
President, National Academy of Sciences

Direct correspondence to:

CORF
Keck Center of the National Academies
of Sciences, Engineering, and Medicine
500 Fifth Street, NW, Keck 954
Washington, D.C. 20001
(202) 334-3520

Appendix

Committee on Radio Frequencies

Members

Liese van Zee, Indiana University, *Chair*
William Blackwell, MIT Lincoln Laboratory
Sandra L. Cruz-Pol, University of Puerto Rico – Mayagüez
Namir E. Kassim, Naval Research Laboratory
David Le Vine, NASA Goddard Space Flight Center
Amy Lovell, Agnes Scott College
James M. Moran, Harvard-Smithsonian Center for Astrophysics
Scott Ransom, National Radio Astronomy Observatory
Paul Siqueira, University of Massachusetts, Amherst

Consultants

Darrel Emerson, retired
Tomas E. Gergely, retired