# National Science Foundation's Future Spectrum Requirements

A report developed in response to Executive policy action under the October 25th, 2018 Presidential Memorandum: *Developing a Sustainable Spectrum Strategy for America's Future*

August 2019

## Introduction

The National Science Foundation (NSF) is an independent federal agency created by Congress in 1950. The statutory mission of NSF is "*to promote the progress of science; to advance the national health, prosperity, and welfare; and to secure the national defense.*"[1] NSF provided nearly $8.1 billion in funding for the advancement of science and technology research in FY 2019, representing approximately one quarter of all federal basic research conducted by colleges and universities in the United States. As an example of the importance of NSF funding for maintaining United States global scientific and engineering leadership, NSF-funded researchers have been awarded more than 235 Nobel Prizes[2]. Additionally, NSF owns, operates and funds major research facilities, including astronomical observatories, geoscience and meteorological research facilities, biological science infrastructure, and other research networks.[3] The Very Long Baseline Array[4] is a perfect representation of the NSF mission, advancing cutting edge astronomical investigations while also providing the most precise Earth-orientation information through observations of distant quasars to improve Global Positioning System (GPS) accuracy in collaboration with the Navy. This astronomy facility, which may be used for extraordinarily high-resolution study of distant objects for scientific study, is thus also important for national defense applications. For many of the efforts in which NSF-funded and/or managed research is involved, the electromagnetic spectrum plays two primary and crucial roles: (1) the active and passive gathering of data from the Earth (terrestrial sources), our Solar System, and cosmological sources, and (2) direct investigation of new techniques in spectrum use (e.g. electromagnetic modulation and propagation), including communication needs.

**Figure 1: NSF Spectrum Needs**

**Protection** | **Innovation**

1. Protection of existing passive and active allocations, especially for RAS and EESS
2. Expanded geographic protection of the National Radio Quiet Zone from airborne emitters and new National Radio Dynamic Zone areas for piloting coordination and dynamic sharing
3. Responsive and flexible regulatory environment for R&D
4. Research and Engineering investment in technical capabilities for RFI excision, avoidance, new methods of RFI protection (e.g. transmitters with shaped beams) and spectrum sharing
5. Funding to support R&D, coordination and dynamic sharing

**NSF has two key spectrum needs now and in the future: <u>protection</u> of existing uses of the spectrum and a framework for facilitating future <u>innovation</u>.** NSF needs continued protection of existing frequencies identified for the radio astronomy service (RAS), the Earth exploration-satellite service (EESS), and for both active and passive frequencies utilized for weather, hydrologic, and climate monitoring and prediction research. NSF also needs advances in modern communications technology to facilitate the effectiveness of remote environmental data sensor networks and exploratory field science, such as in the polar regions and the high seas. With the rapid development of commercial applications, without the forethought to set aside electromagnetic "preserves", scientific progress in the future will be hindered. Especially for radio astronomy, NSF needs expanded

[1] The National Science Foundation Act of 1950 (P.L. 81-507)
[2] https://www.nsf.gov/news/special_reports/nobelprizes/
[3] NSF 2018 – 2022 Strategic Plan: https://www.nsf.gov/pubs/2018/nsf18045/nsf18045.pdf
[4] https://public.nrao.edu/telescopes/vlba/; see also https://rorf.usno.navy.mil/ICRF

protections in specific geographic areas. In addition, NSF needs a framework for flexible testing and development for its wireless research community. A key NSF goal is the development of technologies and techniques to better enable enhanced spectrum efficiency and the co-existence of scientific investigation and other uses of the radio spectrum. NSF has invested substantial funding for innovative technologies and research in spectrum use, efficiency, and compatibility, and plans to undertake new initiatives to continue basic R&D in electromagnetic spectrum use in the coming 10-15 years.

This report is organized into multiple sections. **Section A: NSF-Funded Researchers and Facilities** provides an outline of current spectrum usage given that future requirements will in large part be a continuation and evolution of the current spectrum usage. This section also describes the NSF funding approach to provide context. For example, NSF-funded research is not isolated in Universities, but includes important industry-university partnerships. **Section B: United States Scientific Community Input** briefly outlines the advisory process to NSF. This section highlights the fact that NSF funding is driven by the creativity and innovation of the U.S. scientists, engineers and entrepreneurs who receive NSF support. **Section C: Future Spectrum Requirements** gives an overview of the future spectrum needs for innovation and protection. Finally**, Section D: Conclusions** highlights the five specific spectrum needs identified in Figure 1 and reinforcing the broader spectrum needs of the NSF to *protect* and *innovate*.

## A. NSF-Funded Researchers and Facilities: Spectrum Use

NSF consists of seven research Directorates supporting science and engineering research and education[5]. Significant spectrum usage has been identified in five of these research Directorates (see Figure 2): Mathematical and Physical Sciences (MPS), Geosciences (GEO), Computer and information Science and Engineering (CISE), Engineering (ENG), and Biological Sciences (BIO). In addition, NSF also engages internationally through its Office of International Science and Engineering (OISE) and via its many facilities located outside of the United States[6], including mobile facilities like the United States Academic Research Fleet[7].

**Figure 2: NSF Directorates with significant spectrum usage**

1. **Mathematical and Physical Sciences**
2. **Geosciences**
3. **Computer and Information Science and Engineering**
4. **Engineering**
5. **Biological Sciences**

Historically, spectrum management at NSF has focused on the protection of passive users of the spectrum for RAS and EESS. This is not because this is the only use of spectrum by the NSF, but because the NSF is one of the few agencies representing these scientific interests in the United States. In recent years,

[5] https://www.nsf.gov/about/research_areas.jsp
[6] https://www.nsf.gov/about/budget/fy2018/pdf/36_fy2018.pdf
[7] https://www.unols.org/

scientific uses of the spectrum have expanded significantly beyond these passive uses and continue to grow.

The electromagnetic spectrum needs and usage of the individual NSF Directorates are disparate in nature and include passive sensing of natural objects (MPS, GEO, and BIO), research and support of wireless communications (ENG and CISE), active probing of the environment (GEO, BIO, and MPS), operation and high-rate data transmission from microsatellites, aircraft, ocean platforms, and remote field stations (MPS, GEO, and BIO), and operational communications needs for health and safety (many large NSF facilities, especially the Antarctic program in GEO's Office of Polar Programs).

The advent of new commercial uses for spectrum such as automobile radars, individual wireless devices, and the impending launch of thousands of new satellites to facilitate wireless communication provides opportunities for scientific research and creates threats to incumbent users, especially passive users, in the form of radio frequency interference (RFI). In recognition of both the challenges and opportunities created by the expansion of spectrum usage, NSF's spectrum needs in the coming decade should include both protection and innovation.

## NSF Facilities and Investments

NSF facilities make use of many frequency bands listed in the United States and international tables of frequency allocations, as well as systems listed in the National Telecommunications and Information Administration's (NTIA) Government Master File and the International Telecommunication Union's Radiocommunication Sector Master International Frequency Register. These include both government and private-sector allocations (for example: RAS allocations and footnotes, environmental and meteorological sensing, commercial satellite systems, and the United States GPS). However, NSF's present and future use of the spectrum currently is not well-represented by these frequency assignments.

Research not only depends upon the availability of the electromagnetic spectrum in general, but access to very specific frequencies dictated by physics. NSF researchers cannot simply move to a different frequency band because there is unique physical information accessible only at precise frequencies. For example, a very important frequency band for astronomical scientific research is 1400-1427 MHz. This band includes one of the most important frequencies emitted by neutral hydrogen, which is used as a primary indicator for the presence of the most abundant element in the Universe, hydrogen. The lack of interference-free access to key frequencies like this one would severely hamper the efforts of science in the United States. For example, astronomy has also progressed to studying the distant Universe, and cosmological expansion shifts the hydrogen frequency signal to a lower frequency where there is no official allocation. The frequency signals from many other important elements and molecules are similarly shifted due to the relative motion of the elements and molecules with respect to the Earth. Hence, it has become increasingly important to maintain quiet preserves like the National Radio Quiet Zone (NRQZ; see Section A.1 for more details), where more frequency access is possible than what is represented by frequency assignments.

Another example of spectrum use that follows where the physics leads is that of absorption bands for microwave sensor-based remote sounding of atmospheric levels of water vapor, supported from both space and terrestrial sensors. Global water vapor profiles are essential to the numerical weather prediction of rainfall and drought and help constrain such predictions in general.[8]

Table 1 summarizes the large facilities and major investments at NSF that require spectrum allocations and/or protection from radio-frequency interference. Together these facilities represent billions of dollars in construction costs and hundreds of millions of dollars in annual operating costs. More importantly, they also represent a key source of global U.S. leadership leading to many discoveries and Nobel Prizes. The spectrum needs for these facilities range from a critical need for exceptional radio quiet, in the case of state-of-the-art astronomy observatories, to active remote sensing and operational communications for ocean-going vessels, to radio quiet and operations support for the Antarctic stations and the United States Academic Research Fleet. Facilities listed in Table 1 (and many other scientific projects supported by NSF) also produce primary data products that rely on the interference-free operation of GPS for location, timing, and sounding purposes. Interference to current GPS receivers would be costly. While many of the Major Facilities are within the continental United States, some are at offshore or international locations. The future spectrum requirements we outline include needs within the United States and internationally.

In the following sections, we outline the Major Facilities and Investments in MPS (A.1), GEO (A.2), CISE (A.3), ENG (A.4), and BIO (A.5).

[8] National Research Council. 2010. Spectrum Management for Science in the 21st Century. Washington, DC: The National Academies Press. https://doi.org/10.17226/12800.

Table 1. NSF Major Facilities and Programs with Spectrum Usage

| Directorate | Facility and Programs |
|---|---|
| Mathematical and Physical Sciences | Atacama Large Millimeter/submillimeter Array |
| | Arecibo Observatory |
| | Green Bank Observatory |
| | Very Long Baseline Array |
| | Karl G. Jansky Very Large Array |
| Geosciences | Academic Research Fleet |
| | Geodetic Facility for the Advancement of Geoscience |
| | International Ocean Discovery Program |
| | National Center for Atmospheric Research |
| | Ocean Observatories Initiative |
| | Polar Facilities and Logistics |
| | Seismological Facilities for the Advancement of Geoscience & EarthScope |
| | Space Weather CubeSat Program |
| Computer & Information Science & Engineering | Platforms for Advancing Wireless Research |
| Engineering | Spectrum Efficiency, Energy Efficiency, and Security: Enabling Spectrum for All |
| Biological Sciences | National Ecological Observatory Network |

## *A.1 MPS Large and Mid-Scale Facilities*

The radio telescopes listed in Table 1 represent United States investments of over a billion dollars (FY 2019) in construction and annual operating costs of approximately $100 million. The majority of facility spending is to the National Radio Astronomy Observatory, which includes the Atacama Large Millimeter/submillimeter Array and the Karl G. Jansky Very Large Array (VLA). These telescopes deliver observational data to thousands of US-based researchers who rely on Federal support and radio spectrum protection at frequencies ranging from below 100 MHz to nearly one THz. These facilities will continue to make use of spectrum in the RAS bands, and opportunistic use of other spectrum bands, wherever the physics of astronomical phenomena will lead.

**Figure 3. Atacama Large Millimeter/submillimeter Array (left); Karl G. Jansky Very Large Array (right).**

Photo credit: NRAO

Photo credit: NRAO

Almost all of the radio astronomy done at major NSF facilities is in a passive "listening" mode (with the exception of the Arecibo Observatory which also has an active radar program, partially supported by NSF's GEO Directorate and partially supported by the National Aeronautics and Space Administration, NASA, for the characterization of potentially hazardous Near Earth Objects[9]). The large antennas and cryogenically-cooled low noise receivers make radio astronomy telescopes extremely sensitive to faint and distant astronomical signals, but also much more susceptible to RFI.

**Figure 4. Arecibo Observatory.**

Photo credit: University of Central Florida

There has been a tremendous increase in sensitivity of radio astronomy receivers over the last eight decades – representing an improvement of roughly 14 orders of magnitude. Astronomical observatories employ the most sensitive, cryogenically cooled radio receivers in existence. These

[9] https://www.nasa.gov/planetarydefense

systems are capable of sensing signals millions to billions of times weaker than typical communication systems. Extended interference-free observing times are necessary to carry out scientific investigations. **This extraordinary sensitivity also means RFI can have a profound impact on the usefulness of these investments of public funds and the ability of scientists to carry out their research.**

Table 2. Selected major radio astronomy observatories of importance to the United States

| Facility | Location | Frequency (GHz) | Notes |
|---|---|---|---|
| Allen Telescope Array | Hat Creek, CA | 0.5 – 11.2<br>0.5 – 15* | <br>*future possibility |
| Arecibo Observatory | Arecibo, PR | 0.3 – 10<br>10 – 30* | <br>*future possibility |
| Arizona Radio Observatory | Tucson, AZ | 84 – 116<br>205 – 280<br>275 – 373*<br>325-370<br>385 – 500<br>602-720 | *in development |
| Atacama Cosmology Telescope | Chile | 150 - 270 | |
| Atacama Large Millimeter/submillimeter Array | Chile | 35 – 50*<br>65 – 90*<br>84 - 950 | *in development<br>*in development |
| Cosmology Large Angular Scale Surveyor | Chile | 40, 91, 150, 214 | |
| Green Bank Observatory | Green Bank, WV | 0.3 - 100 | |
| Large Millimeter Telescope | Mexico | 85 - 275 | |
| Long Wavelength Array | New Mexico | 0.015 – 0.09 | |
| Simons Observatory | Chile | 25 – 280 | * in development |
| South Pole Telescope | South Pole | 95, 150, 220<br>* 30, 40, 85, 95, 145, 155, 215, 270 | <br>* in development |
| Submillimeter Array | Mauna Kea, HI | 180 - 900 | |
| Karl G. Jansky Very Large Array | Socorro, NM | 0.07 - 50 | |
| Next-Generation VLA | New Mexico and region* | 0.07 – 115* | * expanded frequency range and geographic region of the VLA |
| Very Long Baseline Array | 10 sites in the USA | 0.3 - 96 | |

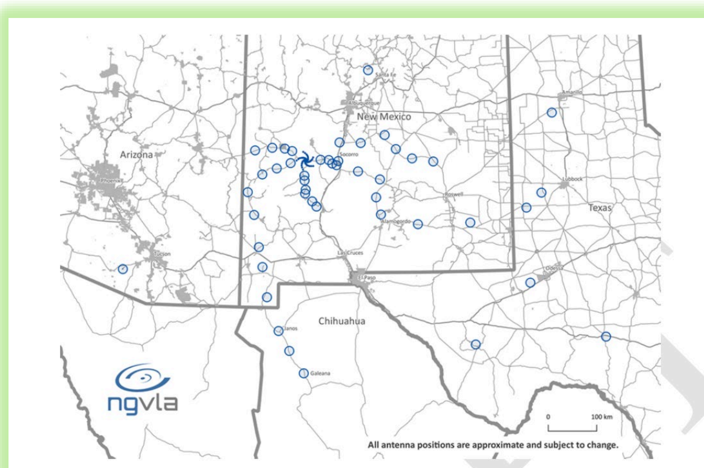
The Green Bank Observatory resides within the NRQZ. Established by the Federal Communications Commission (FCC) and the Interdepartment Radio Advisory Committee (IRAC) in 1958[10] to minimize harmful interference to the sensitive radio astronomy telescopes and to facilities operated by other

[10] See FCC Docket No. 11745 and IRAC Document 3867/2; NRQZ encloses a land area of ~ 13,000 square miles

government agencies, this quiet zone has served its purpose for over 60 years.  However, the rules set forth in 1958 are no longer adequate to protect the Green Bank Observatory from the airborne transmissions, such as airplanes, satellites, and unmanned aerial vehicles.  In order to minimize and coordinate **airborne transmissions, the United States scientific community will need updated rules for the NRQZ that consider the modern progress of technology.**

Future facilities under discussion in the United States astronomical community include the next-generation Very Large Array (ngVLA; see Figure 5)[11]. This facility would operate at frequencies from ~100 MHz to ~115 GHz, which is currently the spectral regime under the most threat from a variety of commercial applications. The ngVLA will represent a significant geographic, signal sensitivity, and spectrum use expansion of the existing Karl G. Jansky Very Large Array in the southwest of the United States.  Currently, there is no quiet zone for the geographic area where the current VLA exists, nor are there any quiet zone protections for the planned ngVLA.  **To protect the important scientific leadership in radio astronomy into the future, the United States needs to establish a new National Radio Dynamic Zone (NRDZ) with quiet zone protections and coordination requirements around the ngVLA.**  NRDZ geographic areas can encompass a new innovative way of exploring frequency sharing by piloting a dynamic coordination process in a geographic area with a relatively small population.

Figure 5. Potential sites for the next-generation VLA observatory.




The system envisioned would enable multiple real-time spectrum sharing techniques and opportunities that go beyond current techniques such as “listen-before-talk” dynamic frequency selection. These techniques could include active feedback of devices regarding spectrum use, geographic awareness, spectrum sensing for real-time waveform detection and characterization, and device control. Such techniques would not only work to the advantage of passive uses of the spectrum, but potentially promote experimental efforts, as well, and far greater spectrum efficiency. In addition, the technology developed in this initiative has the potential to substantially benefit spectrum use beyond the geographic NRDZ area.

[11] http://ngvla.nrao.edu/

The NRDZ initiative would build and expand existing programs such as the Platforms for Advanced Wireless Research (PAWR) (detailed in A.3 below), leveraging current technologies and developing new capabilities. The NRDZ initiative would also benefit the missions of multiple agencies by providing a proving ground for both public and private-sector technologies, enhanced monitoring of spectrum along the U.S.-Mexico border, and better access to spectrum in real-time for passive uses.

## *A.2 GEO Major Facilities and Programs*

The GEO facility portfolio includes the operations of research vessels with a global reach, polar region research stations, and studies of plate tectonics, all of which make use of the radio spectrum.

### *NCAR*

The National Center for Atmospheric Research (NCAR) is the largest single national facility operated by NSF, with an annual budget of approximately $100 million (FY 2019). NCAR operates two aircraft as platforms for atmospheric research that host instrumentation provided by United States scientific researchers. In addition, NCAR supports other atmospheric observing platforms such as a deployable, dual-wavelength Doppler radar and cloud radar systems. The NCAR Coupling, Energetics, and Dynamics of Atmospheric Regions program maintains a central data base of observational data from various types of radars for space weather research. The NCAR Earth Observation Laboratory supports the design, development, deployment, and field operations of dual polarization radars in multiple frequency bands used for severe weather research, often in conjunction with collaborative university development and field programs.

NSF funds NCAR for data processing and archiving of GPS Radio Occultation data from the legacy COSMIC-1[12] small satellite constellation, for the upcoming low inclination COSMIC-2 satellites and from other international polar satellites. This data is used by the NSF funded atmospheric research community. NCAR-related spectrum issues include licensing for disparate uses, analysis of out-of-band emission from the radars and other devices, advice/assistance to researchers using NCAR-provided capabilities, and coordination between active and passive users of the spectrum. Many of the NSF frequency assignments for active use of the spectrum are for NCAR.

NCAR participates in large atmospheric research campaigns over broad stretches of the continental United States. A recent example is the Plains Elevated Convection at Night (June 1–July 15, 2015), studying nighttime severe thunderstorm phenomena, that integrated multiple organizations, instruments and investigators for an intensive campaign covering the central Great Plains (central and western Kansas, and adjacent parts of Nebraska, Texas, and Oklahoma). Federal sponsors were NSF, NASA, the National Oceanic and Atmospheric Administration (NOAA) and the Department of Energy (DOE). The campaign used a significant array of experimental mobile and fixed terrestrial radars,

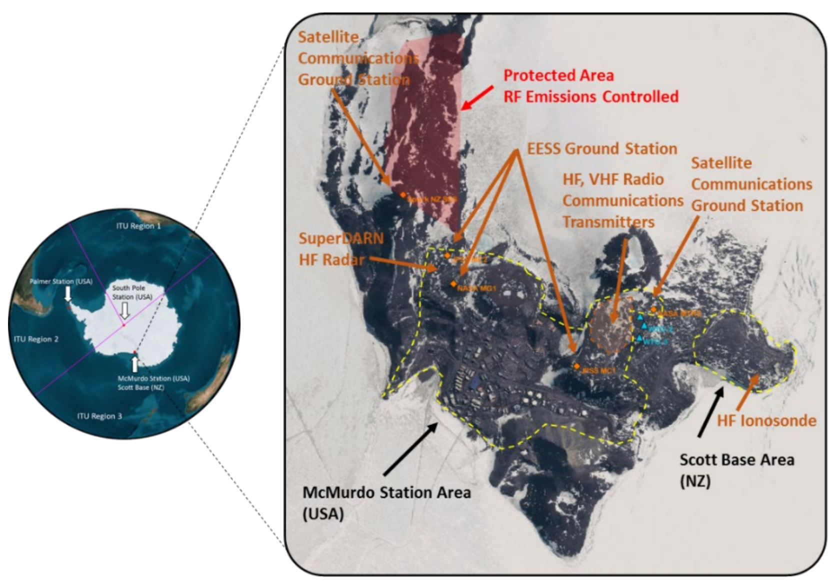
[12] https://www.cosmic.ucar.edu

government operational radars, airborne radars, balloon-borne radiosondes, passive sensors such as radiometers, and GPS-based sensors covering a wide frequency range from 250 MHz to 110 GHz. In addition to spectrum-dependent instrumentation, extensive use of commercial radio and mobile telecommunications was needed to coordinate the campaign.[13]

### *Polar Programs*

The Office of Polar Programs within GEO manages the United States Antarctic Program (USAP) which includes McMurdo, Amundsen-Scott South Pole, and Palmer Stations (see Figure 6). Because the year-round, self-sustaining, stations of the USAP are devoid of underlying civil infrastructure, they incorporate radio spectrum as an essential component of operations critical for life safety, morale, and mission operations. Radio spectrum applications include fixed satellite service broadband communications, mobile satellite communications, long-haul HF radio, VHF/UHF land mobile radio, point-to-point trunking, microwave radio systems, regional Wi-Fi wireless networks, aircraft microwave landing systems, tactical air navigation systems, aviation band air-ground communications, operation of long-duration balloons, radio paging systems, radio telemetry systems, video transmission links, ship-shore VHF communications, vehicle radar for search/rescue, satellite emergency locator/distress beacons, small boating/ship automatic identification systems, meteorological radiosondes, and satellite remote sensing direct readout receptors. Additionally, aircraft flying within the USAP environment utilize all standard equipment needed for aircraft operations per International Civil Aviation Authority and Federal Aviation Administration requirements.

Figure 6. Antarctic facilities.




McMurdo Station is also home to satellite earth stations operating in the EESS and Meteorological Service bands that receive payload data from Earth remote sensing satellites and research satellites. Operated by the National Oceanic and Atmospheric Administration for the Joint Polar Satellite System

[13] https://www.nssl.noaa.gov/projects/pecan/

and NASA for its Near-Earth Network, these ground stations transmit and receive in the Space Operations Band at 2 GHz and receive in the EESS Bands at 8 GHz and 33 GHz. Management of harmful interference from local sources and coordination of spectrum use for future McMurdo Station operations and science programs is necessary to ensure the integrity of the data received by these earth stations.

### *Radar Systems*

Within the GEO Division of Atmospheric and Geospace Sciences, radar systems (listed in Table 3) that cumulatively cost many millions of dollars a year to operate are an important part of the scientific infrastructure. These systems operate at frequencies from a few MHz to over 1000 MHz.

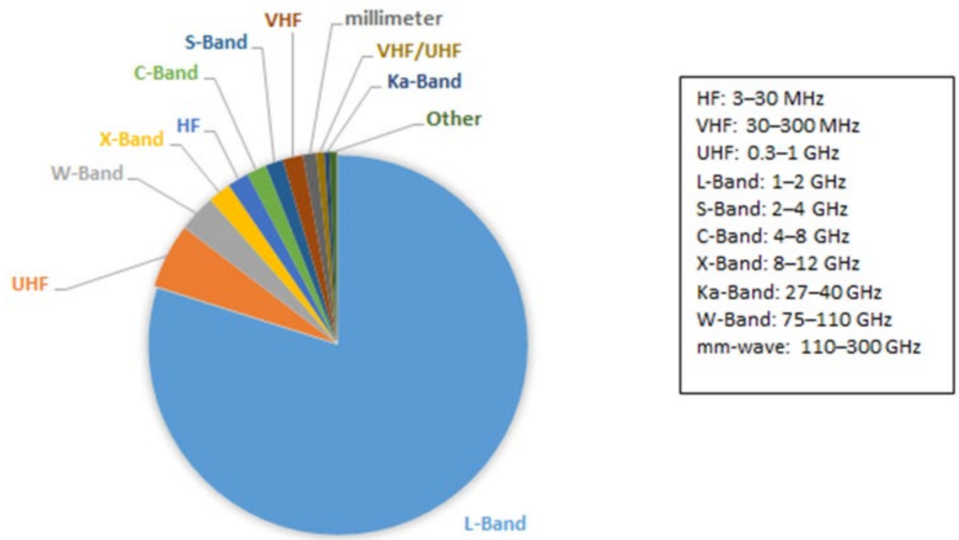
Table 3. NSF Ionospheric Radars and Frequency Bands [14]

| Radar | Location | Frequency (MHz) | License |
|---|---|---|---|
| SuperDARN | Global | 8-20 | Within the United States – FCC experimental, Noninterference Basis |
| Digisonde | Global | 2-30 | NTIA, FCC, and international |
| Arecibo Incoherent Scatter Radar | Arecibo, Puerto Rico | 430 | NTIA |
| Millstone Hill Incoherent Scatter Radar | Westford, Massachusetts | 440.0, 440.2, 440.4 | NTIA, Noninterference Basis |
| Poker Flat Incoherent Scatter Radar | Poker Flat, Alaska | 449.5 | NTIA – Primary Allocation |
| Resolute Incoherent Scatter Radar | Resolute Bay, Nunavut, Canada | 442.9 | Industry Canada |
| Homer VHF & St Croix VHF | Homer, Alaska; St Croix, US Virgin Islands | 29.795 | FCC – experimental, Noninterference Basis |
| Jicamarca Incoherent Scatter Radar | Jicamarca, Peru | 49.92 | Peru |
| High Frequency Active Auroral Research Program | Gakona, Alaska | 2.6 – 9.995 | NTIA |

GEO funding also includes many awards for research which rely on spectrum usage for wireless sensor platforms. From 2009 to 2017, more than $520 million were awarded to these wireless sensor grants. Figure 7 details the breakdown of spectrum usage for this funding; while low frequency is heavily utilized (i.e. below 2 GHz), many higher frequency bands are becoming increasingly important.

[14] Recreated from Table 1.5 of "A Strategy for Active Remote Sensing Amid Increasing Demand for Radio Spectrum, *National Academies of Science, Engineering and Medicine*, 2015, p. 21

Figure 7: Proportion of wireless sensor platform funding awarded in the GEO Directorate utilizing the indicated frequency bands. A total of $526 million was awarded between 2009 and 2017.[15]




### *CubeSats*

CubeSats (small satellites built in increments of ~10-cm cubes) are a growing, low-cost, mechanism for advancing science. A recent program, jointly supported by the GEO, CISE, and ENG Directorates at NSF, seeks to significantly expand the capabilities of CubeSats and develop cutting edge CubeSat technologies that will enable a constellation/swarm of 10-100 satellites and transform space-based science investigations.

## *A.3 CISE: Major Investments*

CISE has several major investments in advanced wireless research, including important public-private partnerships. One such relevant program is the Platforms for Advanced Wireless Research (PAWR) program. PAWR supports advanced wireless research platforms conceived by both the U.S. academic and industrial wireless research communities. PAWR enables experimental exploration of robust new wireless devices, communication techniques, networks, systems, and services that will revolutionize the nation's wireless ecosystem, thereby enhancing broadband connectivity, leveraging the emerging Internet of Things, and sustaining United States leadership and economic competitiveness for decades to come. **The PAWR testbeds require flexible experimental licenses to allow for testing multiple experiments over multiple frequency bands in quick succession over a large (city-scale) area to meet the diverse needs of multiple experimenters.**

[15] Band letter designations correspond to IEEE radar band letter designation nomenclature. For a list, see National Academies of Sciences, Engineering, and Medicine (2015), *Handbook of Frequency Allocations and Spectrum Protection for Scientific Uses: Second Edition*, Washington, DC: The National Academies Press. https://doi.org/10.17226/21774, p. 235, Table B.1.

## A.4 ENG: Major Programs

ENG is pursuing new concepts for increasing spectrum usage efficiency and in spectrum sharing between communications, radar, and passive sensing systems. ENG is also funding research into next-generation wireless networking and mobile communications technology (5G and beyond) through its core programs.

Many major investments within the ENG Directorate are jointly administered with the CISE and/or GEO Directorates.

Spectrum research is concentrated through the Spectrum Efficiency, Energy Efficiency, and Security (SpecEES) program and its predecessor program, the Enhancing Access to the Radio Spectrum (EARS) program. SpecEES is a joint initiative by ENG and CISE. The EARS program was a joint initiative by CISE, ENG and MPS. Including SpecEES and EARS awards, more than $96 million has been invested in spectrum research. The SpecEES program made its first awards in FY 2017, and has, thus far, awarded grants totaling more than $20 million. Awardees are conducting studies into millimeter-wave and terahertz technologies, Multiple-Input Multiple-Output (commonly known as MIMO) communications, spectral efficiency, radio-over-fiber, energy-efficient wireless systems, dynamic spectrum access, wireless security, and other technologies. An example of an award under SpecEES is an investigation at the University of Rhode Island[16] of new network techniques, including Artificial Intelligence, to let radios be aware of their surroundings and keep track of how spectrum is used. The aim of this research is to improve the ability of radios to network with other radios nearby. Prior to SpecEES, EARS promoted the investigation of a wide range of wireless and networking technologies. Research programs included persistent cognitive radios, wide-area spectrum monitoring, crowd-based spectrum monitoring, spectrum sharing, waveform design for spectrum efficiency, and new phased-array designs.

ENG and CISE have been supporting Industry-University Cooperative Research Center[17] Programs for more than 40 years. NSF initiated this program in 1973 to develop long-term partnerships among industry, academia, and government. NSF invests in these partnerships to promote research programs of mutual interest, contribute to the nation's research infrastructure base, enhance the intellectual capacity of the engineering or science workforce, and facilitate technology transfer. This program is an ideal place for future spectrum R&D, as the United States works to find technology and spectrum solutions for every sector of society.

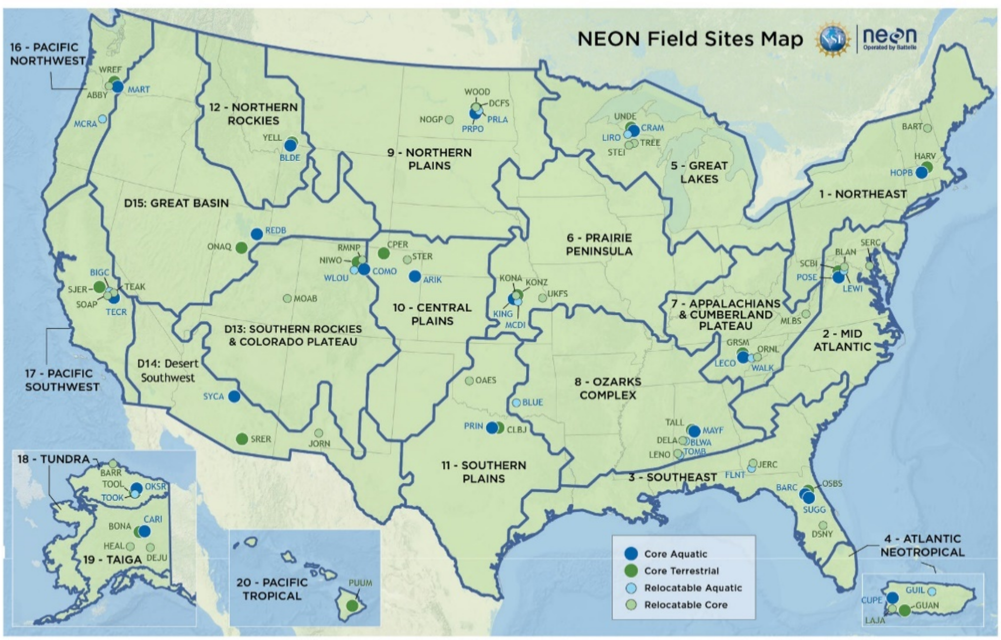
## A.5 BIO: Major Facilities and Programs

There are numerous important research areas relevant to spectrum management in the BIO Directorate. One major investment and example is the National Ecological Observatory Network (NEON; see Figure 8)[18]. NEON is a research network of more than 80 field sites strategically located

[16] https://www.nsf.gov/awardsearch/showAward?AWD_ID=1731672&HistoricalAwards=false
[17] https://www.nsf.gov/eng/iip/iucrc/about.jsp
[18] https://www.neonscience.org

across the United States within 20 ecoclimatic domains that represent regions of distinct landforms, vegetation, climate and ecosystem dynamics.  The main research goal is to understand aquatic and terrestrial ecosystems and how they are changing.  To accomplish this mission, NEON uses radio telemetry for data transmission and reception from a wide variety of instrumentation systems. NEON uses satellite data, cellular data, wireless broadband, and wireless point-to-point backhaul to available internet locations. It is anticipated that in the future, as operations become more routine, NEON will provide a platform for Individual Investigator-supported research. Many of the supported experiments will require radio spectrum for sensing, data transport, or both, and each experiment will need to conform to applicable spectrum regulations. The spectrum usage needs for these research investigations have the potential to conflict with the usage of spectrum for the NEON infrastructure which is based on commercial products. In addition, there are likely to be future uses for unmanned aerial vehicles, which require spectrum for communications, in the surveillance of forest canopy, tracking of wildlife, or any number of other uses.

Figure 8:  NEON Field Sites



The National Ecological Observatory Network which is a major facility funded by the National Science Foundation and operated by Battelle. Any opinions, findings and conclusions or recommendations expressed in this material do not necessarily reflect the views of the National Science Foundation. © 2019.

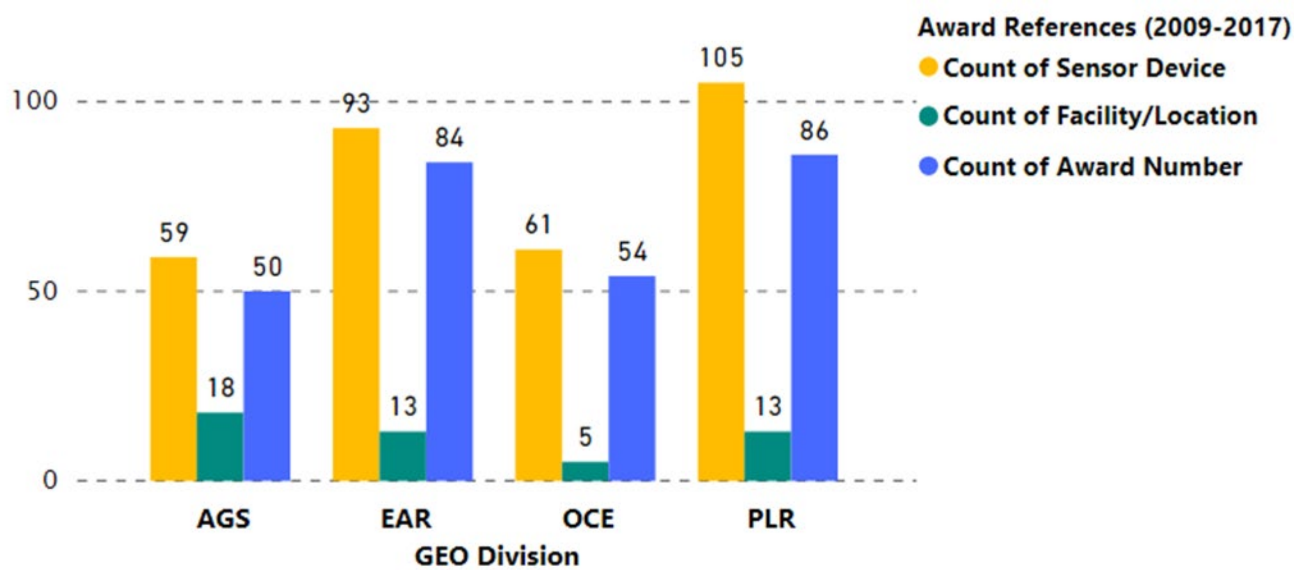
Much of the scientific radar work supported by NSF is carried out by the large facilities, particularly the planetary radar at Arecibo Observatory, and the Doppler and cloud radar work done in GEO. However, the use of radar is growing in BIO where ground penetrating radar is used to assess sub-surface habitats. Broad-scale weather patterns, identified by weather radar, are used to understand plant and animal ecology. Doppler radar is used to track migratory birds, and harmonic radar is used to track insects. In addition to radars, many other scientific instruments make use of the radio spectrum from buoys to dropsondes, and radiosondes to PIT/RFID (Passive Integrated Transponder/Radio-Frequency Identification) tags.

## *Individual Investigator Research*

In addition to spectrum requirements at major facilities, the NSF Individual Investigator Research programs also utilize spectrum resources. The explosive growth of the scientific spectrum needs of individual researchers is largely being driven by the growth in communications including person-to-person, between people and devices, and device-to-device communications. As research programs utilize more "smart" technologies for unmanned aerial vehicles, ground- and water-based vehicles, health-care data transmission, and urban infrastructure, the need for radio spectrum is growing.

GPS is a critical radio technology for science at the large facilities as well as for the science being carried out by the scientific community more broadly. It is a technology that is used for applications such as tomographic views of ionospheric plasma behavior, sounding the lower troposphere for water vapor profiles, supporting weather forecasting research, studying plate tectonics, and tracking the movement of living organisms. The protection of GPS from RFI is extremely important to the entire scientific research ecosystem. This is detailed in Figure 9 for the GEO Directorate; other Directorates also depend upon both position and timing data from radio navigation satellite systems.

Figure 9. Radio navigation satellite system use by GEO: Total number of sensors, facilities, and awards granted (2009 – 2017)




In MPS and GEO (at the South Pole Station) Individual Investigator-led radio astronomy experiments include studies of the reionization of the universe at frequencies between tens of MHz to about 200 MHz and cosmic microwave background experiments that operate between 10 GHz and several hundred GHz. These scientific experiments have typically been in the mid-scale class, but they are almost always preceded by smaller-scale Individual Investigator-led projects focused on the development of advanced technologies and instrumentation in the radio regime.

## B. United States Scientific Community Input

Science and engineering research and education investments made by NSF are guided by community input and are responsive to new discoveries and innovation on a short time-scale. Grants are awarded after a rigorous merit-review process[19], which is so competitive that generally fewer than 25% of proposals are funded, including those with an excellent rating. In addition to the community input via the merit-review proposal review process, NSF also received community input from numerous Federal Advisory Committees representing the areas of science and engineering at NSF[20].

In addition, state-of-the-field reviews assist in setting broader priorities and funding decisions for major facilities and investments. Much of the investment in astronomy and astrophysics facilities, for example, is guided and documented by the recommendations of the scientific community, as summarized in the National Academy of Sciences Decadal Survey[21]. This study provides a pulse on the cutting-edge research questions in the field to determine what investments should be made over the next 10 years, and thus can also provide additional data on what areas of spectrum use may see the greatest emphasis by the field. The next survey ("Astro 2020") is currently being developed; publication is anticipated in Spring 2021. NSF will make funding decisions for research areas and major facilities based on the expert advice of the scientific community, and these decisions will also impact spectrum use emphases going forward.

A good overview of spectrum needs of the United States scientific community to ensure U.S. leadership globally in science, engineering, and technology can be found in the National Academy of Sciences report *Spectrum Management for Science in the 21st Century* (2010)[22]. This report provides a thorough overview of scientific uses of the radiocommunication spectrum, with a focus on astrophysics and environmental/earth sensing. The Committee went into great detail on band-by-band and system-by-system spectrum usage for both areas of investigation. For astrophysics and environmental sensing, this usage (specific frequencies, polarization, radiation levels) is primarily dictated by the physics of the phenomena observed and is not optional for the investigator.[23]

NSF Spectrum usage and needs in the future will continued to be guided by community input.

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[19] https://www.nsf.gov/bfa/dias/policy/merit_review/; see also https://www.nsf.gov/nsb/publications/2015/nsb201514.pdf
[20] https://www.nsf.gov/about/performance/dir_advisory.jsp
[21] https://www.nap.edu/catalog/12951/new-worlds-new-horizons-in-astronomy-and-astrophysics
[22] https://www.nae.edu/24944/Spectrum-Management-for-Science-in-the-21st-Century
[23] National Research Council (2010), *Spectrum Management for Science in the 21st Century*, Washington, DC: The National Academies Press, https://doi.org/10.17226/12800

## C. Future Spectrum Requirements

In general, the Future Spectrum Requirements are a continuation of the presently known spectrum requirements with a few additional requirements in anticipation of the future:

### (1) Protection of existing passive and active allocations, especially for RAS and EESS

- Radio astronomy requires continued protection of currently allocated bands nationwide and internationally; even though most radio astronomy major facilities are in a few limited locations, the protection universally provides guard-bands between other services and enables smaller scale nimble research (e.g. University led radio telescopes)
- EESS requires continued protection of currently allocate bands
- Continued use of dedicated radar bands for active ionospheric and atmospheric research; e.g., ionospheric research at the Arecibo Observatory
- Protection of Global Navigation Satellite Service (GNSS) spectrum (GPS, Galileo, etc.) from harmful interference, both terrestrially and in space, as GNSS is used as a sensor for space physics (ionospheric) and terrestrial (atmospheric) media. New and novel techniques are continually evolving that go beyond being tools for innovative and state-of-the-art research, but can also result in new operational tools for societal benefit (e.g., GPS Radio Occultation - supporting numerical weather forecasting improvements; GNSS passive sensors used for terrestrial-based tropospheric and ionospheric research; GNSS reflectometry and scatterometry using reflected GNSS signals as a passive probe to measure parameters of ocean surface properties, ocean waves, etc.)

### (2) Expanded Geographic Protection of the NRQZ from airborne emitters

- Radio astronomy will require additional protections in a few limited geographic preserves; the NRQZ needs additional protections from airborne transmitters and some of the other major radio astronomy facilities need a new NRDZ coordination area whereby a dynamic sharing process may be piloted to increase access to the spectrum and overall efficiency.
- For astronomical research, the most important need for NSF and U.S. scientific leadership moving into the next 15 years is improved protection in specific geographic areas. The NRQZ needs to have protections from airborne emitters, an update from the 1958 rules which established the NRQZ. The Karl G. Jansky Very Large Array in New Mexico needs a newly established quiet/coordination zone. The ten Very Long Baseline Array stations throughout the United States need similar protection, both for astronomical research and for the important input they provide through the Navy to GPS.
- Meteorological research must utilize spectral bands dictated by the physics of natural phenomena, such as the water vapor absorption bands. Encroachment in these bands by nearby out-of-band emissions or wholesale allocation to radio services will make

essential measurements needed for climatological and weather research difficult or impossible. Broadening of spectrum use must take into consideration effective techniques that will still allow for these sensitive measurements where and when needed.

(3) Responsive and Flexible Regulatory Environment for R&D and new NRDZ areas for piloting Coordination and Dynamic Sharing

- Increased flexibility in the regulatory environment for basic research; for this NSF would require NRDZ areas—possibly constructed in conjunction with new NRQZ efforts (see point 2)—established for testing of various transmitters and piloting dynamic sharing. This would include labs like the Idaho National Lab and expand upon that idea in areas set aside for testing and R&D. Funds and policy to support vibrant R&D in spectrum efficiency and usage is a key future spectrum requirement.
- A spectrum allocation for CubeSats: Effective telecommand/control spectrum allocation, and space-earth data communication, for low cost research SmallSat/CubeSat missions that enable affordable and reliable control of satellites
- Increased communications for research in remote locations (polar regions, high seas, uninhabited desert regions, etc.)

(4) Research and Engineering investment in technical capabilities for RFI excision, avoidance, new methods of RFI protection (e.g. transmitters with shaped beams) and spectrum sharing.

- Radio astronomy facilities currently incorporate spectrum monitoring capabilities. Further work is being conducted by a range of public and private entities to characterize spectrum use and identify specific users of the spectrum.
- Technology may be used to enable real-time coordination between users of the spectrum. Additionally, advanced monitoring capabilities, including the means to identify specific transmitters based upon transmission characteristics across the spectrum, is needed to facilitate and streamline both corrective action and improved coordination action in conjunction with active feedback between spectrum control and clients, or spectrum use communication between users.
- Enhanced, next-generation designs of research instrumentation and algorithm development designed to take advantage of real-time coordination and provide better mitigation including RFI resistant receiver technology and advanced RFI excision techniques in datasets.
- Geographic, spectrum, and radio presence and characteristic awareness, both via sensing and via explicit information provided by radio devices, may be employed to facilitate real-time flexible and efficient use of the spectrum. This technology should be used in conjunction with policy, spectrum availability, specific needs, and sharing features of the environment.

(5) Funding to support R&D, coordination, and dynamic sharing

- Coordination efforts require a well-trained workforce.
- Dynamic sharing will require software development utilizing artificial intelligence and big data techniques.
- Research infrastructure takes funding to develop, operate, and maintain.

## D. Conclusions

NSF has two key spectrum needs now and in the future: protection of existing uses of the spectrum and facilitation of a framework for future innovation. Science research cannot relocate to other bands in most cases due to constraints from the laws of physics. As the demands on spectrum for connectivity increase, innovative and dynamic spectrum sharing methods will be needed to protect science needs adequately while allowing for sharing with other applications and fostering innovative new technologies.

Specific frequency assignments and systems currently allotted to NSF will continue to be used indefinitely. Additional usage will depend upon needs and developments in the academic and research community, as well as enhanced capabilities and advances in the state-of-the-art in several research fields. NSF utilizes more frequencies than are currently recorded as frequency assignments, especially passive use in a few geographic areas. NSF use of the spectrum currently and in the future is underrepresented by the frequency assignments in the United States Government Master File. NSF-funded research initiatives make extensive use of the radio spectrum; this is anticipated to increase in the future. A review of grants and cooperative agreements across the agency have identified over 2,000 existing awards (totaling more than $3.2 billion distributed thus far), some of them ongoing, that employ systems and equipment making use of the electromagnetic spectrum for earth/environmental sensing, meteorological/atmospheric research, astronomical research, biological investigation, engineering/medical/networking research, and other purposes. Many of NSF researchers make use of commercial systems, or a combination of commercial and government spectrum. Many also make use of multiple systems; in some cases, large networks of sensors are employed by a single grantee.

NSF is well-positioned to promote spectrum efficiency, and major initiatives now underway have the potential to benefit users of the radio spectrum, both active and passive, public and private, in line with current and future policy initiatives. NSF is heavily involved in and developing programs to improve spectrum use and make spectrum available for the demands of tomorrow.

Requiring both protection and innovation to thrive, the United States scientific community has the following spectrum needs:

1. Protection of existing passive and active allocations, especially for RAS and EESS
2. Expanded geographic protection of the NRQZ from airborne emitters and new NRDZ areas for piloting coordination and dynamic sharing
3. Responsive and Flexible Regulatory Environment for R&D
4. Research and Engineering investment in technical capabilities for RFI excision, avoidance, and protection; new methods of RFI protection (e.g. transmitters with shaped beams) and spectrum sharing
5. Funding to support R&D, RFI research, coordination and dynamic sharing

With these five points highlighted, NSF emphasizes that the nature of basic research is such that it is not always easy to predict where discoveries will lead or where technological advances will go. NSF strongly advocates for spectrum policies and frameworks that lead to continued and improved **protection** of incumbent services and passive receivers while simultaneously facilitating future **innovation in connectivity technologies**. Robust and secure spectrum management is a challenging endeavor made worthwhile by the benefits to the long-term health and security, global leadership and prosperity of the United States government, industry, and academia. Investment in science and engineering research and education, and the associated spectrum needs, will yield large dividends for future generations.

## List of Acronyms

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| BIO | Biological Sciences |
| CISE | Computer and information Science and Engineering |
| DOE | Department of Energy |
| EARS | Enhancing Access to the Radio Spectrum |
| EESS | Earth Exploration-Satellite Service |
| ENG | Engineering |
| GEO | Geosciences |
| GPS | Global Positioning System |
| MPS | Mathematical and Physical Sciences |
| NASA | National Aeronautics and Space Administration |
| NCAR | National Center for Atmospheric Research |
| NEON | National Ecological Observatory Network |
| ngVLA | Next Generation Very Large Array |
| NOAA | National Oceanic and Atmospheric Administration |
| NSF | National Science Foundation |
| NTIA | National Telecommunications and Information Administration |
| OISE | Office of International Science and Engineering |
| PAWR | Platforms for Advanced Wireless Research |
| R&D | Research and Development |
| RAS | Radio Astronomy Service |
| RFI | Radio Frequency Interference |
| SpecEES | Spectrum Efficiency, Energy Efficiency, and Security |
| USAP | United States Antarctic Program |
| VLA | Karl G. Jansky Very Large Array |