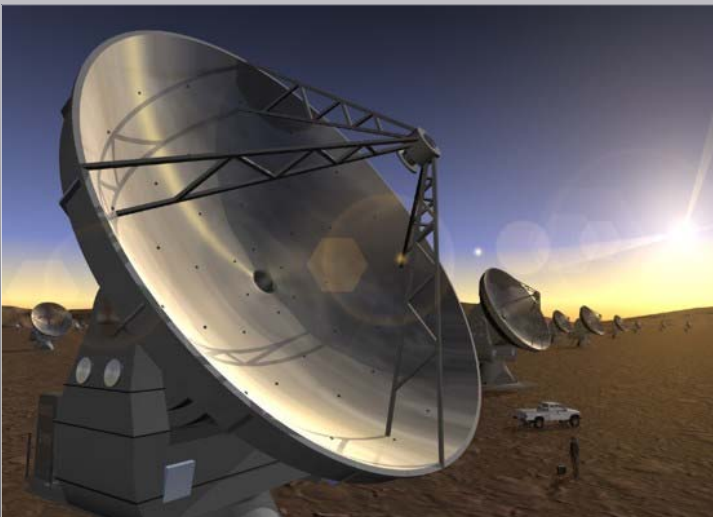
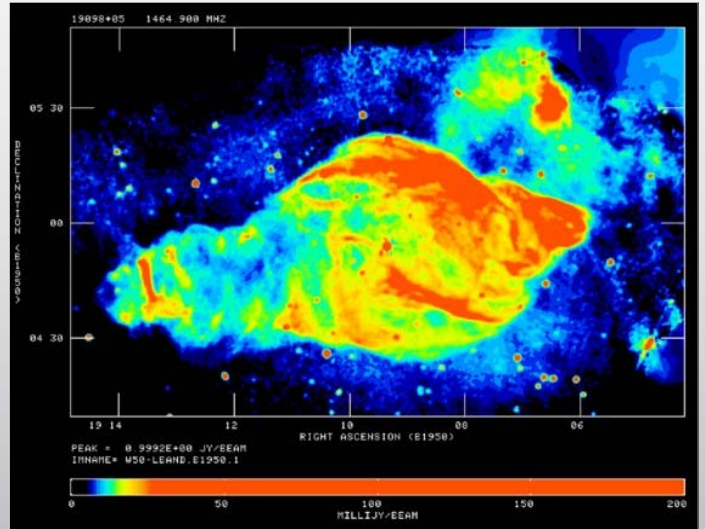
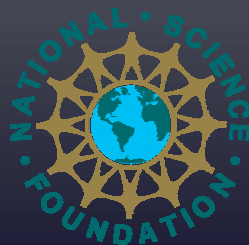


NATIONAL SCIENCE FOUNDATION Strategic Spectrum Plan



November 2007



Note: The organization of this document reflects conformance with requirements established by the National Telecommunications and Information Administration to standardize strategic spectrum plans across all federal government agencies. It is not optimized for presentation of the specific strategic spectrum plan of the National Science Foundation.

Cover page photos, clockwise from top left:

- Communications equipment at Amundsen-Scott South Pole Station. The white sphere is the MARISAT GOES Terminal (SPMGT) satellite communications antenna platform. Behind it to the left is the Radio Frequency (RF) Building and the Avery meteorscatter radar experiment site is in the foreground. SPMGT provides approximately 11.5 hours per day of satellite communications to the world through ground stations in Maryland and Florida that support telephone, e-mail, and Internet communications. *Courtesy NSF/Forest Banks.*
- 1400 MHz continuum map of supernova remnant W 50. This synthesis map covering 1.7 x 3 degrees is a mosaic constructed from 58 observations made using NSF's Very Large Array, an array of 27 individual 25-meter radio dishes located on the Plains of San Agustin in New Mexico. *Courtesy NSF/AUI/NRAO.*
- Incoherent scatter radar dish at the Sondrestrom Research Facility, just north of the arctic circle in Greenland. This facility is host to more than 20 instruments, the majority of which provide unique and complementary information about the arctic upper atmosphere. The suite of instrumentation supports many disciplines of research, from plate tectonics to auroral physics and space weather. The facility is operated by SRI International under the auspices of the NSF, and in joint cooperation with Denmark's Meteorological Institute. *Courtesy NSF/Division of Atmospheric Sciences.*
- The Atacama Large Millimeter Array (ALMA), a millimeter-wavelength interferometric radio telescope. ALMA is an international collaboration under construction in the Chilean Andes. Artist's conception of the completed telescope, superimposed on an actual photograph of the site. *Image courtesy of NSF/AUI/NRAO. Computer Graphics by the European Southern Observatory.*

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I — INTRODUCTION

I.A — THE NSF MISSION

The National Science Foundation (NSF), an independent federal agency, was created by Congress through the National Science Foundation Act of 1950 “to promote the progress of science; to advance the national health, prosperity, and welfare; to secure the national defense, and for other purposes.” To accomplish its mission, the Act authorized and directed NSF to initiate and support:

- Basic scientific research and research fundamental to the engineering process
- Programs to strengthen scientific and engineering research potential
- Science and engineering education programs at all levels and in all fields of science and engineering
- An information base on science and engineering appropriate for development of national and international policy.

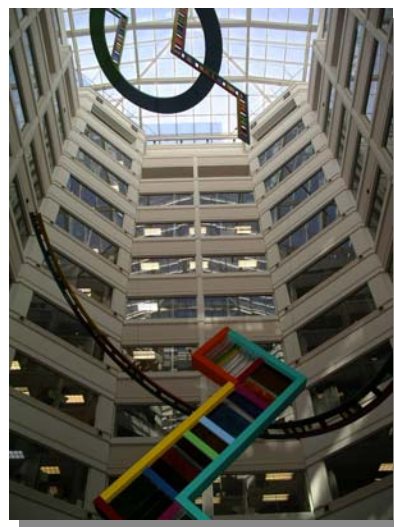
NSF plays a critical role in supporting fundamental research, education, and infrastructure at colleges, universities, and other institutions throughout the country. With an annual budget of about \$5.92 billion, NSF is the funding source for approximately 20 percent of all federally supported basic research conducted by America’s colleges and universities. In many fields such as mathematics, computer science and the social sciences, NSF is the major source of federal backing. To pursue its mission, NSF established strategic goals in terms of Discovery, Learning, Research Infrastructure and Stewardship. These strategic goals can be summarized as:

- Discovery*- Foster research that will advance the frontiers of knowledge, emphasizing areas of greatest opportunity and potential benefit and establishing the nation as a global leader in fundamental and transformational science and engineering.
- Learning* – Cultivate a world-class, broadly inclusive science and engineering workforce, and expand the scientific literacy of all citizens
- Research Infrastructure* – Build the nation’s research capability through critical investments in advanced instrumentation, facilities, cyberinfrastructure and experimental tools.
- Stewardship*- Support excellence in science and engineering research and education through a capable and responsive organization.

The means and strategies that NSF uses to successfully accomplish these strategic goals include the following objectives:

- Expand opportunities for U.S. researchers, educators, and students at all levels to access state-of-the-art S&E facilities, tools, databases, and other infrastructure.
- Provide leadership in the development, construction, and operation of major, next-generation facilities and other large research and education platforms.
- Develop and deploy an advanced cyberinfrastructure to enable all fields of science and engineering to fully utilize state-of-the-art computation.
- Further U.S. economic competitiveness, by investing in basic research and in the tools of science to focus on fundamental discoveries that could have the potential to produce economically important technologies, processes and techniques.

Many NSF-supported researchers and facilities must be able to access portions of the radio spectrum if they are to accomplish these objectives. The U.S. science community’s need to access the radio spectrum provides a direct link between the Foundation’s general strategic plan and its strategic spectrum plan.



The National Science Foundation headquarters building in Arlington, Virginia.

I.B — STRATEGIC VISION FOR SPECTRUM MANAGEMENT

To ensure that the scientific community maintains interference-free access to those portions of the radio spectrum that are needed for research purposes, and to provide spectrum support for the radio communications systems and radio research instruments needed by the NSF's national centers.

II — EXECUTIVE SUMMARY

The National Science Foundation (NSF) is an independent U.S. government agency, responsible for advancing science and engineering in the United States across a broad and expanding frontier. NSF develops state-of-the-art science and engineering facilities, tools, and other infrastructure that enable discovery, learning, and innovation. Many of these facilities (for example, radio telescopes and atmospheric radars) require access to portions of the radio spectrum — a renewable, limited, and vital national resource that must be shared with numerous other users. NSF-sponsored research also requires spectrum access for communications and data relay purposes.

Within NSF, the Electromagnetic Spectrum Management unit (ESM), located within the Division of Astronomical Sciences of the Mathematical and Physical Sciences Directorate, is charged with ensuring access by the scientific community to those portions of the radio spectrum that are required for research. In fulfillment of this mission, ESM staff members participate in the work of national and international regulatory and technical bodies, such as the Interdepartment Radio Advisory Committee (IRAC) and the International Telecommunication Union (ITU).

NSF funds the operation of a variety of radio astronomy facilities within the U.S., and also outside of the U.S. when the science requires such facilities. NSF-supported radio astronomy facilities include the telescopes operated by the National Radio Astronomy Observatory (NRAO) and by the National Astronomy and Ionosphere Center (NAIC). In addition, NSF contributes to the support of university owned and operated radio astronomy observatories.

U.S. radio astronomy facilities, recognized to be among the best and most versatile worldwide, cover practically the entire allocated spectrum. In fact, their coverage extends far beyond the upper limit of currently allocated spectrum (275 GHz), well into the terahertz region. Responding to science requirements, U.S. radio observatories utilize in a passive (non-transmitting) fashion not only the bands allocated to radio astronomy, but also most of the spectrum that is not specifically allocated to radio astronomy. Observations in bands not allocated to radio astronomy are made on an unprotected basis and at reduced efficiency.

Along with its Canadian, European and Japanese partners, NSF is currently building the Atacama Large Millimeter Array (ALMA) in the Chilean Andes. When completed, ALMA will provide unprecedented scientific opportunities for observing the early universe across the 30 GHz to 1 THz spectral region that is particularly important for observations of galaxy and star formation. NSF is involved with the planning and construction of other cutting-edge radio astronomy facilities, with observational capabilities across the spectrum.

Radio astronomy requirements within the range of currently allocated spectrum are expected to be satisfied during the next decade through interference mitigation and limited regulatory action. NSF does not anticipate a requirement for new radio astronomy allocations at frequencies up to 275 GHz. NSF believes however that new allocations in the 275 GHz to 1 THz region of the spectrum to radio astronomy and other science services may be needed within a decade, due to the intense interest of the astronomy community in millimeter wave observations and given the large international investment that is currently going into facilities to observe this spectral region. Spectrum allocations above 1 THz may also become necessary beyond the next decade.

Upper and lower atmospheric scientists also make extensive use of the radio spectrum. Atmospheric research requires the use of transmitters—mostly specialized radars—as well as passive systems. The facilities operated by the National Center for Atmospheric Research (NCAR) and by various universities cover the radar bands in the ~40 MHz to 100 GHz range. The requirements of the atmospheric community are expected to remain largely unchanged, and to remain limited to the radar bands in the foreseeable future.

NSF is the mission agency for the U.S. Antarctic Program (USAP) that maintains a broad portfolio of science programs that make use of the radio spectrum. In addition, spectrum access is essential to communications and for safeguarding life and property in the hostile Antarctic environment. Neither national nor international spectrum regulations cover the polar regions. Spectrum management in Antarctica is largely a matter of local coordination, carried out by a contractor for the USAP.

Radio communications are essential to some other research areas supported by the NSF, such as oceanography. NSF is not directly responsible for spectrum management for the oceanographic fleet, however.

III — CURRENT SPECTRUM USE

III.A — RADIO AND RADAR ASTRONOMY

III.A.1 — Background

NSF supports a broad range of astronomical research based on the reception of radio waves. Radio astronomy observations allow us to discover and study phenomena that are not observable by other means, such as the relic radiation from the Big Bang. Radio observations also complement data obtained at other wavelengths such as optical, infrared, ultraviolet, or X-ray regions of the spectrum.

Radio astronomy traces its origins to some of the earliest experiences of interference mitigation. In 1932 Karl G. Jansky, a Bell Telephone engineer, was tasked with determining the source of interference disrupting HF links, which at that time were used to carry long distance telephone traffic. He traced the interference to two sources: first, the combined effect of local and distant thunderstorms and, second, a well-delineated region of the sky that rose and set periodically with the stars. In noting the second of these sources, Jansky discovered radio emissions that originate in the Milky Way galaxy and established, for the first time, the existence of radio signals from beyond Earth. The basic unit of radio astronomy signal strength was named the jansky (Jy) in his honor.

Although Jansky discovered relatively strong radio signals emanating from our Galaxy, the vast majority of cosmic signals are exceedingly weak and therefore difficult to detect. Cosmic transmissions are the result of natural radiation processes that are, in general, intrinsically weak. Cosmic sources are also very distant, so propagation losses are extreme— at 1400 MHz, free space loss over 40 trillion kilometers (the cosmically short distance to the closest star to the Sun) is large (367 dB); the loss over 95 billion trillion kilometers (the distance to the edge of the observable universe) is a daunting 555 dB. It is only the vast dimensions of cosmic radio sources that allow us to detect their feeble emissions. Radio astronomy research is therefore conducted with extremely sensitive instruments located mostly at sites far removed from predictable sources of ground-based radio interference. In spite of the remoteness of most radio telescopes, the heavy use of the spectrum on the ground, and especially transmissions by air and satellite-borne systems, severely constrain access to the spectrum for astronomical purposes.

Radio astronomy discoveries completely transformed our ideas about the universe in a relatively brief period of time. A reflection of this fact is that three Nobel prizes shared by six radio astronomers have been awarded for radio astronomy-related research, including: the discovery of the remnant radiation from the Big Bang (awarded in 1965); development of techniques for radio interferometry and for the discovery of pulsars (both awarded in 1974); and the confirmation of Einstein’s general theory of relativity through observations of a binary millisecond pulsar (awarded in 1993).

III.A.2 — Radio Telescopes and the Nature of Radio Astronomy Observations

Research in radio astronomy is conducted with two kinds of instruments: single dish telescopes and interferometers (also referred to as arrays). When used as an interferometer, two or more dishes (now considered “elements” of the interferometer) are pointed at the same object, and the data received by each are cross-correlated. An interferometer achieves an angular resolution equivalent to the resolution that would be achieved by a single-dish telescope with a diameter equal to the distance between elements of the interferometer. The mode of operation is relevant to the degree of interference immunity. Because interference received at one element of an interferometer will usually not correlate with interference received at another element, interferometers can generally tolerate higher levels of interference than single-dish telescopes. The degree of interference suppression achieved by an interferometer depends on a large number of factors, however, including the nature and location of the interfering transmitters.

Radio astronomers typically use dedicated arrays for radio interferometry, such as the Very Large Array (VLA) or the Very Long Baseline Array (VLBA), but most single-dish telescopes can occasionally be operated as elements of an interferometer. To increase the sensitivity of an interferometer, one or more single dish telescope(s) with large collecting area (such as the 305 m Arecibo telescope or the 100 m Green Bank Telescope) can be added to an interferometer to greatly increase the sensitivity of the observations.

Telescopes can be configured in multiple ways, depending on the requirements of a given observation. Signal strength measurements integrated over a relatively large bandwidth may be all that’s needed to determine the



NSF's Arecibo Observatory, south of Arecibo, Puerto Rico. At 305 meters in diameter, Arecibo is by far the largest single-dish radio telescope in the world. It is used for radio astronomy, atmospheric/ionospheric research, and as a giant radar transmitter for mapping the structure of the Moon and planets. The telescope operates at various frequencies between 50 MHz and 10 GHz. Arecibo is operated by the National Astronomy and Ionosphere Center/Cornell University. (Photo courtesy NSF/NAIC/Cornell University).

temperature or other bulk physical property of a celestial object. This mode of observing is called continuum observing. Alternately, the back-end of a radio telescope can be configured to break up the observed bandwidth into a large number of narrow bands (like a spectrum analyzer) to observe spectral lines. In this mode, radio telescopes are more susceptible to narrow-band interference, especially when the interference occurs at or near the frequency of the spectral line emissions.

Astronomers who study pulsars often use yet another mode of observation. Pulsars are rapidly spinning neutron stars that emit periodic pulses of radiation that recur on time scales as short as milliseconds. To observe them, astronomers break their data up into intervals of time as short as microseconds or less, so that the pulses may be studied in the time domain. Periodic burst-like interference is especially troublesome to pulsar observations.

III.A.3 — Frequency Bands Used in the Radio Astronomy Service

A number of frequency bands are allocated to the radio astronomy service on a primary or secondary basis. In other bands that are important to radio astronomers but that are not allocated to the radio astronomy service, footnotes to the U.S. (or international) table of allocations call attention to the potential of interference to radio astronomy observations. Appendix D lists the bands allocated to radio astronomy or referred in a footnote.

Many radio astronomy allocations are based on the list of spectral lines of greatest importance to radio astronomy, which is maintained by the International Astronomical Union (IAU) and updated periodically. For example, the 1400 – 1427 MHz band is allocated to radio astronomy for observations of the 1420.406 MHz spectral line emitted by hydrogen, the element that comprises over 90% of the presently observable contents of the universe. Some important spectral lines were discovered only after the band had been allocated to an active service (for example, the 12.178 GHz methanol line, in a band allocated to satellite downlinks). Lines outside allocated bands may occasionally be observed as circumstances permit (e.g. when there are no satellite transmissions), but at greatly reduced efficiency.

Other frequency bands are allocated to the radio astronomy service for continuum observations. These allocations are loosely made in approximately one-octave steps, to allow astronomers to study the variation of broadband source emissions with frequency. Some broadband sources emit strongly at low frequencies and hardly at all at higher frequencies, while others do the opposite; the details of the spectrum provide important information about the sources and physical processes operating in them.

The frequency at which emissions from a cosmic radio source reach the Earth may be modified by the Doppler effect, which changes the frequency at which emissions are observed due to the relative motion of the source with respect to the observer. The frequency at which a source would be observed in the absence of relative motion between the source and the observer is called the rest frequency. When a source is moving towards the observer, its emissions (for example, from a spectral line) are detected at a frequency higher than the rest frequency (that is, the object appears to be “blue shifted”). If the object is moving away from an observer, the frequency at which a spectral line appears will decrease (appears as “red shifted”) relative to its rest frequency.

The shift in frequency is proportional to the relative speed between the source and the observer divided by the speed of light. Since the speed of light is extremely high, most man-made radio systems (with the possible exception of satellite-based systems) are not affected much by the Doppler effect. Cosmic sources, however, can have very large relative speeds with respect to the observer (approaching the speed of light), so the Doppler shift becomes noticeable. Due to the expansion of the universe, distant sources appear to recede faster than closer ones, so the Doppler shift becomes most noticeable for the most distant sources. For example, the 1420 MHz hydrogen line can be redshifted to frequencies as low as 200 MHz when telescopes are pointed at some of the most distant observable sources in the universe. Thus, radio astronomers are forced to observe outside allocated radio astronomy bands to observe sources with high Doppler shift.

Observations outside a radio astronomy band are made possible by the fact that radio astronomy is a passive service, and therefore such observations do not cause harmful interference to allocated services. Out-of-band observing, however, generally means a greatly reduced efficiency, since significant periods of interference can occur due to other services transmitting in the band. Radio astronomers are devoting a great deal of effort into developing hardware and software solutions that may allow them to observe in the midst of varying levels of interference. Such solutions can only be partially effective, however, and always lead to reduced efficiency and, sometimes, to failure acquiring usable data, in spite of the best efforts.

III.A.4 — Existing Facilities

In the U.S., NSF is the major supporter of ground-based radio astronomy and funds the operation of a variety of radio astronomy facilities located both within the U.S. and its possessions and in some other countries. U.S. radio astronomy facilities are widely recognized to be among the best in the world, and NSF intends to retain this leadership position.

Two national centers are dedicated to radio astronomy research: the National Radio Astronomy Observatory (NRAO), operated by Associated Universities, Inc., and the National Astronomy Ionosphere Center (NAIC), operated by Cornell University. Both facilities are operated under cooperative agreements with the NSF. NRAO maintains and operates facilities at 12 sites in the continental U.S., Hawaii and St. Croix, and is building a major new millimeter wave array in Chile. NAIC operates the Arecibo Observatory located near Arecibo, Puerto Rico, which at 305 m (1000 ft) in diameter is the largest single-dish radio telescope in the world. NSF also supports radio astronomy research and/or instrument development at a number of university facilities, consortia of universities, private foundations or public/private partnerships. These telescopes play a vital role in scientific research and, because they allow hands-on experience, are crucial to the training of the next generation of radio scientists. Appendix E lists major radio astronomy facilities in the U.S. and possessions, as well as observatories fully or partially operated by U.S. entities located outside the U.S.

III.A.4.1 — *The National Radio Quiet Zone*

A key regulatory protection that contributed significantly to the development of U.S. radio astronomy and continues to do so today is the protection provided by the National Radio Quiet Zone (NRQZ). The NRQZ was established jointly by Federal Communications Commission (FCC) Docket No. 11745 (November 19, 1958) and by the Interdepartment Radio Advisory Committee (IRAC) in Document 3867/2 (March 26, 1958), to reduce possible harmful interference to NRAO's Green Bank, WV, site and the radio receiving facilities for the United States Navy in Sugar Grove, WV. The NRQZ is bounded by NAD-83 boundaries of longitude at 78° 29' 59.0" W and 80° 29' 59.2" W and latitudes of 37° 30' 0.4" N and 39° 15' 0.4" N, and encloses a land area of approximately 13,000 square miles covering portions of Virginia and West Virginia. NSF is keen on maintaining the controlled radio environment and protection provided by the NRQZ to its Green Bank facilities and is committed to maintaining the integrity of the NRQZ for the foreseeable future.

III.A.5 — Radar Astronomy

The Arecibo radio telescope can be used in "reverse" to project a highly concentrated radio beam toward the Moon or other solar system objects. Although the Moon and planets are hundreds of thousands or even millions of miles away, a faint but usable radar echo can be detected off these objects. Using sophisticated processing techniques, the radar echo is deciphered to produce very detailed maps of the surfaces of solid bodies, such as the Moon, asteroids, Mercury, Venus, the moons of Jupiter, and Saturn's rings.

Arecibo can be used as both the transmitter and receiver if the object is sufficiently distant so that there is time to switch between transmit mode and receive mode by the time the echo returns; but not so distant that the desired object is out of view of Arecibo's sky coverage when the echo returns. Bistatic radar mode—where Arecibo is used as the radar signal transmitter and another telescope (such as the GBT) is used as the receiver—can be used if necessary.

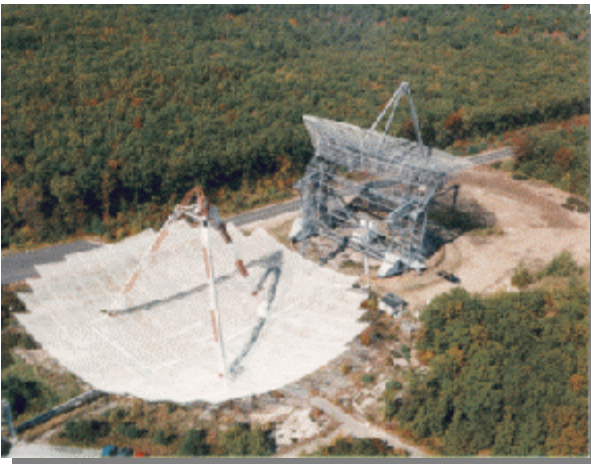
The Arecibo planetary radar operates at 2380 MHz with an RF power of 1 megawatt. With the ~70 dB forward gain of the dish, the effective isotropic radiated power (EIRP) of the planetary radar signal is some 10 trillion watts, making it by far the most powerful radio transmission on Earth. Although the EIRP is very large, the vast distances to the solar system targets, combined with the $1/R^4$ fall-off for radar signals, makes the return signal very weak. The telescope is therefore equipped with a complementary 2380 MHz dual-polarization maser receiver that allows very sensitive observations of the return signal.

III.B — UPPER ATMOSPHERIC RESEARCH

III.B.1 — INCOHERENT Scatter Radar Arrays

NSF supports research from the upper atmosphere of the Earth to the surface of the Sun, with special focus on the physical processes in space that affect Earth's upper atmosphere. The Upper Atmospheric Facilities (UAF) Program is responsible for the operation of a global network of radar facilities. The UAF Program, created in 1983, included incoherent scatter radars in Greenland, Massachusetts, Puerto Rico, and Peru. The approximate longitudinal co-alignment of these four radars provided an excellent opportunity to study the processes by which energy from the Sun is deposited in Earth's atmosphere at high latitudes and the resulting effects on global scale dynamics, energetics, and composition. Recently, a fifth incoherent scatter radar has been added to the program: The Advanced Modular Incoherent Scatter Radar (AMISR), which began operating at Poker Flat, Alaska, in January 2007. The UAF program promotes the cooperation and coordination of the five U. S. radar facilities to study ionospheric processes, space weather, radio science, plasma physics, and global change. In addition to the incoherent scatter radars, the program includes the U. S. contribution to the Super Dual Auroral Radio Network (SuperDARN; <http://superdarn.jhuapl.edu>).

Incoherent scatter radars (ISRs) use a technique that requires high-power transmitters at frequencies ranging from 50 to 1.3 GHz. Large antennas allow concentrating the transmitted energy in narrow beams, from which a small fraction of the outgoing signal is backscattered. The return is referred to as incoherent because the backscattered signal was originally expected to originate from randomly moving electrons in the ionosphere. In fact, the electron motion is ordered by waves tied to the ions in the plasma; the backscattered signal is much larger than one would expect from unordered electron motion. Nevertheless, megawatt transmitters and large antennas are needed to obtain a return signal strong enough to yield the spectral properties of the ambient plasma. Spectral analysis of the received signal yields the total electron density, the ion and electron temperatures, the ion velocity, and



The two antennas of the Millstone Hill Radar at the Haystack Observatory in Massachusetts. Courtesy NSF's Division of Atmospheric Sciences.

information about the ion composition. By combining these measurements with other quantities, either from models or measurements, many basic properties of the ionospheric plasma (for example, the electrical conductance, neutral wind velocity, and exospheric temperature) can be determined.

Each of the radars in the program is unique in terms of its location, transmitting frequency, and antenna design. Appendix F lists the ISRs currently operating for scientific research worldwide. Those operated by NSF are noted. In terms of geomagnetic location, the global ISR network spans the northern hemisphere from the magnetic equator to the edge of the polar cap. The antennas range in size from the 30 m parabolic reflector at Sondrestrom, Greenland, to the 305 m spherical dish at Arecibo, in Puerto Rico. Most of the ISRs employ parabolic or spherical reflectors, while the Jicamarca Radar in Peru, AMISR in Alaska, and the MU (Middle and Upper

atmosphere) Radar in Japan use arrays of dipole antennas. The Jicamarca and MU Radars are also distinct in that they operate at frequencies of about 50 MHz, while most of the remaining ISRs operate at frequencies of a few hundred MHz. The Sondrestrom Radar operates at 1290 MHz. Appendix F lists the distinctive aspects of the ISRs worldwide.

The U. S. incoherent scatter radars often coordinate observations with radars operated by the multi-national European Incoherent Scatter organization (EISCAT) that includes the only non-monostatic ISR in the world. The EISCAT tristatic array has its transmitter at Tromso, Norway, and receiving sites at Kiruna, Sweden, and Sodankyla, Finland. The EISCAT system also includes the EISCAT Svalbard Radar (ESR), which is at the same magnetic latitude as Sondrestrom. With the ancillary instrumentation present in the Scandinavian countries, the EISCAT system provides measurement capabilities of a full range of ionospheric and atmospheric properties throughout the auroral zone.

NSF has supported the U. S. incoherent scatter radars without interruption for three decades. The radars provide space scientists with observations of key ionospheric and atmospheric properties. The measurements support strategic research in disciplinary areas that have strong societal relevance, such as global change, space weather, and basic plasma physics. Because of the complexity and cost of ISR operations, the radars do not operate for more than ~ 2000 hours per year. They are usually operated in a campaign mode, to support experiments of individual investigators or collaborative research involving many scientists. All the radars are operated on a monthly basis to support World Day experiments coordinated by the International Radio Science Union (URSI). These experiments typically last 24 hours, but recently longer experiments have been conducted with occasional operations lasting the entire month. These long experiments respond to the needs of theoreticians and modelers, who require a long baseline to properly test and validate models of the ionosphere and thermosphere.

Due to the isolated locations of the radars and the small number of units involved in the network, no specific spectrum management challenges are generally encountered once the radars are locally coordinated prior to obtaining frequency assignments, despite the high powers used. The radars generally occupy shared Federal/non-Federal spectrum. All of the radars are highly specialized and custom built; no commercial alternatives exist or are likely to exist in the future. Because the radars do not address national security or safety-of-life needs, no COOP or CGO considerations are necessary.

III.B.2 — SuperDARN

SuperDARN (Super Dual Auroral Radar Network) is an international network of high-frequency radar pairs used to study the ionosphere. Each pair of these Doppler radars is capable of measuring a large-scale map (about 4 million square kilometers) of the two-dimensional convection, the electric field, and the field-aligned currents in the F region of the ionosphere. The project includes direct participation from scientists in Canada, the USA, Britain, France, Japan, South Africa, and Australia, and associates in many other nations. The SuperDARN network currently comprises 12 radars in the northern and seven in the southern hemisphere. All radars are virtually identical, with minor differences in antenna design to accommodate differing physical conditions at the various sites. Each of the radars has two arrays of antenna towers, the primary array consists of sixteen towers, and the secondary, interferometer array, consists of four towers. A phasing matrix attached to the antenna array is used for beam forming and to electronically steer the radar into one of sixteen different beam directions.

The SuperDARN radars are designed to operate in the frequency range from 9 to 17 MHz with a bandwidth of about 60 kHz. Personnel at each of the sites work with the local authorities to isolate specific bands within the 9 to 17 MHz range where the radars can operate with no interference. Once the allowable bands are identified, the radars automatically cycle through them to determine the frequencies at which the strongest backscatter is received.

Due to the isolated locations of the radars and the small number of units involved in the network, no specific spectrum management challenges are generally encountered once the radars are locally coordinated prior to obtaining frequency assignments, despite the high powers used. The radars generally occupy shared Federal/non-Federal spectrum. All of the radars are highly specialized and custom built; no commercial alternatives exist or are likely to exist in the future. Because the radars do not address national security or safety-of-life needs, no COOP or CGO considerations are necessary.

II.B.3 — COSMIC Satellite System

COSMIC/FORMOSAT-3 is the Constellation Observing System for Meteorology, Ionosphere and Climate, a joint Taiwan-U.S. project. U.S. government agencies participating in the project include NSF, NASA, NOAA, U.S. Navy, and the U.S. Air Force and its Space Test Program (STP). The purpose of the COSMIC is to gain inexpensive vertical profiles of temperature and moisture across the globe with high spatial and temporal resolution, by intercepting GPS signals with a satellite-based receiver and inferring the deviations in each signal's straight-line path caused by temperature and moisture gradients. Data will be made freely available to the international scientific community in near real time.

COSMIC/FORMOSAT-3 not only has great value for weather, climate, and space weather research and forecasting, but also geodesy and gravity research and other applications. Data assimilation schemes are being developed to effectively integrate the COSMIC data into existing operational weather forecasting models.

The COSMIC/FORMOSAT-3 constellation was launched in April 2006 and is expected to last for five years. Observations of GPS signals will be carried out in a bandwidth of: L_1 (1575.42 MHz) \pm 10 MHz and L_2 (1227.60MHz) \pm 6 MHz. Over the first year, the satellites were gradually boosted from their initial orbit of 400km to the final orbit of approximately 800 km, conducting important geodetic/gravity experiments during this phase.

The system consists of:

- (1) The Space Segment, a constellation of 6 micro-satellites, each weighing less than 70 kg (~170lb). Each satellite takes independent science measurements at all times during the orbit. The six spacecraft carry three instruments each, including GPS radio occultation receiver, tiny ionospheric photometer, and tri-band beacon;
- (2) The Ground Segment: three ground stations and a Multiple Mission Center (MMC). Of the three stations, one each is located in Fairbanks (Alaska), Kiruna (Sweden), and Taiwan. The MMC is located at the NSPO facility in Taiwan as well. The MMC is where the satellites are monitored and controlled. All three stations are used to downlink science & telemetry data from the satellites to the ground;
- (3) All science and some telemetry data are sent to the FORMOSAT-3/COSMIC Data Centers (aka Payload Operations Centers): one each, located in Taiwan and Boulder (Colorado). These centers are responsible for analyzing the received data and providing it to the principal investigators and the science community;
- (4) A global ground fiducial network (built upon existing NASA and international fiducial networks).

III.C — LOWER ATMOSPHERIC RESEARCH

III.C.1 — CHILL Radar and S-POL

The Colorado State University Department of Atmospheric Sciences, under sponsorship of NSF and the National Center for Atmospheric Research (NCAR, an NSF facility), builds and maintains large and deployable polarimetric radar systems that support NSF-funded science programs. These radars provide data that cannot be obtained in any other manner. Polarimetric radar data are used in the study of convective storm development. In many cases the radars would be used to "navigate" a specially armored T-28 aircraft into the center of these convective storms. The aircraft collects *in situ* data and the radars provide high quality images that are correlated to the *in situ* data. The combined data are used in the detailed study of the type and distribution of hydrometeors. This type of research has also been and continues to be supported by the FAA and NASA in support of aircraft icing safety programs and to support their science mission studies. The radars are extremely valuable for the study of storm dynamics, cloud microphysics and electrification systems and will also be used in satellite validation studies, such as NASA's CloudSat.

Dual wavelength polarimetric radar is used to study the initiation of precipitation, and to further develop the algorithms that allow for estimating precipitation type and amount from large-scale convective storms. Algorithms have also been developed, and are being improved, to estimate the rate of precipitation, a factor that is critical in surface runoff and agricultural applications.

The NCAR S-POL (S-band dual POLarimetric) radar consists of one transmitter and two receivers; it can be deployed throughout the United States and overseas. The Colorado State University (CSU) CHILL radar (originally obtained from the university of CHicago and the ILLinois state water survey) is periodically deployed

within the United States. It commonly resides in Greeley, CO and provides an educational service to the broad university community. It consists of a dual transmitter, dual receiver system, eliminating the need for a ferrite polarization switch such as that used on S-POL. Recently CSU purchased a new antenna for the radar, which is currently being installed.

At CSU the team has developed “Virtual CHILL” via the internet. This allows students at university locations throughout the United States to control the CHILL’s scan and collect real-time data. V-CHILL has been an extremely valuable tool for the training of radar meteorologists and for engineering students.

The technical characteristics of NSF’s meteorological radars are listed in Appendix G.

Due to the small number of units involved and their infrequent use, no specific spectrum management challenges are generally encountered once frequency assignments are obtained for the radars. The radars occupy shared Federal/non-Federal spectrum. All of the radars are highly specialized and custom built; no commercial alternatives exist or are likely to exist in the future. Because the radars do not address national security, no COOP or CGO considerations are necessary.

III.C.2 — ELDORA Doppler Radar

The ELDORA Doppler Radar is a one-of-a-kind airborne, dual-beam, meteorological research radar developed jointly by NCAR and CNRS, NSF’s French government counterpart. ELDORA was initially mounted on the tail of an Electra aircraft (ELDORA originally stood for ELeCTra DOPpler RADar). In the early 2000’s, when the aircraft had reached the end of its service life, the radar was transferred to a Naval Research Laboratory (NRL)-operated P-3 aircraft. NSF funded the extensive modifications to the airframe, especially the eppenage, so the large radar could be mounted on the tail of the aircraft.

ELDORA is especially critical for studies of the life cycles of mesoscale convective systems; it has been used in a number of large-scale research programs. Some areas of research where it is employed are described below.

Nearly none of the science programs described could have been carried out without the ELDORA system. They could not have been carried out using other instruments, and they were all interagency and/or international in scope. Typically, several aircraft (up to six) participated in the studies, and suites of ground-based instruments were also used. Each aircraft had a specific, well-defined purpose and the ELDORA provided the detailed structure that only it can provide. The programs requiring ELDORA include:

- The Tropical Ocean and Global Atmosphere Coupled Ocean-Atmosphere Response Experiment, with the Electra aircraft operating out of New Guinea. The primary purpose of the long-duration experiment was to improve the understanding of coupled atmosphere-ocean processes associated with a large mass of warm tropical air. Very little was known about the atmosphere-ocean exchange in the tropics. ELDORA was first used in this experiment.
- The Mesoscale Alpine Experiment (MAP) was based in Innsbruck, Austria and its primary objective was to understand the dynamics of convective storms in mountainous terrain. In these geomorphic regions intense precipitation often leads to major landslides and flooding with consequent damage and loss of life. Both NSF and NOAA participated with separate aircrafts in this study.
- MAP was followed by the International Water Project 2002 (IHOP – 2002), based in the central U.S. This project also used a number of research aircraft, but once again the ELDORA was the key instrument. IHOP’s goal was to improve the characterization of the 4-dimensional distribution of water vapor. The practical application of this study is to further improve our predictive capabilities of convective storm initiation, geographic distribution, and intensity that are critical to agriculture in the Great Plains. Data from ELDORA allows an improved understanding of water vapor distribution and its attendant storm development.
- ELDORA was also a critical instrument in the large-scale and multi-agency CRYSTAL-FACE (Cirrus Regional Study of Tropical Anvils and Cirrus Layers – Florida Area Cirrus Experiment) study, based out of Key West NAS, FL. A total of six aircraft participated in CRYSTAL-FACE, and again ELDORA was the only instrument that could provide the detailed structure of cloud/storm systems. The primary goal of the study was to improve our climate models by measuring the characteristics of clouds and how clouds alter atmospheric temperature. This is critical for an

understanding of radiation balance and convective initiation.

- The Bow Echo and Mesoscale Convective Vortex Experiment (BAMEX) experiment used ELDORA to study the initiation and development of large mesoscale storms that developed bow echoes. Bow echoes result in damaging surface winds and can develop into tornadoes and thus to improve tornado warnings it is critical that we understand their dynamics. BAMEX was based in Illinois, but its field of interest covered most of the middle west.
- Most recently ELDORA was used as the primary instrument in the Hurricane Rainband and Intensity Change Experiment (RAINEX). The experiment was conducted in concert with NOAA research aircraft, and was based in Florida. The primary purpose of the study was to improve our understanding of hurricane dynamics: why do mature storms change rapidly into hurricanes. The P-3 aircraft, equipped with Doppler radar obtained dropsonde data simultaneously in the rainband and eyewall regions. This was a particularly timely study because of the high frequency and intensity of hurricanes in the 2005 season. Research flights were conducted into Hurricanes Katrina and Rita, providing data that had heretofore been unobtainable for such intense hurricanes.

The Doppler radar employed by ELDORA has two antennas that extend back from the rear of the aircraft and spin about the longitudinal axis of the P-3. One of these points is slightly ahead of the aircraft and the other slightly aft and as the aircraft moves the dual antennas trace conical helices through the atmosphere, essentially observing the entire atmosphere. The effective range is 50-100 km of the P-3. Data processing allows producing a view of the 3-dimensional structure of the atmosphere that may then be mathematically sliced through any axis to produce 2 dimensional plots.

The technical characteristics of NSF's meteorological radars are listed in Appendix H.

III.D — POLAR PROGRAMS

III.D.1 — Background

American scientists have been studying the Antarctic and its interactions with the rest of the planet without interruption since 1956. These investigators and supporting personnel make up the U.S. Antarctic Program (USAP), which carries forward the Nation's goals of supporting the Antarctic Treaty, fostering cooperative research with other nations, protecting the Antarctic environment, and developing measures to ensure the equitable and wise use of resources. The program comprises research by scientists selected from universities and other research institutions, and operations and support by a contractor as well as other agencies of the U.S. Government. NSF funds and manages the program by a Presidential Executive Decision Memorandum. Approximately 3,000 Americans are involved in the USAP each year.

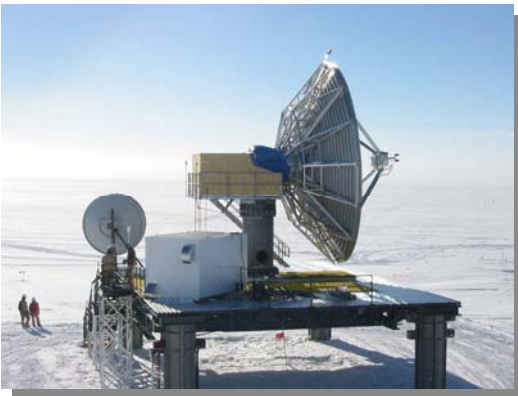
The research has three goals: to understand the region and its ecosystems; to understand its effects on (and responses to) global processes such as climate; and to use the region as a platform to study the upper atmosphere and space. Antarctica's remoteness and extreme climate make field science more expensive than at most places. Research is done in the Antarctic only when it cannot be performed at more convenient locations. A broad portfolio of scientific research disciplines is supported – glaciology, geology/geophysics, terrestrial and marine biology, physical oceanography, astronomy, astrophysics, space science, and atmospheric science.

The program supports three year-round research stations (two coastal stations and one located at the geographic South Pole), and two charter research vessels. In summer (the period of extensive sunlight and comparative warmth that lasts roughly October through February) additional camps are established for glaciologists, earth scientists, biologists, and others. U.S. DoD aircraft and ocean-going ships provide access to the continent. U.S. Air Force heavy lift C-17 cargo aircraft provide access to the largest U.S. station, McMurdo Station, which serves as the gateway for the most U.S. activities in Antarctica. Ski-equipped LC-130 airplanes, unique to the U.S. and operated by the Air National Guard, provide the dominant means of airlift support within the interior of Antarctica for field operations and the support of South Pole Station. Contractor operated helicopters facilitate regional science team activity and logistics during the austral summer. Tracked or wheeled vehicles provide transport over land and snow; small boats are used in coastal areas. The chartered vessel R/V NATHANIAL B. PALMER conducts scientific cruises throughout the entire Southern Ocean, (e.g., latitudes higher than 60°S) year-round, and often makes port calls at McMurdo Station and the second coastal station, Palmer Station. The charter vessel R/V

LAURENCE M. GOULD provides routine logistical support, access, and science cruise support for Palmer Station.

McMurdo Station is essentially a small, self-contained city. Typical summer and winter populations average 1100 and 200 persons, respectively. The station hosts the world's southern-most port and three aerodrome facilities. Power generation, fresh water production, waste treatment, medical care, food services, transportation services, construction, fuels storage and management, port operations, air strip operations, aircraft maintenance, heavy equipment/vehicle maintenance, food service, recreational services, laboratory operations – all are functions necessary to maintain the continuous human presence at McMurdo and provide the platform needed to safely conduct scientific research on a year-round basis.

Amundsen-Scott South Pole Station, with a nominal population of 150, is located at the geographic South Pole and is totally dependent upon McMurdo Station for logistical support. All cargo and personnel who transit to/from South Pole Station pass via McMurdo Station. South Pole Station is home to the most technically advanced science



South Pole Marisat-GOES Terminal (SPMGT) and GOES backup antenna. The 9 meter antenna is a full motion tracking antenna used to provide residents at Amundsen-Scott South Pole Station communication with the rest of the world. Courtesy NSF/Nicolas S. Powell.

supported by NSF in Antarctica, which includes a high density of astronomy and astrophysics projects representing large capital investments, and many years in longevity. South Pole Station sits at an altitude of 9,100 feet above mean sea level and is classed as an arid desert. The extremely low temperatures (to -100°F in the winter), high altitude, location on the Earth's axis of rotation, dry air, and naturally thinner atmosphere due to polar cap weather patterns have made South Pole Station an exceptional location for certain types of astronomical observations, especially sub-millimeter radio astronomy. Additionally, the depth of the polar ice cap with exceptional optical transparency at great depths has been exploited to develop the world's only neutrino telescope, built using a cubic kilometer of the ice cap, beginning at depths of one kilometer. To support the advanced scientific research occurring at South Pole Station, and to address needed safety and infrastructure modernization requirements, NSF is completing an approximate \$150M modernization of the station that replaces the physical station structure, power generation, fuel storage, medical, information systems, telecommunications systems, and radio

communications systems.

Palmer Station, the smallest of the three permanent NSF facilities, is a coastal station with a nominal population of 40-50 people. Marine biology, ecosystems research, and oceanography are the primary science disciplines supported. The station depends heavily upon small boating operations and ships to conduct science programs. As is the case with the other stations, all life-support is self-contained – fuel, power generation, waste disposal, housing, maintenance, etc.

III.D.2 — Existing USAP Radio Communications Needs

The USAP operates in an extreme environment – a continent greater in size than the conterminous U.S. – in the most remote area of the world. There is no indigenous civil infrastructure – all life support and operations must be planned, transported, installed, and maintained by USAP personnel. This occurs at the end of an extremely long logistical supply chain that can be active only during the months of October-February (the austral summer). Delays can reach a year or more if activities are not properly planned. The weather patterns of the continent dominate the conduct of activity – storms of hurricane-force wind strength and days in duration are not uncommon. The cold is perpetual. It is in this environment that people must live safely and productively, year-round, and execute world-class scientific research. Radio communications and radio spectrum management are an important component of the enabling support infrastructure.

The geographic location of the Antarctic continent requires satellite communications as the sole means to interconnect with the global information infrastructure. The conduct of USAP operations and science has embraced the network-centric paradigm as this has evolved in the world-at-large. Modern science is network connected – sensors for data acquisition, computing systems for data reduction, collaboration between field researchers and

colleagues at universities nation-wide – all are reflected in the mode of science research conducted within the USAP. The three USAP stations all have modern gigabit Ethernet computer networks, interconnected via satellite communications links to form a wide area network (usap.gov), and interconnected to the global information infrastructure (commercial Internet, Internet-2, PSTN) at NSF-funded contractor facilities in Colorado. Commercial Fixed Satellite Service (FSS) communications services support the two coastal stations. However, South Pole Station is beyond the range of conventional Geostationary Orbit (GEO) communications satellites. NSF has identified a small, unique set of aged government and end-of-life commercial satellites that are geosynchronous, but allowed to drift into very high inclinations, allowing limited direct line of sight between South Pole Station and the U.S. One of these satellites, GOES-3, has been transferred to NSF control, and the age of the spacecraft telecommand spectrum assignments have become problematic with recent changes in U.S. spectrum policy. This particular satellite factors significantly in the near and mid term satellite architectures for South Pole and its continued operations are extremely important. These satellite links are vital to the health and vitality of the entire NSF science program and the operational conduct of the USAP. Operationally, they support weather forecasting, air traffic control, telemedicine, operational business coordination, logistics/supply chain management, personnel management, science support coordination, emergency response management, and morale.

The USAP deploys remote science field teams during the austral summer months in a vast expanse of the interior of the Antarctic. HF radio communications have been the predominant means of maintaining safety of life communications and logistics deployment communications for these groups. All field teams are deployed using fixed wing aircraft, and HF radio communications are the primary means for flight operations management, air traffic control, and flight following. The USAP has shared jurisdiction with New Zealand for air space management within the ICAO air space sector between South Pole Station and to 60° S latitude, north of McMurdo. Because of the predominance of U.S. DoD aircraft operating within the USAP, and the current doctrine for DoD aircraft command/control, HF radio is a primary means of air operations management. The geographic location of McMurdo Station and the interior deep field operations render DoD tactical satellite communications (UHF satellites) largely unusable.

As Iridium MSS service has become available and affordable via DoD-sponsored air time service plans, NSF has begun a significant deployment of Iridium mobile subscriber units, both voice and data, at the three permanent stations, for deep field science teams, and for science projects requiring low rate/high reliability data transmissions in remote locations. Iridium MSS service is viewed as a strategic resource that will grow over time, with the potential to supplant HF radio communications for deep field safety of life communications. The potential exists to revolutionize USAP air traffic management/air traffic control with the use of Iridium data communications for automatic dependent surveillance, situational awareness, flight following, weather forecaster-pilot communications, etc., although NSF is dependent upon the DoD for aircraft avionics installation approval/certification.

Operational safety is a key concern for USAP operations. Aircraft landing strip and port operations require extensive use of radio communications devices, in the form of precision approach landing radars, tactical navigational beacons (TACAN), non-directional beacons, land mobile radio, ship-shore radio, air-ground radio, etc. Physical separation of the air strips from the main station complex require the use of trunked microwave radio systems to interconnect the air strip data networks and telephone systems with the main station at McMurdo. Weather observations to support weather forecasting, vital to safe flight operations, require radio telemetry links to relay real-time weather data from remote weather sensors to the central forecasting center, critically important due to the high degree of variability and uncertainty of weather patterns in the McMurdo area.

Heavy equipment operations, fuel management activities involving millions of gallons of diesel fuel, electrical utility line maintenance, emergency response, medical operations, and routine base management – all require the use of land mobile radio and paging communications systems, as would any modern municipality. The rapidity of weather changes and the extreme danger to personnel due to cold exposure make these communications resources all the more important.

IV — FUTURE SPECTRUM REQUIREMENTS

IV.A — RADIO AND RADAR ASTRONOMY

The design, development, funding, construction, and/or upgrade of radio astronomy facilities requires a substantial time span (as long as ten years for smaller facilities, and potentially 20 years or more for large facilities), making planning for the spectrum requirements of U.S. radio astronomy facilities over the next decade straightforward. The following sections discuss the significant strategic activities (upgrades to existing facilities, construction of major and minor new facilities and the design and development of next generation instrumentation) that NSF may be involved with during the next decade. The following sections include not only those facilities for which funding has been approved, but all projects on the drawing board that have come to NSF's attention. Inclusion of a project in this long-range spectrum plan involves only strategic spectrum planning for such facilities and implies no commitment on behalf of NSF to actually fund such a facility.

IV.A.1 — Upgrades of Existing Facilities

Subject to the availability of funding, radio astronomy observatories may be upgraded to take advantage of the latest technologies to improve the sensitivity, bandwidth, frequency coverage, spectral agility, sky coverage, angular resolution, and/or other aspects of their operations. The following activities may take place at major NSF-funded radio observatories within the next ten years.

IV.A.1.1 — Robert C. Byrd Green Bank Telescope (GBT)

The Robert C. Byrd Green Bank Telescope (GBT) of the NRAO, the world's largest fully-steerable radio telescope, is located within the National Radio Quiet Zone (NRQZ) at Green Bank, WV. The GBT was dedicated in August, 2000, and is presently conducting scientific observations at frequencies between approximately 1.1 and



The Robert C. Byrd Green Bank Telescope. The telescope is within the 13,000 square mile National Radio Quiet Zone, which affords astronomers the spectrum protection needed to conduct sensitive observations of emissions from the earliest epochs of the universe (among other targets). Courtesy NSF/Andrew Clegg.

50GHz. The GBT is of an unusual design. Unlike conventional telescopes, which have a series of supports in the middle of the surface, the GBT's aperture is unblocked so that incoming radiation meets the surface directly. This increases the useful area of the telescope and eliminates reflection and diffraction that ordinarily complicate a telescope's pattern of response. To accommodate this, an off-axis feed arm cradles the dish, projecting upward at one edge, and the telescope surface is asymmetrical. It is actually a 100-by-110 m section of a conventional, rotationally symmetric 208 m figure, beginning four meters outward from the vertex of the hypothetical parent structure. The telescope's receiving dish and other design characteristics support observing capabilities between 100 MHz and 110 GHz. During the next ten years, NSF anticipates that additional instrumentation will be deployed on the GBT to support radio astronomy observations throughout the full design range of the telescope. These capabilities are a fundamental goal of the GBT and will be added as soon as possible, subject to the availability of funds.

IV.A.1.2 — The Expanded Very Large Array (EVLA)

The Very Large Array (VLA), one of the world's premier astronomical observatories and one of the most productive astronomical instruments at any wavelength, consists of 27 radio antennas (plus one spare) in a Y-shaped configuration on the Plains of San Agustin 50 miles west of Socorro, New Mexico. Each antenna is 25 m (82 ft) in diameter. The data from the antennas are combined electronically to give the resolution of an antenna 36 km (22 miles) across, with the sensitivity of a dish 130 m (422 ft) in diameter. The VLA, which currently operates in eight

discrete frequency bands between 74 MHz and 50 GHz, is undergoing the first phase of an expansion project. Phase 1 of the Expanded Very Large Array (EVLA-I) project will outfit each of the 27 (+ 1 spare) elements of the array with new, more sensitive receivers, with continuous frequency coverage between 1 and 50 GHz, and instantaneous bandwidth of up to 8 GHz in each polarization. The expansion includes a conversion of the IF signal from each telescope to digital, and transmission of the digital IF to the control room over fiber optic cables. The digital IF system replaces the analog waveguide transmission system in place since the array's construction in the 1970's. The EVLA-I project includes a new digital correlator that will provide unprecedented spectral analysis capability at the backend—up to 16,384 channels with resolution down to 1 Hz, and 128 independently tunable sub-bands. EVLA-I is in process and is expected to be complete in 2011. The VLA remains in routine science operations during the EVLA-I deployment.

IV.A.2 —Major New Facilities under Construction

IV.A.2.1 — The Atacama Large Millimeter/submillimeter Array (ALMA)

ALMA's primary function will be to observe and image with unprecedented clarity the enigmatic cold regions of the Universe, which are optically dark, yet shine brightly in the millimeter portion of the electromagnetic spectrum. It will be an instrument capable of producing detailed images of the formation of galaxies, stars, and planets, in both continuum and the emission lines of interstellar molecules. It will image stars and planets being formed in gas clouds near the Sun, and it will observe galaxies in their formative stages at the edge of the universe, which we see as they were roughly ten billion years ago. ALMA will provide a window on celestial origins that encompasses both space and time, providing astronomers with a wealth of new scientific opportunities.

ALMA will be a single instrument composed of 64 high-precision antennas located on the Chajnantor plain of the Chilean Andes, 5,000 meters (16,500 feet) above sea level. Its suite of 12 m and 7 m antennas will allow reconfigurable separations (baselines) ranging from 150 m to 18 km. The ability to reconfigure provides a zoom lens capability, allowing a resolution as fine as 0.01 arcsecond, a factor of five better than the Hubble Space Telescope. ALMA is designed to operate at frequencies between approximately 30 GHz and 1 THz, in specific frequency bands in which the Earth's atmosphere above this high and dry site is largely transparent.

NRAO, The European Southern Observatory (ESO), and the National Astronomical Observatory (NAO) of Japan have collected atmospheric and meteorological data at this site since 1995. These studies show that the sky above the site has the clarity and stability essential for ALMA. The site is large and open, allowing easy re-positioning of the antennas over an area 14 km (10 miles) in extent. At the heart of ALMA's receiving system are sensitive superconducting tunnel junction mixers, operating at just four degrees above absolute zero. Together, the mixer systems on the ALMA antennas will be the most extensive superconducting electronic receiving system in the world. ALMA forms images by continuously combining signals from each antenna with those from every other antenna. From each antenna a bandwidth of 16 GHz will be received from the astronomical object being observed. The electronics will digitize and numerically process these data at a rate of over 16,000 million-million (1.6×10^{16}) operations per second. ALMA will provide an unprecedented combination of sensitivity, angular resolution, spectral resolution, and imaging fidelity at the shortest radio wavelengths for which the Earth's atmosphere is transparent.

In August 2004, by Resolution 1055, the Sub-Secretariat of Telecommunications (SUBTEL) of the Ministry of Transport and Telecommunications of the Republic of Chile established a 30 km diameter Protection Zone, centered on coordinates 23° 01' S, 67° 45' W, within which all transmissions that fall within the ALMA receiver bands are prohibited. In addition, the Resolution established a 120 km radius coordination zone within which emissions at all frequencies are controlled.

ALMA is an equal partnership between Europe and North America, in cooperation with the Republic of Chile. It is funded by NSF, in cooperation with the National Research Council of Canada (NRC), ESO (a consortium of 12 European countries) and Spain. Japan has also joined ALMA as a partner, bringing the Atacama Compact Array (ACA) and additional receiver bands for both arrays. To bolster ALMA's sensitivity on scales between the antenna diameter of 12 m and the shortest baseline of 15 m, the ACA, comprised of four 12 m telescopes along with twelve 7 m antennas, built and equipped to the same specifications as those in the main array, will be contributed by Japan. In addition, Japan is providing two additional receiver bands for all antennas.

IV.A.2.2 — *The Large Millimeter Telescope (LMT)*

The Large Millimeter Telescope Project is a joint effort of the University of Massachusetts at Amherst and the Instituto Nacional de Astrofísica, Óptica, y Electrónica (INAOE) in Mexico. The LMT is a 50 m diameter millimeter-wave telescope designed for operation at frequencies between 85 and 350 GHz. The telescope is being built atop Sierra Negra, a volcanic peak in the state of Puebla, Mexico. Site construction and fabrication of most of the major antenna parts are underway.

IV.A.2.3 — *The Allen Telescope Array (ATA)*

The Allen Telescope Array (ATA) is a joint effort by the SETI Institute and the Radio Astronomy Laboratory at the University of California, Berkeley to construct a radio interferometer that will be dedicated to astronomical and simultaneous search for extra-terrestrial intelligence observations. It is being constructed at the Hat Creek Radio Observatory, 290 miles northeast of San Francisco, California. The completed ATA will consist of approximately 350 6.1-meter offset Gregorian dishes. Given the number of antennas and a very wide field-of-view (2.45° at 1400MHz), this array will have an unprecedented amount of flexibility in observing. Several individual users may simultaneously use the array to observe a different part of the sky at an independent frequency, or image the sky at one or more frequencies within the design range of 500 MHz to 11.2 GHz.

IV.A.2.4 — *Atacama Cosmology Telescope (ACT)*

The Atacama Cosmology Telescope (ACT) is a specialized instrument being installed in the Atacama of Chile to study the cosmic microwave background radiation. It employs the first ever sub-millimeter wave “CCD” type detector with a large number of elements. Lead institutions in this project are the University of Pennsylvania and Princeton, with Rutgers, Columbia, Haverford and the South Africa Astrophysical Observatory also part of it. The ACT will operate in three frequency bands centered at 145, 225, and 265 GHz. The telescope saw “first light” in June 2007. Substantial science operations are expected to commence in late 2007.

IV.A.3 — Next Generation Radio Astronomy Facilities

IV.A.3.1 — *Cornell Caltech Atacama Telescope (CCAT)*

Cornell University and the California Institute of Technology are working jointly to construct a large far infrared/sub-millimeter telescope that will address fundamental questions regarding cosmic origins, including: the origin of galaxies and the early evolution of the universe; the formation of stars and the evolution of interstellar matter; and the histories of planetary systems. The 25 m telescope will be located high in the Atacama of northern Chile, and will operate in several bands between 150 GHz and 1.5 THz. It is expected to become operational in 2012.

IV.A.3.2 — *Murchison Widefield Array (MWA)*

The Murchison Widefield Array is a low-frequency radio array planned for construction in the Shire of Murchison in state of Western Australia. In the next three years, a demonstration array will be built, operating in the 80-300 MHz range, comprising 500 antenna systems, and capable of a variety of frontier scientific investigations. The instrument will feature a number of innovations that exploit modern digital signal processing capabilities, and implement functionality that has not hitherto been possible. The radio frequency interference environment at the exceedingly remote MWA site, as measured in the 80-300 MHz range, is one of the lowest in the world.

IV.A.3.3 — *The Long Wavelength Array (LWA)*

The Long Wavelength Array (LWA) will be a low-frequency radio telescope designed to produce high-sensitivity, high-resolution images in the frequency range of 10-88 MHz, thus opening a new astronomical window on one of the most poorly explored regions of the electromagnetic spectrum. This will be accomplished with large collecting area (approaching 1 square kilometer at its lowest frequencies) spread over an interferometric array with baselines up to at least 400 km. The array will consist of approximately 15,000 dipoles clustered in approximately 52 stations.

IV.A.3.4 — *The Frequency Agile Solar Radiotelescope (FASR)*

The Frequency Agile Solar Radiotelescope is a multi-frequency (50 MHz - 21 GHz) imaging array composed of many (~100) antennas. It is designed specifically for observing the Sun. It will produce high quality images with high spatial resolution (1 arc sec at 20 GHz), high spectral resolution (0.1-1% fractional bandwidth), and high time

resolution (< 0.1 s). The array will consist of three separate antenna systems in order to cover the entire frequency range. The two highest bands will utilize 6 m and 2 m antennas. The low band will utilize fixed log-periodic or active dipoles, or Vivaldi-type feeds. The FASR site has not yet been selected, but may be in Owens Valley, California.

IV.A.3.5 — *The Square Kilometer Array (SKA)*

The Square Kilometer Array (SKA) will be one of a suite of new, large telescopes for the 21st century probing fundamental physics, the origin and evolution of the Universe, the structure of the Milky Way Galaxy, and the formation and distribution of planets. Currently under development by an international consortium, the SKA expects to make a revolutionary break from today's radio telescopes. It is planned to:

- Have a collecting area of one square kilometer, making it 50-100 times more sensitive than today's largest and best radio telescopes
- Cover the frequency range 0.1 to 25 GHz;
- Integrate computing hardware and software on a massive scale, in a way that best captures the benefits of these exponentially-developing technologies.

The United States Square Kilometer Array Consortium (U.S. SKA) is a consortium of universities and research institutes in the United States that is studying and prototyping technologies under development for the SKA. The design being considered by the U.S. SKA Consortium is one composed of a large number (100-1000) of stations, with each station consisting of a number of relatively small diameter antennas similar to those being used in the Allen Telescope Array. This "Large-Number/Small-Diameter" (LNSD) telescope concept offers considerable advantages over traditional designs, including superb image fidelity and dynamic range, multibeam capabilities, instantaneous imaging, improved interference suppression, flexibility, and expandability. The SKA will be located in either southern Africa or in Australia.

IV.B — UPPER ATMOSPHERIC RESEARCH

The following upgrades are planned to systems discussed in section III.B:

IV.B.1 — AMISR

An additional AMISR facility will be constructed at Resolute Bay, Canada, in 2008.

IV.B.2 — SuperDARN

The SuperDARN network continues to expand; there are current plans to add radars near the northern polar cap and at mid-latitudes across the continental United States. A SuperDARN site at Blackstone, Virginia (outside Petersburg) was recently licensed, and is expected to be on the air in early 2008.

IV.C — LOWER ATMOSPHERIC RESEARCH

The following upgrades are planned to systems discussed in section III.C:

IV.C.1 — S-POL & CHILL

Both radars are currently undergoing refurbishment and upgrades and NSF expects them to be in operation for at least another 5 years.

IV.C.2 — ELDORA

ELDORA has been identified as the instrument of choice for several research programs. A successor radar is currently under planning, because the life of the current ELDORA is estimated to be of the order of 5-7 years and will, at the end of its life cycle have to be replaced. It is not expected at this time that this change will result in additional spectrum requirements.

IV.D — POLAR PROGRAMS

The dominant technologies that the USAP will pursue are:

- Narrowband trunked land mobile radio
- Iridium voice and data communications, for mobile users, embedded in scientific instrumentation, aircraft operations, and (via inverse multiplexing) to provide limited routed Internet service to deep field camps and gap-filling coverage of South Pole Station
- Wireless LAN clouds in the McMurdo regional area to enable network/Internet access to regional science encampments, mobile comm-on-the-go to field teams, RFID inventory management, embedded sensors in operational and scientific equipment, etc.
- Upgraded commercial satellite communications at McMurdo Station to move from C-Band to Ku-Band FSS services
- Pursuit of innovative satellite communications solutions for improving the capacity, contact time, and future longevity of broadband satellite communications for South Pole Station, which may include working with satellite operators to adapt systems designed for other purposes to communications (spectral bands implicated are L-Band MSS subscriber links, Ka-Band MSS feeder links, and X/S-Band DARS feeder/subscriber links)
- Continued deployment of GPS-based applications for surveying, navigation, and science research support (particular interest is in the use of DGPS for Category I precision approach landing of aircraft to displace the current microwave landing system precision approach landing aids)

NSF's USAP operates a challenging program in a remote, hostile location, with an annual budget that is small given the scope/breadth of what the USAP is called to do. Innovations in the marketplace, such as RFID for inventory management, or technology-driven life-cycle obsolescence of established applications (e.g., narrowband channelization of land mobile radio) are important factors for the USAP budget. State-of-the-market commercial technology is the dominant mode of USAP technology acquisition, whether for government spectral band assignments or for commercial spectral band assignments. A high degree of churn in the marketplace is destabilizing in the sense that the USAP cannot afford, either economically or logistically, to have a corresponding high churn rate in its installed infrastructure. The expense, effort, and time required to physically implement a system in Antarctica needs to have a 5-10 year operational lifetime, if at all possible.

The plans articulated for USAP radio communications reflect the need to inject modern technology into the conduct of the program in order to remain effective, efficient, and viable. The stakes are high – safety of life in many cases, and the effective return of the national investment in the scientific research conducted in Antarctica in all cases.

V — CURRENT AND FUTURE USE OF NON-FEDERAL SPECTRUM OFFERED BY COMMERCIAL SERVICE PROVIDERS

Like all other agencies, NSF makes use of cellular telephone, specialized mobile radio, paging, and other commercial telecommunications applications in the conduct of its business.

NSF's Office of Polar Programs plans to continue use of the Iridium mobile satellite system, due to its ability to cover remote areas of the Antarctic.

Beyond these applications, most of NSF's spectrum use is for highly specialized research and development activities, and therefore the agency makes limited use of commercial service providers in its mission.

VI — CURRENT AND FUTURE USE BY NSF OF “NON-LICENSED” DEVICES

NSF will continue to make routine use of unlicensed devices, especially wireless LANs, in the conduct of its own operations and in the operations of a variety of research projects funded by the agency.

With specific reference to NSF’s USAP operations, the evolving nature of science, with increasing dependence upon computing tools as an embedded component of experiment design and support, is leading NSF to explore the deployment of ISM band commercial grade wireless networking and data communications equipment in the regions surrounding the three stations. McMurdo Station in particular, with a high density of researchers operating within 100 miles of McMurdo and in rugged terrain, are candidates for the use of IEEE 802.11 wireless LAN systems, linking them into the McMurdo campus LAN infrastructure, and from there to the global information infrastructure. The ubiquity and commodity status of WiFi systems mean that the science community is already invested in this technology, thus it is a logical infrastructure investment to take for adding capability in the USAP. As the commercial sector evolves wireless technology (e.g., WiMAX, 802.11n, etc.), NSF will evolve the infrastructure to ensure interoperability with the science community. Although nascent at present, the incorporation of wireless networking within the USAP is viewed as strategically important for the next few years.

VII — NEW TECHNOLOGIES

NSF encourages the use of new technologies by the science community it supports. Rather than being a consumer of new technologies, however, NSF generates them through its support of basic scientific and engineering research. The following projects exemplify the NSF supported research that has a broad impact on the efficient use of the radio spectrum.

VII.A — EXTENDING THE FREQUENCY RANGE OF RADIO TECHNOLOGY

Radio astronomers and engineers funded by the NSF pioneered the development and widespread use of low noise Superconductor-Insulator-Superconductor (SIS) receivers used in mm and sub-mm oscillators that work up to 1 THz. They are in demand for radio astronomy, as well as advanced radar and secure communications systems.

VII.B — LOCATION TECHNOLOGY

NSF-funded researchers at Haystack Observatory adapted techniques developed for radio astronomy and geodesy purposes to the cellular phone system. This system is being used, e.g. to pinpoint the positions of emergency calls, through the E911 system.

VII.C — DISASTER COMMUNICATIONS

Wireless networks become saturated soon after a disaster and remain saturated for critical periods. NSF-funded research deals with analyzing data on cell phone usage of when, with whom and for how long calls take place under disaster scenarios, and whether the calls are incoming or outgoing. Such data helps in the modeling of communication network behavior and in understanding how such technologies may be utilized or extended in future emergencies.

VIII — STRATEGIC SPECTRUM PLANNING

The NSF Spectrum Management office consists of two Program officers: Drs. Tomas E. Gergely and Andrew W. Clegg. Dr. Gergely is assigned to the office full time; Dr. Clegg has a number of additional responsibilities in addition to his spectrum management-related duties. Given the small staff, spectrum planning is discussed between the program officers. In drawing up the NSF Long Range Spectrum Plan (LRSP), input is solicited from the various offices and divisions with spectrum related interests. The following NSF organizations were requested to provide input to the Plan:

- Office of the Director:
 - Office of Polar Programs
- Directorate for Mathematical and Physical Sciences:
 - Division of Astronomical Sciences
- Directorate for Geosciences:
 - Division of Atmospheric Sciences
 - Division of Ocean Sciences
- Directorate for Engineering:
 - Division of Electrical, Communication and Cyber Systems
- Directorate for Computer and Information Sciences & Engineering:
 - Division of Computer and Network Systems
- Directorate for Social, Behavioral and Economic Sciences:
 - Division of Social and Economic Sciences

The input received is processed and factored into the NSF LRSP. The above list shows that NSF spectrum planning is broad-based, cutting across many disciplines.

NSF spectrum requirements are of two kinds: routine and non-routine. Routine requirements are used to satisfy the communication needs of NSF supported National Centers, e.g. the National Radio Astronomy Observatory (NRAO) or the National Center for Atmospheric Research (NCAR). About 80 frequency assignments, mostly in the fixed and mobile services, satisfy these requirements. Assignments are tailored to the needs and requirements of the individual centers requesting them; their number is small enough so that no planning is required beyond following general Federal Radio Frequency Management principles and guidelines, as given in the Manual.

NSF's non-routine spectrum requirements are divided between passive and active services. Radio astronomy and some meteorological observations fall into the first category, while many meteorological observations and experiments, oceanography and networking require active transmitters. These requirements are, for the most part, science-driven and do not lend themselves easily to planning. For example, certain astrophysical phenomena must be observed at specific spectral line frequencies, or atmospheric turbulence must be observed within a certain range of frequencies due to the scale of the turbulence.

NSF spectrum management does advise scientists on the viability of their spectrum choices, and will integrate such advice with system certification and frequency assignment requests. These processes have been in place for some time, did not change since 2003, and are not expected to change in the near future.

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IX — ADDITIONAL COMMENTS AND RECOMMENDATIONS

There are no additional comments or recommendations.

X — APPENDICES

APPENDIX A — LIST OF REFERENCES

- National Science Foundation Electromagnetic Spectrum Management Unit:
http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=5654&org=AST&from=home
- National Astronomy and Ionosphere Center Puerto Rico Coordination Zone home page:
<http://www.naic.edu/techinfo/prcz/prczinfo.htm>
- National Radio Astronomy Observatory radio spectrum management home page:
<http://www.cv.nrao.edu/~hliszt/RFI/RFI.htm>
- National Radio Quiet Zone:
<http://www.gb.nrao.edu/nrqz/>

APPENDIX B — GLOSSARY

Please refer to Chapter 6 of the *Manual of Regulations and Procedures for Federal Radio Frequency Management* for a complete glossary. The *Manual* is available on the NTIA web site at <http://www.ntia.doc.gov/osmhome/redbook/redbook.html>.

APPENDIX C — TABLE OF ACRONYMS

ACA	Atacama Compact Array
ACT	Atacama Cosmology Telescope
ALMA	Atacama Large Millimeter/submillimeter Array
AMISR	Advanced Modular Incoherent Scatter Radar
ATA	Allen Telescope Array
AUI	Associated Universities, Inc.
BAMEX	Bow Echo and Mesoscale convective vortices EXperiment
CGO	Continuity of Government Operations
CHILL	Lower atmospheric radar originally obtained from U. CHicago and ILLinois state water survey
CNRS	Centre National de la Recherche Scientifique, France
COOP	Continuity Of Operations
COSMIC	Constellation Observing System for Meteorology, Ionosphere and Climate
CRYSTAL-FACE	Cirrus Regional Study of Tropical Anvils and Cirrus Layers - Florida Area Cirrus Experiment
DARS	Digital Audio Radio Service
DGPS	Differential GPS
DoD	Department of Defense
EIRP	Effective Isotropic Radiated Power
EISCAT	European Incoherent SCATter organization
ELDORA	Originally, ELeCtra DOppler RADar; now installed on P3 aircraft instead of Electra aircraft
ESM	National Science Foundation's Electromagnetic Spectrum Management Unit
ESO	European Southern Observatory
ESR	EISCAT Svalbard Radar
EVLA	Expanded Very Large Array
FAA	Federal Aviation Administration
FASR	Frequency Agile Solar Radiotelescope
FCC	Federal Communications Commission
FORMOSAT-3	Taiwanese acronym for COSMIC satellite system
FSS	Fixed-Satellite Service
GBT	Green Bank Telescope
GEO	GEOstationary orbit
GOES-3	Third in a series of Geostationary Operational Environmental Satellites
GPS	Global Positioning System
HF	High Frequency (3-30 MHz)
ICAO	International Civil Aviation Organization
IAU	International Astronomical Union
IEEE	Formerly the Institute of Electrical and Electronics Engineers; now IEEE
IF	Intermediate Frequency
IHOP	International H2O Project
INAOE	Instituto Nacional de Astrofísica, Óptica, y Electrónica, Mexico
IRAC	Interdepartment Radio Advisory Committee
ISR	Incoherent Scatter Radar
ITU	International Telecommunication Union
LAN	Local Area Network
LMT	Large Millimeter Telescope
LNSD	Large Number, Small Diameter
LWA	Long Wavelength Array
MAP	Mesoscale Alpine Program
MSS	Mobile-Satellite Service
MU	Middle and Upper atmosphere
MWA	Murchison Widefield Array
NAIC	National Astronomy and Ionosphere Center
NAO	National Astronomical Observatory, Japan
NASA	National Aeronautics and Space Administration

NCAR	National Center for Atmospheric Research
NOAA	National Oceanographic and Atmospheric Administration
NRAO	National Radio Astronomy Observatory
NRC	National Research Council
NRL	Naval Research Laboratory
NRQZ	National Radio Quiet Zone
NSF	National Science Foundation
PSTN	Public Switched Telephone Network
RAINEX	The hurricane Rainband And INtensity change EXperiment
RFID	Radio Frequency IDentification
S-POL	S-band dual POLarimetric radar
S&E	Science and Engineering
SETI	Search for Extraterrestrial Intelligence
SIS	Superconductor-Insulator-Superconductor
SKA	Square Kilometer Array
STP	U.S. Air Force Space Test Program
SUBTEL	Subsecretaría de Comunicaciones, Chile
SuperDARN	Super Dual Auroral Radar Network
TACAN	Tactical Air Navigation
UAF	Upper Atmospheric Facilities
UHF	Ultra High Frequency (300 MHz - 3 GHz)
URSI	French acronym for the International Union of Radio Scientists
USAP	United States Antarctic Program
V-CHILL	Virtual CHILL
VLA	Very Large Array
VLBA	Very Long Baseline Array
WiFi	Wireless Fidelity

APPENDIX D — U.S. RADIO ASTRONOMY FREQUENCY ALLOCATIONS

The following table summarizes the primary and secondary allocations to the radio astronomy service, and also the frequency bands for which radio astronomy is mentioned in footnotes to the table of frequency allocations.

- **PRIMARY EXCLUSIVE:** the frequency bands that are allocated in the U.S. solely to services such as radio astronomy that are passive (non-transmitting). No fundamental emissions from other spectrum users should be evident in these bands, at any location in the U.S. and possessions. However, unwanted (spurious and/or out-of-band) emissions and emissions from some weak unlicensed services can impact these bands.
- **PRIMARY SHARED:** the bands in which the radio astronomy service shares primary status with other services. Shared primary services may coordinate with one another to avoid interference. Any services within these bands that are allocated on a secondary basis must not cause interference to the primary services, including radio astronomy.
- **SECONDARY:** the bands in which the radio astronomy service operates on a secondary basis. Within these bands, the radio astronomy service cannot claim interference protection from primary services, but may coordinate spectrum use with other services allocated on a secondary basis.
- **FOOTNOTE:** the bands for which footnotes to the table of frequency allocations mentions that radio astronomy observations may be taking place.

U.S. Radio Astronomy Frequency Allocations

13.36 - 13.41 MHz	15.35 - 15.4 GHz	123 - 130 GHz
25.55 - 25.67 MHz	22.01 - 22.21 GHz (1)	130 - 134 GHz
37.5 - 38 MHz	22.21 - 22.5 GHz	134 - 136 GHz
38 - 38.25 MHz	22.81 - 22.86 GHz (1)	136 - 148.5 GHz
73 - 74.6 MHz	23.07 - 23.12 GHz (1)	148.5 - 151.5 GHz
322 - 328.6 MHz (1)	23.6 - 24 GHz	151.5 - 158.5 GHz
406.1 - 410 MHz	31.2 - 31.3 GHz (1)	164 - 167 GHz
608 - 614 MHz	31.3 - 31.8 GHz	168.59 - 168.93 GHz (1)
1330 - 1400 MHz (1)	36.43 - 36.5 GHz (1)	171.11 - 171.45 GHz (1)
1400 - 1427 MHz	42.5 - 43.5 GHz	172.31 - 172.65 GHz (1)
1427 - 1610.6 MHz (2)	48.94 - 49.04 GHz	173.52 - 173.85 GHz (1)
1610.6 - 1613.8 MHz	56.24 - 56.29 GHz (4)	182 - 185 GHz
1613.8 - 1660 MHz (2)	58.422 - 58.472 GHz (4)	195.75 - 196.15 GHz (1)
1660 - 1660.5 MHz	59.139 - 59.189 GHz (4)	197 - 200 GHz (2)
1660.5 - 1668.4 MHz	59.566 - 59.616 GHz (4)	200 - 209 GHz
1668.4 - 1670 MHz	60.281 - 60.331 GHz (4)	209 - 226 GHz
1670 - 1718.8 MHz (2)	60.41 - 60.46 GHz (4)	226 - 231.5 GHz
1718.8 - 1722.2 MHz (3)	62.461 - 62.511 GHz (4)	241 - 248 GHz
1722.2 - 1727 MHz (2)	76 - 77.5 GHz	248 - 250 GHz
2655 - 2690 MHz	77.5 - 78 GHz	250 - 252 GHz
2690 - 2700 MHz	78 - 86 GHz	252 - 275 GHz
3260 - 3267 MHz (1)	86 - 92 GHz	275 - 323 GHz (5)
3332 - 3339 MHz (1)	92 - 94 GHz	327 - 371 GHz (5)
3345.8 - 3352.5 MHz (1)	94 - 94.1 GHz	388 - 424 GHz (5)
4825 - 4835 MHz (1)	94.1 - 100 GHz	426 - 442 GHz (5)
4950 - 4990 MHz (1)	100 - 102 GHz	453 - 510 GHz (5)
4990 - 5000 MHz	102 - 109.5 GHz	623 - 711 GHz (5)
6650 - 6675.2 MHz (1)	109.5 - 111.8 GHz	795 - 909 GHz (5)
10.6 - 10.68 GHz	111.8 - 114.25 GHz	926 - 945 GHz (5)
10.68 - 10.7 GHz	114.25 - 116 GHz	
14.47 - 14.5 GHz (1)	116 - 122.25 GHz (2)	

PRIMARY EXCLUSIVE - PRIMARY SHARED - SECONDARY - FOOTNOTE

- (1) US342; (2) 5.341/SETI
- (3) US311; (4) US353/Space RA
- (5) 5.565

APPENDIX E — RADIO ASTRONOMY FACILITIES

The table on the following page lists the radio astronomy observatories currently operating in the United States and its possessions, or operated wholly or partially by one or more U.S. managing organizations outside of the United States. Small radio observatories that are used for teaching purposes are not included. The table also lists significant U.S. radio astronomy facilities that are currently under construction or under design and development.

U.S. Radio Astronomy Facilities

Telescope/Observatory	Location	Type ⁴	Coordinates		Elevation (m)	Nominal Frequency Range
			Latitude (N)	Longitude (E)		
Operational Radio Telescopes as of November 2007						
Allen Telescope Array (ATA)	Hat Creek, CA	INT	40° 49' 02.5"	-121° 28' 18.5"	1043	0.5 - 11.2 GHz
Antarctic Submillimeter Telescope and Remote Observatory (AST/RO)	Antarctic	SD	-89° 59' 40"	-45° 53'	2847	230 - 809 GHz (non-continuous)
Caltech Submillimeter Observatory (CSO)	Mauna Kea, HI	INT	19° 49' 34"	-155° 28' 18"	4100	250 - 850 GHz
Combined Array for Research in Millimeter-wave Astronomy (CARMA)	Cedar Flat, CA	INT	37° 16' 43"	-118° 08' 32"	2200	26 - 350 GHz (non-continuous)
Cosmic Background Imager (CBI)	Llano de Chajnantor, Chile	INT	-23° 01' 43"	-67° 45' 42"	5045	26 - 36 GHz
Five College Radio Astronomy Observatory (FCRAO)	New Salem, MA	SD	42° 23' 30"	-72° 20' 42"	314	86 - 115 GHz
Haystack Observatory	Westford, MA	SD	42° 37' 24"	-71° 29' 18"	122	1420 MHz - 115 GHz (non-continuous)
Heinrich Hertz Submillimeter Telescope Observatory (SMT0)	Mt Graham, AZ	SD	32° 42' 06"	-109° 53' 28"	3186	125 - 1100 GHz
James Clerk Maxwell Telescope (JCMT)	Mauna Kea, HI	SD	19° 49' 33"	-155° 28' 47"	4092	100 - 900 GHz (non-continuous)
NAIC Arecibo Observatory	Near Arecibo, PR	SD	18° 20' 39.2"	-66° 45' 09.7"	380	50 MHz - 10 GHz (non-continuous)
NRAO Green Bank 45-ft Solar Radio Burst Telescope	Green Bank, WV	SD	38° 25' 59.9"	-79° 49' 20.9"	828	10 - 1070 MHz
NRAO Green Bank 140-ft telescope	Green Bank, WV	SD	38° 26' 13.9"	-79° 50' 10.3"	825	50 MHz - 25 GHz
NRAO Green Bank Telescope (GBT)	Green Bank, WV	SD	38° 25' 59.2"	-79° 50' 23.3"	806	100 MHz - 110 GHz
NRAO Very Large Array (VLA)	Plains of San Agustin, NM	INT	34° 04' 44"	-107° 37' 06"	2115	73 MHz - 55 GHz (non-continuous)
	Mauna Kea, HI	INT	19° 48' 05"	-155° 27' 20"	3763	300 MHz - 86 GHz (non-continuous)
	Brewster, WA	INT	48° 07' 52"	-119° 41' 00"	250	300 MHz - 86 GHz (non-continuous)
	Owens Valley, CA	INT	37° 13' 54"	-118° 16' 37"	1196	300 MHz - 86 GHz (non-continuous)
	Kitt Peak, AZ	INT	31° 57' 23"	-111° 36' 45"	1902	300 MHz - 86 GHz (non-continuous)
	Pie Town, NM	INT	34° 18' 04"	-108° 07' 09"	2365	300 MHz - 86 GHz (non-continuous)
	Los Alamos, NM	INT	35° 46' 30"	-106° 14' 44"	1962	300 MHz - 86 GHz (non-continuous)
	Fort Davis, TX	INT	30° 38' 06"	-103° 56' 41"	1606	300 MHz - 86 GHz (non-continuous)
	North Liberty, IA	INT	41° 46' 17"	-91° 34' 27"	222	300 MHz - 86 GHz (non-continuous)
	Hancock, NH	INT	42° 56' 01"	-71° 59' 11.7"	296	300 MHz - 86 GHz (non-continuous)
	St. Croix, VI	INT	17° 45' 24"	-64° 35' 01"	16	300 MHz - 86 GHz (non-continuous)
	Owens Valley 40 m Telescope	SD	37° 13' 55.7"	-118° 16' 53.8"	1236	12 - 18 GHz
	Owens Valley Radio Observatory	INT	37° 13' 54"	-118° 16' 37"	1196	300 MHz - 270 GHz (non-continuous)
	Owens Valley Solar Array	INT	37° 13' 53.8"	-118° 17' 36"	1200	1 - 18 GHz
	Pisgah Astronomical Research Institute (PARI)	SD	35° 11' 59"	-82° 52' 19"	895	17 MHz - 49 GHz (non-continuous)
	South Pole balloon flights	SD	-81° - -75°	0° - 360°	28000 - 38000	<2 THz
	South Pole Telescope ¹ (SPT)	SD	-89° 59'	-45° 53'	2800	<1.5 THz
	Steward Observatory Kitt Peak	SD	31° 57' 12"	-111° 36' 53"	1914	68 - 300 GHz
	Submillimeter Array (SMA)	INT	19° 49' 27"	-155° 28' 39"	4080	180 - 900 GHz
	Sunyaev-Zeldovich Array (SZA)	INT	37° 13' 57"	-118° 17' 46"	1200	26-36 GHz and 85-115 GHz
	University of Michigan Radio Astronomy Observatory (UMRAO)	SD	42° 23' 56"	-83° 56' 11"	327	4.7 - 25 GHz (non-continuous)
Under Construction, in Design & Development Phase, or Planned for Long-Range Use as of November 2007						
Atacama Cosmology Telescope ² (ACT)	Cerro Toco, Chile	SD	-22° 57' 29"	-67° 47' 09"	5200	130 - 280 GHz (non-continuous)
Cornell Caltech Atacama Telescope ² (CCAT)	Llano de Chajnantor, Chile	SD	-22° 59' 08.3"	-67° 44' 25.0"	5612	150 GHz - 1.5 THz (non-continuous)
Dome C ³	Dome C, Antarctic	TBD	~75°	~125°	~3200	TBD
Frequency Agile Solar Radiotelescope ² (FASR)	Big Pine, CA (proposed)	INT	-37° 14'	-118° 18'	~1200	50 MHz - 21 GHz
Large Millimeter Telescope ¹ (LMT)	Sierra Negra, Mexico	SD	18° 59' 06"	-97° 18' 48"	4580	85 - 350 GHz
Long Wavelength Array ² (LWA)	Plains of San Agustin, NM	INT	~34° 05'	~107° 37'	~2115	10 - 88 MHz
Murchison Widefield Array ² (MWA) (test facility)	Mileura Station, Australia	INT	-26° 42' 15"	116° 39' 32"	381	80 - 300 MHz & 800 - 1600 MHz
NRAO Atacama Large Millimeter/submillimeter Array ¹ (ALMA)	Llano de Chajnantor, Chile	INT	-23° 01' 22"	-67° 45' 18"	5059	30 GHz - 1 THz
Owens Valley 6.1 m Telescope (#1) ²	Big Pine, CA	SD	~37° 14'	~118° 18' 40"	~1200	4.5 - 7 GHz
Owens Valley 6.1 m Telescope (#2) ²	Big Pine, CA	SD	~37° 14'	~118° 18' 40"	~1200	12 - 18 GHz
QU Imaging Experiment (QUIET) ²	Llano de Chajnantor, Chile	INT	~23° 02'	~67° 46'	5045	36 - 44 & 81 - 99 GHz
Square Kilometer Array ² (SKA)	TBD (possibly western Australia or South Africa)	INT	TBD	TBD	TBD	150 MHz - 25 GHz

¹Under construction; ²Design and development phase; ³Long-range plan
⁴SD = Single Dish; INT = Interferometer

APPENDIX F — CHARACTERISTICS OF INCOHERENT SCATTER RADARS WORLDWIDE

Observatory	Location	Latitude	Longitude	Frequency (MHz)	Antenna Type	Antenna Size	Peak Power (MW)	Maximum Duty Cycle %
EISCAT UHF	Tromsø, Norway	69.58	19.22	928	Steerable parabolic dish	32 m diameter	2	12.5
EISCAT VHF	Tromsø, Norway	69.58	19.22	224	Offset parabolic cylinder	120 m X 40 m	3	12.5
EISCAT Svalbard Radar	Longyearbyen, Norway	78.15	16.03	500	One fixed and one steerable parabolic dish	32 m steerable; 42 m fixed	1	25
Sondrestrom Radar Facility	Kangerlussuaq, Greenland	66.99	309.05	1290	Steerable parabolic dish	32 m	3.5	3
Jicamarca Radio Observatory	Jicamarca, Peru	-11.95	283.13	50	Square phased array	290 m X 290 m	3	6
Millstone Hill Observatory	Westford, Massachusetts	42.62	288.51	440	One fixed and one steerable parabolic dish	46 m steerable; 68 m fixed	2.5	6
Arecibo Observatory	Arecibo, Puerto Rico	18.35	293.24	430	Spherical dish	305 m	2.5	6
Middle and Upper Atmosphere (MU) Radar	Shigaraki, Japan	34.85	136.1	46.5	Circular phased array	103 m diameter	1	4
Kharkov Radar	Kharkov, Ukraine	50.00	36.23	150	Fixed Dish	68 m	2.5	6

NSF operates only the Sondrestrom, Jicamarca, Millstone Hill and Arecibo facilities, and only the millstone Hill and Arecibo facilities are located within the US&P. Millstone Hill operates at 440.0, 440.2, and 440.4 MHz with a bandwidth of 750 kHz at each frequency. Arecibo operates at 430.0 MHz with a 2 MHz bandwidth. Sondrestrom operates at 1290.0 and 1290.6 MHz with a 2 MHz bandwidth at each frequency. Jicamarca operates at 49.92 MHz with a 1 MHz bandwidth.

The AMISR system at Poker Flat, Alaska will operate at 449 MHz with a 1 MHz bandwidth. The AMISR system at Resolute Bay, Canada and future AMISR systems at other locations will require a 2 MHz bandwidth centered on any frequency in the range 430 to 450 MHz.

APPENDIX G — CHARACTERISTICS OF NSF-SPONSORED METEOROLOGICAL RADARS

Instrument	Frequency (MHz)	Bandwidth	Transmit Power (kW)	Pulse Width
SPOL	2809	750kHz	750	1 μ sec
	34930	750kHz	40	.5 μ sec
CHILL	2725	750kHz	800	1 μ sec
Pawnee	2730	750kHz	380	1 μ sec
ELDORA	9600	1 MHz	40	4 μ sec
AIMR	37000	1.5 GHz	NA	NA
	95000	2.0 GHz	NA	NA

APPENDIX H — FREQUENCY BANDS USED FOR ANTARCTIC COMMUNICATIONS

BAND	FREQUENCY	USES	MAX BANDWIDTH
ELF - LF	1 Hz - 140 kHz	Science (arrival heights)	Passive receive-only
HF	2 - 30 MHz	Voice point-to-point (field party, air-ground, air-air, air-ground, ship-shore, ship-ship, amateur radio etc.)	6 kHz
VHF	30 MHz - 225 MHz	Radionavigation; science (ice-penetrating radar); broadcast (AFAN); local air-ground; aeronautical navigation (REILS, AFLCS); ELT beacon; aeronautical mobile; maritime mobile; paging; weather alerting	
	46.3 MHz	Meteor radar (full-time emitter)	12.5 kHz
	136.38 MHz	GOES-3 telemetry beacon downlink	60 kHz
	148.56 MHz	GOES-3 telemetry beacon uplink	60 kHz
UHF	225 MHz - 1 GHz	Air-air aeronautical mobile; GCA air-ground; MILSAT; flight following	
	700 - 900 MHz	Microwave	25 kHz
	902 - 928 MHz	ISM spread spectrum	650 kHz
L Band	1 - 2 GHz	TERASCAN receive; microwave links BI/M; navigational aids; NAILS (NASA); microwave landing systems (MLS) and distance measuring equipment (DME); TACAN; MMLS	
	1990 - 2110 MHz	GOES-3 uplink	12 MHz
	1675 - 1700 MHz	GOES-3 downlink	12 MHz
	1616 - 1626.5 MHz	IRIDIUM	
	1535 - 1543.5 MHz	INMARSAT Downlink	
S Band	1636.5 - 1645 MHz	INMARSAT Uplink	
	2200 - 2300 MHz	TDRSS uplink	
	2020 - 2123 MHz	TDRSS downlink	
	2412 - 2473 MHz	Wireless LAN	
C Band		NAILS (NASA)	
	4 - 8 GHz	USES receive; Mobile Microwave Landing Sys(MMLS); Microwave Landing System (MLS); Flight Telemetry Earth/Sat; USES Beacon; Science (experimental testing); Surveillance Radar	
X Band	8 - 12 GHz	Surveillance Radar; Experimental Testing	
Ku Band	12 - 18 GHz	Future (satellite use) NPOESSExperimental testing	
	13747 - 13802 MHz	TDRS Ku band downlink	
	14887 - 15119	TDRS Ku band uplink	
K Band	18 - 26 GHz	IRIDIUM gateways and inter-satellite links.Satellite USA-2Experimental testing	
Ka Band	26 - 40 GHz	IRIDIUM gateways	



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