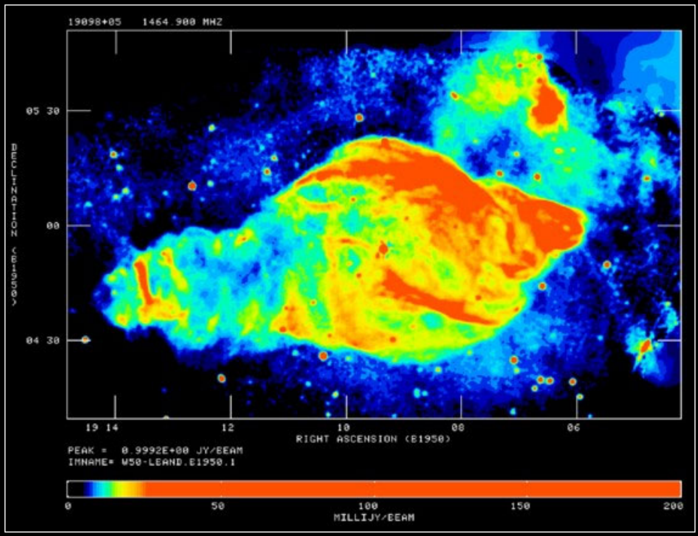
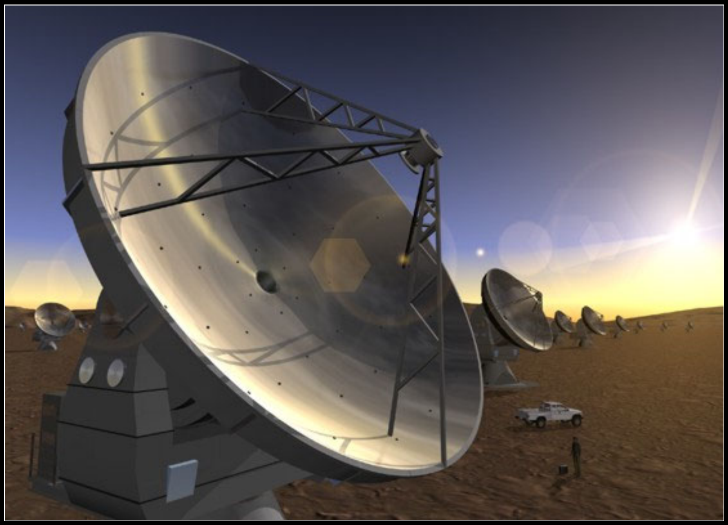
NATIONAL SCIENCE FOUNDATION

Long Range Spectrum Plan





November 2005

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Director

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 development in the Chilean Andes. Artist's conception of the 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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0. 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, which is a renewable, limited, and vital national resource that must be shared with numerous other users. NSF-sponsored research also requires spectrum access for communications or 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 of 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 abroad when the science requires. 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 cover 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 going currently 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 at 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 of spectrum management for the oceanographic fleet, however.

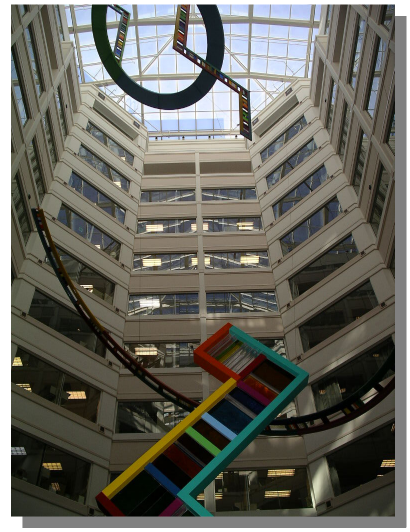
This tethersonde was used to gather data during the Hawaiian Rainband Project (HaRP), a research project that studied recurrent rainbands that form just offshore near Hilo, Hawaii. A tethersonde carries a package of instruments that take standard meteorological measurements such as wind, pressure, temperature, and humidity. HaRP is an example of NSF's involvement in cooperative research. More than 75 staff members from the NSF-supported National Center for Atmospheric Research (NCAR), researchers from universities and scientific institutions in five nations, and dozens of instruments were stationed near Hilo for this project. *Courtesy NCAR/NASA/San Francisco State University/D. Dempsey.*

1 — INTRODUCTION

1.1 — 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.



The National Science Foundation headquarters building in Arlington, Virginia.

NSF plays a critical role in supporting fundamental research, education, and infrastructure at colleges, universities, and other institutions throughout the country. Although NSF represents less than four percent of the total federal funding for research and development (R&D), it accounts for approximately 13% of all federal support for basic research and 40% of non-life-science basic research at U.S. academic institutions. NSF's broad support for basic research, particularly at U.S. academic institutions, provides not only a key source of funds for discovery in many fields, but also unique stewardship in developing the next generation of scientists and engineers.

To pursue its mission, NSF established strategic goals in terms of People, Ideas and Tools that can be summarized as:

- *People* – The creation of a diverse, competitive, and globally engaged U.S. workforce of scientists, engineers, technologists and well-prepared citizens
- *Ideas* - Discovery across the frontier of science and engineering, connected to learning, innovation, and service to society
- *Tools* – Broadly accessible, state-of-the-art science and engineering (S&E) facilities, tools, and other infrastructure that enable discovery, learning, and innovation

The means and strategies that NSF uses to successfully accomplish the *Tools* goal include the following specific 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.
- Provide for the collection and analysis of the scientific and technical resources of the U.S. and other nations to inform policy formulation and resource allocation.

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 long-range spectrum plan.

1.2 — NSF SPECTRUM USE AND REQUIREMENTS

Access to the radio spectrum is essential for some areas of science. For example, access to appropriate portions of the radio spectrum is required to enable radio astronomy observations, to conduct ionospheric and upper atmospheric research, or research in computational networking. U.S. scientists also need to access the radio spectrum for data relay or logistical purposes, e.g. when carrying out NSF's Antarctic mission, oceanographic research, or wildlife tracking and telemetry. Communications with NSF's Antarctic facilities are inconceivable without appropriate access to certain bands of the radio spectrum. Radio astronomers and other scientists use the spectrum in a purely passive (receive only) mode. Some science applications, such as ionospheric research, may require the use of both passive and active radio techniques.

Scientific research often requires access to specific, well-defined parts of the spectrum. For example, radio astronomers cannot always choose the frequencies of their observation arbitrarily, as many of the cosmic signals that they study take the form of spectral lines covering a limited frequency range. These lines are generated at characteristic frequencies associated with transitions between quantized energy states of atoms or molecules, and in order to obtain the information that the astronomer seeks they must be observed at these specific frequencies. Nor can they limit their observations to a few bands. For example, establishing the chemical composition and dynamics of interstellar matter requires measurements of many spectral lines across the millimeter wave spectrum. Similar considerations apply to observations of other natural phenomena. In addition, international observing programs or campaigns may necessitate the use of common equipment, and dictate the choice of frequencies for a given experiment.

Examples of NSF-Funded Facilities and Programs that Require Access to the Radio Spectrum

- *Federally-Funded Research & Development Centers*
  - National Astronomy and Ionosphere Center (NAIC)
  - National Center for Atmospheric Research (NCAR)
  - National Radio Astronomy Observatory (NRAO)
- *Polar Tools, Facilities, and Logistics*
  - Antarctic facilities and operations
  - Antarctic logistics
  - Arctic logistics
- *Research Programs*
  - Academic Research Fleet
  - Advanced Modular Incoherent Scatter Radar (AMISR)
  - Alaska Regional Research Vessel (ARRV)
  - Ocean Observatories
  - Advanced Networking Infrastructure
  - Projects in the Major Research Instrumentation (MRI) grants programs
  - Projects in the Advanced Technologies and Instrumentation (ATI) grants program

Researchers are interested not only in observations in the allocated part of the spectrum, they are also interested in studies of emissions at frequencies below 9 kHz and above the current 275 GHz upper limit of the allocations. Scientists also cover an enormous range in terms of power. Radio astronomers routinely make observations of cosmic sources with power flux densities at the Earth of ~ 10^{-30} W m^{-2} Hz^{-1} (amounting to ~ 10^{-24} watts of detected power), and even less. Such observations are among the most sensitive ones made by humans. On the other hand, ionospheric researchers and radar astronomers routinely use some of the most powerful transmitters ever built, beaming effective radiated powers of the order of several terawatts toward distant objects.

Scientists continue to pioneer the use of ever-higher radio frequencies. Astronomical observations up to 1000 GHz and even higher are not unusual. Some of the highest-frequency radio instruments have begun to blur the line between radio and infrared detection techniques.

1.3 — MISSION STATEMENT OF THE ELECTROMAGNETIC SPECTRUM MANAGEMENT UNIT

The Electromagnetic Spectrum Management unit (ESM), located within the Division of Astronomical Sciences of the Mathematical and Physical Sciences Directorate of NSF, is charged with ensuring the access of the scientific community to portions of the radio spectrum that are needed for research purposes. ESM strives to accomplish its mission by representing the interests of the NSF and the science community it supports in the fields of telecommunications management and regulation through:

- Participation in the establishment of radio regulations, operating procedures, and technical standards related to government uses of the radio spectrum, by representing the NSF on the Interdepartment Radio Advisory Committee (IRAC) and its subcommittees and ad-hoc committees
- Participation in the establishment of radio regulations, operating procedures, and technical standards related to private sector uses of the radio spectrum, by providing input into Federal Communication Commission (FCC) proceedings, either directly or through the National Telecommunication and Information Administration (NTIA)
- Participation in the establishment of international radio regulations by providing input into U .S. government preparations for World Radiocommunication Conferences through the Radio Conference Subcommittee of the IRAC (RCS), and serving as technical advisor to U.S. delegations to World Radiocommunication Conferences, when appropriate.

1.4 Programmatic Responsibilities

Programmatic responsibilities of the NSF ESM staff include, but are not limited to, the following:

1.4.1 — National Activities

- *Representation on the Interdepartment Radio Advisory Committee (IRAC), and its subcommittees and Ad-Hoc committees.* The IRAC assists the Assistant Secretary of Commerce for Communication and Information in developing and executing policies, programs, procedures and technical criteria pertaining to the allocation, management and use of the electromagnetic spectrum, by advising him/her of the spectrum related uses and requirements of the Federal Agencies. The various subcommittees of the IRAC deal with the assignment of frequencies to government radio stations, the planning of the use of the spectrum by various major systems, the technical uses of the spectrum and coordination of satellite systems, nationally as well as internationally through the formal international process. NSF participation in the IRAC and its subcommittees is essential to preserve access to the spectrum by the U.S. science community.
- *Spectrum Planning Subcommittee (SPS) of the IRAC.* The NSF SPS representative is responsible for scrutinizing the impact that systems planned by other agencies may have on NSF systems (for example, radio astronomy observatories), as well as putting NSF-sponsored systems (such as AMISR, an upper atmospheric incoherent radar facility) through SPS review. There is a statutory requirement to review all major radio systems, including all space systems, for spectrum availability through the SPS process prior to committing funds for the development of such systems.
- *Frequency Assignment Subcommittee (FAS) of the IRAC.* The NSF FAS representative is responsible for obtaining licenses and coordinating radio stations operated by the national centers (e.g. the National Radio Astronomy Observatory or the National Center for Atmospheric Research). Conversely, the FAS representative is responsible for scrutinizing other agencies' license applications to avoid an impact of such an assignment on NSF systems.

1.4.2 — International Activities

Most science activities that involve the use of the radio spectrum are inherently international in nature (for example, weather campaigns are often carried out in more than one country; astronomers may need to carry out Very Long Baseline Interferometer (VLBI) observations in various countries simultaneously), and thus require the participation of ESM staff in international spectrum management fora.

- *World Radiocommunication Conferences* (WRCs) are held regularly at 2-3 year intervals to revise and update the Radio Regulations, an international treaty that includes the international table of frequency allocations. WRCs require extensive preparations before each conference. During the conference itself, WRCs demand the presence and exclusive attention of one or more NSF staff members, depending on the number of items of interest on the agenda to the science community. Preparations for WRCs are carried out within the National Telecommunications and Information Agency (NTIA, which deals with federal government requirements) and at the FCC (which deals with private sector issues) and they include preparation of proposals and position papers for the conference. The NSF representative to this process is regarded (along with the NASA and NOAA representatives) as the authoritative voice on the impact of new international regulation to science interests.

- *Technical Studies within the International Telecommunication Union.* The technical work of the ITU is carried out within the Radiocommunication Sector Study Groups, (ITU-R, which is the technical organ of the ITU). In addition to the dedicated radio astronomy group (Working Party 7D), and the analogous group dealing with Earth remote sensing and meteorology within the ITU-R (Working Party 7C), studies of interest and related to science activities are conducted in a variety of ITU-R groups. The U.S. ITAC-R, an advisory group set and chartered by the Department of State, mirrors the international ITU-R study group structure. Within the U.S. structure, NSF presently provides the Chair and Vice-chair of the radio astronomy group and leads the U.S. Delegation to international Working Party 7D meetings. Activities within the ITU-R are likely to increase further due to the growing need to share the radio spectrum and the attending need to study the sharing conditions between the various radio services.

1.4.3 — Joint National/International Activities

- *Satellite Coordination.* A number of satellite systems (for example, GPS, Iridium and the Russian GLONASS system) that are operational and others that are in the planning phase downlink from space-to-Earth near bands of importance to radio astronomers. Coordination with these systems is essential, complex, and time-consuming. In addition, in the future NSF may acquire its own satellite systems, either for scientific research (NSF currently provides substantial funding to one non-U.S. satellite system performing ionospheric research), or for Antarctic communications. Satellite systems must be registered, and sometimes extensively coordinated, through the procedures established at the International Telecommunication Union.

1.4.4 — Spectrum Management in the U.S. Antarctic Program

Spectrum utilization in Antarctica and at the Arctic is not covered either by national or international regulations. NSF's Office of Polar Programs utilizes the services of the U.S. Navy Space and Warfare Systems Center Charleston (SSCC) to provide spectrum management services at these regions. SSCC provides an individual trained in DoD base operations/tactical operations spectrum management techniques to serve as spectrum manager. This individual maintains a database of all operational and science-related spectrum assignments issued locally within the USAP, and also provides a coordination interface with the U.S. national spectrum management environment for USAP HF radio frequency assignments, as these are managed by the DoD for NSF at the national level. The same individual also assists with radio communications information sharing with other Antarctic Treaty operators in fulfillment of U.S. Treaty obligations.

Special coordination for local spectrum management is needed for McMurdo and South Pole stations, due to the presence of sensitive science activities. At McMurdo station, there is an Antarctic Treaty-designated area of special management that has established a small area with international management controls on human activities, including radio frequency emissions. Coordination of science and operational activities within this zone involve a complex process dealing with Antarctic Treaty environmental management plan compliance, science impact coordination between U.S. and New Zealand scientist-volunteers, and the SSCC spectrum manager. In the case of South Pole station, straight-forward coordination of radio spectrum applications are managed jointly by the SSCC spectrum manager and a prime contractor retained by NSF for USAP logistics and operations support.

1.5 — Staffing

The NSF Electromagnetic Spectrum Management Unit is located in the Division of Astronomical Sciences (AST), within the Mathematical and Physical Sciences Directorate (MPS), reflecting the fact that most (but by no means all) spectrum management issues at the NSF relate to radio astronomy. The staffing of the unit presently consists of one full-time and one part-time Ph.D. level scientist. It is expected that the part-time staff member will become full time as soon as staff that will take over his other present duties is acquired. Assuming that the workload does not increase substantially in the next few years, two Ph.D.-level staff members are just barely sufficient to cover the workload. This level of staffing assumes that the U.S. Antarctic Program (USAP) and the U.S. oceanographic communities will continue to cover their spectrum management related activities through contractors or other federal agencies.

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The NSF's Very Large Array, operated by the National Radio Astronomy Observatory and located on the Plains of San Agustin in New Mexico. The VLA is a 27-element interferometer that operates at frequencies between 74 MHz and 50 GHz. The individual telescopes are each 25 meters in diameter. The VLA is presently undergoing a major upgrade to enhance its receivers, increase its frequency coverage, and take advantage of the latest digital IF transmission technology. Like all major radio astronomy facilities, the VLA operates 24 hours a day, 365 days a year. Measured by the number of scientific publications resulting from its use, the VLA is the world's most productive ground-based telescope, at any wavelength. *Courtesy NSF/Andrew Clegg.*

2 — RADIO AND RADAR ASTRONOMY

2.1 — 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.

Full-scale replica of Karl Jansky's directional 14.5 MHz antenna used in 1932 to discover radio waves originating from beyond the Earth. The replica is on the grounds of the National Radio Astronomy Observatory in Green Bank, West Virginia. Courtesy Andrew Clegg/NSF.

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 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 transformed completely 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).

The Jansky

The jansky (abbreviated Jy) is the basic unit of radio astronomy signal strength:

$$1 \text{ Jy} = 10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1}$$

To bring the small magnitude of a jansky "down to Earth," consider that it is equivalent to a signal strength of approximately –197 dBm as it would be received by an 800 MHz GSM cell phone, assuming a 0 dBi receiving antenna. Radio astronomers often observe sources with signal strengths one million times less (1 microjansky).

2.2 — RADIO TELESCOPES AND THE NATURE OF RADIO ASTRONOMY OBSERVATIONS

Research in radio astronomy is conducted with two kinds of instruments: single dish telescopes or 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

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).

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 diameter 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 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 observation.

Astronomers who study pulsars often use 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.

2.3 — 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. Annex A 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 (or lower) 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, means generally 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.

2.4 — 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. Annex B 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.

2.4.1 — 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 minimize 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.

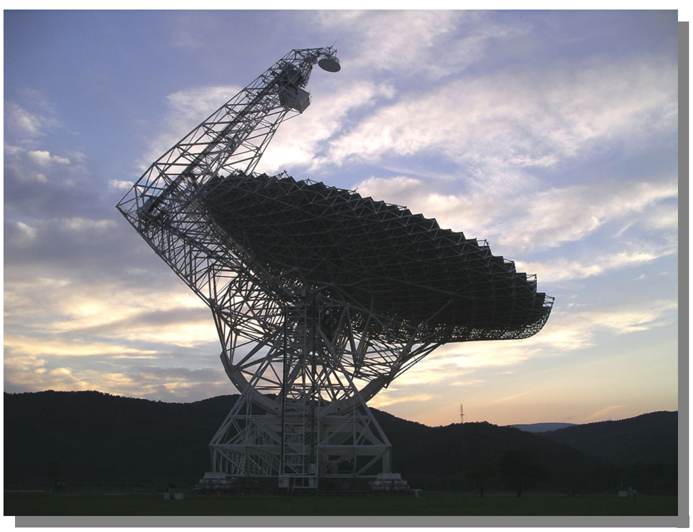
2.5 — Strategic Plan for Future Radio Astronomy Facilities

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. It should be emphasized that 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.

2.5.1 — 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.

2.5.1.1 — Robert C. Byrd Green Bank Telescope (GBT)



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.

The Robert C. Byrd Green Bank Telescope (GBT) of the NRAO, the world's largest fully-steerable radio telescope, is located within the 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 50 GHz. 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 meter section of a conventional, rotationally symmetric 208-meter 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.

2.5.1.2 — 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 in a Y-shaped configuration on the Plains of San Agustin fifty miles west of Socorro, New Mexico. Each antenna is 25 meters (82 feet) 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 meters (422 feet) 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.

A second phase of the expansion project (EVLA-II) proposes to add 8 new antennas, spread throughout the state of New Mexico, to enhance the VLA's angular resolution, and would also add a new very-compact configuration of the existing array which allows for better sensitivity to angularly extended radio emissions. EVLA-II is still in the design and development phase, and is subject to the availability of funds.

2.5.1.3 — The Combined Array for Research in Millimeter-wave Astronomy (CARMA)

The millimeter-wave interferometer array operated by an association of the University of California at Berkeley, the University of Illinois, and the University of Maryland (the "BIMA Array"), formerly located at Hat Creek, California, and the Owens Valley Radio Observatory, operated by Caltech and formerly located at Owens Valley, CA, are being combined and moved to a higher-elevation site. The new, much more powerful telescope is called the Combined Array for Research in Millimeter-wave Astronomy, or CARMA. The new array will consist of 15 telescopes operating together as an interferometer, in three bands centered on 115, 230, and 345 GHz. The telescopes have been physically relocated and initial operations of the new array are just beginning. It is anticipated that CARMA will be fully operational by the end of 2005.

2.5.2 —Major New Facilities Under Construction

2.5.2.1 — The Atacama Large Millimeter 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 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, where the Earth's atmosphere above a high, 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 64 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 23º 01' S; 67º 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. An unofficial translation of Resolution 1055 of SUBTEL is shown in Annex F.

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 form Enhanced ALMA. 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 80 antennas in Enhanced ALMA.

2.5.2.2 — 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, with telescope construction expected to be complete in 2007.

2.5.2.3 — The South Pole Telescope (SPT)

A new 10 m diameter telescope is being constructed for deployment at the NSF South Pole research station. The telescope is designed for conducting large-area millimeter and sub-millimeter wave surveys of faint, low contrast emission, that is required to map primary and secondary anisotropies in the cosmic microwave background. The SPT is collaboration between the University of Chicago, the University of California at Berkeley, Case Western Reserve University, the University of Illinois, and Smithsonian Astrophysical Observatory, and it is primarily funded through the NSF Office of Polar Programs. It will be assembled and tested in the U.S. in January - May 2006, prior to deployment at the South Pole in November 2006 - January 2007. The telescope will be capable of observations up to approximately 1.5 THz.

2.5.2.4 — 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 1400 MHz), 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.

2.5.3 — Next Generation Radio Astronomy Facilities

2.5.3.1 — Atacama Cosmology Telescope (ACT)

The Atacama Cosmology Telescope (ACT) is a specialized instrument being installed in the Atacama desert 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 goal is to have ACT running and ready for initial receiver tests in November 2006.

2.5.3.2 — 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 Desert of northern Chile, and will operate in several bands between 150 GHz and 1.5 THz. It is expected to become operational in 2012.

2.5.3.3 — Mileura Widefield Array (MWA)

The Mileura Widefield Array is a low-frequency radio array planned for construction in the outback 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.

2.5.3.4 The Primeval Structure Telescope (PaST),

PaST will be used to locate and study the earliest luminous objects in the universe, including the first stars, supernova explosions, and/or black holes. All of these objects were strong sources of ultraviolet radiation, so they ionized the material surrounding them: it is this ionization that will be detected and studied. The structure of this ionization reflects the overall density structure at the redshift of luminous-object formation.

Consisting of an array of some ten-thousand log-periodic antennas spread over several square kilometers, PaST, now under construction, will capture a detailed radio image of the sky in the range of 50 to 200 MHz. To do so, the telescope will be located in a remote area away from most manmade radio signals, near Ulastai, China.

2.5.3.5 — 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." A site for the LWA has not been selected.

2.5.3.6 — The Frequency Agile Solar Radiotelescope (FASR)

The Frequency Agile Solar Radiotelescope is a multi-frequency (0.03 - 30 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 3 decades of frequency from 30 MHz to 30 GHz. The two highest bands will utilize 6 m and 2 m antennas, respectively. 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 near the VLA in New Mexico or in Owens Valley, California.

2.5.3.7 — 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. A site for the SKA is expected to be identified in 2007; potential locations under consideration are outside the U.S.

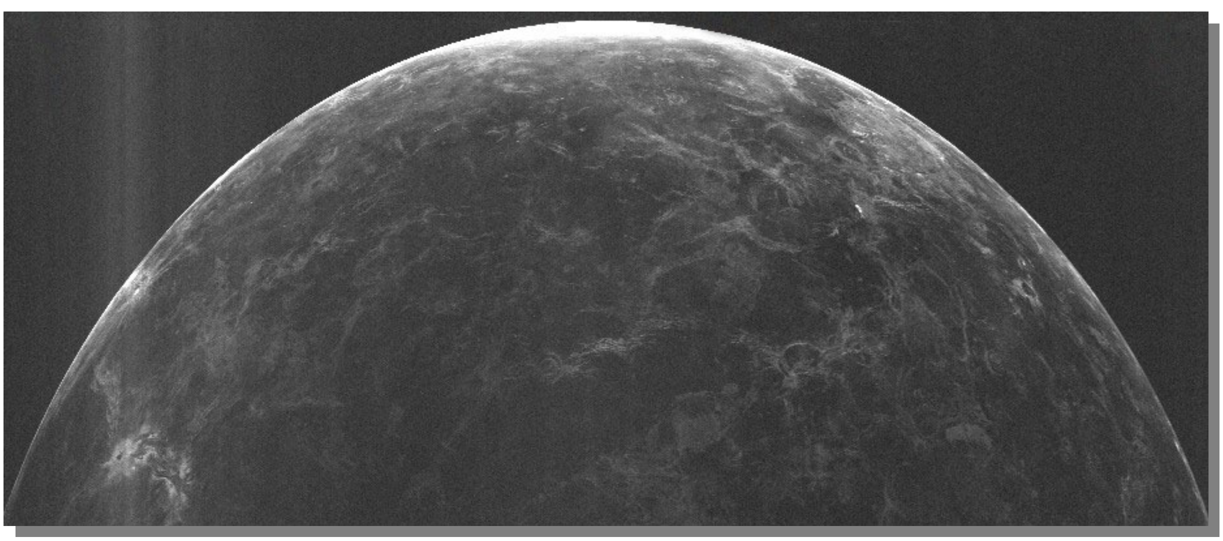
2.6 — Radar Astronomy

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.

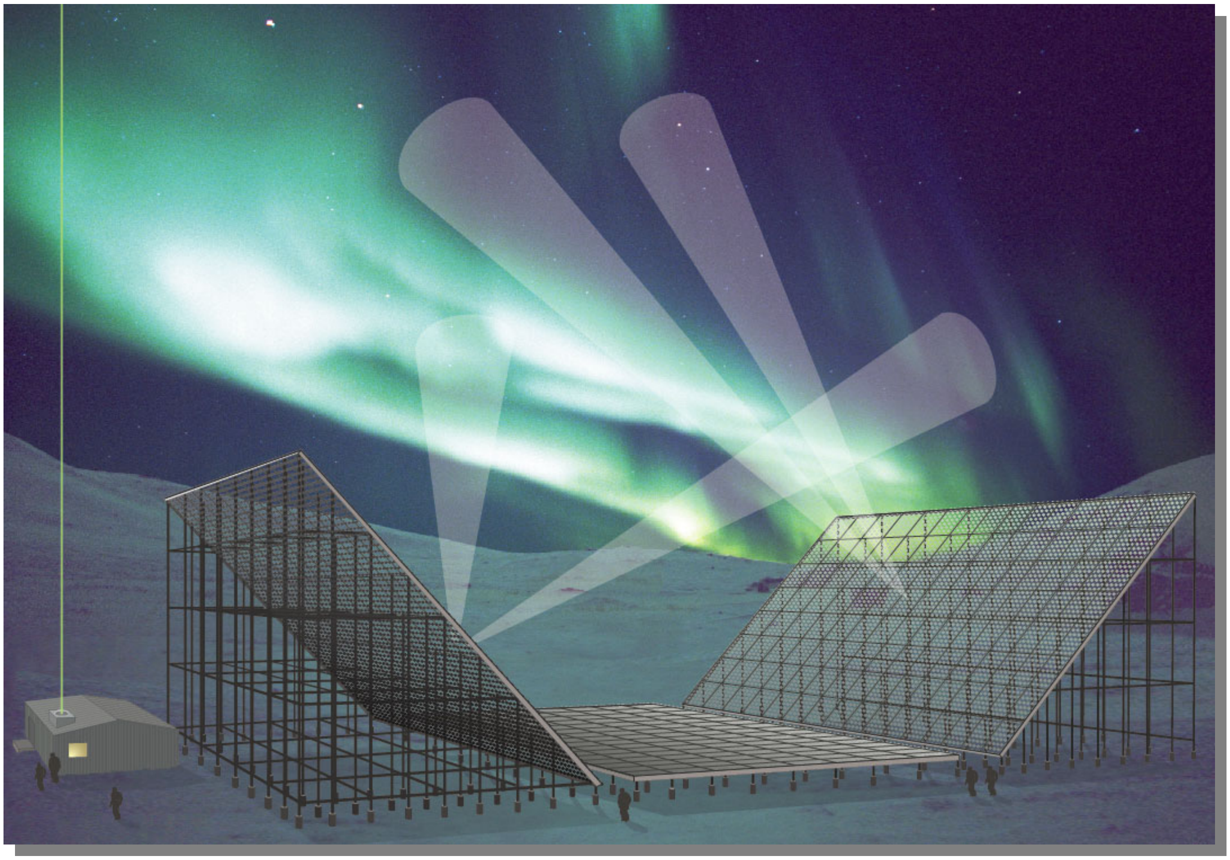
Arecibo can be used as both the transmitter and receiver if the object is sufficiently distant so that there is time to switch between transmit mode and receive mode by the time the echo returns; but not so distant that the desired object is out of view of Arecibo's sky coverage when the echo returns. 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.

The Arecibo radar was recently upgraded under joint funding by NASA and NSF. Further upgrades to Arecibo's radar system are not anticipated in the near future.



An Arecibo radar image of Venus, a planet that is permanently shrouded in thick clouds that make optical, infrared, and ultraviolet observations of the surface impossible. Detailed radar imagery of Venus will allow planetary scientists to study possible geological activity on the surface by comparing "before" and "after" imagery. The data were acquired with the 2380 MHz planetary radar system. NSF/Cornell University/NAIC/ Arecibo.



Artist's conception of the Advanced Modular Incoherent Scatter Radar (AMISR) currently under construction in Alaska. The three faces can be deployed and operated independently. AMISR will study the physics of the upper atmosphere and ionosphere and will operate at a frequency of 420 - 450 MHz. *Courtesy NSF's Division of Atmospheric Sciences.*

3 — UPPER ATMOSPHERIC RESEARCH

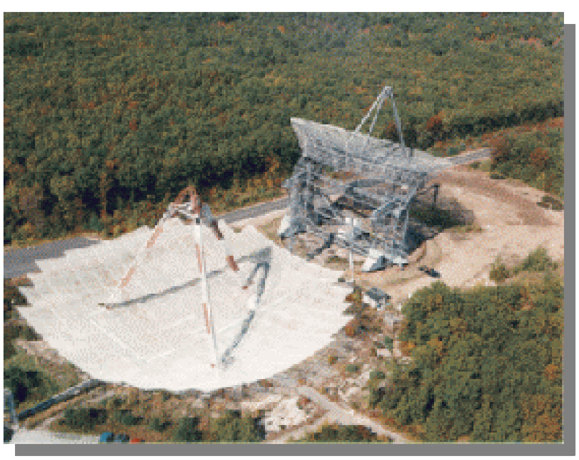
3.1 — EXISITING INCOHERENT SCATTER RADAR ARRAYS

NSF supports research from the upper atmosphere of the Earth to the surface of the Sun, with special attention to 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. The program promotes the cooperation and coordination of the four U. S. radar facilities aligned in a meridian chain extending from the boundary of the polar cap to the magnetic equator. In the last ten years, the program has expanded to include the U. S. contribution to the Super Dual Auroral Radio Network (SuperDARN).

The phased-array antenna of the Jicamarca Radio Observatory near Lima, Peru. Courtesy NSF's Division of Atmospheric Sciences.

Incoherent scatter radars use a technique that requires high-power transmitters at frequencies ranging from 50 MHz 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 information about the ion composition. By combining these measurements with other quantities, either from models or measurements, many basic properties of the ionospheric plasma, e.g. 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. Annex C lists the ISRs currently operating for scientific research worldwide. Those operated by NSF are highlighted in the table. 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 and the MU 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. Annex C lists the distinctive aspects of the ISRs worldwide.



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

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

The Sondrestrom Radar Facility located 12 km from the town of Kangerlussuaq, Greenland. Courtesy NSF's Division of Atmospheric Sciences.

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 four 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.

3.2 — Future Incoherent Scatter Radar Systems

Although the existing ISRs can continue to operate for ten years, the ionospheric physics community has been studying alternative technologies. Like the military, this community has turned to solid-state transmitter technology, with phased-array antennas. NSF funded the development and construction of the Advanced Modular Incoherent Scatter Radar (AMISR), a solid-state, phased-array radar operating in the 420 to 450 MHz frequency range. AMISR employs a modular design that will enable the radar to be easily disassembled and relocated to provide observing capabilities in different locations depending on scientific needs or missions of opportunity. The basic design element is a single dipole antenna attached to a transmit/receive unit with a 500 watt solid state power amplifier. Thirty-two of these antenna element units are mounted on a single panel of dimensions 2 m by 4 m. Current plans call for assembling 128 of these panels into an array of dipoles called a face, with dimensions of approximately 30 m by 30 m. Over the next few years, enough antenna elements will be manufactured to populate three faces. The first face is scheduled to be deployed at Poker Flat Alaska in 2006, while the second and third faces will be deployed in 2007at Resolute Bay, Canada, within the polar cap. However, other antenna configurations are possible as the cabling to the antenna panels allow for 16 panels to be operated independently. This will allow interferometer modes using received signals from the eight 16-panel modules that comprise a face.

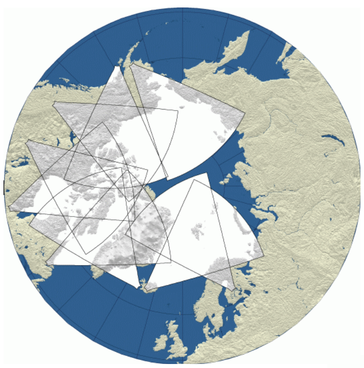
AMISR features pulse-to-pulse electronic steering capabilities within 25° of the bore-sight direction. The single face at Poker Flat will be canted northward to provide better coverage of flight paths of rockets launched from Poker Flat. The two faces at Resolute Bay will be arranged to provide the extended coverage necessary for polar cap science. Given the modularity of the design, many other antenna configurations are possible, and these can be optimized according to the location of the radar and the specific science objectives. Other locations that will be considered for AMISR deployment include the Antarctic; Hawaii; Wallops Island, Virginia; Florida; and Argentina. An AMISR system may also be constructed on a sea-going barge that would enable it to make observations from sea throughout the world.

It is possible to replace the transmitters at the existing ISR sites with AMISR solid-state units, but combining the power from many low-power transmitters to feed into the single antennas used at Sondrestrom, Millstone, and Arecibo may not be cost effective. To continue operations at these sites after current technology can no longer be sustained, a new source of high-power klystrons must be found. One possible alternative to is to deploy a network of fixed-dish radars based on commercially available technology that will reduce cost of acquisition and operation.

In this concept, a large zenith directed antenna is combined with a medium power Digital Television Transmitter based on Constant Efficiency Amplifier (CEA) technology. The ZIP design has low construction and operation costs, excellent performance, and is well suited to automated, continuous operations. Elements that contribute to the low cost of this instrument include a modest average power level (20-30 kW), high transmitter efficiency (60-70%), a simple offset feed spring suspended mesh antenna design, the use of high power coax instead of waveguide, and full remote operations using software radar technology. A low cost incoherent scatter radar design is useful because it can be widely deployed in reasonable numbers. A network of such low cost ISR systems would be much more powerful collectively than any individual instrument. If the ZIP alternative is adopted, it would probably operate at 440.0 +/-1 MHz. However, there may be advantages in operating at a higher frequency, e.g. using one of the unused digital television channels in the 500-750 MHz range, depending on location, but with a smaller bandwidth than the 6 MHz channel width.

3.3 — SuperDARN

SuperDARN 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 is currently comprised of nine radars in the northern and six 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.



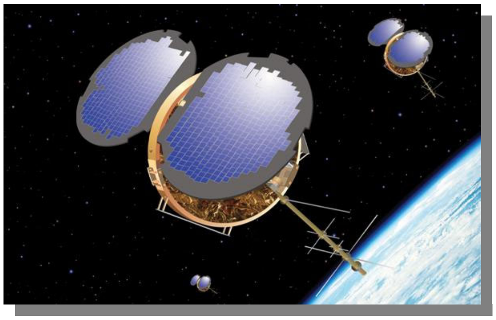
Northern and southern hemisphere locations of the SuperDARN radar sites and coverage. Courtesy NSF and Johns Hopkins University.

The SuperDARN radars are designed to operate in the frequency range from 9 to 17 MHz with a bandwidth of about 30 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. 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.

3.4 — 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, US Air Force, US Navy, and 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 is currently planned to be launched in the December of 2005, and is expected to last for five years. Observations of GPS signals will be carried out in a bandwidth of: L_1±10 MHz and



Artist's conception of the COSMIC/FORMOSAT-3 constellation. Courtesy NSF.

$L_2 \pm 6$ MHz. Over the first year, the satellites will be gradually boosted from their initial orbit of 400 kilometers to the final orbit of roughly 800 kilometers, conducting important geodetic/gravity experiments during this phase.

The system will consist of: (1) The Space Segment, a constellation of 6 micro-satellites, each weighing less than 70 kg (~110lb). Each satellite takes independent science measurements at all times during the orbit. The six spacecraft will 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 will be 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).

4 — LOWER ATMOSPHERIC RESEARCH

4.1 — CHILL RADAR AND S-POL

The Colorado State University Department of Atmospheric Sciences, under sponsorship of NSF and NCAR, 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.

CHILL Radar at Greeley, Colorado. Its size and construction allow deployments in the United States but it is too massive for international deployments. Courtesy NSF's Division of Atmospheric Sciences.

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 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 is periodically deployed within the United State. 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, that is currently being installed.

S-POL Radar (NCAR) – its modularity allows for reasonably easy breakdown and set up. Courtesy NSF/NCAR.

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.

S-POL, operated and maintained by NCAR for NSF, is similar to CHILL, but can be broken down and transported in crates by trucks or sea containers. Thus, S-POL is very attractive for overseas field studies. Both radars are currently undergoing refurbishment and upgrades and NSF expects them to be in operation for at least another 5 years.

4.2 — 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. 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. IHOPs 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

Naval Research Laboratory P-3 with the ELDORA Doppler radar attached to the tail. The P-3 airframe is the only airframe that could be modified to hold the ELDORA. Courtesy NSF's Division of Atmospheric Sciences.

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 (2005) 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 helixes 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.

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.

A worker at the South Pole waves goodbye to an LC-130 military aircraft as it departs the station with about 35 employees who spent the winter at the bottom of the world. Courtesy NSF/Mark Buckley.

5 — Polar Programs

5.1 — 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.

Speaking from McMurdo Station, Sir Edmund Hillary talks via high-frequency radio to a communications operator at Amundsen-Scott South Pole Station. Hillary led the first team to reach the South Pole by motorized vehicles -- farm tractors -- in 1958. Courtesy NSF/Brien Barnett.

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.

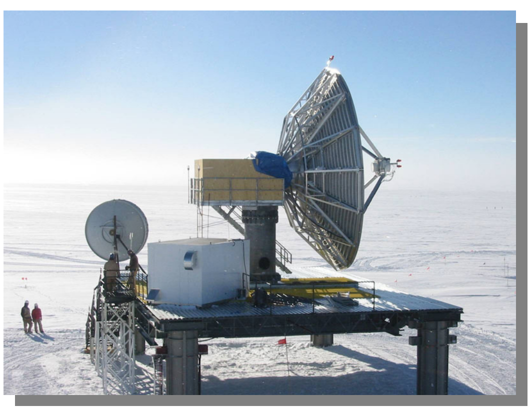
McMurdo Station is essentially a small, self-contained city. Typical summer and winter populations average 1100 and 200 persons, respectively. The station hosts the world's southern-most port and three aerodrome facilities. Power generation, fresh water production, waste treatment, medical care, food 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 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, esp. sub-millimeter radio astronomy. South Pole Station will house a 10 m radio telescope. 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.

5.2 — 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.



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.

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.

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.

5.3 — USAP Radio Communications Plans

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)

5.4 — Considerations for the Future

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.

Former bush pilot Liza Lobe of Cordova, Alaska, works at Amundsen-Scott South Pole Station as a communications technician. She communicates with remote field camps around the continent. Courtesy NSF/Melanie Conner.

6 — OTHER NSF-SUPPORTED RESEARCH THAT RELATES TO THE USE OF THE RADIO SPECTRUM

NSF supports research in some other science areas that require access to or that otherwise relates to the radio spectrum. Of interest for this Long Range Spectrum Plan are the following:

- Oceanographic Research. The academic research fleet and the ocean observatories are clearly major users of the spectrum, both for navigational and data relay purposes. Spectrum management for these facilities and for oceanographic research in general has been and continues to be carried out not by NSF, but by the US Navy, the US Coast Guard, other agencies of the US government or in some cases private sector entities. During the last decade the oceanographic community has sought advice and assistance from the NSF ESM unit only on a limited number of occasions, mostly in areas related to spectrum policy and to acquire and register IINMARSAT terminals. This situation is not expected to change. Should it change, however, the spectrum related needs of the oceanographic community would place a very large additional burden on the existing NSF spectrum management staff, and additional staff members (or contractors) would be needed.

- Networking and Dynamic Spectrum Access. The directorate of Computer and Information Science & Engineering (CISE) supports research into spectrum occupancy, dynamic spectrum access networking, and related topics. These areas of research do not require additional spectrum or spectrum management resources. On the contrary, this type of research is oriented towards achieving high spectrum efficiency, broadening access to the Internet and other communication networks and generally speaking a more intensive utilization of the spectrum. These are prime goals of the President's spectrum management agenda for the 21st Century.

- Research in Terahertz Spectroscopy. The terahertz region of the spectrum (above 1,000 GHz) has been unexplored until recently. This portion of the electromagnetic spectrum, intermediate between the infrared and optical spectrum, holds great promise for some areas of science, e.g. astronomy. Terahertz spectroscopy also holds great promise as an approach to combat terrorism, as its usefulness in detecting explosives and biohazards through the detection of only a few molecules is increasingly promising. No additional spectrum or spectrum management resources are expected to be needed for terahertz spectroscopy.

7 — FUTURE SPECTRUM REQUIREMENTS

The previous sections describe how NSF researchers use the spectrum and their plans for the future. When examining future projects, particularly those of the radio astronomy community, two trends become apparent.

First, radio astronomers are very interested in observing across the entire allocated spectrum, not just in bands specifically allocated to the radio astronomy service. The tendency to observe outside bands allocated to radio astronomy is driven by science requirements. Astronomers are interested in observations of cosmic sources that are faint, sometimes even by astronomical standards. Sensitive observations of faint sources require wide bandwidth and/or long integration times. Most radio astronomy allocations are relatively narrow, and the sensitivity required to observe faint sources can be reached only by integrating for hours or even days, if at all. Hence, to increase the sensitivity of the observations astronomers attempt to observe using bandwidths wider than the allocated bands. In addition, much interesting science must be accomplished outside allocated radio astronomy bands, either because the spectral line astronomers are interested in observing occurs in a band that is already allocated to other services, or because the line has been Doppler shifted out of the radio astronomy band.

In spite of this trend, **NSF does not anticipate proposing additional radio astronomy allocations within the allocated portion of the radio spectrum**. It expects instead to accommodate observations outside allocated radio astronomy band through a combination of interference mitigation techniques, geographical separation, and regulations, such as the establishment of coordination zones around observatories. Research on interference mitigation techniques is increasing, and while no single method has been found to be useful in eliminating all types of interference, some show promise, within certain limits. It is clear that interference mitigation will be helpful but it will not eliminate the need for exclusive and primary radio astronomy bands throughout the spectrum.

Second, radio astronomers and atmospheric scientists are conducting research at higher and higher frequencies, well into the THz region of the spectrum. The ALMA mm-wave telescope, possibly the most expensive ground based astronomical instrument that has been built to date, plans on conducting observations up to 1 THz. To protect its investment in ALMA and other mm-wave telescopes **NSF anticipates the need for spectrum allocations in the 300 to 1000 GHz range within the next decade**. Studies have begun within ITU-R WP 7D regarding the uses of this spectral range by the radio astronomy community, and other communities are conducting related studies as well. It appears unlikely at this time, however, that the studies will advance sufficiently to allow developing a U.S. proposal for allocations in the 300-1000 GHz spectrum range in time for the World Radiocommunication Conference to be held in 2010 (WRC-10).

Use of the radio spectrum by the rest of the scientific community is also expected to intensify within the next decade. No need for new allocations is anticipated, however.

ANNEX A — U.S. RADIO ASTRONOMY FREQUENCY ALLOCATIONS

The following tables summarize 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.

- Table A.1 shows 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.
- Table A.2 shows 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.
- Table A.3 shows 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.
- Table A.4 shows the bands for which footnotes to the table of frequency allocations mentions that radio astronomy observations may be taking place. Some of these bands encompass sub-bands in which the radio astronomy service is already allocated on a primary or secondary basis (i.e., those bands in Tables A.1—A.3). In those sub-bands, the level of protection for the radio astronomy service is based upon its primary or secondary allocation. Outside of those sub-bands (i.e., within the bands that radio astronomy is mentioned only by footnote), other users of the spectrum are requested to take into consideration the use of the bands for radio astronomy, but are not otherwise required to protect the radio astronomy service.

Frequency Bands Allocated Exclusively to Radio Astronomy and Other Passive Services
13.36 - 13.41 MHz
25.55 - 25.67 MHz
73 - 74.6 MHz
1400 - 1427 MHz
1660.5 - 1668.4 MHz
2690 - 2700 MHz
4990 - 5000 MHz
10.68 - 10.7 GHz
15.35 - 15.4 GHz
23.6 - 24 GHz
31.3 - 31.8 GHz
86 - 92 GHz
100 - 102 GHz
109.5 - 111.8 GHz
114.25 - 116 GHz
148.5 - 151.5
164 - 167 GHz
182 - 185 GHz
200 - 209 GHz
226 - 231.5 GHz
250 - 252 GHz

Table A.1: Bands allocated exclusively to passive services.

Primary Radio Astronomy Allocations Shared with Primary Active Services	
Band	**Primary Services with which Radio Astronomy Shares the Band**[1]
38 - 38.25 MHz	Fixed (G), Mobile (G)
406.1 - 410 MHz	Fixed (G), Mobile (G)
608 - 614 MHz	Land Mobile (G & NG)
1610.6 - 1613.8 MHz	Mobile Satellite (Earth-to-Space) (G&NG); Aeronuatical Radionavigation (G&NG); Radiodetermination-Satellite (Earth-to-space) (G&NG)
1660 - 1660.5 MHz	Mobile-Satellite (R) (Earth-to-space) (G&NG)
1668.4 - 1670 MHz	Meteorological Aids (radiosondes) (G & NG)
10.6 - 10.68 GHz	Fixed (NG)
22.21 - 22.5 GHz	Fixed (G&NG); Mobile (except aeronautical mobile) (G&NG)
42.5 - 43.5 GHz	Fixed (G); Fixed-Satellite (Earth-to-space) (G); Mobile (except aeronautical mobile) (G)
48.94 - 49.04 GHz	Fixed (G&NG); Fixed-Satellite (Earth-to-space) (G&NG); Mobile (G&NG)
76 - 77 GHz	Radiolocation (G&NG)
77 - 77.5 GHz	Radiolocation (G&NG)
78 - 79 GHz	Radiolocation (G&NG)
79 - 81 GHz	Radiolocation (G&NG)
81 - 84 GHz	Fixed (G&NG); Fixed-Satellite (G&NG); Mobile (G&NG); Mobile-Satellite (Earth-to-space) (G&NG)
84 - 86 GHz	Fixed (G&NG); Fixed-Satellite (G&NG); Mobile (G&NG)
92 - 94 GHz	Fixed (G&NG); Mobile (G&NG); Radiolocation (G&NG)
94.1 - 95 GHz	Fixed (G&NG); Mobile (G&NG); Radiolocation (G&NG)
95 - 100 GHz	Fixed (G&NG); Mobile (G&NG); Radiolocation (G&NG); Radionavigation (G&NG); Radionavigation-Satellite (G&NG)
102 - 109.5 GHz	Fixed (G&NG); Mobile (G&NG)
111.8 - 114.25 GHz	Fixed (G&NG); Mobile (G&NG)
130 - 134 GHz	Earth-Exploration-Satellite (active) (G&NG); Fixed (G&NG); Inter-Satellite (G&NG); Mobile (G&NG)
136 - 141 GHz	Radiolocation (G&NG)
141 - 148.5 GHz	Fixed (G&NG); Mobile (G&NG); Radiolocation (G&NG)
151.5 - 155.5 GHz	Fixed (G&NG); Mobile (G&NG); Radiolocation (G&NG)
155.5 - 158.5 GHz	Fixed (G&NG); Mobile (G&NG)
209 - 226 GHz	Fixed (G&NG); Fixed-Satellite (Earth-to-space) (G&NG); Mobile (G&NG)
241 - 248 GHz	Radiolocation (G&NG)
252 - 265 GHz	Fixed (G&NG); Mobile (G&NG); Mobile-Satellite (Earth-to-space) (G&NG); Radionavigation (G&NG); Radionavigation-Satellite (G&NG)
265 - 275 GHz	Fixed (G&NG); Fixed-Satellite (Earth-to-space) (G&NG); Mobile (G&NG)

[1]G = Allocation to Federal government services; NG = Allocation to non-Federal government services

Table A.2: Bands allocated to the radio astronomy service on a shared primary basis.

Secondary Allocations to the Radio Astronomy Service		
Band	Active Services Primary in the Band[1]	Secondary Services with which Radio Astronomy Shares the Band[1]
37.5 - 38 MHz	Land Mobile (NG)	
2655 - 2690 MHz	Fixed (NG); Mobile (except aeronautical	
77.5 - 78 GHz	Amateur (NG); Amateur-Satellite (NG)	Space research (space-to-Earth) (G&NG)
94 - 94.1 GHz	Earth-Exploration-Satellite (active) (G); Radiolocation (G&NG); Space Research (active) (G)	
123 - 130 GHz	Fixed-Satellite (space-to-Earth) (G&NG); Mobile-Satellite (space-to-Earth) (G&NG); Radionavigation (G&NG); Radionavigation-Satellite (G&NG)	
134 - 136 GHz	Amateur (NG); Amateur-Satellite (NG)	
248 - 250 GHz	Amateur (NG); Amateur-Satellite (NG)	

[1]G = Allocation to Federal government services; NG = Allocation to non-Federal government services

Table A.3: Bands allocated to the radio astronomy service on a secondary basis.

Frequency Bands in which Radio Astronomy Operates by Footnote Designation		
Band	Footnote	Remark
1350 - 1400 MHz	US311	
1400 - 1727 MHz	5.341	Search for Extraterrestrial Intelligence (SETI) (partial overlap with passive allocations)
1718.8 - 1722.2 MHz	US311	
4825 - 4835 MHz	US203	
4950 - 4990 MHz	US311	
14.47 - 14.5 GHz	US203	
56.24 - 56.29 GHz	US353	Space-based radio astronomy
58.422 - 58.472 GHz	US353	Space-based radio astronomy
59.139 - 59.189 GHz	US353	Space-based radio astronomy
59.566 - 59.616 GHz	US353	Space-based radio astronomy
60.281 - 60.331 GHz	US353	Space-based radio astronomy
60.41 - 60.46 GHz	US353	Space-based radio astronomy
62.461 - 62.511 GHz	US353	Space-based radio astronomy
101 - 120 GHz	5.341	Search for Extraterrestrial Intelligence (SETI) (partial overlap with passive allocations)
197 - 220 GHz	5.341	Search for Extraterrestrial Intelligence (SETI) (partial overlap with passive allocations)
275 - 323 GHz	5.565	Beyond the nominal upper frequency of the table of allocations
327 - 371 GHz	5.565	Beyond the nominal upper frequency of the table of allocations
388 - 424 GHz	5.565	Beyond the nominal upper frequency of the table of allocations
426 - 442 GHz	5.565	Beyond the nominal upper frequency of the table of allocations
453 - 510 GHz	5.565	Beyond the nominal upper frequency of the table of allocations
623 - 711 GHz	5.565	Beyond the nominal upper frequency of the table of allocations
795 - 909 GHz	5.565	Beyond the nominal upper frequency of the table of allocations
926 - 945 GHz	5.565	Beyond the nominal upper frequency of the table of allocations

Table A.4: Bands for which radio astronomy is mentioned by footnote.

ANNEX B — 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.

Telescope	Location	Type[4]	Coordinates: Latitude (N)	Longitude (E)	Elevation (m)	Nominal Frequency Range
Operational Radio Telescopes as of November 2005						
Allen Telescope Array (ATA)	Hat Creek, CA	INT	40° 49' 04"	-121° 28' 24"	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	100 - 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	2240 MHz - 115 GHz (non-continuous)
Heinrich Hertz Submillimeter Telescope Observatory (SMTO)	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' 37"	-66° 45' 11"	497	50 MHz - 10 GHz (non-continuous)
NRAO Green Bank 140-ft telescope	Green Bank, WV	SD	38° 26' 08"	-79° 49' 42"	825	50 MHz - 25 GHz
NRAO Green Bank Telescope (GBT)	Green Bank, WV	SD	38° 25' 59"	-79° 50' 23"	807	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
NRAO Very Long Baseline Array (VLBA)	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)
Pisgah Astronomical Research Institute (PARI)	Rosman, NC	SD	35° 11' 59"	-82° 52' 19"	895	17 MHz - 49 GHz non-continuous
South Pole balloon flights	Antarctic	SD	-81° - -75°	0° - 360°	28000 - 38000	<2 THz
Steward Observatory Kitt Peak	Kitt Peak, AZ	SD	31° 57' 12"	-111° 36' 53"	1914	68 - 300 GHz
Submillimeter Array (SMA)	Mauna Kea, HI	INT	19° 49' 27"	-155° 28' 39"	4080	180 - 900 GHz
Sunyaev-Zeldovich Array (SZA)	Bishop, CA	INT	37° 13' 57"	-118° 17' 46"	1694	26-36 GHz and 85-115 GHz
University of Michigan Radio Astronomy Observatory (UMRAO)	Stinchfield Woods, MI	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 2005						
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)	Near Llano de Chajnantor, Chile (exact location TBD)	SD	~-22° 50'	~-67° 45'	~5200	150 GHz - 1.5 THz (non-continuous)
Dome C[3]	Dome C, Antarctic	TBD	~-75°	~125°	~3200	TBD
Frequency Agile Solar Radiotelescope[2] (FASR)	TBD; possibly Plains of San Agustin, NM or Owens Valley, CA	INT	TBD	TBD	TBD	30 MHz - 30 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)	TBD	INT	TBD	TBD	TBD	10 - 88 MHz
Mileura Widefield Array[2] (MWA) (test facility)	Mileura Station, Australia	INT	-26° 25' 50"	117° 12' 25"	381	80 - 300 MHz & 800 - 1600 MHz
NRAO Atacama Large Millimeter Array[1] (ALMA)	Llano de Chajnantor, Chile	INT	-23° 01' 22	-67° 45' 18"	5059	30 GHz - 1 THz
Primeval Structure Telescope[2] (PaST)	Near Ulastai, China	INT	42° 56'	86° 41'		40 - 210 MHz
South Pole Telescope[1] (SPT)	Antarctic	SD	-89° 59'	-45° 53'	2800	<1.5 THz
Square Kilometer Array[2] (SKA)	TBD	INT	TBD	TBD	TBD	150 MHz - 25 GHz

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

Table B.1: U.S. Radio Astronomy Observatories

ANNEX C — 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, under construction at Poker Flat, 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.

ANNEX D — CHARACTERISTICS OF NSF-SPONSORED METEOROLOGICAL RADARS

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

ANNEX E — 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	
	1636.5 - 1645 MHz	INMARSAT Uplink	
S Band	2200 - 2300 MHz	TDRSS uplink	
	2020 - 2123 MHz	TDRSS downlink	
	2412 - 2473 MHz	Wireless LAN	
		NAILS (NASA)	
C Band	4 - 8 GHz	USES receive; Mobile Microwave Landing Sys(MMLS); Microwave Landing System (MLS); Flight Telemetering 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	

Annex F — Unofficial Translation of Resolution 1055 of the Sub-Secretariat of Telecommunications (SUBTEL) of the Ministry of Transport and Telecommunications of the Republic of Chile establishing a 30 km Diameter Protection Zone Surrounding ALMA

REPUBLIC OF CHILE

MINISTRY OF TRANSPORT AND TELECOMMUNICATIONS

SUB-SECRETARIAT OF TELECOMMUNICATIONS

MODIFIES PERMIT FOR LIMITED <u>TELECOMMUNICATIONS SERVICE</u>

EXEMPT RESOLUTION Nº **1055**

Santiago 17 AUG 2004

On this date the following has been resolved:

CONSIDERING :

a) Decree Law Nº 1.762 of 1977,

b) Law Nº 18.168 of 1982, the General Telecommunications Law,

c) The Technical Framework relating to Limited Telecommunications Services, Exempt Resolution Nº 391 of 1985 modified by Exempt Resolution Nº 524 of 1989 and Exempt Resolution Nº 563 of 2003, all of the Sub-secretariat of Telecommunications,

d) Resolution Nº 520 of 1996 that established the rearranged, coordinated and systemized text of Resolution Nº 55 of 1992, both of the General Comptroller of the Republic,

e) Exempt Resolution Nº 1 of 1999 of the Sub-secretariat of Telecommunications that authorizes Heads of Divisions and Departments to sign "By order of the Sub-Secretary of

Telecommunications" and delegates the powers mentioned therein.

WHEREAS :

What was requested by the petitioner with SUBTEL ingress Nº 42111 of 10.06.2004. (SL-383/2004).

I HEREBY RESOLVE :

1.- To modify the Limited Telecommunications Service Permit granted to ASSOCIATED UNIVERSITIES INC (AUI), Tax Nº 69.507.700-9 domiciled at Camino El Observatorio Nº 1515 in the Municipality of Las Condes, Metropolitan Region, granted by means of Resolution Nº 1096 of 08.09.2003 of the Sub-secretariat of Telecommunications.

2.- The period of this modification expires on the same date as the one mentioned in the Resolution that granted the permit mentioned in Nº 1.

3.- The deadline for commencing the works will be (2) two months and for completing them it will be (5) five months. Likewise, the deadline for beginning the service will be (6) six months. All of these deadlines will come into force as of the date this Resolution has been totally dealt with.

4.- The technical characteristics and the location of the facilities of the system granted, including this modification, are as follows :

4.1. It is possible to accept what was requested, so use of the frequency bands is authorized with the technical characteristics that are mentioned hereafter:

Receiving frequency bands of the radio telescope:

31,3 – 45 GHz
67 – 90 GHz
84 – 116 GHz
125 – 163 GHz
163 – 211 GHz
211 – 275 GHz
275 – 370 GHz
385 – 500 GHz
602 – 720 GHz
787 – 950 GHz

The radio telescope may operate within all of the frequency bands mentioned; however, protection cannot be guaranteed in the frequency bands, or part of them, that are not allocated to radio astronomy on a primary basis.

Type of station	:	Radio astronomy station, an array of receiving only antennas.
Location	:	Chajnantor Plain, Municipality of San Pedro de Atacama, 2nd Region. Area centered on 23º 01' S by 67º 45' W.
Number of antennas	:	64 Cassegrain type parabolic antennas
Diameter of antennas	:	12 m.

4.2. For the purpose of protecting the radio telescope's reception, the following zones have been defined:

a) Protection Zone centered on 23º 01' S by 67º 45' W and with a radius of 30 km within national territory, inside which the installation of any other radio communications system will not be authorized to any third parties operating on the receiving frequency bands mentioned in point 4.1.

b) Coordination Zone; coordination being understood as the process whereby the opinion of the petitioners, ESO and AUI will be sought regarding certain requests by third parties that this Sub-secretariat deems could interfere or affect the operation of the radio telescope. Likewise, in case such petitioners detect any emissions that affect the operation of the radio telescope, they will notify this Sub-secretariat for its coordination. The deadlines involved for each coordination process will depend on each case.
The coordination zone will be centered at 23º 01' S by 67º 45' W with a radius of 120 km inside national territory. Within this zone, any emissions by other petitioners or licensees will be limited, bearing in mind the following cases:

- Any emissions from each equipment authorized to third parties and which transmit on frequencies lower than those of the radio telescope's reception (<31.3 GHz), will limit their equivalent isotropic radiated power (EIRP) in accordance with the values included in Table 1, as a function of the distance measured from the emission source to the edge of the area of the observatory, which is equivalent to a power flow density of less than 2×10^{-6} W/m^2 within the observatory area. The area of the observatory will be understood as a circle of 20 km radius whose center coincides with the coordination zone.

  Furthermore, such equipment shall limit any out-of-band and non-essential emissions within the range of receiving frequencies authorized for the radio telescope, for which the protection criteria established in recommendation ITU-R RA.769-1, or any other that replaces or complements it, will apply.

Distance d (km)	EIRP (kW)
10	2,5
20	10,0
30	22,5
40	40,0
50	62,5
60	90,0
70	122,5
80	160,0
90	202,5
100	250,0

Table1 EIRP maximum acceptable as a function of distance

- At frequencies higher than 31.3 GHz, any equipment authorized to third parties shall limit their in-band, out-of-band and non-essential emissions, so as not to produce any harmful interference in the reception frequencies authorized for the radio telescope, for which the protection criteria established in recommendation ITU-R.RA.769-1, or any other that replaces or complements it, will apply.

4.3 It is worth mentioning that it is not possible to guarantee protection against interferences generated by the following types of services or systems that operate on bands not allocated to radio astronomy:

- Those performing space radio communications.
- Those performing terrestrial radio communications with installations authorized outside the protection zone and using mobile stations.
- Systems using high altitude platform stations (HAPS).

5.- The petitioner shall provide whatever information is necessary for undertaking the procedure of international coordination of frequencies with ITU. It is worth mentioning that such procedure will only allow the coordination of those frequencies included in the bands allocated to the radio astronomy service on a primary basis.

6.- The petitioner may not initiate services unless the works and installations required by the approved modification have been previously authorized by the Sub-secretariat. For this purpose he shall request by registered letter that it be checked that the works and installations have been properly executed and that they correspond to the project approved.

7.- The petitioner is under the obligation to be aware of and comply with the provisions of the General Telecommunications Law, its Regulations and its amendments, in what they are applicable to him.

BE IT NOTED, NOTIFIED AND COMMUNICATED.
BY ORDER OF THE SUB-SECRETARY OF TELECOMMUNICATIONS

(signature and seal)

VICTOR GARAY SILVA
HEAD OF CONCESSIONS DIVISION

NATIONAL SCIENCE FOUNDATION
Electromagnetic Spectrum Management Unit
4201 Wilson Boulevard, Suite 1045 Arlington, Virginia 22230