NASA
IN-89-CR
162010
63P.

JPL Publication 88-? Rev. 1

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The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

ABSTRACT

The National Aeronautics and Space Administration (NASA) Deep Space Network operates and maintains the Earth-based two-way communications link for unmanned spacecraft exploring the solar system. It is NASA's policy to also make the Network's facilities available for radio astronomy research. Three percent of Network time is currently reserved for radio astronomy observations.

The Network's microwave communication systems and facilities are being continually upgraded. This revised document, first published in 1982, describes the Network's current radio astronomy capabilities and future capabilities that will be made available by the ongoing Network upgrade.

The Bibliography, which includes published papers and articles resulting from radio astronomy observations conducted with Network facilities, has been updated to include papers to May 1987.

PREFACE

The National Aeronautics and Space Administration develops, operates, and maintains extensive ground-based radio communications facilities around the world. Known as the Deep Space Network, these facilities provide and operate the two-way communications links between the Earth and unmanned spacecraft exploring the solar system. To maintain and enhance the scientific value of current and future deep space missions, the Network is continually upgraded to incorporate the state of the art in microwave technology.

In addition to providing radio navigation data, radio science data, and two-way spacecraft communications, the Network's facilities are made available for radio astronomy research. Currently, up to 3 percent of Network time is made available for radio astronomy observations, which are conducted on a noninterference basis with scheduled spacecraft view periods.

The experiments that are approved for these facilities are those that exploit the unique high sensitivities and the geographic locations of the telescopes. A "Friend of the Telescope," who in each case is a practicing radio astronomer intimately familiar with the instrumentation and its capabilities, is available at each of the three Network complexes.

This document was originally published in 1982. It has been updated to reflect the current capabilities of the Network telescopes, to outline the cooperative relationships with other radio observatories, and to describe future capabilities for radio astronomy experiments that will be made possible by the ongoing Network upgrade. Also included are a history of Network radio astronomy experiments accomplished over the last 20 years and a chronology of experiments conducted from May 1967 to May 1987.

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JPL Telecommunications
and Data Acquisition
Science Office

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I. INTRODUCTION

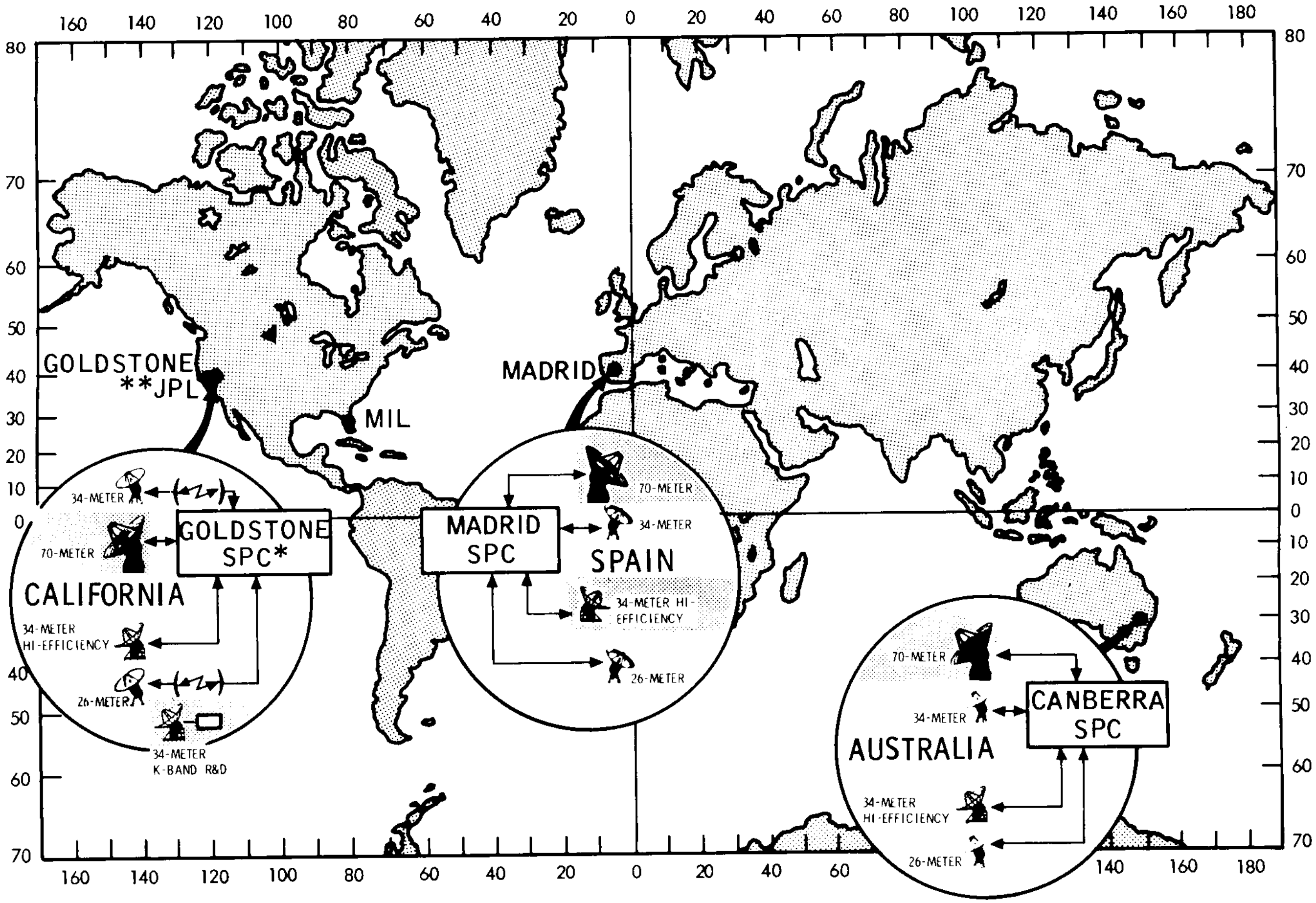
The NASA Deep Space Network is the largest and most sensitive scientific telecommunications and radio navigation network in the world. It is managed, technically directed, and operated for NASA by the Jet Propulsion Laboratory (JPL) of the California Institute of Technology (Caltech) in Pasadena, California. The Network (Figure 1) consists of three Deep Space Communications Complexes located on three continents: at Goldstone in Southern California's Mojave Desert; near Madrid, Spain; and near Canberra, Australia. The Network Operations Control Center, which controls and monitors operations at the three complexes, is located at JPL in Pasadena. The Ground Communications Facility provides the communications circuits that link together the complexes, the Control Center, and the remote mission operations centers.

From its inception in 1958, the principal responsibility of the Network has been to design and operate the two-way communications link between the Earth and unmanned lunar, planetary, and interplanetary spacecraft missions. The Network is also responsible for maintaining and upgrading its facilities to accommodate all of its users. This includes not only the implementation of enhancements to improve the scientific return from current spacecraft missions but also long-range research and development to meet the navigation and telemetry requirements of future missions.

This ongoing technological evolution has resulted in advanced radio-frequency instrumentation that can also be effectively utilized as a unique, Earth-based scientific instrument for certain kinds of astronomical research. The Network's ultrasensitive high-gain, low-noise transmitting and receiving systems, diverse polarization capabilities, precision frequency and time standards, versatile recording instrumentation, and very long baselines between antenna stations (Figure 1) have attracted international attention from scientists in the fields of radio and radar astronomy as well as from experimenters in the fields of celestial mechanics, relativity, gravitation, and Earth physics.

The Network's facilities are available to any qualified scientist on a noninterference basis with spacecraft mission support. The Network encourages the utilization of its facilities for those radio astronomy observations that exploit its unique elements and capabilities. These include highly sensitive receivers in certain frequency bands and advantageous locations for viewing specific objects or obtaining particular baselines for very long baseline interferometry experiments.

To the extent consistent with meeting its other commitments, the Network provides the fullest possible support to ensure a successful venture for the experimenter and the Network. A Friend of the Telescope, who is a radio astronomer, is available at each complex to assist guest investigators with technical advice and support. At JPL, a radio astronomy support staff is available to assist with proposal handling, scheduling, and experiment support. The agreements with Spain and Australia, authorizing the establishment of Network complexes within those countries, also provide for their use by host-country scientists. Host-country experiments conducted at the Canberra and Madrid complexes are accepted and scheduled through the complex director's office. Approximately 250 hours per year will be made available to each host country if requested from NASA.



SHADING INDICATES CHANGES FROM 1985

*SPC: SIGNAL PROCESSING CENTER

** JPL INCLUDES THE NETWORK OPERATIONS CONTROL CENTER, THE CENTRAL COMMUNICATIONS TERMINAL, A COMPATIBILITY TEST AREA, A MOBILE COMPATIBILITY TEST FACILITY, AND OFFICES AND LABORATORIES OF THE DEEP SPACE NETWORK

Figure 1. The Deep Space Network

A scientist in the United States may obtain the use of Network facilities by submitting a written proposal to JPL for evaluation by the Radio Astronomy Experiment Selection Panel, which is composed of distinguished radio astronomers. The panel will evaluate the scientific merit of the proposal and determine the suitability of the Network to meet the experiment's performance requirements. There is no charge to the scientist for the use of Network facilities. It is assumed that the investigator is funded by non-NASA sources for data reduction and scientific interpretation.

The inventory of Network telescopes is listed in Table 1. The Australian complex is located 40 kilometers (25 miles) south of Canberra near the Tidbinbilla Nature Reserve. The Spanish complex is located 60 kilometers (37 miles) west of Madrid at Robledo de Chavela. The Goldstone complex is located in Southern California's Mojave Desert on the United States Army's Fort Irwin Military Reservation approximately 72 kilometers (45 miles) north of Barstow. The complexes are situated in semimountainous, bowl-shaped terrain to aid electromagnetic isolation.

Table 1. Deep Space Station Inventory

		Antenna	
Location	Deep Space Station number (name)	Diameter in meters (feet)	Mount
Goldstone, California	12 (Echo)	34 (111)	Equatorial
	13 (Venus)*	26 (85)	Azimuth-elevation
	14 (Mars)	70 (230)	Azimuth-elevation
	15 (Uranus)+	34 (111)	Azimuth-elevation
	16 (Apollo)**	26 (85)	X-Y
Canberra, Australia (Tidbinbilla)	42	34 (111)	Equatorial
	43	70 (230)	Azimuth-elevation
	45+	34 (111)	Azimuth-elevation
	46**	26 (85)	X-Y
Madrid, Spain (Robledo de Chavela)	61	34 (111)	Equatorial
	63	70 (230)	Azimuth-elevation
	65+	34 (111)	Azimuth-elevation
	66**	26 (85)	X-Y

*Deep Space Network research-and-development station
**Earth orbiter subnet
+High-efficiency antenna

All deep space stations are fully steerable parabolic reflectors with Cassegrainian optics and are usually equipped for simultaneous reception at 2.3 and 8.5 gigahertz, which are the current United States deep space frequency bands. More detailed technical information is provided in Section III.

The 34- and 70-meter-diameter antenna stations are remotely operated from the complex signal processing center, which houses the various subsystems that point and control the antennas, transmit commands, and receive, process, and record spacecraft data. The 26-meter-diameter X-Y mount stations, which primarily support Earth-orbiting satellites, have not yet been equipped for remote operation.

As part of the ongoing Network upgrade program, the 70-meter-diameter antenna stations at Canberra and Madrid (Figure 2), which were originally 64 meters in diameter, have recently been extended to their new dimension. The 70-meter extension of the Goldstone 64-meter antenna (Figure 3) is scheduled for completion in June 1988.

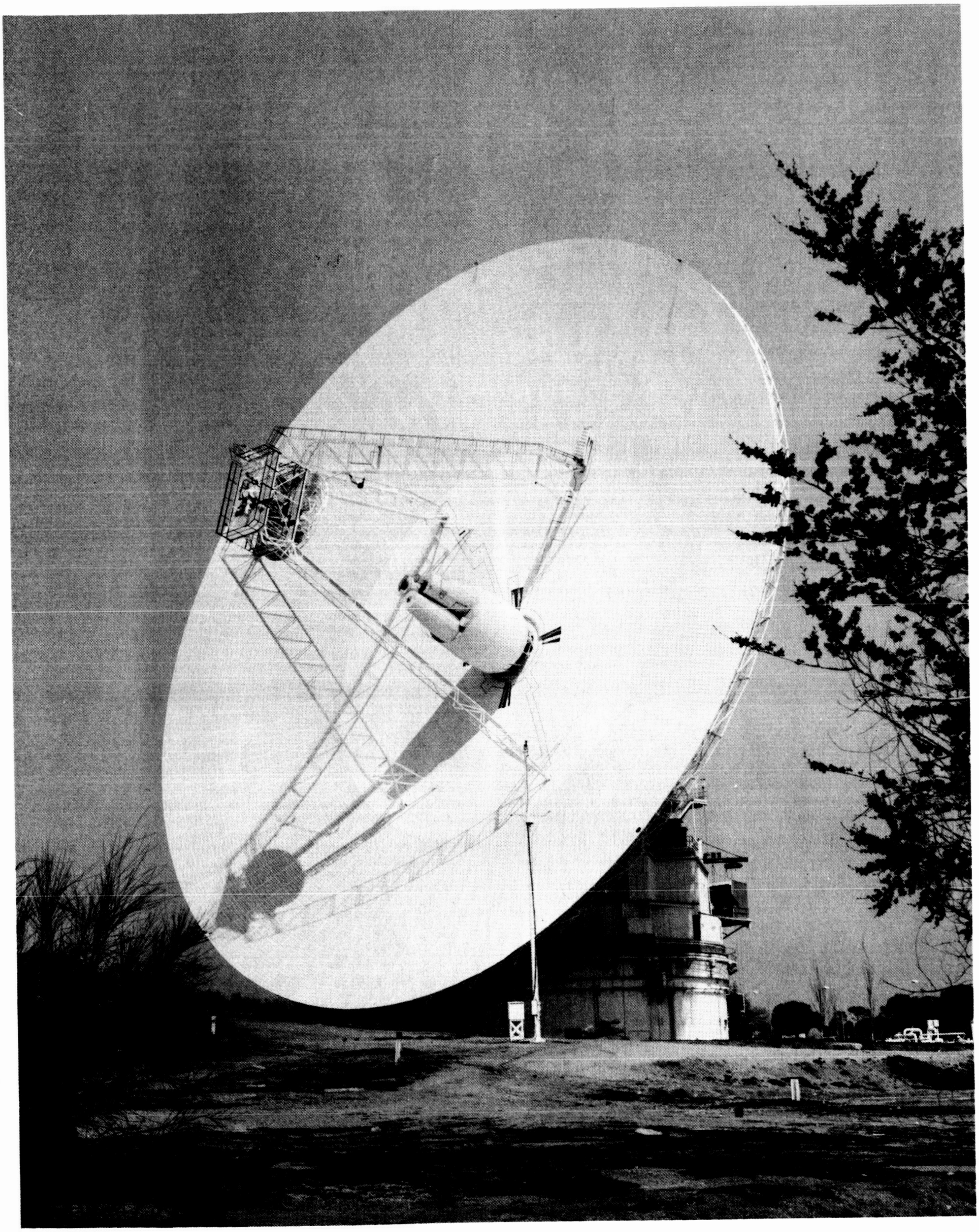


Figure 2. The 70-meter-Diameter Antenna at the Madrid Complex, Spain (1987)

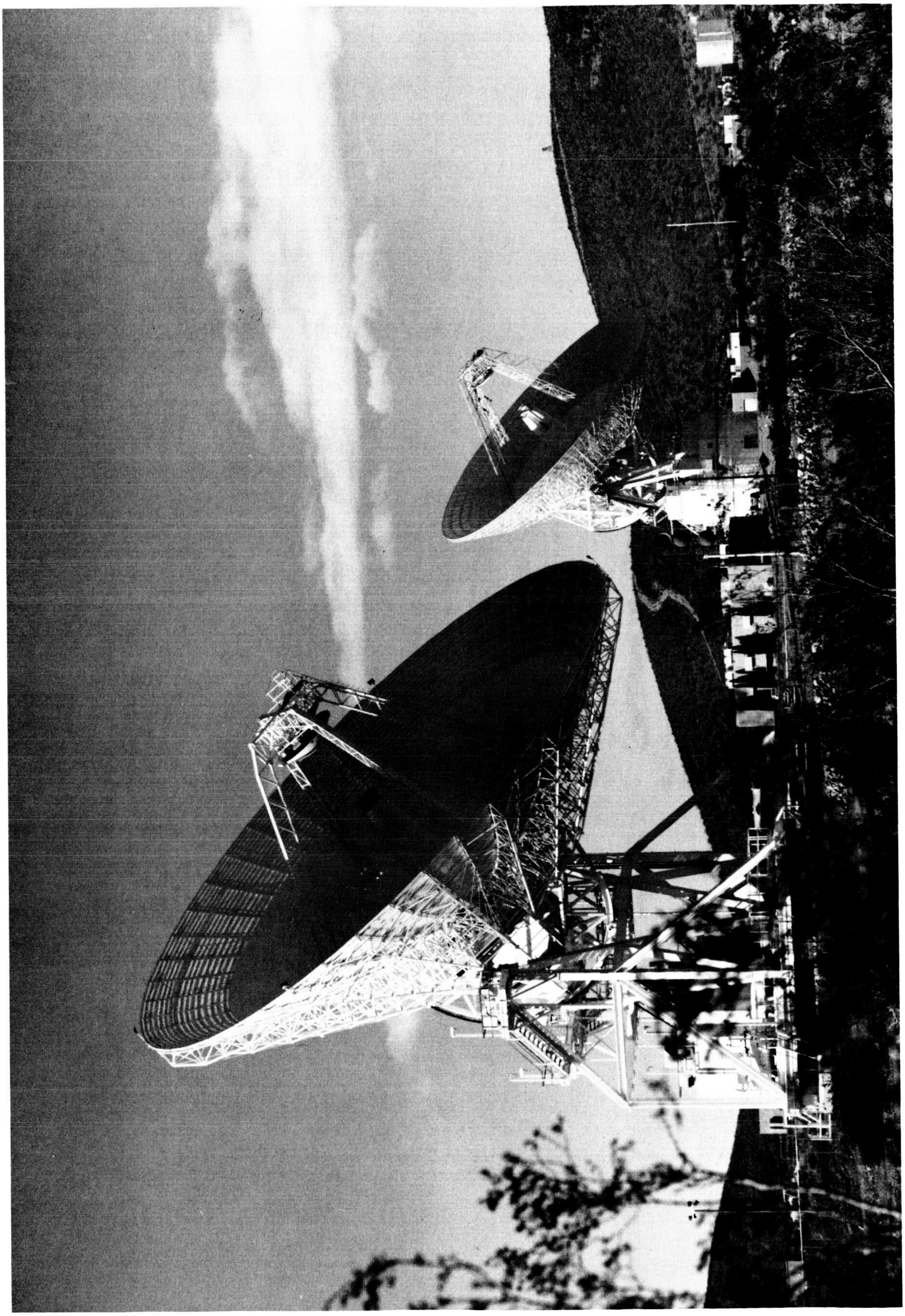


Figure 3. The 34-meter-Diameter (Front) and 64-meter-Diameter Antennas at Goldstone, California (1987)

II. EXPERIMENT HISTORY

Over the last 20 years, radio astronomers have used the unique capabilities of the Deep Space Network to conduct experiments that range from pulsar timing observations to outer-planet radio emission variations, and from interstellar scintillation experiments to very long baseline interferometry surveys of the structure of compact radio sources. At the same time, radio astronomy has had a valuable synergistic effect on the Network. Astronomical studies of natural radio sources, the effects of the media, and the propagation environment have made direct contributions to the technical development and operational performance of the two-way deep space communications link.

Notable radio astronomy achievements accomplished with the Network's facilities include (1) the first detection of the broadband emissions from pulsars at 2295 megahertz; (2) variation in the radio emission from Uranus, indicating a difference in the atmospheric opacity and temperature from pole to equator (i.e., prediction of the Uranus polar "hole" well before the Voyager Uranus encounter); (3) the slowing of the spin rate of pulsars and the propensity of some pulsars to exhibit occasional "jumps" that speed up the spin rate temporarily; (4) variation in the synchrotron emission from Jupiter; (5) first detection and high-angular-resolution mapping of 2-centimeter formaldehyde emission; (6) the detection of recombination lines of sulfur; (7) precise position determination of southern-sky quasars, leading to their optical identification, and to the discovery of one of the most distant quasars; (8) high-angular-resolution observations of ammonia sources in the southern sky; and (9) interferometric observations using an Earth-orbiting antenna in conjunction with a Network radio telescope in Australia and the Usuda radio telescope in Japan. Many non-NASA observatories have collaborated in successful multiaperture observations over the years, and many lasting relationships have been established.

1. The Early Years

The Network's first 64-meter-diameter antenna (Figure 3) was completed at Goldstone in 1966. The antenna provided 6-1/2 times the receiving sensitivity of the Network's original 26-meter antennas and extended the range of the Network 2-1/2 times. Recognizing that these performance characteristics also provided the best instrument available for radio astronomy at that time, NASA approved the allocation of some of the available antenna time for radio astronomy research. Notice of the availability of this new facility was issued to the radio astronomy community, which quickly responded.

Early in 1967, radio astronomers in England reported the first observations of pulsating radiation from natural sources. By April-May 1967, A. T. Moffet and R. D. Ekers of Caltech had detected pulsars at 2295 megahertz using the 64-meter antenna station at Goldstone. In 1968, R. M. Goldstein of JPL detected pulsars at approximately 80 megahertz, initiating a two-year investigation into the feasibility of using pulsars as timing references for station clock synchronization. A program of constant surveillance of a number of pulsars was carried out using the Venus 26-meter antenna at Goldstone. The data from these observations revealed that pulse rates were steadily decreasing with time, and that several pulsars were undergoing abrupt changes in decay rates. These discoveries readily eliminated pulsars as timing references but generated much interest in the pulsar phenomenon within the radio astronomy community. (Recent investigations of millisecond pulsars appear to have reopened interest in the use of these objects as timing references.)

These first pulsar observations were followed by an ongoing study of pulse characteristics by G. S. Downs of JPL that lasted until 1983, representing one of the longest radio astronomy experiments in the Network. Pulsars represent the neutron star stage in stellar evolution, making them unique objects for studying dense states of matter. Their pulse periods and space velocities are important parameters for determining the star's redundant spin rate and its origin. Observationally, the Network is well suited to the patrol-like nature of pulsar investigations, as evidenced by the longevity of the pulsar program and by the volume of data it has acquired, which includes the longest continuous record of pulse periods ever assembled.

Beginning in July 1967, A. Maxwell of Harvard University conducted measurements of the intensity variation of several galactic radio sources during lunar entrance and exit occultation. The data were later processed to determine the size, brightness, and fine structure of these sources.

A 9-meter antenna at Goldstone (now out of service) was used over a 4-year period as an 18- to 24-gigahertz planetary radiometer for the study of the absorptive and emissive properties of Venus.

In September 1967, the Network was approached by D. S. Robertson of the Australian Department of Supply, Space Research Group, who proposed long-baseline interferometry measurements of a number of galactic radio sources using the baseline between the Goldstone and Canberra deep space stations. A baseline of this dimension has a resolving power of about 2×10^{-3} arc-seconds. A. T. Moffet of Caltech joined Robertson as a coexperimenter. Observations were made in September 1967, November 1967, and May 1968 and several times thereafter.

Beginning in October 1967, R. D. Ekers of Caltech conducted several measurements at Goldstone of scintillation effects on known noise sources caused by passage through the solar corona. These observations made it possible to infer a measure of the solar wind structure in the region through which the radio waves passed.

Signals from Quasar 3C273 have been used by the Network to measure the time difference between two deep space stations at Goldstone to about 30 nanoseconds. The received noise-like signals were correlated, allowing for the time-of-arrival difference between stations. The additional time difference measured was the difference between the two station clocks.

By 1969, the volume of radio astronomy requests required the establishment of the Radio Astronomy Experiment Selection Panel at JPL to evaluate and select the most appropriate and worthy non-NASA proposals to compete for the available station time. Members of the Selection Panel were drawn from distinguished astronomers nationwide. A Radio Astronomy Support Group was also formed at JPL, and the establishment of these organizations was announced in December 1969 in technical journals throughout Europe, Africa, Asia, Australia, and North and South America.

The year 1969 was also a banner year on the technical front. The number of regularly observed pulsars doubled by the end of the year, and the first jump in the pulse period of the Vela pulsar was observed. Very long baseline interferometry experiments, which had already been carried out at the National Radio Astronomy Observatory and at the Massachusetts Institute of Technology, were initiated. S. Gulkis and B. Gary of JPL conducted linear and then circular polarization measurements of Jupiter. An apparent discrepancy in the flux stimulated a study, using the Goldstone Venus station, that revealed long-term variations in the synchrotron radio emissions (1971). Following this, a Jupiter monitoring program was started at the Venus station and was then expanded in 1977 to include Madrid, with occasional support provided by the Goldstone 64-meter antenna throughout the 1970s. The high precision of the 64-meter antenna polarization and flux data led to an improved refinement in the Jovian rotation period. Additional linear polarization observations were made, and the results were combined with data obtained with the Australian 64-meter antenna at Parkes and with Caltech data to produce a 16-year history of the time variability in the polarization properties of the synchrotron emission.

2. Deep Space Network Radio Astronomy Formally Established

In 1971, NASA issued formal management instructions setting forth the policy and responsibilities for "Ground-Based Radio Science" and establishing a NASA Ground-Based Radio Science Panel to provide assistance and advice to the Associate Administrator for Space Science and the Associate Administrator for Tracking and Data Acquisition on matters pertaining to ground-based radio science. Currently, these are the Office of Space Science and Applications and the Office of Space Operations. This panel was disbanded in 1973, although programs are still carried out under the sponsorship of these two NASA offices.

During 1970-1971, the brightness temperature of Jupiter was measured at 13 discrete frequencies between 20 and 24 gigahertz. At frequencies near the strongest ammonia absorption, the spectrum supports a model atmosphere in which ammonia is saturated but not supersaturated, as had been indicated by some earlier microwave observations. Recent data from the Voyager 1 and 2 spacecraft have confirmed these results.

Microwave brightness temperature calculations were also made for a number of model atmospheres for Saturn. The best agreement with the observed spectrum was found to be models with solar composition of ammonia. Ground-based studies of Uranus and Neptune show ammonia-depletion-related variations. These variations suggest a potentially rich area of investigation.

By 1972, the number and variety of radio frequency experiments had led to the adoption of the following definitions to prevent confusion: <u>radio science</u> refers to the acquisition and extraction of information from spacecraft-originated signals that have been affected by celestial bodies or have interacted with the propagation media; <u>radio astronomy</u> refers to the acquisition and extraction of information from signals emitted or reflected by natural (non-spacecraft) sources. This convention separates current radio-frequency experiments but does not unravel early Network experiment references, all of which carry the term <u>radio science</u>.

High-resolution interferometric experiments with 3C273 and 3C279 resulted in the unique discovery that both objects exhibit superluminal components. By 1981, six such objects, displaying apparent component velocities from 3 to 10 times the speed of light, had been identified. Also at this time, interferometry was used extensively to (1) look at characteristics of variable quasars (Robertson and Moffet); (2) observe many sources for flux measurements (Cohen); and (3) study extragalactic radio sources at 3 centimeters with high resolution. This last experiment involved implementing an interferometric net with the Goldstone 64-meter station, the National Radio Astronomy Observatory's 43-meter antenna, and the Center for Astrophysics Observatory's 22-meter antenna, and was the Network's first close cooperative association with experimenters from the National Radio Astronomy Observatory, Cornell, Caltech, the Crimean Astrophysical Observatory (Soviet Union), and the Institute for Cosmic Research (Soviet Union).

Cygnus X-3, a violent radio variable, was observed from the Goldstone 64-meter station at wavelengths of 13.1, 3.55, and 2.07 centimeters to determine its instantaneous spectrum during an outburst. The resulting map of the region (0.5 x 0.6 arc-degrees; 8.15 arc-minute resolution) revealed several nearby partially resolved confusion sources. A search was also made of several objects to observe variability of radiation over periods less than one day. Unique to this particular search were simultaneous observations of 3C120, BL LAC, and OJ287 in radio, optical, and infrared wavelengths.

Early in the 1970s, a 15-gigahertz maser was installed at the Goldstone 64-meter station in anticipation that this frequency would be the next allocation for deep space communications. Initial pulsar observations at 15.1 gigahertz were conducted in 1973, along with simultaneous 2.3- and 8.4-gigahertz observations. The latter frequencies proved not to be as accurate for dispersion. A jump in the Vela pulsar period was recorded for the third time in 1975 and again in 1976. The period remained quite regular until the fifth jump was observed in 1981.

The 15-gigahertz maser also made possible high-angular-resolution observations of the 2_{11} - 2_{12} k-doublet of interstellar formaldehyde. N. J. Evans conducted observations with the Goldstone 64-meter antenna that provided an understanding of the excitation mechanisms for formaldehyde and, in 1973, resulted in his doctoral thesis.

During 1974 and 1975, the Goldstone 64-meter station was used for a series of observations of the Orion nebula to map the distribution of ionized carbon (15.3 gigahertz) with angular resolutions not achievable elsewhere. The presumption was that the emission arises from a thin layer of dense, cold, and predominantly neutral gas surrounding the HII region, thus providing a mappable boundary.

The mid-1970s also saw Network support for ongoing work in planetary radio astronomy. Model atmosphere calculations of Venus, Jupiter, and Saturn were compared with then-recent microwave data. Brightness temperatures, weak emissions, narrow spectral lines, flux, and polarization were all areas of investigation. Precision measurements of relative flux densities of selected radio sources were also made.

During 1977, M. J. Klein and S. Gulkis of JPL and J. A. Turegano of the University of Zaragoza, Spain, began an 18-month program of measuring calibration sources at 8420 megahertz to improve the precision of microwave data for planetary studies. The program resulted in the publication of a precision calibration source list for radio astronomy use. Also during this observation program, measurements of Uranus revealed fluctuations indicative of temperature changes consistent with the problem of ammonia distribution.

3. The Quasar Patrol

The Quasar Patrol was formally so christened in June 1972, after having been in progress since October 1970. It originally involved only the Goldstone 64-meter station as an interferometric element in an extensive interferometry network accumulating data on the structure of--and, in some cases, the structural changes in--radio sources with small angular diameters. In some instances, these regular observations enabled experiments that captured dramatic structural changes on a time scale of a few weeks or less. Initial attempts to explain some of the observed structural changes necessitated revisions in theories concerning energy-release mechanisms and the dynamics of these objects. The results involved a complex scheme of moving components, each of which may have a time-variable intensity and size as a consequence of the expansion or acceleration of relativistic electrons. Several other observations revealed small-scale structure of a partially resolved halo surrounding an unresolved core (the so-called onion-skin model for 3C454.3 and the M87 nucleus). With each increase in resolution, a smaller unresolved core has been revealed.

By mid-1975, the goals of the Quasar Patrol had been solidified into three succinct areas: (1) the study of the structure, kinematics, and (insofar as is possible) polarization of compact, continuum extragalactic radio sources; (2) the determination of the relative positions of these sources and their proper motions; and (3) the estimations of station locations, Earth's rotational variations and polar motion, precession and nutation constants, and the appropriate tidal Love numbers. Results from these experiments were the first to utilize closure phase to develop improved structure models of several of the sources. Another technique was to cycle 5-minute scan observations of two sources and then connect the fringe phase for each source unambiguously over each of four observation periods spanning nearly 3 years. The differences in the fringe phases for the individual sources are virtually freed from the effects of clock errors and propagation-medium variations, thereby allowing the relative positions to be determined with a high degree of accuracy. Many of these techniques are also invaluable for ongoing interferometry experiments. The Network's clock synchronization interferometry is fast emerging as an international standard for frequency and timing, as well as for universal time and polar-motion data. Delta-differenced one-way ranging, an interferometric observation technique originally developed for Voyager spacecraft navigation, has also come to the forefront in navigation data types, and now augments traditional Doppler navigation.

By 1979, the Network had become a central participant in some of the most exciting discoveries of modern astronomy. The Quasar Patrol continued to investigate compact extragalactic radio sources into 1980. A sample of known superrelativistic expanding sources was observed in order to monitor their evolution, and new candidates for this class of sources were observed with the intention of witnessing an early stage in their development. Polarization-sensitive measurements of extended structure in extragalactic radio sources proved so useful in determining the emission mechanism and magnetic-field structure in these sources that these types of measurements were applied to compact sources.

The observing programs carried out in 1980 and 1981 also included SS433, the cosmic "lawn sprinkler," and 0957+561 A and B, the twin quasi-stellar objects exhibiting properties similar to those of a gravitational lens caused by an intervening cluster of galaxies. By 1982, reduction of the twin object data had revealed that the long-sought central image in the lens may have been found, possibly supporting the mass distribution model for the cluster of galaxies. These two programs alone point out the Network's role at the exotic leading edge of astronomical investigations.

4. The Tidbinbilla Two-Element Interferometer

The Tidbinbilla interferometer is the only instrument in the southern hemisphere capable of carrying out rapid radio source astrometry with second-of-arc accuracy. The sensitivity of the instrument allows the measurement of radio source flux densities to the millijansky level. Observations of quasars, radio stars, and X-ray stars all require this level of sensitivity.

The interferometer was proposed in 1972 by S. Gulkis of JPL, in association with D. L. Jauncey and M. J. Yerbury, then of Cornell University. The proposal was to implement a high-sensitivity, phase-stable, real-time interferometer using existing Network antennas, preferably at Tidbinbilla in Australia. The science objective was to measure weak radio source positions with an accuracy of a few arc-seconds for unambiguous identification with cataloged infrared and optical objects. The Parkes 2.7 gigahertz surveys of the southern hemisphere conducted during the late 1960s and throughout the 1970s covered the whole sky accessible to the Parkes 64-meter telescope. The Parkes catalog lists over 12,000 radio sources with positional accuracies given to about 15 arc-seconds, which is sufficient for only a limited number of optical identifications. The Parkes survey also revealed a large number of flat spectrum compact radio sources that had not been detected in earlier low-frequency sky surveys. The first optical identifications, which were accomplished with Palomar sky survey plates, showed that many of the flat spectrum sources coincided with quasars.

The Tidbinbilla antennas (which in 1972 were 26 and 64 meters in diameter and are now 34 and 70 meters in diameter) are separated by 195 meters on a north-south baseline. The baseline, and the availability of low-noise maser amplifiers and a common operating frequency at 2.3 gigahertz, offered a unique opportunity to implement at minimal cost a high-sensitivity interferometer with a positional capability of approximately 2 arc-seconds.

The interferometer was constructed and tested between 1977 and 1979. Astronomical observations began in 1980. The system was upgraded to operate simultaneously at 2.3 and 8.4 gigahertz in 1986.

To date, some 1500 radio sources listed in the Parkes 2.7 gigahertz catalog have been measured, and over 500 optical identifications have been made. Compact radio sources have been measured with an rms position error of less than 2 arc seconds at both 2.3 and 8.4 gigahertz. Optical identifications are being made on the basis of radio-optical positional coincidence alone, without recourse to optical color or morphology. Positional coincidence identifications have revealed quasars with redshifts over 2 that have no ultraviolet excess, and quasars at the highest redshifts (more than 3) with colors close to those of normal stars. The identification in 1982 of quasar PKS 2000-330 (Jauncey et al., 1982), then the most distant yet discovered ($z = 3.78$), resulted solely from the accuracy of the position measurement made with the Tidbinbilla interferometer.

The Tidbinbilla identifications in the -30 to -45-degree declination zone form a significant part of a complete sample of flat spectrum radio quasars that are actively being investigated (Savage et al., 1986 and Jauncey et al., 1987). The complete sample contains approximately 400 sources in the +10 to -45-degree declination zone that have 2.7 gigahertz flux densities greater than 0.5 jansky. Optical identifications using both the UK Schmidt Telescope Unit and Palomar surveys were completed in 1983. Redshifts have been measured for some 240 of this sample (Jauncey et al., 1984 and White et al., 1987).

A second area of importance is the search for radio emission from optically selected (radio-quiet) quasars. The sensitivity of the Tidbinbilla interferometer will allow searches for radio emissions below the millijansky level. It is expected that the Space Telescope and other all-sky coverage astronomical spacecraft will make use of this program; in particular, the southern quasars and active galaxies identified with the interferometer are expected to form a significant part of the Space Telescope extragalactic object observational program.

A sensitive survey of the brighter southern hemisphere stars that are candidates for radio emission was initiated in 1986 (Batty et al., 1986). The survey is being conducted at 8.4 gigahertz where the chance of confusion with background galactic sources is greatly reduced by the narrowness of the beam. To date, over 100 stars have been observed; of these, radio emissions have been detected from 7 or 8 objects. The known flaring RS CVn star AB Doradus (HD 36705) has been detected on each of three occasions. The accuracy of the radio position measurement has uniquely identified this object with HD 36705 (White et al., 1987).

As well as studying such objects for their intrinsic astrophysics, the radio star survey will be of considerable value in establishing stars for inclusion in the Astrometry Satellite Hipparcos program. The identification of bright stars that are radio sources (and can have milliarc-second radio positions determined by interferometry) will permit the radio and optical position reference frames to be tied together via the Hipparcos position measurements.

5. Host-Country Programs

The growth of multiaperture observations is a measure of the increase in radio astronomy activity at the Network overseas sites. In addition to the Radio Astronomy Experiment Selection Panel activities, each Network facility may support observations conducted by cooperating agencies sponsored by the local government; i.e., the "host country" agreement. A primary host-country activity in Spain is the Instituto Geografico Nacional Interferometric Survey project, which is primarily concerned with interferometric measurements of baseline parameters of the European Geodetic Net. A similar survey of geodetic and geophysical parameters for the Australian continent was performed in early 1982. The primary host-country activity supported in Australia has been pulsar observations conducted for the Commonwealth Scientific and Industrial Research Organization. Since 1975, a program of pulsar observations has been conducted using a 26-meter antenna at the Canberra complex; use of a similar 26-meter antenna at Honeysuckle Creek (now deactivated) began in 1980. The objective of this program was to determine accurate positions and pulsation periods for a set of southern pulsars and to monitor variations in the observed period. The program was inaugurated in time to capture the third and fourth jumps in the Vela pulsar in addition to valuable data on other pulsars. By 1978, pulsar observations were also being carried out in Spain.

6. Organized Network Support

The late 1970s also mark the emergence of an established Deep Space Network technical and administrative organization to support radio astronomy. Even though NASA and JPL managements have consistently recognized the importance of radio astronomy, formally organized Network support was slow in developing until a sharp increase in radio astronomy activity emphasized that a formal support organization was necessary. The position of Network Operations Project Engineer was established as an interface between experimenters and the Network. Similarly, a Network Development and Radio Astronomy Unit was established to provide real-time expertise and support at Goldstone.

1983 saw the remodeling of the Network with updated, centralized computer control of antennas and concomitant systems, which required each facility, in turn, to be taken out of service. Prior to the onset of this upgrade, a concentrated number of astronomical observations took place, coinciding with the discovery of the Iras-Araki-Alcock comet. These observations included continuing research into gravitational lenses and examination of the galactic center.

The monitoring of Uranus and Jupiter, which began in 1972, is continuing through the 1980s. Uranus has been of particular interest to observers who have used the Network for a number of years to investigate its ammonia depletion, unusual atmospheric warming, and polar opacity. The Voyager 2 Uranus encounter data will certainly augment the ground-based data. Jupiter data are still being acquired and combined with the efforts of the international Jupiter watch for ongoing investigations.

7. Very Long Baseline Interferometry Using a Telescope in Earth Orbit

The first use of an Earth-orbiting satellite as part of an interferometric network was successfully accomplished in July and August 1986, when fringes were detected on three sources. The experiment was conducted at 2.3 gigahertz using the 4.9-meter antenna of a geosynchronous NASA Tracking and Data Relay Satellite and its ground station in New Mexico; the Network's 64-meter antenna in Australia; and the 64-meter telescope of the Institute for

Space and Astronautical Science at Usuda, Japan. In January 1987, 23 of 24 extragalactic sources were detected on baselines as long as 2.15 Earth diameters.

The increased resolution from these baseline lengths provided much better sensitivity to high brightness temperatures than has been achieved with Earth-based interferometers, which are limited by the physical dimensions of the Earth. Brightness temperatures one to four times the 10^{12} kelvin inverse Compton limit were measured for 12 sources, suggesting bulk relativistic motion in these sources. Coherence values of approximately 85 percent were obtained for integration times of 360 seconds.

The success of these experiments has positive implications for the future of orbiting interferometry. These observations, using a satellite designed for an entirely different purpose, confirm the results of design studies for dedicated orbiting interferometry spacecraft, which have concluded that no new technology is required. The feasibility of orbiting very long baseline interferometry has been shown by demonstrating that:

(1) A ground-based frequency reference can be accurately transferred to an orbiting interferometric spacecraft.

(2) Radio astronomical signals can be acquired by a spacecraft, coherently amplified, transmitted, and recorded at a ground terminal.

(3) Adequate orbit determination measurements can be made with existing systems and used for data correlation.

(4) An existing interferometry correlator with minor software modifications can process orbiting interferometric data.

8. Other Recent Experiments

The ongoing Jupiter Patrol (since 1971) continues to record variations in the radio emission from the Jovian radiation belts. The set of observations defined a nonperiodic intensity variation of about 30 percent with time scales of months to years. When combined with measurements by other observers, the data set provides a record that extends over 24 years (2 Jovian "years"). The combined data reveal considerable variability that may be directly related to the high-energy electron population of the inner magnetosphere. Preliminary results of a search for plausible relationships between the Jovian synchrotron emission and solar-related phenomena indicate that a positive correlation may exist with one or more solar wind parameters. The ion density is a prime candidate for verification and further study. If this correlation is correct, it will be the first evidence that the solar wind has a major influence on the energetic electronics in Jupiter's radiation belts.

Supernova 1987A, a rare event in its proximity to the Milky Way galaxy as well as in its physical characteristics, is under regular observation at the Australian complex. The initial supernova burst was detectable in the microwave region of the spectrum but quickly faded below that level of detectability. An increase in emissions is anticipated; until then, monitoring continues at 8.4 and 2.2 gigahertz.

The 1986 reappearance of Halley's comet was observed by the Australian complex during the comet's period of closest approach. Although no ammonia was detected, an upper limit on its detectability was established. The Halley radio astronomy observations provided the Network with a great deal of engineering information about the 24-gigahertz aperture efficiency; a considerable quantity of high-quality calibration data was acquired.

The Canberra 64-meter antenna (now 70 meters) has been used to study the structure of, and the physical conditions in, regions of star formation. Observations of ammonia transitions have yielded data on the temperature and density of these regions. The antenna's high angular resolving power revealed structure not discernible with the lower-resolution 22-gigahertz system at Parkes.

Installation of a 1.6-gigahertz receiver to support the Soviet Vega spacecraft balloon mission to Venus and its Pathfinder navigation mission at Halley's comet, coupled with a microwave link between the Canberra complex and Parkes, has permitted interferometric research into the structure of the envelopes of evolved stars and the regions around newly formed stars, using oxygen-hydrogen maser emissions as a probe of these regions.

Recent work also includes a study of sulfuric acid effects in the atmosphere of Venus. In a collaboration with P. Steffes (Georgia Institute of Technology), a coordinated set of measurements were made at Goldstone and the National Radio Astronomy Observatory to study the effect of gaseous sulfuric acid on the microwave opacity of the Venus atmosphere between 8 and 22 gigahertz (3.75- to 1.35-centimeter wavelength).

Over the years, significant benefits have accrued to the Network from radio astronomy users. Radio astronomy experiments have served as a rigorous testing vehicle for both research and development and in-place operational systems. By exercising Network systems and facilities to their performance limits, radio astronomers have provided the technical experience essential to ensuring state-of-the-art operational performance for spacecraft missions. Radio astronomy techniques have been adapted to spacecraft navigation, timing standards, antenna pointing and gain calibrations, and spectral analysis of spacecraft signals.

III. PRESENT CAPABILITY

The Network's ability to support radio astronomy observations is an outgrowth of the following:

(1) The availability of high-sensitivity radio telescopes developed for communication with, and orbit determination of, planetary spacecraft.

(2) Radio astronomy techniques for rapidly measuring the performance of radio telescopes (i.e., rapid boresighting and radiometry).

(3) The emergence of very long baseline interferometry as a spacecraft navigation data type.

(4) The recognition by NASA that the Network is a unique resource for certain kinds of radio astronomy research.

The parameters of the Network's 70- and 34-meter-diameter radio telescopes and the Goldstone 26-meter-diameter antenna are listed in Tables 2, 3, and 4, respectively.

Radio astronomy research with Network facilities is made possible by equipment that has been installed for that purpose or for related purposes by the Network, by engineering or scientific research groups at JPL, or by guest radio astronomy investigators. The available equipment and level of on-site support vary from station to station.

The present capability of the Network to support radio astronomy research can be conveniently divided into two configurations: (1) single-aperture support, which runs the gamut from precision radiometry to microwave spectroscopy; and (2) multiaperture support, in which two or more Network and non-Network antennas can be configured as an interferometer.

The 26-meter Venus antenna at Goldstone (Figure 4) is reserved exclusively for research and development and therefore is exempt from the spacecraft tracking schedule. The station is equipped with 2.3- and 8.4-gigahertz receivers and has generally been more available for radio astronomy. Some of the heavy-element recombination-line experiments carried out in the previous decade used this station as much as 8 hours per week on a continuous basis, or on three consecutive days at greater intervals. There is no percentage restriction on the amount of time the Venus station may be used for radio astronomy.

The following paragraphs are an overview of current capabilities; bear in mind, however, that these are constantly changing as the programmatic needs and funding of these investigations change.

1. Radiometry

All station receivers are equipped with precision power monitor assemblies. The power monitor modulates noise diodes to compute real-time estimates of operating (system) temperature. The controller can be accessed by authorized nodes on the complex local area network or via its maintenance

Table 2. 70-meter-Diameter Antenna Technical Data

Antenna Diameter	70 meters (230 feet)
Antenna Mount	Azimuth-elevation
Sky Coverage	Full azimuth; 6-88 degrees elevation
Maximum Slew Rate	0.2 degree per second
Pointing System	Master equatorial or azimuth-elevation encoders
Pointing Accuracy	Master equatorial: 0.002 degree each axis Azimuth-elevation encoders: 0.006 degree each axis
Optics	Cassegrainian, tricone
Frequency Standard	Redundant hydrogen masers

Band	L	S[1]	X[1]	K
Frequency Range (gigahertz)	1.66-1.675	2.2-2.3	8.4-8.5[2]	18-24
Antenna Gain (decibels, isotropic) (at 45 degrees elevation)	58.8	63.1	74.0	81.2
Antenna Beamwidth (arc-minutes)	10.8	6.5	1.8	0.75
Aperture Efficiency (percent)	60	72	65	50
Sensitivity (kelvin per jansky)	0.84	1.00	0.90	0.70
Feed Polarization[3]	RC	RC, LC, RL	RC, LC	LC
Low-Noise Amplifier	FET[4]	maser	maser	maser
System Temperature (kelvins)	35	18.3	21	55
Intermediate Frequencies (megahertz)	10, 55, 325	55, 325	55, 325	50[5]

[1]Simultaneous S- and X-band capability with two circular polarizations
[2]At Mars station, research-and-development maser: 7.9 to 8.7 gigahertz
[3]RC - right circular, LC - left circular, RL - rotatable linear
[4]Field-effect transistor
[5]Canberra 70-meter station, 150 megahertz

Table 3. 34-meter-Diameter High-Efficiency Antenna Technical Data (Deep Space Stations 15, 45, and 65)

Antenna Diameter	34 meters (111 feet)		
Antenna Mount	Azimuth-elevation		
Sky Coverage	Full azimuth, 6-90 degrees elevation		
Maximum Slew Rate	0.4 degree per second		
Pointing System	Azimuth-elevation shaft encoders		
Pointing Accuracy	0.010 degree (approximately)		
Optics	Cassegrainian		
Frequency Standard	Hydrogen maser		
Band	S	X	X
Frequency Range (gigahertz)	2.2-2.3	8.4-8.5	8.2-8.6
Antenna Gain (decibels, isotropic) (at 45 degrees elevation)	55.8	68.1	68.1
Antenna Beamwidth (arc-minutes)	16.2	4.2	4.2
Aperture Efficiency (percent)	57	72	72
Sensitivity (kelvin per jansky)	0.19	0.24	0.24
Feed Polarization[1]	RC, LC	RC, LC	RC, LC
Low-Noise Amplifier	FET[2]	maser	FET[2]
System Temperature (kelvins)	55	21	60
Intermediate Frequencies (megahertz)	10, 50, 300	10, 50, 300	300

[1]RC - right circular, LC - left circular
[2]Field-effect transistor

port. In rare instances, the station director may authorize a bypass to control the appropriate noise diode assembly with the investigator's own equipment.

Currently, all stations are also equipped with noise-adding radiometers (designated BP 80). These are stand-alone, nonprogrammable controllers that modulate noise diodes, read the output from the appropriate square-law detector, and provide a real-time display of operating (system) temperature.

Table 4. Goldstone Venus 26-meter-Diameter Antenna Technical Data

Antenna Diameter	26 meters (85 feet)	
Antenna Mount	Azimuth-elevation	
Sky Coverage	Full azimuth; 5-88.2 degrees elevation	
Maximum Slew Rate	Azimuth: 0.20 degree per second Elevation: 0.05 degree per second	
Pointing System	Azimuth-elevation shaft encoders	
Pointing Accuracy	0.010 degree (approximately)	
Optics	Cassegrainian	
Frequency Standard	Hydrogen maser	
Band	S	X
Frequency Range (gigahertz)	2.26-2.40	8.2-8.6
Antenna Gain (decibels, isotropic) (at 45 degrees elevation)	53.6	63.5
Antenna Beamwidth (arc-minutes)	22	5.5
Aperture Efficiency (percent)	59	42
Sensitivity (kelvin per jansky)	0.11	0.08
Feed Polarization[1]	RC, LC	RC, LC
Low-Noise Amplifier	HEMT[2]	HEMT[2]
System Temperature (kelvins)	31	33
Intermediate Frequencies (megahertz)	100-500 center frequency = 300	100-500 center frequency = 300

[1]RC - right circular, LC - left circular
[2]HEMT - high-electron-mobility transistor

The metric data assembly can also be configured as a noise-adding radiometer. It is normally used for automated antenna pointing-error determination. Time-tagged system temperature values are stored continuously on disk during a track. Antenna gain analysis software is available to combine these data with antenna pointing-command data to produce tables of boresight and efficiency data. This capability exists at all complexes.

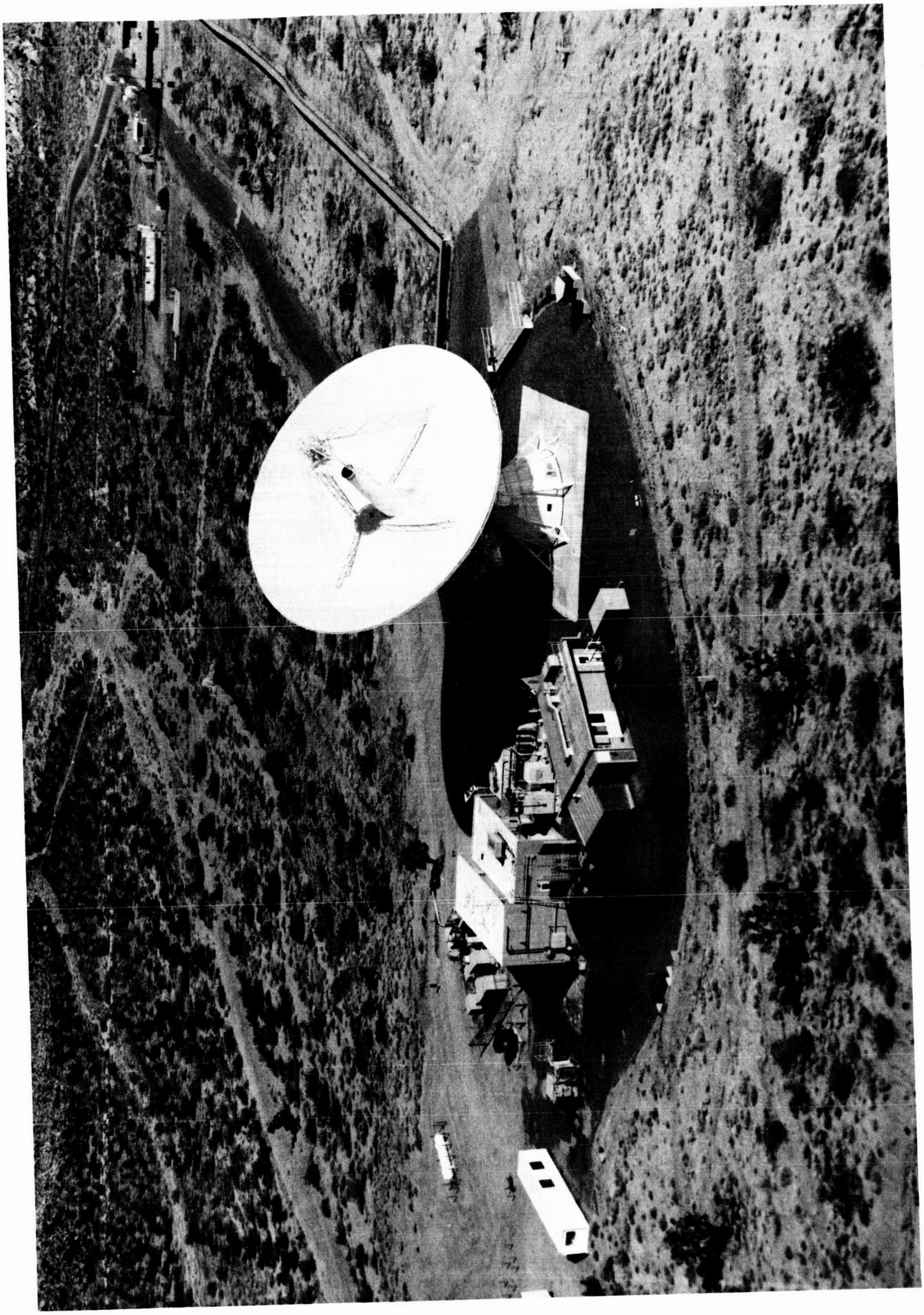


Figure 4. The 26-meter Research-and-Development Antenna Station at Goldstone, California (1987)

The optimum system for a given application depends on the investigator's requirements. Investigators select their configuration, or establish their own, in consultation with the network operations project engineer, the local Friend of the Telescope, or the station staff.

2. Very Long Baseline Interferometry

The complexes are equipped with the Network version of the Mark III data terminal. Although the computers and the integration into the receivers are different from what is in common use in the interferometry community, the data rates and formats are compatible. Any station in a complex (but normally only one at a time) can be used as an interferometric network node. It is possible to provide operations personnel experienced in interferometric procedures, so that an investigator is not normally required on-site for data acquisition.

3. Connected-Element Interferometry

At the Canberra complex, the 70-meter antenna and one of the 34-meter antennas are configured as a connected interferometer capable of phase-stable measurements at 2.3 and 8.4 gigahertz. Delay lines, correlators, and a computer controller are available for interferometric data acquisition.

The Canberra complex is connected via an Australian Telecom microwave link to the Parkes Radiotelescope, forming the Parkes-Tidbinbilla Interferometer. A number of interferometric experiments have already been carried out. It is planned that the link will soon be capable of supporting broadband, phase-stable interferometry. Eventually, Canberra will be an occasional element in the extended Australia Telescope.

The 70-meter and 34-meter stations of the Goldstone complex are being linked by broadband optical fibers to permit telemetry data arraying for future planetary encounters. Phase-stable, connected interferometry will be possible in principle. For example, the high-speed data acquisition subsystem described below will be configurable for cross correlation.

4. Spectroscopy

In the area of spectroscopy, the Network offers extremely high sensitivity in selected frequency bands, as well as the largest and most sensitive antenna in the Southern Hemisphere. Some examples of current projects that exploit these unique capabilities include mapping of southern molecular sources at wavelengths between 1.2 and 1.8 centimeters and measurements of $^{3}He^{+}$ at 8664 megahertz. In general, the Network complements the spectroscopic capabilities of radio observatories because the latter have sensitive receivers selected for radio astronomy bands but rarely in the space communications bands. Thus observations, particularly of complicated large organic molecules with many transitions throughout the microwave spectrum, can benefit from the high sensitivity available at non-radio-astronomy frequencies.

The Goldstone complex has a variety of radio frequency spectrometers. A 65,536-channel, 20-megahertz spectrometer is part of the Radio Frequency Interference Surveillance System normally residing at the 26-meter Venus site. It can be connected by microwave or fiber-optic links to the various Goldstone stations. There is limited real-time data display capability. The JPL Radio Astronomy Group has software on its VAX computer at JPL for processing data acquired with this system.

The high-speed data acquisition subsystem, which is nearing completion at the Goldstone 70-meter station, includes sixteen 256-lag correlators capable of a 10-megahertz clock rate. These will be configurable in various ways, yet to be determined, and depending in part on available funding. Also, because no funding has yet been identified, there are currently no plans to write software dedicated to radio astronomy observations.

The Canberra complex has a 10-megahertz, 256-channel digital spectrometer along with some real-time data processing and display capability. Software for more extended data reduction is available at Mount Stromlo Observatory (c/o John Reynolds), Commonwealth Scientific and Industrial Research Organization Radiophysics (Rick Forster), JPL (Tom Kuiper), and Steward Observatory (Bill Peters). While normally connected to the 70-meter antenna K-band receiver, the spectrometer can be connected with relative ease to any receiver in the complex.

5. Polarimetry

Operational 2.3- and 8.4-gigahertz masers may be configured to amplify simultaneously the two orthogonal outputs from the orthomode feeds. This potential for deriving polarization data has not been utilized in recent years. However, the high-speed data acquisition subsystem described above will be configurable for cross correlation so that the potential exists for making polarimetric measurements.

6. Pulsar Timing

A program for monitoring pulsar timing was discontinued when the program funding was stopped. However, users with appropriate recording equipment have the potential to measure transient events. Interested astronomers may also wish to investigate whether spectral analysis equipment is configurable for their application.

IV. FUTURE CAPABILITIES FOR RADIO ASTRONOMY

Future Network capabilities for radio astronomy depend, to a large extent, on the ongoing upgrade program. Five drivers for Network enhancement, which may result in greater radio astronomy capabilities, are:

(1) The requirement for ever-larger effective aperture area has led to the extension of the 64-meter antennas to 70 meters and to the use of collocated Network antennas in real-time array configurations, along with the arraying of cooperating radio astronomy observatories for critical spacecraft mission events.

(2) The requirement for improved navigation accuracy has resulted in the implementation of interferometry as a Network navigation type and the use of hydrogen masers as frequency standards.

(3) New missions will require the use of the 32-gigahertz deep space communications band. To facilitate the installation of this band and to improve the performance at other bands, beam waveguide feeds will be employed. Beam waveguides will make it less expensive to use other desired radio astronomy frequencies.

(4) The NASA Search for Extraterrestrial Intelligence program will require frequency coverage from 1 to 10 gigahertz, along with other discrete bands at higher frequencies. The Search for Extraterrestrial Intelligence will also employ very advanced spectral analysis equipment with potential for unique radio astronomy applications.

(5) Orbiting interferometry may require the Network to provide direct support for radio astronomical observations. These developments are described in the following paragraphs.

1. Interferometry Arrays

In January 1986, during the Voyager spacecraft encounter with Uranus, the need to achieve high data rates across a communications distance of 3 billion kilometers (1.9 billion miles) led to the cooperative use of the Parkes 64-meter radio telescope in Australia as an element in a real-time array with the Canberra complex. As a result of this successful collaboration, an agreement was reached to utilize the Parkes-Tidbinbilla Interferometer for radio astronomy observations, providing an opportunity for a real-time connected-element interferometer in the Southern Hemisphere. The utility of this interferometer is now being demonstrated by observations of Supernova 1987A.

For the Voyager encounter with Neptune in 1989, the Very Large Array in New Mexico will be arrayed with the Goldstone complex in California. The Parkes-Tidbinbilla Interferometer will again be used for telemetry enhancement, and in addition, the 64-meter facility of the Institute for Space and Astronautical Science at Usuda, Japan, will be used for the acquisition of radio science data. Spacecraft signal combining was designed to maximize the communication signal-to-noise ratio and to eliminate angular information.

The availability of Network interferometric equipment that is compatible with both Mark II and Mark III data terminals makes it possible to use Network antennas with existing interferometry consortia as additional elements for selected observations, or as part of an ad hoc array for a specialized activity. It is anticipated that Network facilities may also be used, as appropriate, with future arrays, such as the Australia Telescope, which will become operational in December 1988, and the Very Long Baseline Array, which will start operations in 1992. The Very Long Baseline Array will consist of 10 dedicated 25-meter radio telescopes located in the United States from Hawaii to the Virgin Islands. The Australia Telescope will consist of the Compact Array, located at Culagoora, with six 22-meter antennas movable over 6 kilometers, and the Long Baseline Array, which will tie in antennas at Sydney Springs and Parkes. The Long Baseline Array also has provision for tying in the Canberra complex by means of the Parkes-Tidbinbilla microwave link. The former NASA antenna from Orroral Valley, now operated by the University of Tasmania near Hobart, will also be a part-time member of the Australia Telescope.

2. Beam Waveguides and Low-Cost Frequency Diversity

The 32-gigahertz band has been allocated for deep space use in the United States, Spain, and Australia. To implement this band, the Network will employ a beam waveguide configuration, which will provide a very good gain/system temperature ratio for all Network communication bands, and at the same time provide the operational convenience and low-cost frequency diversity inherent in this design concept.

Starting in 1988, a new 34-meter-diameter research-and-development antenna will be built to replace the Goldstone 26-meter Venus antenna, which has been in operation since 1962. Initial radio frequency testing is scheduled for 1990. The new antenna will be equipped with a beam waveguide to facilitate the use of various receivers. A 32-gigahertz receiving system will be available in 1991. The new antenna surface panels will be adjusted to achieve 30 percent efficiency at 90 gigahertz, which may be compared to an aperture efficiency of 53 percent measured for the 30-meter telescope in Granada, Spain. Recent holographic measurements of the 34-meter high-efficiency antenna at the Madrid complex indicate that achieving this percentage is a realistic expectation. Even without further panel alignment, the Madrid 34-meter antenna has an efficiency of 52 percent at 32 gigahertz.

3. Enhanced Spectral Analysis

The Network's wideband spectrum analyzer currently under development will have 2 million channels covering 40 megahertz. It will normally reside at the Goldstone Venus site but may be used elsewhere in support of spacecraft or Search for Extraterrestrial Intelligence requirements. The spectrum analyzer will have software suitable for real-time display and analysis of radio astronomy spectra. It will be equipped with a multiuser interface and is scheduled for field testing in late 1989.

The Search for Extraterrestrial Intelligence will cover the spectrum from 1 to 10 gigahertz and at some higher spot bands. This program will use very extensive spectral analysis receiver equipment, which will have sufficient versatility to permit its use for various radio astronomy applications. This equipment will provide 30-hertz resolution for spectral observations over bandwidths as large as 300 megahertz.

4. Improved Resolution, Sensitivity, and Gain

The attractiveness of Network facilities for spectroscopy will increase greatly when all three upgraded 70-meter antennas are operating. Performance predictions indicate that the new antennas will have a sensitivity of 1.4 kelvins per jansky, equal to the Bonn 100-meter telescope at wavelengths of 1 centimeter and below. The 70-meter antenna at the Canberra complex will be the only high-resolution, high-sensitivity, centimeter-wavelength telescope in the Southern Hemisphere for the rest of this century, and probably much longer. The addition of 32-gigahertz masers, optimally designed with wide tunability, will offer further unique opportunities. The 70-meter antennas can also be used to complement existing arrays such as the Very Large Array and the Australia Telescope by providing data for the short spacings that are missing in these arrays (i.e., by removing the "high-pass" spatial filtering inherent in maps made with these arrays).

One promising area of research yet to be exploited is the search for increasingly complex organic molecules, investigating the extent to which interstellar chemistry may lead toward the formation of prebiotic and biotic molecules. Another area opened up by the upgraded 70-meter antennas is the study of molecular clouds in the Magellanic Clouds, a subject of interest stimulated by indications that the chemistry in these nearby galaxies is much less fertile than that in our own.

5. Orbiting Very Long Baseline Interferometry

The Network has successfully participated in a feasibility demonstration of the orbiting interferometry technique using the NASA Tracking and Data Relay Satellite System. There are several orbiting interferometry flight missions being considered; the Network may participate by communicating with and tracking the spacecraft, by serving as part of the ground array, or by participating in both functions.

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APPENDIX A

NETWORK RADIO ASTRONOMY EXPERIMENT CHRONOLOGY

Part 1. 1967–1971

Experiment	Investigator	Telescope	Date
Pulsar measurements (2295 MHz)	A. T. Moffet R. D. Ekers	Mars	Apr. 1967 May 1967 Mar. 1969
Lunar occultation of radio sources (2295 MHz)	A. Maxwell J. H. Taylor	Mars Pioneer	July 1967 Oct. 1967 Jan. 1968 Apr. 1968
Very Long Baseline Interferometer (narrow data bandwidth, S-band)	J. S. Gubbay A. J. Legg D. S. Robertson A. T. Moffett B. Seidel	Mars Pioneer Echo Woomera Tidbinbilla	Sept. 1967 Nov. 1967 May 1968 June 1969
Study characteristics of radio source signals after passage through solar corona (2295 MHz)	R. D. Ekers	Pioneer	Oct. 1967
Planetary radio metric observations	D. Jones B. L. Gary M. J. Klein	Venus 9-meter	1967–1971
Jupiter occultation of radio sources (2295 MHz)	B. L. Gary G. D. Nicolson	Hartebeesthoek	Sept. 1968
Jupiter polarization experiment (2295 MHz)	B. L. Gary S. Gulkis	Mars	Apr. 1969 May 1969
Solar scintillation (2295 MHz)	R. D. Ekers L. Little (CIT)	Mars Pioneer Echo Venus	Apr. 1969

APPENDIX A

NETWORK RADIO ASTRONOMY EXPERIMENT CHRONOLOGY

Part 1. 1967-1971 (Contd)

Experiment	Investigator	Telescope	Date
Very Long Baseline Interferometer (NRAO wideband terminal, S-band)	M. H. Cohen A. T. Moffet D. B. Shaffer B. G. Clark K. I. Kellerman D. L. Jauncey S. Gulkis	Mars Tidbinbilla	June 1969
General relativity interferometer experiment	D. O. Muhleman R. D. Ekers E. Fomalont	Mars Venus	Oct. 1969
Very Long Baseline Interferometer (narrow data bandwidth, S-band)	J. S. Gubbay A. J. Legg D. S. Robertson A. T. Moffett B. Seidel	Mars Pioneer Tidbinbilla	Dec. 1969 June 1970 Jan. 1971
SCO-XR-1 observations	M. Lampton S. Boyer J. Welch G. Grasdalen	Mars	June 1970
X-band pulsar	A. T. Moffet	Mars	July 1970
General relativity VLBI (X-band)	B. Burke T. A. Clarke R. M. Goldstein A. Rogers I. I. Shapiro	Mars Haystack	Oct. 1970 Feb. 1971
Pulsar polarization measurements	A. T. Moffet R. D. Ekers	Mars	Oct. 1970 Apr. 1971
Indian Ocean VLBI (narrow data bandwidth, 2295 MHz)	D. S. Robertson G. D. Nicolson	Woomera Hartebeesthoek	Nov. 1970
VLBI (2295 MHz, NRAO recording terminals)	J. J. Broderick B. G. Clark M. H. Cohen D. L. Jauncey K. I. Kellermann	Venus NRAO 42-meter	Nov. 1970

APPENDIX A

NETWORK RADIO ASTRONOMY EXPERIMENT CHRONOLOGY

Part 1. 1967-1971 (Contd)

Experiment	Investigator	Telescope	Date
Earth physics VLBI (S-band)	P. F. MacDoran	Echo Mars	Jan. 1971
X-band VLBI	K. I. Kellerman M. H. Cohen B. G. Clark D. L. Jauncey	Mars Haystack	Feb. 1971
Jupiter radiation-belt study	S. Gulkis B. L. Gary M. J. Klein	Mars	Mar. 1971

Part 2. 1971-1987

Radio Astronomy Experiment Selection Panel Research	NASA-Sponsored Ground-based Radio Astronomy Programs
1971-1987	1972-1987
67 Proposals	o Interstellar microwave spectroscopy
60 Experiments	o Planetary radio astronomy
(See Appendix B)	o Hipparcos VLBI
	o Quasar and galactic nuclei VLBI
	o Tidbinbilla interferometer
	(See Appendix C)

APPENDIX B

RADIO ASTRONOMY EXPERIMENT SELECTION PANEL RESEARCH

Experiment	Investigator	Telescope	Date
RA 100 Very long baseline interferometry (medium data bandwidth, S-band)	J. S. Gubbay A. J. Legg D. S. Robertson	Mars Woomera	June 1971 Jan. 1972 Feb. 1972 June 1972
RA 128 Spiral galaxy mapping	H. Arp	Venus Mars	Oct. 1971 Dec. 1971 Apr. 1972
RA 129 Quasar structure by X-band	T. A. Clark R. M. Goldstein H. F. Hinteregger C. A. Knight G. E. Marandino A. E. Rogers I. I. Shapiro D. J. Spitzmesser A. R. Whitney	Mars Haystack	June 1971 Sept. 1971 Oct. 1971 Jan. 1972 Feb. 1972 Mar. 1972 May 1972
RA 130 X-band VLBI	J. J. Broderick B. G. Clark K. I. Kellerman D. L. Jauncey M. H. Cohen D. B. Shaffer	Mars Haystack	Feb. 1971 Nov. 1971 Feb. 1972 Mar. 1972 Apr. 1972 May 1972 June 1972
RA 131 Small-scale variations in cosmic background radiation	R. L. Carpenter S. Gulkis T. Sato	Mars	Jan. 1972 Feb. 1972 Mar. 1972 May 1972
RA 132 Weak radio source observations	D. L. Jauncey M. J. Yerbury J. J. Condon D. J. Spitzmesser	Mars	June 1972
RA 134 Transcontinental baseline VLBI	T. A. Clark H. F. Hinteregger C. A. Knight S. Lippincott A. E. Rogers I. I. Shapiro A. R. Whitney	Mars Haystack 37-meter NOAA Alaska 26-meter	Mar. 1972 Apr. 1972 May 1972 June 1972

APPENDIX B

RADIO ASTRONOMY EXPERIMENT SELECTION PANEL RESEARCH (Contd)

Experiment	Investigator	Telescope	Date
RA 135 Pulsar observations	T. A. Clark G. S. Downs N. C. Erickson P. E. Reichley N. R. Vandenberg	Mars NRAO Greenbank 42-meter	May 1972
RA 141 Ionized hydrogen observations	J. G. Hills M. J. Klein	Mars	May 1972
RA 146 North-south baseline VLBI	A. T. Moffet I. Pauliny-Toth G. Nicholson A. J. Legg	Robledo Effelsberg, Hartebeesthoek	Apr. 1973
RA 151 K-band mapping of weak extended sources with variable components	H. N. Ross	Mars	May 1973 June 1973
RA 152 Survey of weak, compact components in extended extragalactic radio objects	H. N. Ross R. T. Schilizzi K. Y. Lo M. H. Cohen	Mars	April 1973 Sept. 1973
RA 153 Mapping formaldehyde radiation in M17	C. Lada A. E. Lilley	Mars	Apr. 1974 June 1974
RA 154 Galactic dark cloud	A. H. Barrett R. N. Martin	Mars	May 1974
RA 155 Cosmic microwave background radiation	J. C. Pigg A. T. Moffet	Mars	Feb. 1975
RA 156 Extragalactic source VLBI	M. H. Cohen	Mars Haystack	Aug. 1974

APPENDIX B

RADIO ASTRONOMY EXPERIMENT SELECTION PANEL RESEARCH (Contd)

Experiment	Investigator	Telescope	Date
RA 157 Interplanetary scintillations	W. A. Coles B. J. Rickett S. L. Scott	Pioneer Echo Mars, OVRO	Sept. 1974 Oct. 1974
RA 160 Goldstone/OVRO VLBI	R. T. Schilizzi	Pioneer, OVRO	May 1976
RA 163 Dark cloud lines	G. R. Knapp T. B. H. Kuiper R. L. Brown	Mars	Aug. 1975 Dec. 1975
RA 164 VLBI observations of the compact radio source in the galactic center	K. Y. Lo R. T. Schilizzi M. H. Cohen A. C. S. Readhead H. N. Ross	Mars Fort Davis, Greenbank, Hat Creek, Haystack, NRL, OVRO, VRO	Apr. 1976 July 1976 Sept. 1977 Feb. 1977
RA 168 Galactic center VLBI	K. I. Kellerman D. L. Jauncey	Mars NRAO, Haystack	June 25, 1977
RA 169 Compact nuclei VLBI	K. I. Kellerman D. L. Jauncey R. A. Preston	Mars Tidbinbilla NRAO, Haystack	Feb. 1980
RA 170 Radio emission VLBI	D. B. Shaffer D. L. Jauncey A. Harris R. A. Preston	Mars NRAO, Haystack	June 1978
RA 171 M87 ISS	A. C. S. Readhead W. L. W. Sargent M. H. Cohen K. Y. Lo	Mars Robledo OVRO	May 1978 Feb. 1980
RA 174 VLBI of a compact source in M82	D. Jones N. Cohen D. Stinebring P. Clark J. R. Houck	Mars Tidbinbilla	Feb. 1980

APPENDIX B

RADIO ASTRONOMY EXPERIMENT SELECTION PANEL RESEARCH (Contd)

Experiment	Investigator	Telescope	Date
RA 175 VLBI investigation of SS 433	A. E. Neill R. A. Preston T. G. Lockhart	Venus Mars Tidbinbilla Robledo Haystack, NRAO, Onsala, Hartebeesthoek, VLA, OVRO, Hat Creek	May 1979 May 1980
RA 176 VLBI observations of 0957 + 561A, B and 1038 + 528A, B	M. V. Gorenstein J. M. Marcaide N. L. Cohen B. E. Corey E. E. Falco I. I. Shapiro R. A. Preston R. A. Porcas	Mars Robledo Effelsberg, NRAO, Haystack, OVRO	Feb. 1980 Mar. 1981
RA 177 A statistical VLBI investigation of milliarc-second nuclei in quasars and galaxies	R. A. Preston M. V. Gorenstein I. I. Shapiro	Mars Robledo	Mar. 1981 Mar. 1981
RA 178 Superluminal radio sources at 13 cm	M. H. Cohen R. S. Simon S. C. Unwin R. S. Booth P. N. Wilkinson	Robledo Onsala, Jodrell Bank, Greenbank, Fort Davis, OVRO	Nov. 1981
RA 180 Nuclei of M81 and M104 at 2.3 and 8.5 GHz	N. Bartel B. E. Corey I. I. Shapiro A. E. E. Rogers I. I. K. Pauliny-Toth R. A. Preston	Mars Robledo 64-meter MPIFR, Onsala, NRAO, Fort Davis, Haystack	May 1983
RA 181 Black hole candidate CYG X-1	N. Bartel		May 1983

APPENDIX B

RADIO ASTRONOMY EXPERIMENT SELECTION PANEL RESEARCH (Contd)

Experiment	Investigator	Telescope	Date
RA 182 VLBI observations of the galactic center	M. H. Cohen	Venus	1982
RA 183 VLBI observations of SS433 at 1.3 cm	B. Geldzahler A. Niell J. Romney C. Walker	Mars Haystack, NRAO, VLA, OVRO, MPI	May 1983
RA 184 VLBI observations of 0957 +561A, B and 1038 +528A, B at 3.6 and 13 cm (second EPOCH)	M. V. Gorenstein J. M. Marcaide N. Bartel R. J. Bonometti M. L. Cohen E. E. Falco B. E. Corey I. I. Shapiro R. A. Preston	Mars Robledo 64-meter Effelsberg, Onsala, OVRO, Greenbank, Haystack, Fort Davis	May 1983
RA 185 Simultaneous 3.6/13-cm and very sensitive 3.6-cm observations of the galactic center	J. M. Marcaide N. Bartel M. V. Gorenstein I. I. Shapiro R. A. Preston	Mars Robledo 64-meter Effelsberg, Haystack, Greenbank, OVRO, Fort Davis	May 1983
RA 186 Compact sources in M82	N. Bartel B. E. Corey M. V. Gorenstein J. M. Marcaide A. E. E. Rogers I. I. Shapiro J. D. Romney	Mars Robledo 64-meter Onsala, Effelsberg, OVRO, Fort Davis, Greenbank, Haystack	May 1983
RA 187 Mapping of the galactic center compact radio source at 8.5 GHz	K. Y. Lo D. C. Backer M. H. Cohen	Mars NRL, Hat Creek, OVRO, Fort Davis, NRAO, Haystack	May 1983

APPENDIX B

RADIO ASTRONOMY EXPERIMENT SELECTION PANEL RESEARCH (Contd)

Experiment	Investigator	Telescope	Date
RA 188 High-resolution, sensitivity, and dynamic-range observations of 3C273	K. I. Kellerman J. D. Romney I. Pauliny-Toth J. Benson C. Walker	Mars Haystack, NRAO, OVRO, Bonn, Onsala, Crimea, VLA, ARO, Itapatenga	
RA 189 Observation of an extragalactic source seen through a galactic H II region	J. M. Moran D. C. Backer L. Rodriquez	Mars OVRO	
RA 190 Mapping of the SGR, a compact radio source at 1.35 cm	K. Y. Lo K. I. Kellermann D. C. Backer M. H. Cohen R. D. Ekers J. M. Moran	Mars Haystack, NRAO, OVRO, VLA	
RA 191 Search for 3.46-cm hyperfine emission from cosmic $^{3}HE^{+}$	G. M. Heiligman D. G. York	Mars	May 1983
RA 192 Weak superluminal quasar 3C179	R. W. Porcas	Mars Robledo 64-meter	May 1983
RA 194 Mesospheric water vapor measurements from Goldstone, California	S. Gulkis G. S. Levy P. N. Swanson W. J. Wilson R. M. Bevilacqua P. R. Schwartz J. J. Olivero	Venus	Jan. 1984
RA 195 Superluminal sources at a wavelength of 13 cm	S. C. Unwin M. H. Cohen J. A. Biretta P. N. Wilkinson R. S. Booth	Venus Robledo 64-meter Onsala, Jodrell Bank, Haystack, NRAO, Fort Davis, OVRO, Hat Creek, Arecibo, Hartebeesthoek	

APPENDIX B

RADIO ASTRONOMY EXPERIMENT SELECTION PANEL RESEARCH (Contd)

Experiment		Investigator	Telescope	Date
RA 200	VLBI observation of 2300-189: a quasar with a jet of known orientation in space	J. J. Broderick J. J. Condon D. L. Jauncey G. D. Nicolson R. A. Preston	Mars Tidbinbilla 64-meter Robledo 64-meter Haystack, VLA, Nobeyama, Hartrao	July 1986
RA 204	3.6-cm mapping of the SGR, a compact radio source	K. Y. Lo D. C. Backer K. J. Johnston M. H. Cohen	Mars	May 1987

APPENDIX C

NASA-SPONSORED GROUND-BASED RADIO ASTRONOMY PROGRAMS

Experiment	Investigator	Telescope	Date
Interstellar microwave spectroscopy	T. B. H. Kuiper F. F. Gardner J. B. Whiteoak G. M. Heiligman W. L. Peters J. E. Reynolds	Mars Venus Tidbinbilla 70-meter	1972- Ongoing
Planetary radio astronomy	M. J. Klein S. Gulkis E. T. Olsen B. T. Tsurutani D. L. Jauncey A. Rius	Mars, Venus, Echo Tidbinbilla 70, 34-meter Robledo 70, 34-meter	1972- Ongoing
Hipparcos VLBI	R. A. Preston J. F. Lestrade R. Mutel	Mars Tidbinbilla 70-meter Robledo 70-meter	1981- Ongoing
Quasar and galactic nuclei VLBI	R. A. Preston D. L. Jones R. P. Linfield D. L. Meier J. S. Ulvestad D. G. Payne D. L. Jauncey	Mars, Venus Tidbinbilla	1972- Ongoing
Tidbinbilla interferometer; southern hemisphere radio source positions	S. Gulkis D. L. Jauncey J. E. Reynolds	Tidbinbilla 70, 34-meter	1972- Ongoing

APPENDIX C

NASA-SPONSORED GROUND-BASED RADIO ASTRONOMY PROGRAMS (Contd)

Experiment	Investigator	Telescope	Date
Tracking and Data Relay Satellite System (NASA) orbiting VLBI demonstration	G. S. Levy R. P. Linfield J. S. Ulvestad C. D. Edwards J. F. Jordan, Jr. S. J. DiNardo C. S. Christiansen R. A. Preston L. J. Skjerve L. R. Stavart B. F. Burke A. R. Whitney R. J. Cappallo A. E. E. Rogers K. B. Blaney M. J. Maher C. H. Ottenhoff D. L. Jauncey W. L. Peters T. Nishimura T. Hayashi T. Takano T. Yamada H. Hirabayashi M. Morimoto M. Inoue T. Shiomi N. Kawaguchi H. Kunimori	Tidbinbilla 64-meter Usuda Kashima TDRSS satellite and ground station	July, Aug. 1986 Jan. 1987