NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Report 32-1533

Volume I

A History of the Deep Space Network

From Inception to January 1, 1969

Edited by

N. A. Renzetti

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
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Foreword

The Deep Space Network (DSN) grew out of tracking and data recovery techniques that evolved from the guided missile weapons system work of the Jet Propulsion Laboratory at White Sands Proving Ground during the 1950s. The Laboratory has developed the DSN into a worldwide network of tracking stations capable of supporting unmanned, automated flights to the Moon and the terrestrial planets, as well as the Grand Tour type of missions that will circumnavigate the solar system later in this century. With the completion of the overseas 64-meter antennas, the Network will be able to provide telecommunications out to the very threshold of intragalactic space.

This history documents the development of the DSN during its formative period—the decade of the 1960s. As we look ahead to the coming years, it is clear that the DSN will have to extend its capabilities in all the parameters required to support missions penetrating deep into interplanetary space. The Jet Propulsion Laboratory stands ready to meet these challenges in providing a tracking and data acquisition instrument that will keep the United States in the forefront of space exploration.

W. H. Pickering

Acknowledgment

History is made by people. Those who contributed scientific, engineering, and operations skills to make the Deep Space Network possible have been or are members of the Office of Tracking and Data Acquisition at NASA Headquarters, headed first by E. C. Buckley and subsequently by G. M. Truszynski; and the Tracking and Data Acquisition organization at the Jet Propulsion Laboratory, headed first by Dr. Eberhardt Rechtin and more recently by W. H. Bayley, under the direction of Dr. W. H. Pickering.

It was a basic principle in the implementation and operation of the network that the role of the Jet Propulsion Laboratory should be equivalent to that of an architect/engineer in the design and construction of a major facility. The operating hardware was built by American industry, which provided design, manufacturing, and installation skills to the network facilities in the United States and overseas. American industry also played a key role in the operation of the network.

Also acknowledged is the considerable support given by the Republic of South Africa, the Commonwealth of Australia, and Spain, for supporting the implementation phases, constructing the basic facilities such as roads, buildings, power stations, and providing operations personnel for the stations.

Finally, the editor wishes to acknowledge J. R. Hall and D. J. Mudgway, who carried out the specific role of writing the material presented herein, and M. S. Glenn, R. Santiestevan, F. M. Flanagan, and R. C. Chandlee for their support.

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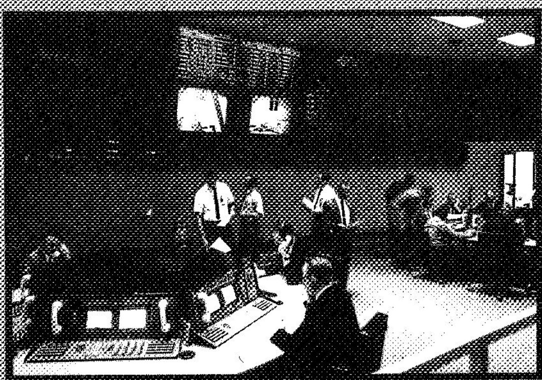
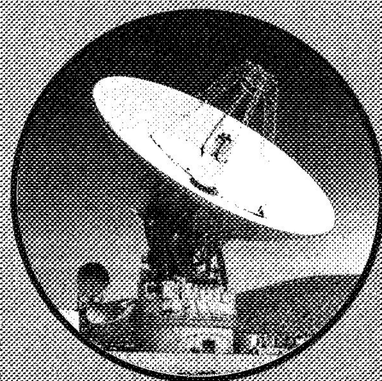
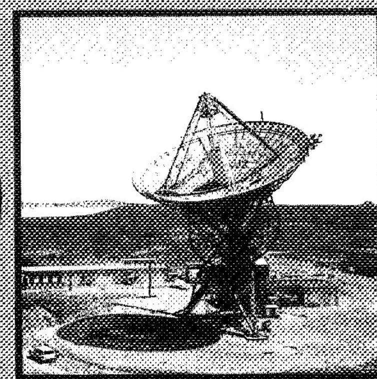
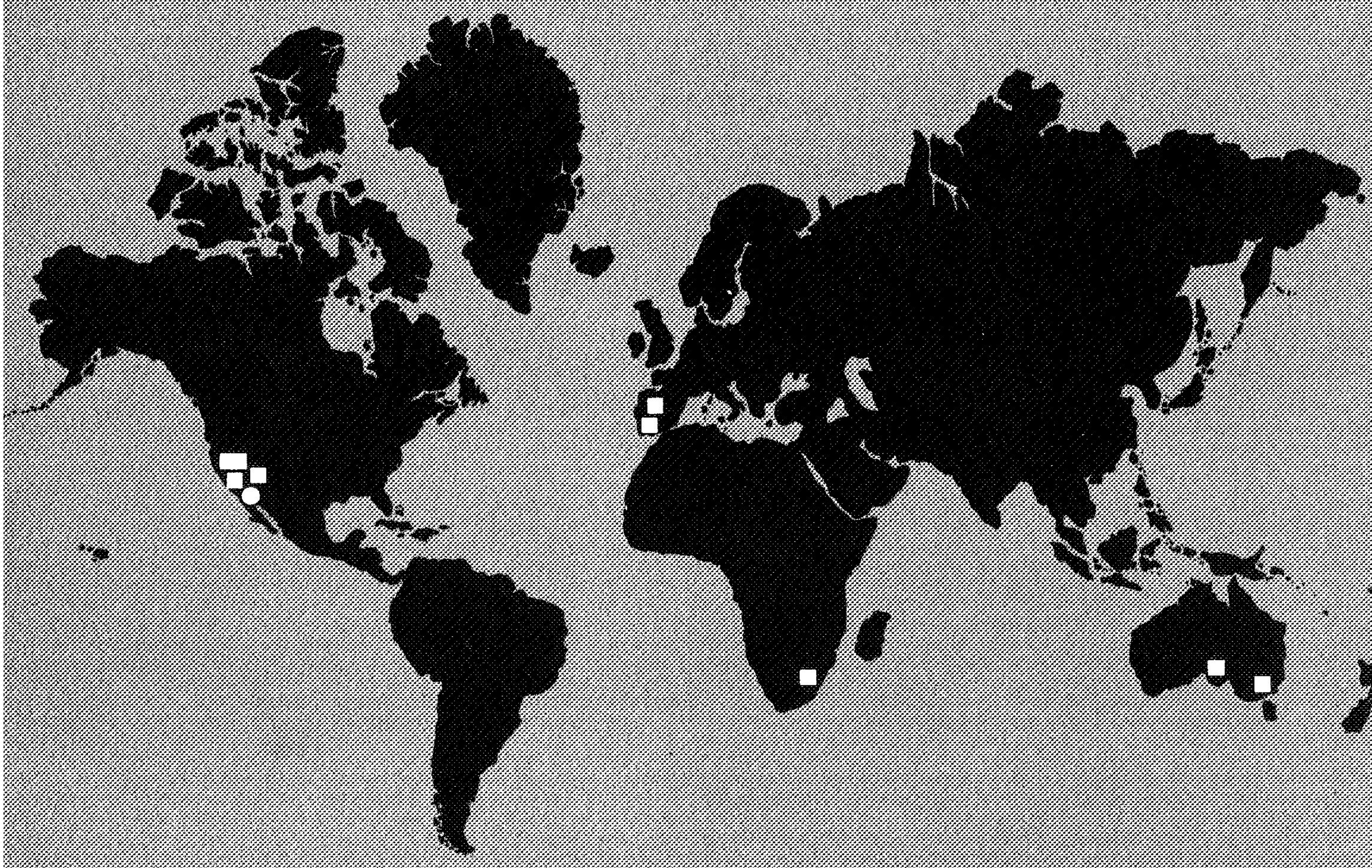
Abstract

The Deep Space Network is a precision communications system designed to communicate with and control unmanned spacecraft in the exploration of deep space. The DSN utilizes large antennas, low-noise phase-lock receiving systems, and high-power transmitters located at stations positioned approximately 120 deg around the Earth. A special world-wide communications system connects these stations to the DSN mission control center in Pasadena, California. It is the policy of the DSN to continuously conduct research and development of new systems, components, and techniques and to incorporate them into the DSN to maintain a state-of-the-art capability. This history relates the development and results of this policy through January 1, 1969.

OVERLEAF

Deep space stations, located approximately 120 deg apart around the earth, maintain continuous communications with the spacecraft, generate navigation data, and return science and engineering data to the Space Flight Operations Facility in Pasadena, California. The large square shows one of the 26-m-diameter steerable parabolic antennas that currently make up the world-wide Deep Space Network. The large circle shows the 64-m-diameter steerable parabolic antenna installed at Goldstone, California. Similar antennas are planned for Spain and Australia. The large rectangle shows the Network Control Area in the Space Flight Operations Facility.

Chapter I
Introduction

Scope of the Document

This document describes the history of the Deep Space Network from its beginning to January 1969. The DSN is a facility of the National Aeronautics and Space Administration (NASA), Office of Tracking and Data Acquisition (OTDA) under the management and technical direction of the Jet Propulsion Laboratory (JPL), California Institute of Technology. The DSN is capable of two-way communication with spacecraft at interplanetary distances and provides the control and data-handling capability to support deep space missions.

Our history begins with the early work in radio astronomy, the precursor of the scientific and engineering field known today as telecommunications, and traces JPL's technological developments in the field of tracking and communications, starting in the late 1940s with the *Corporal* surface-to-surface missile under U.S. Army sponsorship, and ending with the flight of *Apollo 8* (December 1968), the first manned flight out of Earth orbit to the vicinity of the Moon. During this period the DSN grew from a single portable station to a world-wide telecommunications network capable of continuous 24-hour, two-way communication with spacecraft gathering scientific data at interplanetary distances.

The historical evolution of the DSN is traced from its early beginnings at JPL with the U.S. Army through subsequent developments after transfer to NASA in 1958. Deep space stations were constructed, and the communication capabilities of the networks were developed along with computer applications as data processing requirements became increasingly more extensive. The DSN advanced from a single-mission support capability to a multiple-mission capability. Research and advanced development activities continuously improved the technical capabilities of the DSN and its support for other programs, such as Earth-based radio science.

Finally, the history concludes with a look both backward and forward in time to summarize how the DSN met its initial objectives and the continuing demands of the NASA Deep Space Program, and how the network may evolve to meet the next decade of space research and development.

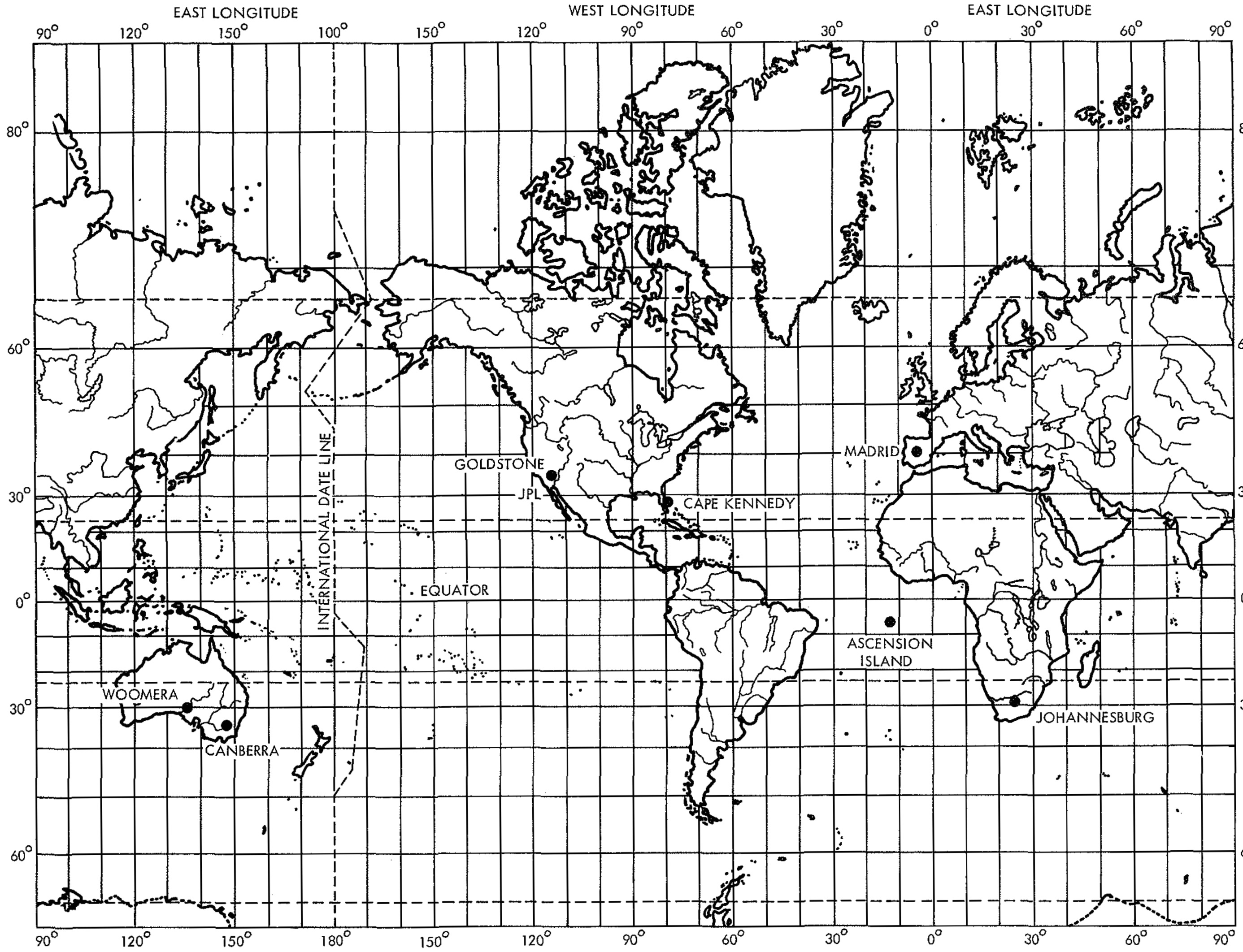


Fig. I-1. The world-wide Deep Space Network

The Deep Space Network as of January 1, 1969

The present Deep Space Network consists of three facilities: the Deep Space Instrumentation Facility (DSIF), the Ground Communication Facility (GCF), and the Space Flight Operation Facility (SFOF). The DSN is considered, for functional purposes, to comprise six systems: tracking, telemetry, command, simulation, monitoring, and operations control.

The Deep Space Instrumentation Facility

The DSIF consists of a group of tracking and space communications stations strategically situated around the world (Fig. I-1). Each station provides Earth-based capability for telemetry, tracking, and command functions for communication between the DSN and the spacecraft.

The Ground Communications Facility

The GCF consists of voice, teletype, and high-speed data circuits provided by the NASA communications network (NASCOM) between each overseas station, Cape Kennedy, and the SFOF. NASCOM is managed by the NASA Goddard Space Flight Center. Voice, teletype, high-speed data, and video circuits between the SFOF and the Goldstone stations are provided by microwave link.

The Space Flight Operations Facility

The SFOF is the Network and Project Mission Control Center, located at JPL. This facility contains the computers and displays necessary for network control functions and the analysis of spacecraft performance, space science experiment performance, and spacecraft flight path, as well as for the control of mission operations.

DSN Systems

Although the DSN evolved as a consolidation of facilities, its primary function in supporting spacecraft in flight can best be described in terms of its three primary data systems: the DSN Tracking, Telemetry and Command Systems.

The DSN Tracking System provides the configuration that permits the generation of radiometric data at each of the deep space stations and the formatting and transmission of these data to the Control Center for validation. These data—consisting of angle, two-way doppler, and range—are used for trajectory-related computations. The deep space stations generate these data types while radio tracking the spacecraft in angle and frequency.

The DSN Telemetry System provides the configuration that permits the reception of the engineering and science information generated aboard the spacecraft. The information is telemetered to Earth, formatted and transmitted to the Control Center, and provided to the mission control analysts who control the mission. The data are received on a subcarrier of the same carrier that is used by the DSN Tracking System.

The DSN Command System provides the configuration that permits the transmission of commands from the Mission Control Center to a deep space station and then to the spacecraft in flight. The system accepts coded commands that are processed by a central computer for transmission to the deep space station. The command is then sent to the spacecraft by modulating the same basic carrier used for transmitting tracking and telemetry information. The command signal is received by the spacecraft, decoded, and used to operate equipment on board.

The configuration of the systems described above consists of a particular interconnection of parts of all the facility subsystems. These parts may vary from mission to mission.

Three other DSN systems provide testing, operational control, and monitoring. The Operations Control System provides for network operations, allocation, failure reporting, and other related functions that make possible continuous network operations for 24 hours a day. The Monitor System provides instrumentation for continuously checking the operational status of the network and the quality of the data being transmitted to the user. The Simulation System can inject simulated data at selected points to exercise parts of the network. It also serves as a source of simulated flight project data for testing mission operational procedures and training mission personnel.

Multiple Uses of the DSN

The primary use of the DSN has always been the direct support of deep space flight project requirements for tracking and data acquisition. The DSN can thus be characterized as a scientific instrument which uses a single up- and-down-link radio carrier, in combination with a coherent spacecraft transponder, to perform high-precision radio tracking while simultaneously transmitting uplink commands and receiving downlink telemetry. The change in frequency due to the relative motion of the Earth and the spacecraft can be measured, thus generating one- and two-way doppler, which makes possible the computation of the radial velocity of the spacecraft relative to the Earth. The time of flight can be measured by transmitting a coded radio signal from Earth to the spacecraft and then back to Earth, thus giving the range data, or the distance between the spacecraft and the Earth. This distance is determined by multiplying the time of flight by the speed of propagation.

The research and development activity supporting the operational network has continually provided the DSN with a capability close to the state of the art of deep space communications. This capability has led to the use of the network as a precision instrument in several major areas of scientific investigation: (1) research in the field of Earth-based radio science and continued experiments with natural radio sources such as quasars and pulsars, (2) experiments leading to planetary radar studies of the surfaces of planets, (3) experiments in celestial mechanics, some of which involve testing theories of relativity, (4) experiments in lunar gravity fields and (5) more recently, experiments into Earth physics involving such phenomena as crustal movements, continental drift, etc.

Chapter II
Principal Characteristics, Rationale, and Technical Baseline of the DSN

Characteristics and Rationale

The DSN as a Scientific Instrument

The primary purpose of the DSN activities has been the development of an instrument for the scientific investigation of deep space, primarily through communication with, and control of, unmanned, automated spacecraft. The end result of the DSN functions is the placing of reliable scientific data in the hands of scientists—to provide new knowledge about our solar system and the universe beyond.

Multiple-Mission Support

A prime characteristic of the DSN is its capability to support many space flight missions simultaneously. The development of this capability has been due primarily to the expense and impracticality of duplicating a specialized tracking and communications network for each unmanned flight project. The history of multiple-mission support is seen in the DSN's engineering effort toward a state-of-the-art, standardized interface to meet the requirements of new space missions while incorporating the current interface with existing projects.

24-hour Coverage

The intent of United States deep space missions is to maintain continuous radio communication with the spacecraft, beginning as early as possible during the initial trajectory leaving the Earth and continuing until the end of the mission. Continuous, 24-hour coverage dictated a need for several Earth-based stations to compensate for the Earth's daily rotation. Station locations were selected approximately 120 deg apart in longitude and between 40 deg both north and south of the equator in latitude. This placement ensured that spacecraft at distances exceeding 16,000 km (10,000 miles) from Earth would be under continuous observation and that suitable overlap existed for transferring the communications link from one station to the next. Overhead tracking of the spacecraft was minimized, and finally, the antennas could follow the spacecraft at minimum rates of motion.

State of the Art

The most significant characteristic of the Deep Space Network has been its rapid and continuous evolution. Under the program direction of NASA/OTDA and JPL, the DSN has developed from a single space communication station on the California desert, with a lunar tracking capability, to a world-wide station network capable of communicating with spacecraft at the edge of the solar system. Not only has the DSN responded to meet flight project requirements, it has also developed the appropriate ground station technology in order to maintain a proper balance between the spacecraft and the ground system performance. The objective in maintaining this balance has been to maximize the return of scientific information in terms of information bits per dollar.

Technical Baseline

Radio Astronomy

All of man's information about the universe beyond the earth has come to him through two apertures or "windows" in the sky. The first "window" is the narrow band of electromagnetic energy waves in the visible region of light which extends from ultraviolet to infrared. The second "window" is radio energy, which extends from approximately a few centimeters in wavelength to several meters. All other electromagnetic radiation is completely absorbed by the earth's atmosphere or the ionosphere.[1] Engineers logically looked to the radio frequency bands as a means for transmitting data from a space probe through the Earth's atmosphere to a receiving antenna on the ground.

A spacecraft, however, provides a small, distant, and fast-moving target, which is difficult to locate from the Earth without sophisticated and complex systems and techniques. The basic framework for modern tracking and data acquisition was established in 1931 when Karl Jansky, an American electrical engineer, first detected radio signals emanating from outside the solar system. Jansky, in effect, founded the science of radio astronomy. His equipment consisted of a radio receiver that was adequate enough to detect the high-frequency cosmic radio waves, along with an antenna array of rods mounted on a revolving, wooden platform 30.5 meters (100 feet) long. The antenna array, powered by a small motor, rotated once every 20 minutes on four Model T Ford wheels. At the time of his discovery, Jansky was working for Bell Telephone Laboratories at their field station in Holmdel, New Jersey, where he was trying to determine the cause of high-frequency interference in the company's long-distance telephonic and radio communications circuits.

Jansky discovered that one source of static came from nearby thunderstorms, and a second from distant storms whose radio waves were returned to Earth by the ionized atmosphere. But there was still another source, quite different from the first two. This third source, without any obvious atmospheric disturbance, produced a residual noise or hiss in the receiver, with an intensity that varied throughout the day. In April, 1933, at a meeting of the American Section of the International Scientific Radio Union, he announced his conclusion that these radio emissions appeared to be from beyond the solar system and might be from one or a great many sources. Jansky's discovery, however, was not taken seriously by professional astronomers.[2]

Jansky's conclusions were confirmed in a report published in 1940 by Grote Reber, a radio engineer who was also an amateur astronomer. Some time in the late 1930s, Reber built what is considered to be the prototype of of the modern radio telescope. Reber's radio telescope, a 9-m (30-ft) diameter parabolic antenna with a primary feed attached to the focal point of the tripod legs, was mounted so that it could be pointed to any part of the sky. With his telescope, Reber was able to prepare the first real radio map of the sky with a reasonable degree of precision. He was able to show that the signal strength was greatest when the antenna was pointed toward a region of the sky where visible stars were plentiful; i.e., along the Milky Way or the galactic center, in a band approximately 15 deg wide.

In March 1951, Edward M. Purcell of Harvard University and a colleague, Harold J. Ewen, detected steady hydrogen emission signals at a wavelength of 21 cm. The discovery of the 21-cm emissions gave a boost to the science of radio astronomy and the development of large radio telescopes. Following Purcell and Ewen's discovery, 21-cm studies were begun at three United States institutions: the Naval Research Laboratory (NRL), Harvard University, and the Carnegie Institute of Washington, Division of Terrestrial Magnetism (CIW-DTM). In addition, investigation of discrete sources and galactic emission were begun by Ohio State University, NRL and CIW-DTM.[3]

Research in large radio telescopes was also being conducted by Ohio State University, the Massachusetts Institute of Technology, Stanford Research Institute, and the

[1]Purcell, E., *Radio Astronomy and Communication Through Space*, Brookhaven Lecture Series No. 1, Brookhaven National Laboratory, Atomic Energy Commission, Nov. 15, 1960.

[2]Kundu, M. R., *Solar Radio Astronomy*, Wiley Interscience Division, New York, 1965.

[3]*Plan for a Radio Astronomy Observatory*, National Science Foundation, Associated Universities, Inc., New York, 1956.

California Institute of Technology, Jet Propulsion Laboratory. As was well known to the radio astronomers, galactic noise is not uniformly distributed across the heavens. The largest source of noise lies along the Milky Way, or galactic center, in a band approximately 15 deg wide. This region also includes the expected trajectories of space vehicles. To reject this interference, it is desirable to use the highest practical frequencies and an antenna with a beamwidth of only a few degrees. Dr. Eberhardt Rechtin emphasized in his paper, "Communication Techniques For Space Exploration,"[4] that a low point in the combination of galactic and atmospheric noise occurs in the region of 1,000 to 5,000 MHz. It was also known that galactic noise is diminished as the transmission frequencies are increased, both because the galactic noise is less at higher frequencies, and because the galactic sources themselves become considerably smaller and more widely spaced. The effect of the atmosphere on a received signal, however, could be minimized by avoiding, wherever possible, trajectories that would necessitate viewing the spacecraft near the Earth's horizon and by keeping the transmission frequencies less than 5,000 MHz.

Early communications design studies established that it would be possible to stabilize lunar and interplanetary vehicles so that antennas aboard the spacecraft could be pointed roughly in the direction of the Earth. The size of the spacecraft antenna would be limited for many years, also limiting the gain of the transmitted signal and making it desirable to use as high a frequency as possible. On the Earth, the equipment for receiving the spacecraft signal was subject to a different limitation.

Telescopes for extreme sensitivity application, such as the 500-cm (200-in.) optical telescope at Mount Palomar, were probably about as large as optical tolerances would permit; larger telescopes would not produce stronger images and might, in fact, produce weaker images due to differential cancellation. Radio telescopes were faced with the same problem as it affects radio frequencies. The effective diameter of the ground-based antenna is directly proportional to the wavelength of the received signal. By using manufacturing tolerances of 1 to 4000, a 26-m (85-ft) parabola might be used for frequencies as high as 1500 MHz, or a 75-m (250-ft) parabola with the same fractional tolerances might be used with frequencies up to 500 MHz. The Earth antenna, therefore, was gain-limited, whereas the vehicle antenna, for the time being at least, was area-limited.

[4]Rechtin, E., "Communication Techniques For Space Exploration," *IRE Trans. Space Explor. Telem.*, Sept. 1959.

Early Developments

The JPL tracking and communications technology had its origin in the late 1940s, concurrent with and supporting the development of instrumentation and guidance for the liquid-fueled *Corporal* missile series of experimental flight research vehicles. This early work in communications was performed under United States Army sponsorship. High-quality telemetry was a primary objective, and work in this area led to the development of telemetry systems utilizing frequency modulation and phase modulation techniques. Doppler techniques were extensively used for test range trajectory instrumentation during this early Army period. The method used was essentially an adaptation of the doppler technique used for V-2 development at Peenemunde, Germany, during World War II. The essentials of this system were a ground transmitter, several passive ground receivers located in appropriate geometry, and a transponder aboard the flight vehicle. An adaptation of this Doppler Velocity And Position (DOVAP) technique was employed aboard the *Corporal* vehicle to investigate and extend guidance technology. The ground equipment consisted of a specialized doppler transmitter and receiver and a missile tracking radar. This equipment composed the essential radio guidance for the first U.S. ballistic missile. Testing on the *Corporal* began at White Sands Proving Grounds, New Mexico, in 1947, and culminated in the operational deployment of the missile system in 1954. During this developmental period, on February 24, 1949, a *WAC Corporal* rocket boosted by a V-2 reached an altitude of 390 km (244 miles) and a speed of 8816 km/h (5510 mi/h), the greatest altitude and velocity for a man-made object to that date. In 1950, this same combination was used in the first launch from the U.S. Air Force's newly activated Long Range Proving Ground at Cape Canaveral, Florida.

The use of a phase-locked loop as a narrow-band tracking filter was first suggested by Lehan and Parks of JPL[5] in early 1953; their memorandum anticipated its use in recovery of doppler data and as an optimum demodulator for improved performance of frequency modulation/phase modulation (FM/PM) subcarrier detection.

In 1953, studies by Dr. Eberhardt Rechtin and Richard Jaffe of JPL emphasized that phase-locked loops could provide an efficient method of detecting and tracking narrow band signals in the presence of wideband noise.

[5]Lehan, F. W., and Parks, R. J., *Theory of Optimum Demodulation*, External Publication 164. Jet Propulsion Laboratory, Pasadena, Calif., Mar. 15, 1953.

They explained how minimum error loops could be designed if the input signal level, input noise level, and a specification for transient performance were provided.

Rechtin and Jaffe analyzed and developed the technique of using a bandpass limiter in a phase-locked loop as a narrow-band tracking filter to optimize its performance over a large range of signal-to-noise ratios by adaptively narrowing its bandwidth at low signal levels.[6]

As the *Corporal* program drew to a close, JPL was requested by the Army to begin an intensive study into the development of a more flexible surface-to-surface missile, using a solid fuel propellant. Early in 1954, JPL proposed and completed the preliminary design for the *Sergeant* surface-to-surface advanced missile system. The original guidance technique proposed was a combination radio-inertial system. Range and velocity information was provided by the radio system, and acceleration information by the inertial system. The radio system was called Coded Doppler and Ranging Communications (CODORAC). Later, the *Sergeant* guidance system was modified to an all-inertial system as a defense against countermeasures. CODORAC, however, was to become the source of much of the current DSN radio technology.

Also during 1954, JPL scientists were requested to review a report called *Project Orbiter* prepared by the Army Ballistic Missile Agency (ABMA) and the Office of Naval Research (ONR). The report presented a plan to the Department of Defense for placing a 2.3-kg (5-lb) Earth satellite in a 322-km (200-mile) orbit using existing hardware consisting of a modified Army *Redstone* missile as a first stage with a cluster of 37 JPL-developed *Loki* rockets for the upper stages.[7]

The JPL study produced a recommendation for a major change. In place of the *Loki* rockets, JPL recommended using 15 scaled-down *Sergeant* rockets which would increase reliability and allow for an increase in the weight of the satellite to 8.2 kg (18 lb). The JPL cluster was designed in three stages. The first stage consisted of 11 scaled-down *Sergeants* formed in an annular ring; the second stage consisted of three scaled *Sergeants* nested inside the first-stage ring; and the final stage consisted of a single scaled *Sergeant* that would speed the payload into orbit. The entire upper stage cluster, mounted atop the *Redstone*, would be spin-stabilized.

In the summer of 1955, *Project Orbiter* was submitted to the Department of Defense along with two other proposals for orbiting a scientific Earth satellite as part of the United States' contribution to the upcoming International Geophysical Year (IGY), which was to begin on July 1, 1957.[8] In addition to *Project Orbiter*, proposals were submitted by the Naval Research Laboratory (NRL) and the Air Force. On September 9, 1955, the Department of Defense announced its decision in favor of the NRL proposal, called *Project Vanguard*. The *Vanguard* launch vehicle consisted of the NRL-designed *Viking* as the first stage, an improved *Aerobee* sounding rocket as the second stage, and a yet-to-be developed solid-propellant third stage.

At JPL, work on the preliminary design of the upper stages of the *Orbiter* launch vehicle was nearing completion when the selection of *Vanguard* was announced and *Project Orbiter* was terminated. Later that September, Army Ordnance requested JPL to resume work on the *Orbiter* upper stages for a slightly different but nonetheless critical application. In the mid 1950s, the problem of how to keep a ballistic missile re-entry vehicle from burning up as it plunged down with tremendous speed through the thickening atmosphere was particularly urgent. In the view of Army Ordnance, *Project Orbiter's* launch vehicle was particularly well suited for achieving the height and velocity necessary for a series of vital nose cone re-entry tests. The *Orbiter*, consisting of ABMA's modified *Redstone* and JPL's scaled *Sergeant* cluster, was renamed the *Jupiter C*. By January 1956, JPL had completed the design of the high-speed upper stages, and in September 1956, the first *Jupiter C* was successfully launched down the Atlantic Missile Range to test the vehicle design and the telemetry system. The vehicle reached an altitude of 1040 km (650 miles) on a ballistic curve that ended 5310 km (3300 miles) downrange. Telemetry was successfully received from a phase-locked telemetering system also developed by JPL and known as Microlock. This system consisted of a minimum power (10 mW), minimum weight (under 0.9 kg, or 2 lb) flight transmitter and mobile ground receiving stations using an array of helical antennas. Microlock's central feature, however, based on the investigations of Rechtin and Jaffe, was a narrow-band tracking

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[6]Rechtin, E., and Jaffe, R., "Design and Performance of Phase-Lock Circuits," *IRE Trans. Inform. Theory*, Mar. 1955.

[7]Swenson, L. S., Jr., Grimwood, J. M., and Alexander, C. C., *This New Ocean, A History of Project Mercury*, NASA SP-4201. National Aeronautics and Space Administration, Washington, D.C., 1966.

[8]R. C. Hall, *Project Ranger, A Chronology* (JPL Internal Document), JPL/HR-2. Jet Propulsion Laboratory, Pasadena, Calif., Apr. 1971.

filter. A typical Microlock ground receiving station is shown in Fig. II-1, and the receiving equipment is shown in Fig. II-2. In August 1957, the re-entry test vehicle program was concluded after the successful flight and recovery of an ablative-type *Jupiter* nose cone.

On October 4, 1957, the USSR announced the launching into Earth orbit of a scientific package of instruments named *Sputnik*, their contribution to the International Geophysical Year (IGY) and the world's first artificial Earth satellite. The announced weight of *Sputnik* was 83.5 kg (184 lb), indicating a fairly significant Soviet ballistic missile capability. A month later, *Sputnik II*, weighing 508 kg (1120 lb), was launched into a high, elliptical orbit carrying a dog named Laika. Despite announcements by Soviet scientists in 1955 that the Russians, too, were planning to launch a scientific satellite during the IGY, the effect of *Sputnik* on most Americans, both in and out of government, scientific, and engineering circles, was total surprise, followed by hurt pride and embarrassment. The military implications were obvious: the Russians had a proven, operational intercontinental ballistic missile capability ahead of the United States. A Senate investigation under Lyndon B. Johnson was launched into the state of the nation's missile and satellite programs. The nation's attention now turned toward *Project Vanguard* and its attempt to orbit a 2.3-kg (5 lb) scientific package about the size of a grapefruit. On December 6, 1957, national attention, including national television, was focused on the *Vanguard* launch site at Cape Canaveral for the United States' first attempt to catch up in the space race. The *Vanguard* team had planned this first launch of the new three-stage rocket only as an engineering test that might, with luck, place a test satellite in orbit. What the nation saw was at least spectacular. The first stage

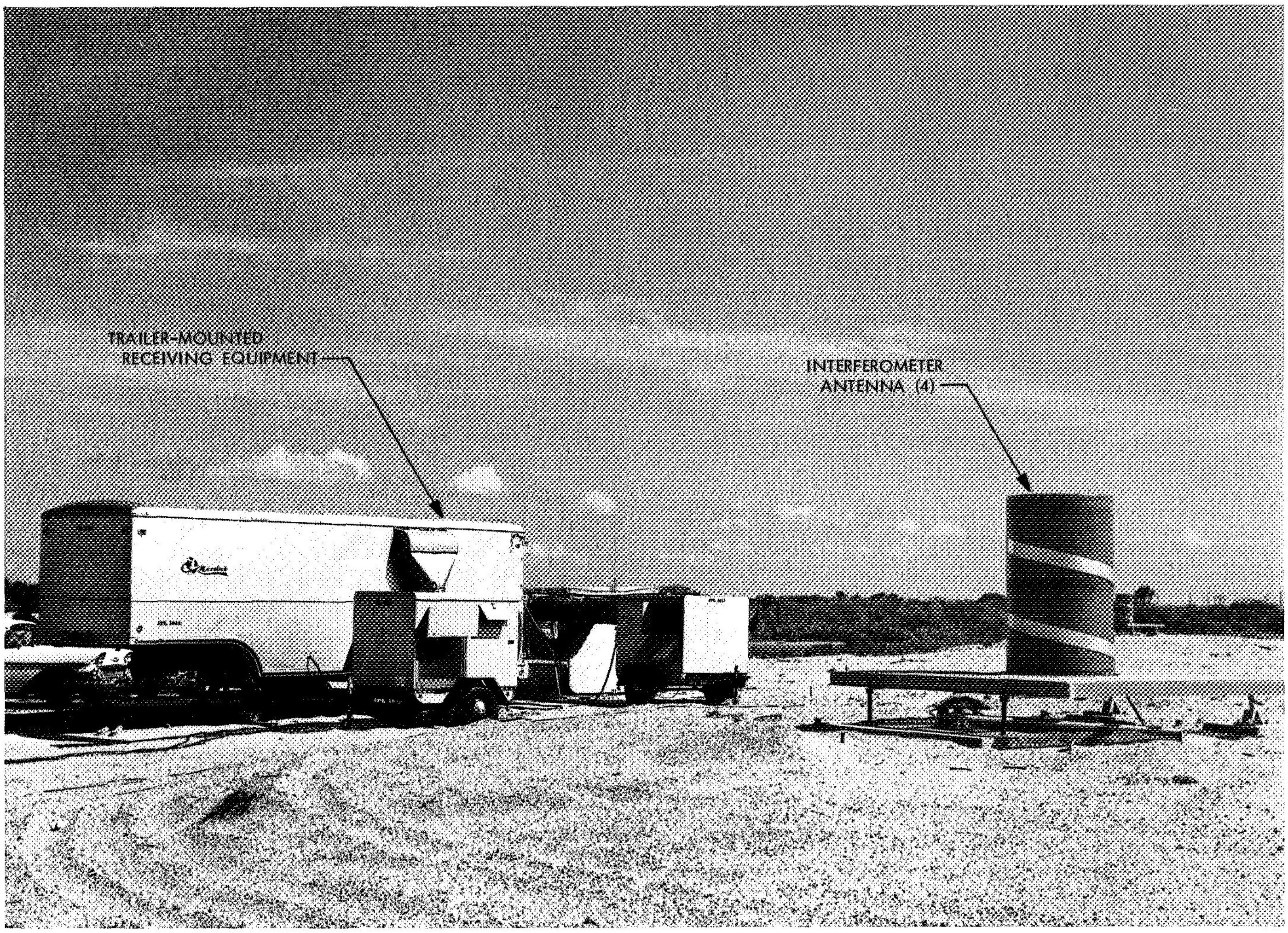

Fig. II-1. Typical Microlock ground receiving station

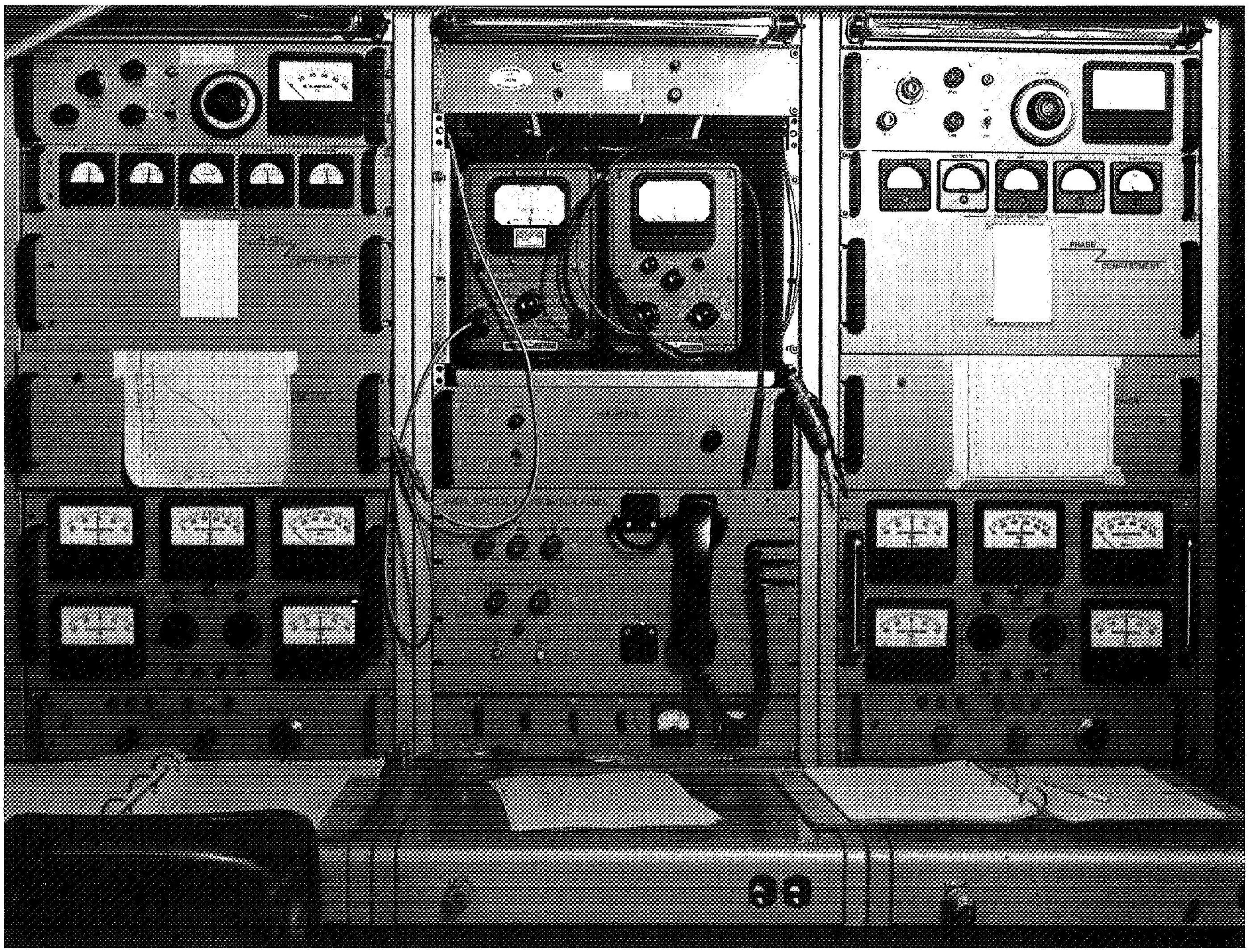

Fig. II-2. Microlock receiving equipment exploded, generating a giant ball of flame which enveloped the rest of the buckling rocket as it fell back, adding more fuel to the eruption on the pad, and more prestige to the Soviet accomplishment named *Sputnik.*

Two months before the *Vanguard* collapse, Neil H. McElroy was appointed Secretary of Defense after the resignation of Charles E. Wilson. In early November, after receiving reports that *Project Vanguard* was experiencing delays due to problems with construction and testing, McElroy authorized the Army to revive *Project Orbiter* and proceed with all deliberate speed. The Army Ballistic Missile Agency responded with a pledge to accomplish the first launch within 90 days. Under the direction of Wernher von Braun, ABMA hurried the modification of the *Redstone-Jupiter C* to its original conception as a satellite launcher. Von Braun christened the new configuration *Juno I*. At JPL, Dr. Jack E. Froehlick, one of the three Laboratory department heads, was appointed Project Manager with responsibility for the scaled *Sergeant* upper stages, including the integration of the scientific instrument payload into the 152-mm (6-in.) diameter, fourth-stage rocket. The payload consisted of radiation-measuring equipment designed by Dr. James A. Van Allen of the State University of Iowa, plus additional scientific instruments designed by JPL. The tracking and data acquisition system was JPL's Microlock. The Microlock ground stations used for the *Jupiter C* re-entry test vehicle program at Cape Canaveral were reactivated and new stations were located in Earthquake Valley near San Diego, California, at Singapore, and in Nigeria. Ground communications overseas were provided by teletype. At JPL, this crash, 90-day effort was given the title *Project Deal.*

Also during November, Dr. William H. Pickering, Director of JPL, and Dr. Lee A. DuBridge, President of the California Institute of Technology (Caltech), presented a proposal to the Department of Defense for launching a space probe to the Moon by June 1958. The scientific objectives were to take a picture of the far side of the Moon and to refine guidance and communication techniques.

The program would be based on the *Jupiter* launch vehicle and would utilize the technology and momentum generated by *Project Deal* to recoup some of the United States' prestige by being first to the Moon. At the same time, Secretary of the Air Force Donald Quarles requested that the Air Force be given an opportunity to make a competitive proposal. Both the JPL proposal and the Air Force request were taken under advisement.

On January 31, 1958, again on national television and 84 days after receiving the go-ahead from McElroy, a *Jupiter C* launch vehicle, now named *Juno I*, successfully boosted into orbit *Explorer I*, the first American satellite. Telemetry data received by the Microlock ground stations revealed that Van Allen's Geiger counters had discovered the existence of a high-altitude zone of radiation encircling the Earth. The discovery of the Van Allen radiation belts was one of the most significant events of the IGY.

On February 7, 1958, Secretary of Defense McElroy, acting on President Dwight D. Eisenhower's instructions, announced the establishment of an Advanced Research Project Agency (ARPA) to manage all existing military and civilian space activities. ARPA was to function only as an interim organization, pending congressional establishment of a civilian space management agency. Toward the end of March, McElroy announced the approval of a lunar program to be directed by ARPA as part of the United States participation in the IGY. The program involved three launches by the Air Force, using a *Thor-Able* combination, and two Army launches utilizing the new *Jupiter* Intermediate Range Ballistic Missile (IRBM), designated by von Braun as *Juno II*. The scientific objectives were to measure cosmic radiation, establish a lunar probe trajectory, verify the tracking and communications design, and more accurately determine the Moon's mass. The targeted launch dates established for the Army's *Juno II* missions (designated *Pioneers III* and *IV*) were November 11 and December 14, 1958.

At JPL, research into the tracking and communications requirements for lunar and deep space probes had been in progress for some time. Studies of the communications link efficiency indicated that 108 MHz used for the *Explorer* Earth satellites was not an optimum frequency for lunar and deep space communications. The low-power spacecraft transmitter also dictated the need for a more efficient, high-performance, Earth-based antenna. After consideration of antenna gain and automatic tracking performance, minimum galactic noise, the use in the near future of high-gain spacecraft antennas, and the present state of the art, the 960 MHz L-band frequency was selected as near-optimum for a spacecraft transmitter. A large-diameter, steerable, parabolic dish antenna was determined to be the necessary ground adjunct for the *Pioneer* lunar missions and for the support of expected follow-on deep space missions. Implementation time and cost were also important factors governing the selection. To meet the year-end launch dates scheduled for *Pioneer*, the antenna had to be built and operable in approximately 6 months, and at the same time should represent an advanced and reliable design. An antenna that met a great majority of these requirements was fortunately already in existence. It had been designed for use as a radio astronomy antenna and was being fabricated for a number of scientific institutions. The antenna was a 26-m (85-ft) diameter parabolic dish with surface tolerances approximately 0.32 cm (0.125 in.) and pointing characteristics (0.1 deg) that would permit efficient use at frequencies from 1 to 3 GHz, which were expected to be the long-term, deep space allocations. The antenna structure was designed for automatic, closed-loop steering control. The 26-m dish was constructed of punched aluminum panels bolted to an open steel framework mounted atop a 34-m (110-ft) high tower-like equatorial mount steering mechanism.

Of equal importance with the selection of the antenna design was the selection of the antenna site. To obtain the full benefit of the extremely sensitive ground receiver, the site had to be remote from man-made electrical and radio interference, that is, away from metropolitan centers but still close enough to be practical. JPL engineers considered the Mojave Desert, approximately 160 km (100 air miles) north of Pasadena. During March, 1958, a JPL survey team made a series of radio interference tests and selected a remote natural bowl-shaped area near Goldstone Dry Lake on the Fort Irwin military reservation, 72 km (45 miles) northwest of the desert city of Barstow. In April, a construction company was selected, access roads were started, and in early June steel workers began construction on an accelerated basis to meet the scheduled *Pioneer* launch dates. With work underway at Goldstone, a mobile tracking station using a 3-m-diameter antenna was located near Mayaguez, Puerto Rico, to obtain initial trajectory data downrange from the Florida launch site (Fig. II-3). Arrangements were also made with the 76-m-diameter radio astronomy antenna at Jodrell Bank, Manchester, England, to track the spacecraft.

On October 1, 1958, the National Aeronautics and Space Administration officially began operations. Discussions quickly followed regarding the status of the Jet Propulsion Laboratory and its possible acquisition by NASA as a component field center. On October 15, 1958, NASA outlined a proposal to Secretary of Defense McElroy concerning the transfer of JPL from the Army.[9]

[9]Suggested Program for Implementation of Proposal Made to the Honorable Neal H. McElroy, Secretary of Defense, National Aeronautics and Space Administration, Oct. 15, 1958.

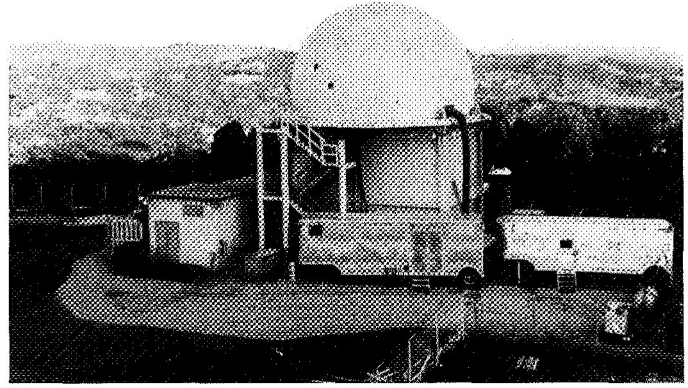

Fig. II-3. Trailer-mounted Microlock ground receiving station at Puerto Rico (1958)

As the situation regarding JPL's goal in the space program under NASA developed, a proposal to conduct a space flight program study with support from ABMA was made to Dr. Abe Silverstein in NASA.[10] The proposal offered to design a deep space exploration program for NASA and JPL which would include experiments and developmental work necessary to create a continuing effort.

During November, construction of the new 26-m antenna at Goldstone was completed (Fig. II-4). A communications system consisting of voice and teletype circuits was installed connecting Goldstone, the Atlantic Missile Range, and Mayaguez with JPL in Pasadena. By the end of November 1958, the Department of Defense notified NASA[11] that conditions established for the transfer of JPL were acceptable. During the next few days, a cooperative agreement was drawn, together with an Executive Order directing the transfer. On December 3, President Eisenhower issued Executive Order 10793 transferring the functions and facilities of the Jet Propulsion Laboratory of the California Institute of Technology from the Department of the Army to NASA.[12] Three days later, on December 6, 1958, the modified four-stage *Jupiter* launch vehicle called *Juno II* lifted a 6-kg (13-lb) conical space probe named *Pioneer*

[10]Proposal for Space Flight Program Study, Nov. 7, 1958; cover letter to A. Silverstein from V. C. Larsen, Jet Propulsion Laboratory, Pasadena, Calif., Nov. 7, 1958.

[11]Letter, Dr. D. Quarles to Dr. K. Glennan, JPL Historical Files, Jet Propulsion Laboratory, Pasadena, Calif., Nov. 28, 1958.

[12]*First Semiannual Report to the Congress.* National Aeronautics and Space Administration, Washington, D.C., June 16, 1959, p. 36

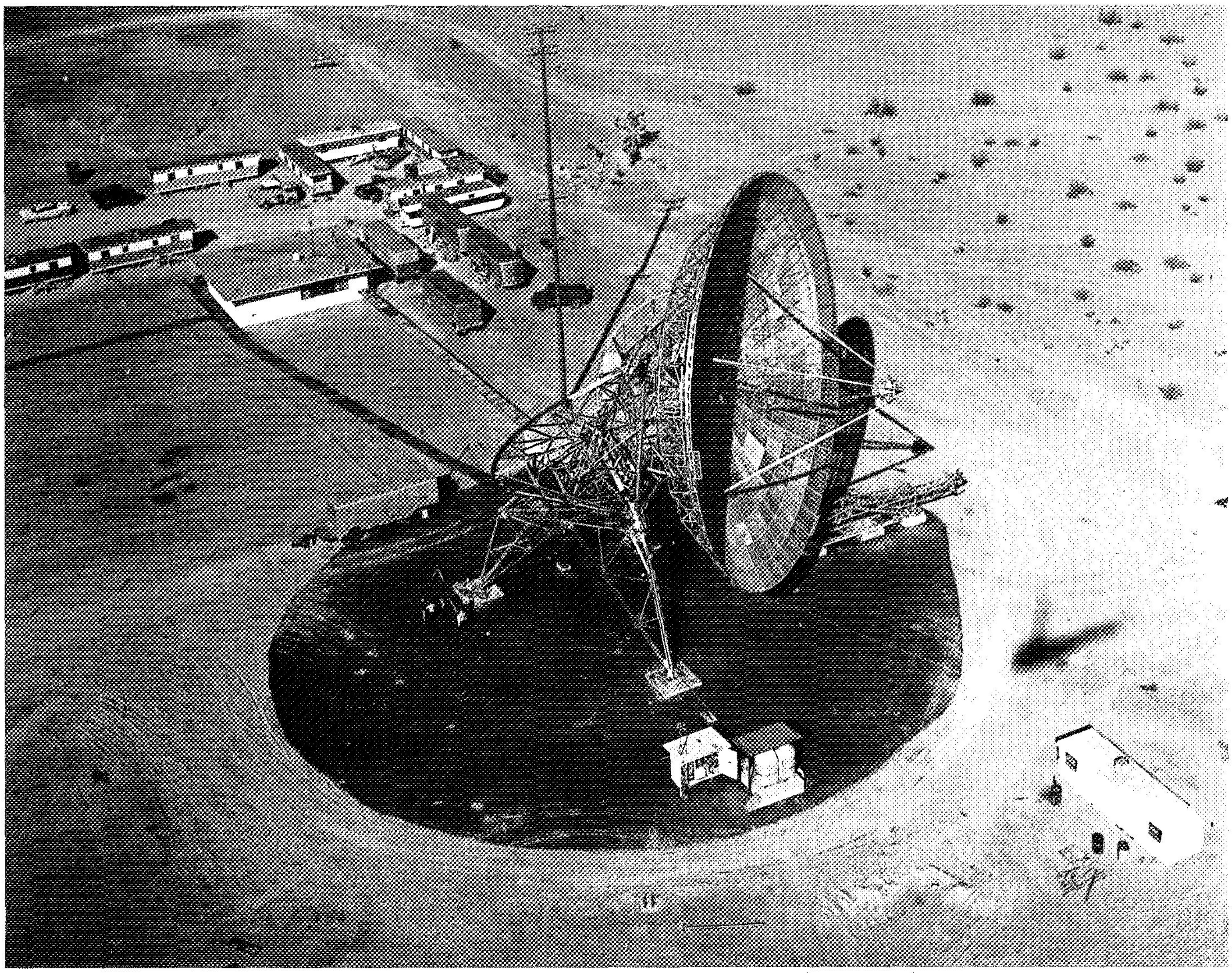

Fig. II-4. The first 26-m-diameter deep space station at Goldstone

III on a trajectory toward the Moon. Due to an early cutoff of the booster, the probe failed to achieve the 40,000 km/h (25,000 mi/h) escape velocity and plunged back into the Earth's atmosphere 38 hours and 6 minutes later after reaching an altitude of 101,728 km (63,580 miles). The ground tracking system successfully followed the probe, gathering telemetry data that revealed a second radiation belt 16,000 km (10,000 miles) above the Earth. On March 3, 1959, another *Juno II* stood ready for a second try at the Moon. This time, all four stages functioned successfully, accelerating *Pioneer IV* beyond the grasp of Earth's gravitational field. After 41 hours of flight, and traveling at 7,184 km/h (4,490 mi/h), *Pioneer IV* passed 59,680 km (37,300 miles) from the Moon's surface on a flight path that was a good deal ahead of and below the planned trajectory. The unexpected range defeated one of the on-board experiments —a photoelectric sensor that was to be triggered by reflected light from the hidden side of the Moon. The purpose was simply to report that the probe "saw" the far side of the Moon as it passed. Radiation counters on board provided more significant information, discovering an apparent third belt of radiation at an altitude of 32,000 km (20,000 miles), as well as sensing significant differences in the radiation intensity of the earlier discovered belts. Tracking operations were again successful, with 24.6 hours of telemetry information being recorded. Finally, 82 hours after liftoff, the continuously transmitted signal stopped as the probe's batteries became exhausted. The calculated range was a new long-distance communication record: 651,200 km (407,000 miles).

Deep Space Instrumentation Facility

Early proposals. When President Eisenhower, early in 1958, announced the intention of the United States to enter into the space program, a number of interested agencies and contractors, including JPL, began studying possible ground surveillance networks which might fit the requirements. JPL proposed a three-station network for the tracking of deep space probes. Initial site locations were Goldstone, California; Nigeria, Africa; and Luzon, Philippine Islands. This network was approved by the Advanced Research Projects Agency[13] and submitted to the Department of Defense as part of ARPA Order No. 1.

However, in July 1958, Dr. Donald Quarles of the Department of Defense questioned the utility of the network and the locations of the overseas sites. Richard Cesaro of ARPA, therefore, asked the Jet Propulsion Laboratory to consider a proposed network relative to other space programs. The resulting JPL study, completed in July 1958, demonstrated that, by careful selection of overseas site locations, and by relatively minor modification in the equipment, it would be possible to make the interplanetary network considerably more useful to the United States. For example, the Nigeria station was shifted to Southern Portugal or Spain, and the station in the Philippines was relocated to South Central Australia. These sites added many more orbits (particularly at 34–51 deg inclination) to the station coverage.[13]

Goldstone. Dr. Eberhardt Rechtin, who led the proposal team and later became the Assistant Laboratory Director for Tracking and Data Acquisition at JPL, had already assembled and was leading the team that designed and built the first antenna at Goldstone, California, to support *Pioneers III* and *IV*. The station was subsequently named the Pioneer Deep Space Station.

The antenna was patterned after the radio astronomy antennas then in use by the Carnegie Institute of Washington, the Associated Universities, and the University of Michigan. There were significant differences, however. First, the Goldstone antenna incorporated a closed-loop device for automatically pointing the antenna at the space probe. The electrical simplicity of a steerable parabolic reflector made this a good choice for maintaining continuous contact with the spacecraft. Second, to track the space probe automatically, the antenna had to possess an electrical feed capable of utilizing the space probe signal for driving the servo control system. Third, the antenna had to be able to operate without failure for many continuous hours without being impaired by wind or temperature. The single significant feature borrowed from the radio astronomy antenna was the design of the gear system that moved the antenna. The axis of the polar, or hour angle, gear wheel was parallel to the polar axis of the Earth and pointed precisely at Polaris, the North Star. The declination gear wheel was mounted on an axis parallel to the Earth's equator (perpendicular to the polar axis), which enabled the antenna to move up and down. The gear wheels could be moved either separately or together. Since the spacecraft moved much like a celestial object in space after traveling several thousand miles away from the Earth, it was natural to choose a mount that would steer the antenna from one horizon to the other at a sidereal rate, thus simplifying the mechanical complexity. All of these design features were successfully incorporated into the construction and operation of the Goldstone 26-m antenna.

Woomera and Johannesburg. The first overseas station location was near Woomera, Australia. This location offered at least three advantages. First, it was located in a country which had considerable technical competence in its own right, and where English was the spoken language. Second, this location met the general requirement of being approximately 120 deg in latitude from Goldstone and was in the southern hemisphere at a latitude of less than 35 deg. Finally, the site was one that had been used by the British and Australians for testing missiles, and a Minitrack station had been placed there in late 1957, during the International Geophysical Year.

This site was known locally as "Island Lagoon" because of the dry lake bed near the station site, which had what appeared to be an island in the center. Starting in early 1960, antenna construction proceeded on schedule, and by midyear, the installation of the electronic equipment in vans was proceeding. The station (Fig. II-5) was completed in September and was operational by November 1960.

By the end of 1959, it had become clear that the location of a third deep space station in the Union of South Africa would fulfill the need for providing continuous coverage for deep space probes. The site chosen was near Johannesburg, where a Minitrack station was already in operation, since it was desirable for the new

[13]Rechtin, E., Richter, H. L., Jr., and Victor, W. K., *National Ground-Based Surveillance Complex* (JPL Internal Document), Technical Memorandum 39-9. Jet Propulsion Laboratory, Pasadena, Calif., Dec. 15, 1958

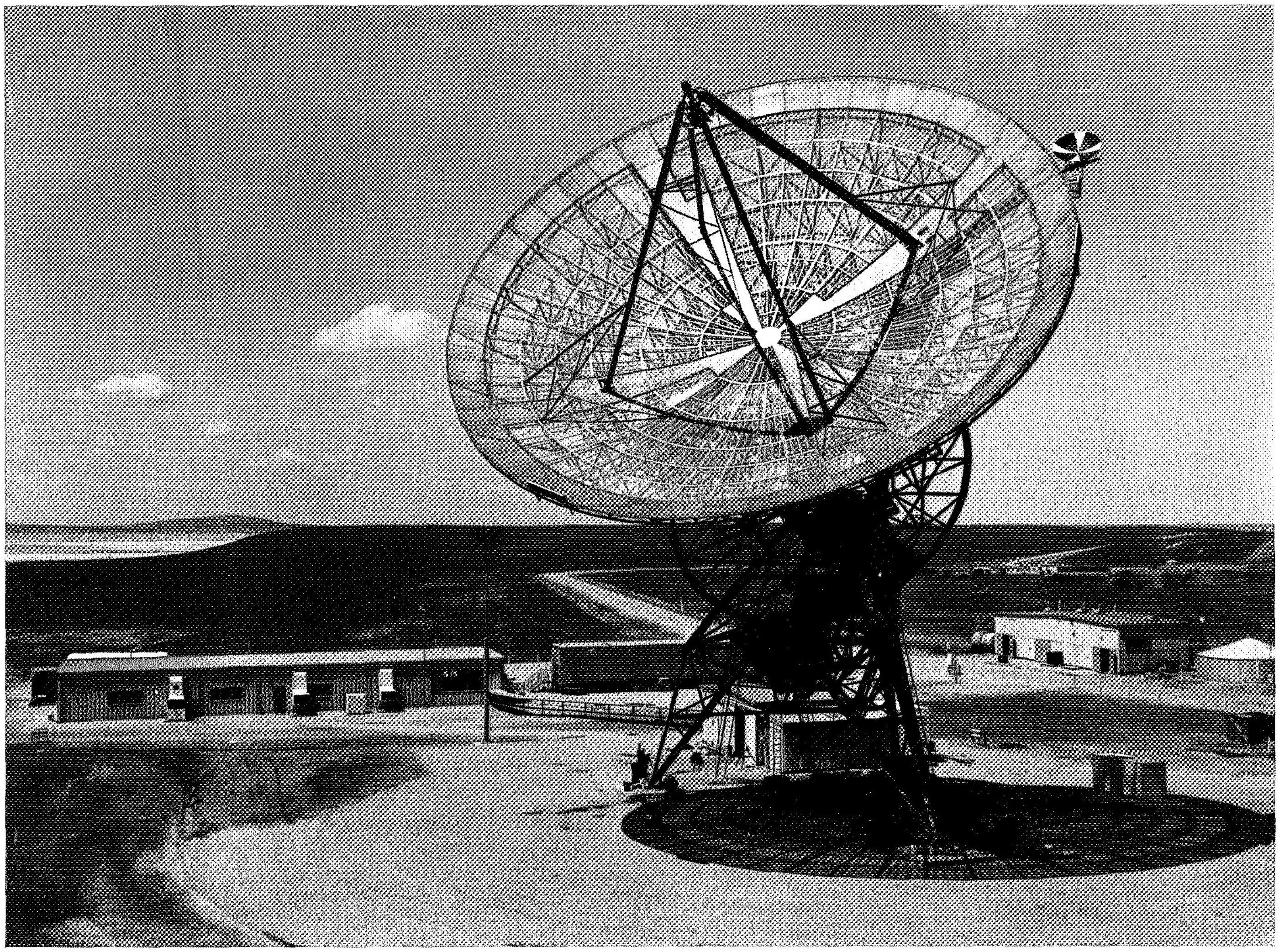

Fig. II-5. The first overseas deep space station, Woomera, Australia

deep space station and the Minitrack station to be in the same vicinity.

In September 1960, an agreement between South Africa and the United States permitted NASA to issue a contract to the South African Council for Scientific and Industrial Research (CSIR) for the construction, management, and operation of a station. Construction was to be completed by July 1961, in time to support the first *Ranger* launch in August. In view of this, a preliminary contract had been issued to CSIR in April 1960, to permit initial planning to proceed. In addition to the permanent 26-m station, the mobile tracking station, located in Puerto Rico, was also to be moved to the Johannesburg site.

By January 1961, the antenna foundation had been completed, and by March 1961, erection of the antenna was finished and the operations building ready for occupancy. The station (Fig. II-6) was ready for operation by the end of June 1961. Teletype equipment and communication circuits were provided by the South African Postmaster General Department, allowing the station to participate in its first *Ranger* test by July 1961.

Tidbinbilla. By 1962, plans had been accomplished to expand the DSN to provide another 26-m-diameter antenna in Australia. Detailed work, which included preparation for procurement of the equipment for the station, had been started by the engineering and operations organization at JPL under Dr. N. A. Renzetti. At the same time, NASA Headquarters had made arrangements for a survey in Australia to determine the best site location. In keeping with NASA policy of colocating facilities wherever possible, the site was to be large

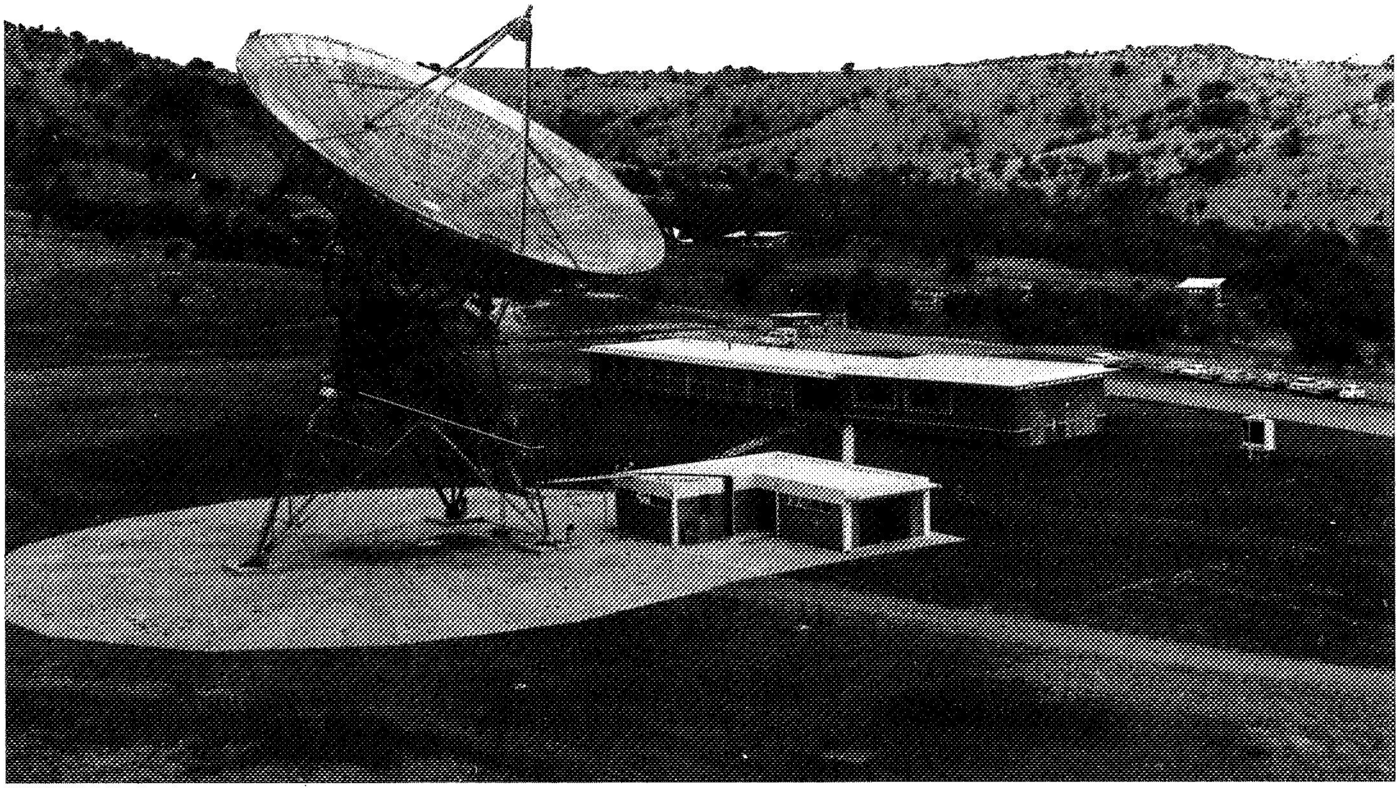

Fig. II-6. The second overseas deep space station, Johannesburg, South Africa

enough to include three to four additional antennas to support the DSN, the Satellite Tracking and Data Acquisition Network (STADAN), and the Manned Space Flight Network (MSFN). The site occupied by the minitrack station and the Deep Space Station at Woomera, Australia, was considered unsuitable because of the difficulty of obtaining staff and the expense of operating at a location that was remote from any major city.

In August 1962, after a survey of possible locations, Canberra, Australia, was selected, principally because it was in a relatively noise-free area. Canberra was the federal capitol of Australia and was expected to be a city of over 100,000 in a few years. In addition, since the government had set aside nearly 2590 square kilometers (1000 square miles) as federal land, the maintenance of a noise-free area would be relatively easy. The city of Canberra is at an average altitude of about 579 meters (1900 feet) and is encircled by a mountain range which extends to the southwest for some 160 kilometers.

By January 1963, a specific suitable site was found 16 km southwest of the city of Canberra, in a location known as Tidbinbilla. In the summer of 1963, a temporary road was started into the site location, so that building materials could be moved in for the facility construction. By November 1963, the power building was completed and ready for the installation of generators. On March 19, 1965, the Tidbinbilla station was officially opened by the Prime Minister of Australia, Sir Robert Menzies. Along with a number of representatives of the Australian, U.S.A., and foreign governments were E. C. Buckley from NASA and General Alvin R. Luedecke and Dr. Eberhardt Rechtin from JPL (Fig. II-7). The station became fully operational in March 1965. It participated in the *Surveyor* launch and backed up the

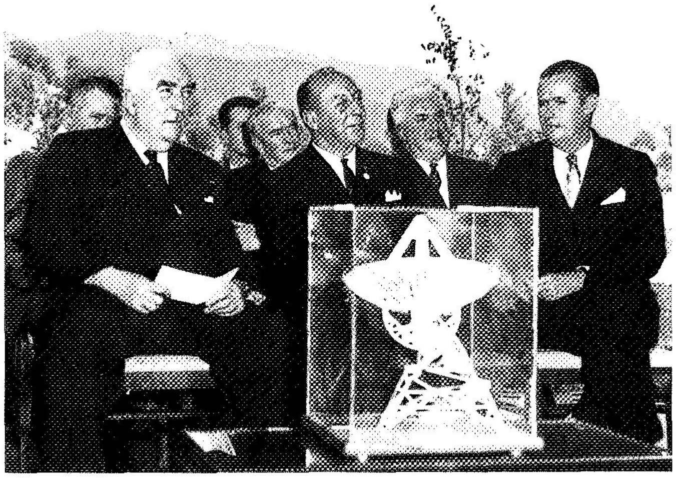

Fig. II-7. Prime Minister Robert Menzies of Australia (front row left) joins NASA and JPL officials for the dedication of the Tidbinbilla station, near Canberra

Mariner IV flyby of Mars in July 1965. Since that time, the station has participated in *Surveyor, Lunar Orbiter, Pioneer, Apollo,* and all of the *Mariner* programs.

Robledo. In response to a request from E. C. Buckley, Dr. Rechtin[14] proposed that areas in Sardinia, Southern Italy, and Sicily be investigated as possible sites for a 26-m deep space station. Such a station was considered necessary because of the increased DSN mission loading in the mid-1960s. Since NASA was already in a cooperative agreement with Italy for launching an Italian satellite, Professor Luigi Broglio, President of the National Institute of Space Research, provided invaluable assistance.

After careful analysis, it became clear that site locations in Italy would be too far away in longitude to provide a good overlap with the station at Goldstone. Therefore, the survey was expanded to include Spain. By early 1963, areas close to Seville, Toledo, Malaga, and Madrid had been chosen as suitable for antenna sites. A decision was made to concentrate on Robledo, an area southwest of Madrid, which presented an ideal location because of its nearness to a large population center from which could be drawn a technical staff to operate a deep space station. The Spanish Institute National de Technica Aeronautica (INTA), headed by General Antonio Perez-Marin, was contacted and assisted in the further survey work.

On February 3, 1964, E. C. Buckley requested that the United States Navy Department's Bureau of Yards and Docks, which was responsible for the construction of U.S. Government facilities in Europe, begin the design and construction of the station. By the end of 1964, construction was under way and the roof was placed on the engineering and operations building. Granite stone, which was relatively inexpensive and in plentiful supply in the area, was used for the walls. In the first month of 1965, a 150-kW generator was operating. During April, May, and June, 1965, work was concentrated on installing the electronic equipment. The station (Fig. II-8) became operational July 1, 1965, and supported the *Mariner IV* mission as a backup to the Johannesburg station.

Cebreros. In the spring of 1964, NASA decided to install a DSN station and an MSFN station in the Madrid area. It was also decided at this time to add a separate MSFN Control wing to the Robledo station.

Since a number of possible sites had been located during the initial site survey in 1963, it was relatively easy to review these and to select locations for the two new antennas. A team of NASA and INTA personnel reviewed the possible locations and eliminated all but four: Cebreros, Fresnedillas, Robledo de Chavela, and Rio Cofio. The team reviewed all the data and made extensive surveys of the areas. In the fall of 1964, NASA chose the Fresnedillas site for the prime MSFN station.

Dr. Eberhardt Rechtin visited Madrid in September 1964 and, together with INTA and NASA personnel,

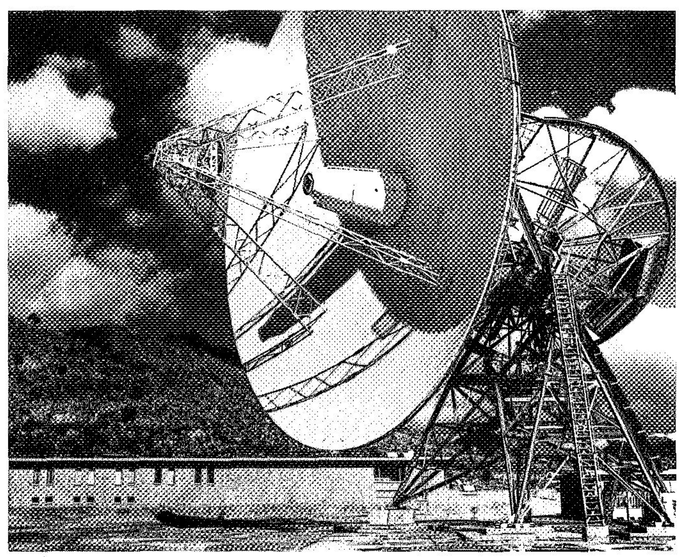

Fig. II-8. The Robledo Deep Space Station in Spain

[14]Letter, E. Rechtin, Jet Propulsion Laboratory, Pasadena, Calif., to E. C. Buckley, NASA, May 11, 1962.

reviewed proposed sites for the DSN station. After a survey and visits to locations, it was decided to locate the DSN station at Cebreros and to reserve the Rio Cofio site for a future 64-m antenna. In November 1964, contracts were let for the design of the DSN and MSFN stations.

In the spring of 1965, the Spanish Ministry of Foreign Affairs became concerned about the installation of two additional stations in the Madrid area, since the government agreement stated there should be only one station. After a number of discussions between the American Embassy, Spanish Ministry of Foreign Affairs, NASA, and INTA, the American Embassy and the Ministry of Foreign Affairs exchanged notes on October 11, 1965, defining the complex as a group of four facilities, each having an antenna. The note also stated the maximum amount of land available for each antenna. The initial construction of the DSN station at Cebreros was started in January 1966. The completion date was December 1966, and the station became operational in January 1967.

In late 1962, planning was initiated to make the temporary DSN launch station at Cape Canaveral (Kennedy)[15] a permanent facility. A permanent DSN facility at the Cape was needed for spacecraft compatibility testing for the ongoing *Pioneer, Surveyor,* and *Mariner* programs. These plans also provided for converting from L-band to S-band concurrent with the frequency change at the other DSN stations. In December 1962, JPL prepared a preliminary report which proposed a building layout and possible locations for a permanent DSN facility on Cape Kennedy. The location was important in order to meet the need for RF line-of-sight transmission between the proposed station and the *Pioneer, Mariner* and *Surveyor* launch pads and the JPL Explosive Safe Facility. The possible masking of the site by buildings and other obstructions was to be avoided. Location at the NASA Kennedy Space Center was rejected because of the distance and the presence of large bodies of water between the proposed site on NASA property and the launch complexes located on Cape Kennedy AF Station. The site selected was on Air Force property that provided an unobstructed view of the launch complex area from approximately 2.4 km away.

Following the authorization of funds, a JPL/NASA conference was held at Cape Kennedy on February 12, 1964, to establish procedures and initiate action to procure the facility. The NASA Kennedy Space Center had the responsibility for NASA construction; Air Force participation was limited to review of criteria and approval of site plans. Dr. Eberhardt Rechtin reviewed the history of the project and described the function of the proposed installation, and Dr. N. A. Renzetti outlined the general scope and configuration of the building and RF siting requirements. The final criteria for construction of the station were delivered to the U.S. Army Corps of Engineers on May 6, 1964.

Formal notification of site approval was received from the Air Force in June 1964. The final design and contract award proceeded on schedule, and construction was started in October 1964. The station was completed in April 1965, became operational in May, and supported the launch of *Pioneer VI* in December 1965.

Ascension Island. In late 1963 and early 1964, NASA began planning for a first acquisition station to cover the gap between Cape Kennedy and Johannesburg, South Africa. The requirement was for early acquisition and command capability in support of the *Surveyor* program. Ascension Island, a British possession located about 8150 km (4400 nautical miles) southeast of Cape Kennedy and approximately midway between South America and Africa, was designated as the most desirable site to fulfill the requirement. Since the Goddard Space Flight Center was also proposing a unified S-band station at Ascension, it was decided and approved by JPL and the NASA Goddard Space Flight Center to build an "Integrated Apollo and Deep Space Station" complex. An agreement was concluded with the United Kingdom which permitted the U.S. Government to construct and operate two tracking sites on the island. This agreement remains in force until July 20, 1975.

Initial site investigations were made by a NASA team in April 1964 and several reports were subsequently published and presented to the appropriate agencies (JPL, Goddard Space Flight Center, Air Force, Kennedy Space Center, and the U.S. Navy). The U.S. Navy, Bureau of Yards and Docks Contracts Office, was responsible for the design and construction of the facility.

On July 8, 1964, JPL personnel traveled to Ascension Island to conduct radio frequency interference tests and found no appreciable RF interference at the proposed Devil's Ashpit site. The location was approved by all responsible agencies in July 1964.

Initial construction of the facility was started in January 1965, with highest priority for completion because

[15]Cape Canaveral was renamed Cape Kennedy after the death of President John F. Kennedy in 1963.

of the *Surveyor* support commitment. Testing of subsystems was begun in November 1965 and system testing in January 1966. Construction was completed in March 1966; the station became operational in April 1966 and supported the *Surveyor I* mission in May.

Ground Communications Facility

The Ground Communications Facility had its beginnings in 1958 when a combination operations and communications facility was established at JPL for *Explorer I* (Fig. II-9). The GCF was formally established as a separate entity in November 1958. This early system consisted of voice and teletypewriter facilities installed by JPL to provide a reliable means for transmission of digital data, technical liaison, and administrative messages between the various deep space stations, computer centers, and communication centers. The system was capable of data transmission up to 60 words per minute and established voice communication between local stations at JPL, Goldstone, and Cape Kennedy. The GCF provided two teletypewriter circuits and one voice circuit between all points, with switching capabilities at message centers located at JPL and Cape Kennedy.

This early GCF configuration was first used to support the *Pioneer III* mission and was divided into two separate nets. One, called the Red Net, consisted of all teletypewriter nets and one voice net. The other, called the White Net, consisted of one voice circuit primarily between the deep space stations and the Computing Center at JPL, with monitoring capabilities at the two message centers for coordination and troubleshooting.

A basic problem faced by the DSN in 1960 was the design and implementation of a reliable ground communication system between the deep space stations and

Fig. II-9. Communications area (1959)

Fig. II-10. Communications Center (1961)

the JPL Pasadena Communication Center. The establishment and development of this communication system was guided by three major principles: (1) flexibility to meet changing mission requirements, (2) high reliability, based on maintenance, backup circuits and equipment, and operational planning, and (3) provision for increasing capability to accommodate new deep space stations and new circuits.

By 1961, the communications system was readied for the support of the *Ranger* Project. Each deep space station was connected to the Pasadena Communications Center (Fig. II-10) by two teletype circuits and one voice circuit. For convenience and accessibility, the spacecraft controllers (i.e., personnel who controlled the spacecraft maneuvers and the flow of data from the spacecraft to the Earth) were located in the Pasadena Communications Center, and teletype messages between the controllers and the communications personnel were passed through a slot in an intervening window. The controllers monitored their own voice circuits, and a wave and shout through the window brought a communications man when needed. The Communications Center was equipped with a manual patching (switching) capability that permitted any teletype machine to be connected to any of the long distance lines in order to print out the incoming data. The same data were also recorded on teletype tape and subsequently converted to punched cards for direct entry into the computer.

During this era, NASA evaluated the costs of the communications circuits used by JPL and other networks and determined that it would be more economical for JPL to share circuits. The leasing and control tasks were given to the Goddard Space Flight Center in Greenbelt, Maryland. This concept of providing all circuits from a common pool later evolved into the NASA Communications (NASCOM) network.

The *Ranger* spacecraft flights, which extended from August 1961 through March 1965, each lasted approximately 3 days. Even including "extensive" prelaunch testing, the entire test and operational period seldom exceeded 2 weeks. With launches occurring every 2 to 3 months, it was therefore quite practicable for NASA to lease teletype circuits on a short-term basis, releasing the circuits after the operation was completed. In many cases, it was not economical to lease full-period voice circuits; instead, conventional telephone calls were placed to overseas stations, such as Johannesburg. These commercially placed telephone calls were of variable quality and usually depended upon high-frequency radio for the overseas link. As launch time neared, more and more telephone operators would listen in, thereby lowering the volume on the line. At first, the cause for this volume loss was unknown, but the secret finally emerged when a JPL controller called out "Operator" and several voices answered almost simultaneously. After that, specific routings were used via special telephone operators which largely eliminated the "listening-in" problem, but did little to really improve the poor quality provided by high-frequency radio. As the global underseas commercial telephone cable network expanded, radio circuits were discontinued in favor of the much more reliable and higher quality submarine cable circuits.

Rangers I through *IV*, which were launched from mid-1961 through early 1962, indicated the need for improved communications control and switching techniques. Accordingly, the JPL Communications Center was physically reconfigured in 1962 to provide a separate Communications Control Room in which a new teletype line switcher, controlled entirely by push buttons, was installed. Also, a pushbutton-controlled voice conference system was installed in the Communications Center. This new equipment significantly reduced operator errors. The Communications Center was further modified by installing raised floorings, which permitted underfloor cabling. Closed circuit television was installed for the first time, and prototype consoles were fabricated from wood to house the television monitors and the voice and teletype pushbutton switching controls. These wooden consoles were installed in the Communications Center and used as test beds to demonstrate the intended features of the consoles which would be used in the forthcoming Space Flight Operations Facility. Finally, a four-wire voice communication system was installed at the deep space stations because of the need for multivoice conference nets. The new voice system allowed any operator to talk on any of the several nets.

The early *Ranger* missions and the approaching *Mariner*-Venus missions also pointed out the need for improved communications operational planning. Until the *Mariner Venus* operation in 1962, the communications operational planning for the *Ranger* 3-day missions had consisted of two sheets of paper per mission—one page denoting the circuit patching/interconnections and a second page containing the duty schedule for communications personnel. The *Mariner Venus* mission, however, required more comprehensive planning, since it was scheduled to last a minimum of 3 months. The early 3-day missions had resulted in heavy fatigue, which could not be tolerated on a 3-month mission. Vacations and sicknesses, plus a need to support three missions simultaneously (*Mariner I* (Venus), *Mariner II* (Venus), and *Ranger V*), required detailed planning. Consequently, a full-time communications operation supervisor was appointed in mid-1962, with the task of planning the *Mariner Venus* and subsequent *Ranger* communication operations. *Ranger V* was supported simultaneously with the *Mariner II* mission during October 1962, a first for both the communications function and for the rest of the DSN organization. (*Mariner I* was destroyed by the range safety officer shortly after launch.)

A break in mission operations during 1963 permitted a major effort to be devoted to the design of the new Space Flight Operations Facility and to the design of improved voice distribution facilities (tactical intercom) for the deep space stations. The wooden consoles built in 1962 proved a number of control center concepts, including the value of closed-circuit television for both data and time distribution. Area surveillance by closed-circuit television also proved to be worthwhile. Further, the consoles demonstrated the value of providing each operator with a number of voice conference loops which he could select. All these concepts were incorporated into the permanent SFOF equipment that was being designed. The earlier two-wire voice conferencing arrangement at the stations suffered from volume control problems as well as noisy operation under some conditions. Further, the two-wire conference arrangement permitted the JPL voice circuit to be heard only by the station manager.

Operation of the Communications Center focused attention on the difficulty of maintaining operator interest and skill levels during the long, low-activity cruise phase periods of planetary missions. Operator interest was easy to maintain during short lunar missions, but lagged somewhat during the cruise portion of the months-long *Mariner* missions. Although this problem has never been completely solved, it has been greatly reduced through improved staffing plans and the multi-mission environment.

During 1963, a third teletype circuit was installed between JPL and each of the four deep space stations. These three circuits, plus one voice line per station, were adequate for all control and data communications purposes. Late in the year, a broad-band microwave link was installed between JPL in Pasadena and the Goldstone communications center at the Echo Station. This microwave link, which was not placed into service until 1964, carried reliable voice, teletype, high-speed data, and a wide-band channel between the two locations.

In December 1963, JPL officially established the Deep Space Network as an organizational entity to more efficiently accommodate the increasing number of unmanned flight projects. Under the direction of Dr. Eberhardt Rechtin, the DSN brought together under one organization the Deep Space Instrumentation Facility, the Space Flight Operations Facility, and the Ground Communication Facility. Until this time the Tracking and Communication (Extraterrestrial) system (TRACE), developed in 1958 for deep space tracking of the *Pioneer* lunar probes, had unofficially been referred to as the DSN. In 1964, all mission operations were formally shifted to the newly completed Space Flight Operations Facility in support of *Ranger VII* and *Mariners III* and *IV*. *Ranger VII* operations, though conducted from the new SFOF, used the same operational procedures that had been employed for the previous *Ranger* missions. Because the *Ranger* operations and communications personnel were functioning smoothly with existing procedures, the risks involved in the introduction of new procedures to utilize the new SFOF and GCF equipment did not appear warranted. *Ranger VII* returned over 4,000 lunar photos to Earth, demonstrating that the old equipment and procedures were still workable.

It was also during this time (1964) that NASA Communications, which had supplied the long distance lines since 1961, installed a computer-based communications processor at the Goddard Space Flight Center in Maryland. This communications processor (CP) automatically routed teletype messages to their destinations and to individual machines–an improvement differing greatly from the manual line switching employed by the GCF. Again, to eliminate the possible risks involved in the use of new equipment and procedures, *Mariners III* and *IV*, launched in November 1964, were committed to the older line switching procedures, and the NASCOM CP was bypassed for these two *Mariner* missions.

The majority of the stations received and installed the newly designed tactical intercom voice assemblies in 1964 and pressed them into immediate service. These units permitted a large number of station operators to use a single large voice conference loop simultaneously, and also allowed the long distance lines from the SFOF to be entered into one of these conferences. The tactical intercom was the first piece of station communications equipment specifically designed to rigorous DSN standards. The stations at Woomera and in Johannesburg were not initially supplied tactical intercoms because of the difficulty in obtaining local government permission to interconnect the tactical intercom to the communications lines provided by the Australian and South African governments. In time, these objections were allayed and the tactical intercoms became standard at all DSN stations.

The Ground Communications Facility personnel quickly adapted to the new capabilities provided by the SFOF. Closed-circuit television was used for area surveillance, teletype data distribution, time distribution, and the display of data from one area of the building to another. The voice system allowed the same headset to be switched to the telephone, intercom, or voice conference net by the push of a button. Speakers and microphones could be used flexibly on the conference net, the intercom, or the telephones. Teletype switching was accomplished by a semiautomatic push button switcher unit located in the basement of the SFOF. A large wall display indicated the switching status. This teletype switching system also permitted more than 100 users to individually select the teletype data to be displayed on their teleprinters. At the same time the teletype data were being directly inserted into the computers, eliminating the need for card punching. These new capabilities supported the *Mariner IV* flyby of Mars in late 1964.

The heavy growth of the DSN during 1964-1965 required constant enlargement of the communications capability. It was soon realized that circuits for three additional stations (Canberra, Madrid, and Cape Kennedy), plus other new facilities under construction, would overtax the teletype switching capability in the SFOF. Design studies during late 1964 and early 1965 indicated that the SFOF should be equipped with a communications processor similar to the one used by NASCOM. The SFOF Communications Processor design was completed in 1965 and the procurement action started. The SFOF teletype switching system was temporarily modified to permit it to handle the additional teletype circuits brought into being by the three new stations: Canberra, Robledo, and Cape Kennedy. These stations began operations in 1965. To accommodate the upcoming *Pioneer*, *Surveyor*, and *Lunar Orbiter* missions, scheduled for 1965 and 1966, the SFOF initiated a phased expansion. This expansion consisted largely of providing additional mission support areas, communications, and instrumentation.

Perhaps of greatest importance in 1965 was the introduction of high-speed data to support the upcoming *Surveyor* Project, which would generate telemetry data rates that far exceeded the 30–50 bits per second transmitted by existing teletype circuits. Even the early *Mariner Venus* mission required the use of two teletype circuits to handle all of the data transmitted back to Earth by the spacecraft. In contrast, the *Surveyor* would have data rates up to 4400 bits per second, which would have to be transmitted back to the SFOF. Thus JPL had to engineer and provide a high-speed data capability from the Goldstone, Johannesburg, Madrid, Australia, and Cape Kennedy stations to the SFOF. A second voice circuit was added to each station to handle bit rates between 137.5 and 1200 bits per second, and a special high-frequency circuit was installed to handle the 4400-bit telemetry data rate, thus greatly increasing the data handling capability. The teletype circuits were increased to four per station for the transmission of radio metric operational control, and backup teletype data. The NASCOM communications processor at Goddard Space Flight Center was working well and all GCF teletypes were shifted to the format required by this automatic switcher.

During 1965, the wide-band 6-MHz channel between Goldstone and the SFOF was rigorously tested and upgraded in preparation for the *Surveyor* and *Lunar Orbiter* missions, which were both scheduled to return television data to Goldstone for relay back to the SFOF.

The Ground Communications Facility grew over these years (1961–1965) from supporting one small control center and three stations to supporting a large computer-oriented control center and 11 deep space stations. By the end of 1965, it had quadrupled its circuit handling capability, developed procedures to support a multimission environment, and changed in many other ways, all of which contributed to maturity and operational finesse.

Space Flight Operations Facility

The first version of an operations and communications facility was established at JPL in January 1958 (Fig. II-11). Communications and flight data from *Explorer I* were received in one room which included communications and timing equipment along with a few chairs and desks for about a half-dozen engineers and scientists. Desk calculators operated by an additional half-dozen "computresses" were used for handling radio metric data and computing trajectories.[16] The backup calculator, using a pencil stub and the back of an envelope, was Dr. Richard Feynman, Caltech physicist and later Nobel Laureate.

Essentially, this forerunner of the Space Flight Operations Facility received metric data from the deep space stations via teletype. Digital telemetry data were recorded at the station on magnetic tape in analog form and shipped by mail to JPL, where an oscillograph strip chart was produced for analysis by scientists and engineers. In late 1958, the digital computing capability at JPL consisted of one IBM 704 computer, which was used for orbit determination. In 1960, the 704 computer was replaced by a bigger, faster IBM 709 computer. Both were all-vacuum-tube computers and generated large amounts of heat, which required extensive air conditioning.

The procedure of recording telemetry data on tapes, which were then shipped to JPL for processing, obviously resulted in an appreciable delay in getting the data into the hands of scientists and engineers. An attempt to speed up the process was made in 1961 to support the upcoming *Ranger* program. The design involved the installation of a "science data translator" at the station, which removed the data from the spacecraft signal, translated it from binary to octal arithmetic coding, and then transmitted the information by teletype to JPL, where it was printed out on teletype machines.

By August 1961, a comprehensive space flight operations organization designed to support *Ranger*, JPL's first lunar space flight project, was completed. The organization consisted of facilities, equipment, computer programs, operations personnel, and the planning and procedures needed for spacecraft tracking, data transmission, data processing, and analysis. A portion of this early version of the SFOF is shown in Fig. II-12.

In 1962, in keeping with the DSN policy of constantly improving its capabilities, the IBM 709 was replaced by the new IBM 7090 computer, a transistorized version of the 709. This computer processed and reduced the volume of the data, which was then forwarded to users for analysis. Spacecraft signals received at a deep space station were converted, formatted, and encoded at the station for transmission by teletype to the SFOF in Pasadena. The arriving raw telemetry and metric data were printed out on teletype and on punched tape which was used to transfer the data to IBM punched cards. The printouts, containing the raw data samples, were taken from the teleprinters and given a point-by-point scanning that provided a rough estimate of the spacecraft status and the condition of the data itself. When a prespecified number of samples had been accumulated and transferred to punched cards, the cards were fed into the IBM 7090, which performed computations. Plots and tabular listings were printed by the computer and manually distributed to the analysts for detailed study.

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[16] *The First Decade of Space Research,* JPL Internal Document 754 1-68. Jet Propulsion Laboratory, Pasadena, Calif., Feb. 1, 1968.

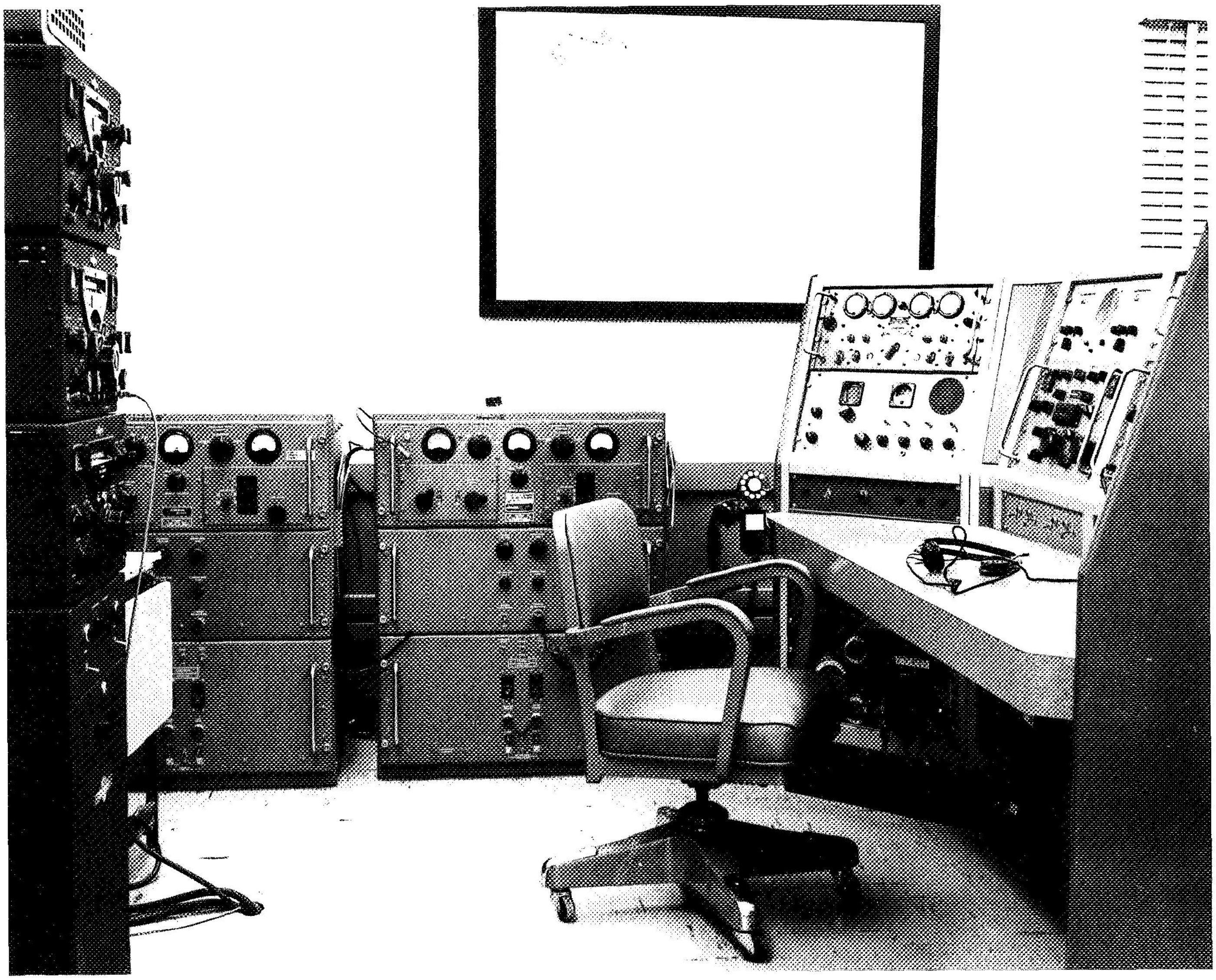

Fig. II-11. Operations area for *Explorer I* (1958)

Again, it was determined that additional processing capability would be required to meet the requirements of the coming concurrent flights of *Ranger V* and *Mariner II*. These requirements involved bringing back both science and engineering data by teletype for simultaneous processing in real time. JPL devised a dual computer configuration consisting of the IBM 7090 and a PDP-1 computer. The PDP-1 was connected to the teletype terminals and produced three reels of magnetic tape plus a limited printout on an associated typewriter. One reel logged the complete incoming engineering and scientific data stream. The second reel logged decommutated engineering data, while the third reel recorded decommutated scientific data. The tape reels were removed from the PDP-1 and hand-carried to the IBM 7090 for batch processing. Metric data, however, were transmitted on a separate teletype circuit, punched on paper tape, and converted to IBM cards for batch entry into the IBM 7090. The core of the PDP-1 computer was split into two parts to accommodate both *Ranger V* and *Mariner II* engineering and scientific data formats, engineering unit conversion, and limited alarm monitoring. This dual computer configuration successfully supported both *Ranger* and *Mariner II* requirements.

The experience acquired from using two computers in series was applied to the next evolutionary SFOF design in late 1962 and early 1963. This configuration consisted of one IBM 7040 computer used as an input/output

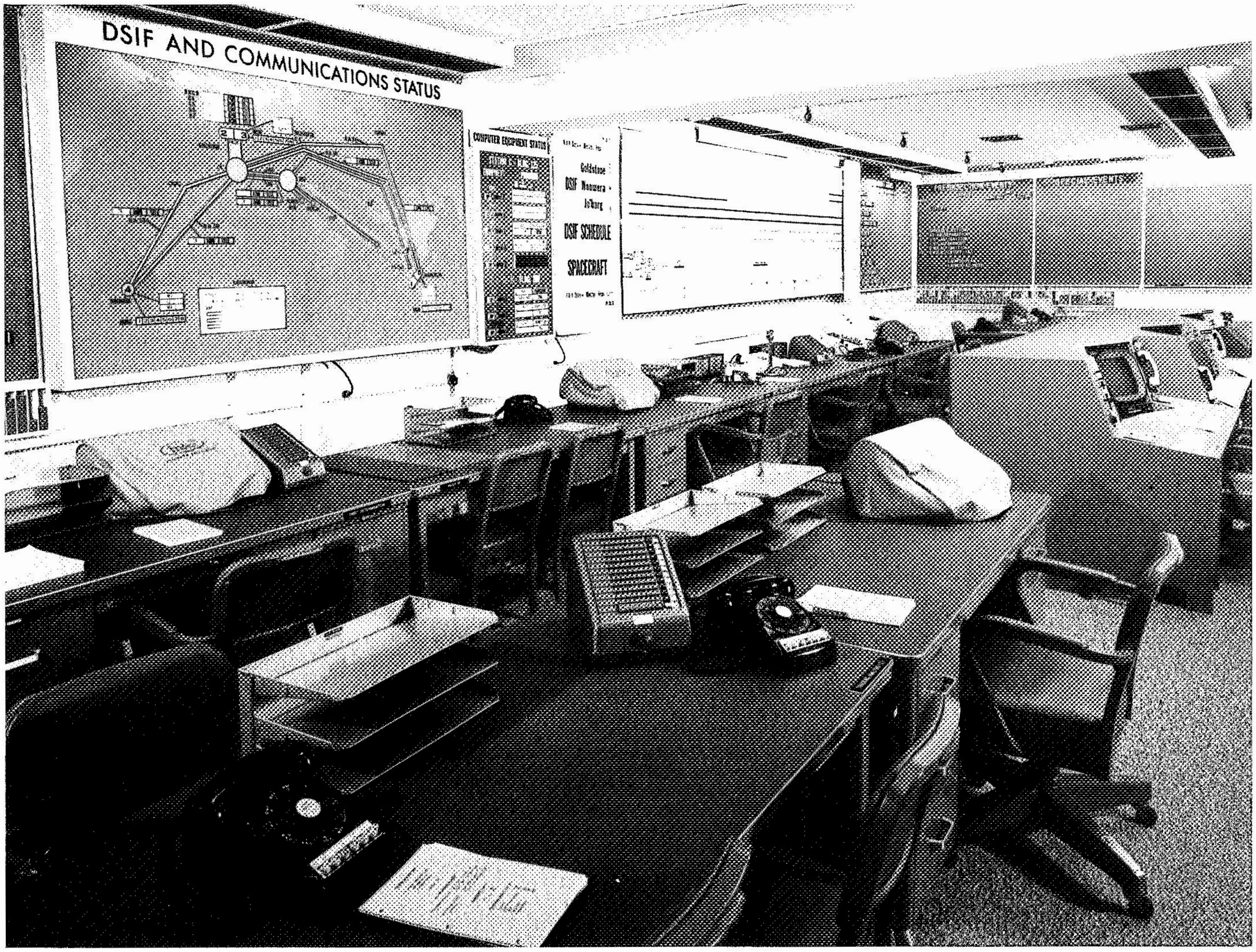

Fig. II-12. Operations area (1962)

processor and connected to teletype lines in the SFOF, a 1301 disk storage file, and an IBM 7094 computer. This arrangement was to enable the 7094 to process data in non-real-time and permit data to be printed out in various user areas in the SFOF via the 7040 I/O computer. Both the 7040 and 7094 would have access to the common 1301 disk storage file. Considerable difficulty was encountered in the initial development of this configuration, and the 7040 computer was replaced by a 7044 computer in time to meet the *Mariner IV* launch date. *Mariner IV* was the first project to be supported with this new SFOF combination real-time/non-real-time computing capability.

The *Ranger* program chose to continue using the PDP-1 and the IBM 7094 computer configuration until termination of *Ranger IX* in March 1965. In effect, this amounted to having two data processing systems in the SFOF during 1964 and 1965: the 7044–7094 combination supporting *Mariners III* and *IV* and the PDP-1 7094 configuration supporting the *Ranger* program.

Frequency Conversion, L- to S-Band

In 1958, the 960 MHz L-band frequency was chosen as an optimum frequency for the *Pioneer III* and *IV* lunar missions. The Earth-based *Pioneer* Deep Space Station located at Goldstone had dual simultaneous receiving capability. It could use 960 MHz (L-band) for communication receiving and could use 2388 MHz (S-band) for receiving angle tracking radar. The S-band frequency was chosen, both because of the availability of the spectrum and because of the frequency's application to future deep space communication design. For example, galactic background noise was high at the L-band; the higher S-band frequency decreased the noise while providing additional advantages by increasing the gain of the spacecraft antennas, which were limited in area.

In mid-1962, Dr. Eberhardt Rechtin recommended the development of an S-band configuration as a standard for the DSN. The conversion of an entire network from L-band operation to S-band operation without jeopardizing established commitments to the flight projects posed a significant challenge for the fast-growing Deep Space Network. By late 1962, a preliminary design had been completed, and by the spring of 1963, the project was well under way. JPL's goal was to use the S-band on the *Mariner III* and *IV* missions in November 1964. By the summer of 1963, the full implementation of an S-band configuration seemed unlikely for the *Mariner 1964* mission. At that time, all stations in the network were operating on L-band and had successfully supported the *Ranger* and early *Mariner* missions, as shown in Table II-1. But the goal to have at least three stations ready in time to support two *Mariner* launches in November 1964 with the new S-band transmit-and-receive frequencies appeared out of reach. The task was complicated by the need to keep the full L-band capability to support the remaining *Ranger VIII* and *IX* missions. These missions were planned to follow the *Mariner 1964* launches in February and March 1965 (Table II-2).

Table II-1. DSN conversion from L-band to S-band operation

Station	No.	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967
Pioneer	11	L 12/58	L	L	L	L	L	L/S 9/64	L/S	S	S
Echo	12			L 4/60	L	L	L	L	S 6/65	S	S
Mars	14									S 5/66	S
Woomera	41			L 11/60	L	L	L	L/S 8/64	S 12/65	S	S
Tidbinbilla	42								S 3/65	S	S
Johannesburg	51				L 7/61	L	L	L/S 9/64	L/S	L/S	S 3/67
Mobile Station		L	L	L	L	L	L				
Robledo	61								S 7/65	S	S
Cebreros	62									S 5/66	S
Spacecraft Monitor	71				L	L	L	L	S 5/65	S	S
Ascension	72									S 2/66	

Table II-2. DSN L-band and S-band mission support

Type of mission support	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967
L-Band	PN III	PN IV	PN V	RA I RA II	RA III RA IV RA V MA I MA II		RA VI RA VII	RA VIII RA IX		
S-Band							MA III MA IV	PN VI	PN VII SU I SU II LO I LO II	MA V PN VIII SU III SU IV SU V SU VI LO III LO IV LO V

[a]PN = *Pioneer*, RA = *Ranger*, MA = *Mariner*, SU = *Surveyor*, LO = *Lunar Orbiter*.

Some of the S-band equipment was available: the S-band maser and transmitter, the antenna cone, the feed, and the subreflector. The Pioneer, Echo, Woomera, and Johannesburg Deep Space Stations already had operational L-band receivers, preamplifiers, and antenna feeds.

Some time earlier, it had been suggested that perhaps the new S-band system could be coupled to the L-band system to make a temporary L/S hybrid arrangement. This idea was abandoned, however, because of the problem of extracting the S-band doppler information in such a way as to be compatible with the existing L-band data handling system.

A JPL design team suggested the idea of mixing each of the S-band transmitter and receiver voltage-controlled oscillators with a synthesizer driven by a high-reliability rubidium standard oscillator. The synthesizer could be set to make the resulting S-band doppler frequencies compatible with the existing L-band data handling system. The two sets of data, one representing the transmitter frequency, and the other representing the receiver frequency containing the desired doppler offset, could be manipulated in the SFOF computer to extract the required two-way doppler. This design was designated the "L/S Conversion Project."

Essentially, the L-band system remained intact, and suitable cabling and switching permitted the servo, telemetry, and doppler data streams to be derived from either the L/S receiver or the L-band receiver. The L/S receiver and transmitter were located beside the L-band equipment, while the S-band maser, parametric amplifier, and transmitter were installed in their final positions in the S-band Cassegrain cone (Fig. II-13). The major mechanical task involved in the change from L- to S-band operation required replacing the L-band turnstile feed with a new hyperbola subreflector.

Using the existing L-band receiver at the Goldstone Pioneer station, a prototype L/S model was rapidly assembled and tested. Minor modifications and improvements were completed, and the unit was shipped immediately to Woomera, where it was installed, checked out, and ready to operate by July 1964.

The L-band receiver, which had been used as a test bed for all the L/S work, was moved over to the completed but vacant MSFN control room portion of the Pioneer station so that the station could support either S-band or L-band operations.

The launch station at Cape Kennedy, which consisted at that time of L-band equipment mounted in trailers, along with a 1.2-m (4-ft) hand-pointed antenna (Fig. II-14), had not been converted to S-band. The mobile station was used as an acquisition aid. The new S-band system had a built-in acquisition aid; hence it was decided to retire the mobile station after the last *Ranger* flight.

With the introduction of the S-band system to the DSN, new problems began to appear. The low reliability of the rubidium standards used in the L/S conversion became a significant error source, until it was shown that the reliability could be improved by leaving the station equipment running continuously.

The narrow antenna beam width (0.3 deg) associated with S-band operations posed an intriguing problem in the initial acquisition of the spacecraft and the establishment of two-way lock. The development of successful acquisition techniques, which afforded a compromise between the often conflicting engineering and operational techniques, was carried out at Goldstone. Refined by operational experience, these techniques eventually became standard network practice.

With the approach of the *Surveyor* lunar soft lander mission, there was some concern about the L/S capability of the important initial acquisition station at Johannesburg. The *Surveyor* spacecraft telemetry required a ground system bandwidth of approximately 3.3 MHz, switchable in steps from 4.5 KHz. Although the S-band receivers had been designed to meet this requirement, the L/S receivers were limited to about 4.5 KHz by the old L-band receiver. In addition, there was some doubt about the response of the L/S-band automatic gain control system when dealing with the higher signal levels expected from *Surveyor*. JPL worked out a temporary solution by modifying some existing equipment which had been used to record S-band telemetry on a previous *Mariner* mission. This equipment was shipped to Johannesburg, where it was installed, checked out, and used for the first two *Surveyor* missions.

Work began in December 1966 to convert the Johannesburg station to full S-band capability. Problems encountered in packaging, sea freight, and delivery to the station impeded the implementation plan, which had been geared to support the third *Surveyor* launch set for April 1967. However, in less than 2 months, 90 percent of the control room had been relocated, all the

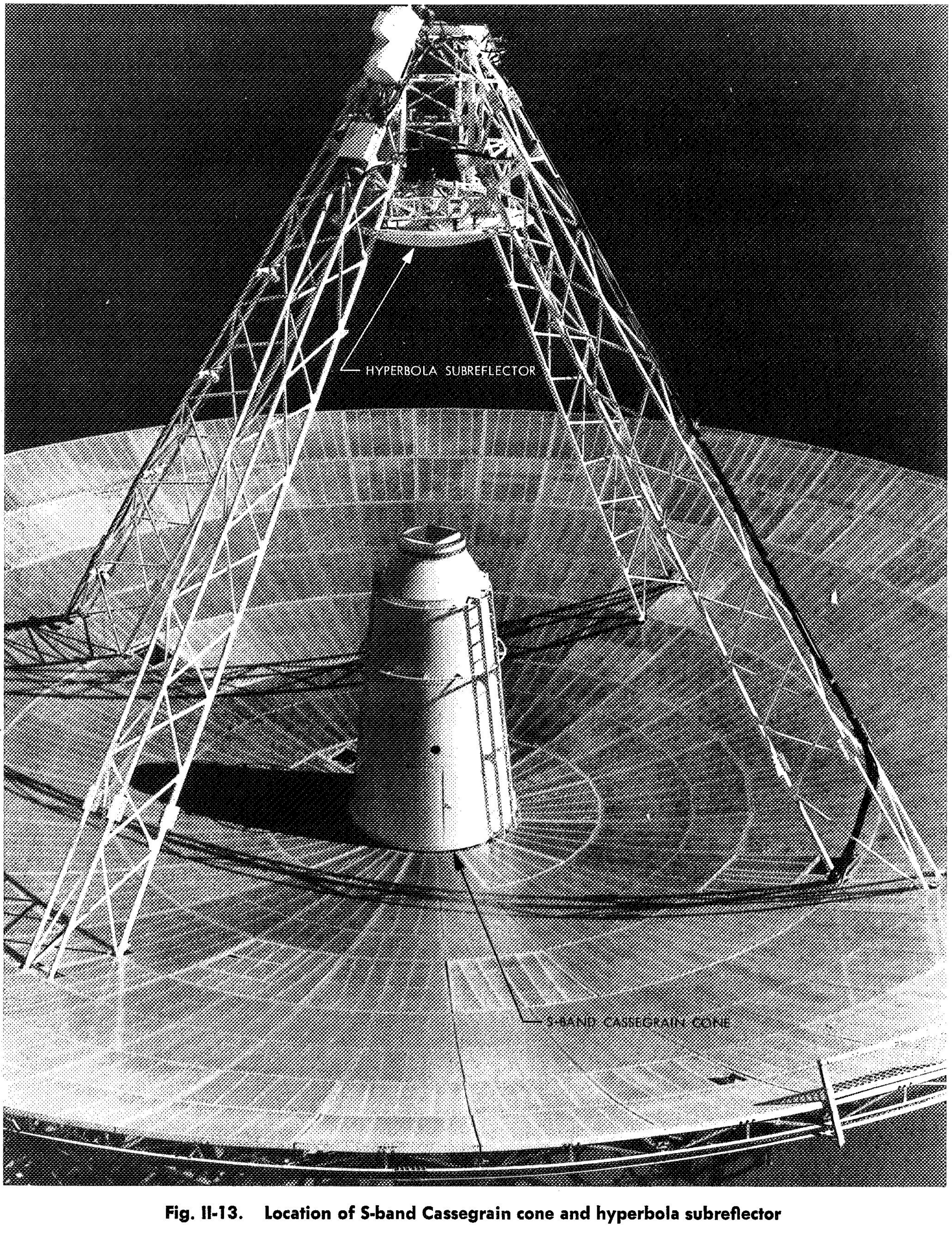

Fig. II-13. Location of S-band Cassegrain cone and hyperbola subreflector system cabling had been replaced, and much of the equipment had been either rebuilt or replaced. By the end of March 1967, the station was able to demonstrate one-way RF lock on a *Pioneer VII* signal. Between that date and April 17, the individual subsystems were tested, and various discrepancies resolved. The Johannesburg station participated in prelaunch countdown tests and supported the *Surveyor III* launch on schedule. This completed the transition of the DSN from L-band to S-band—an ambitious and demanding task carried out without significant failure under the most exacting conditions.

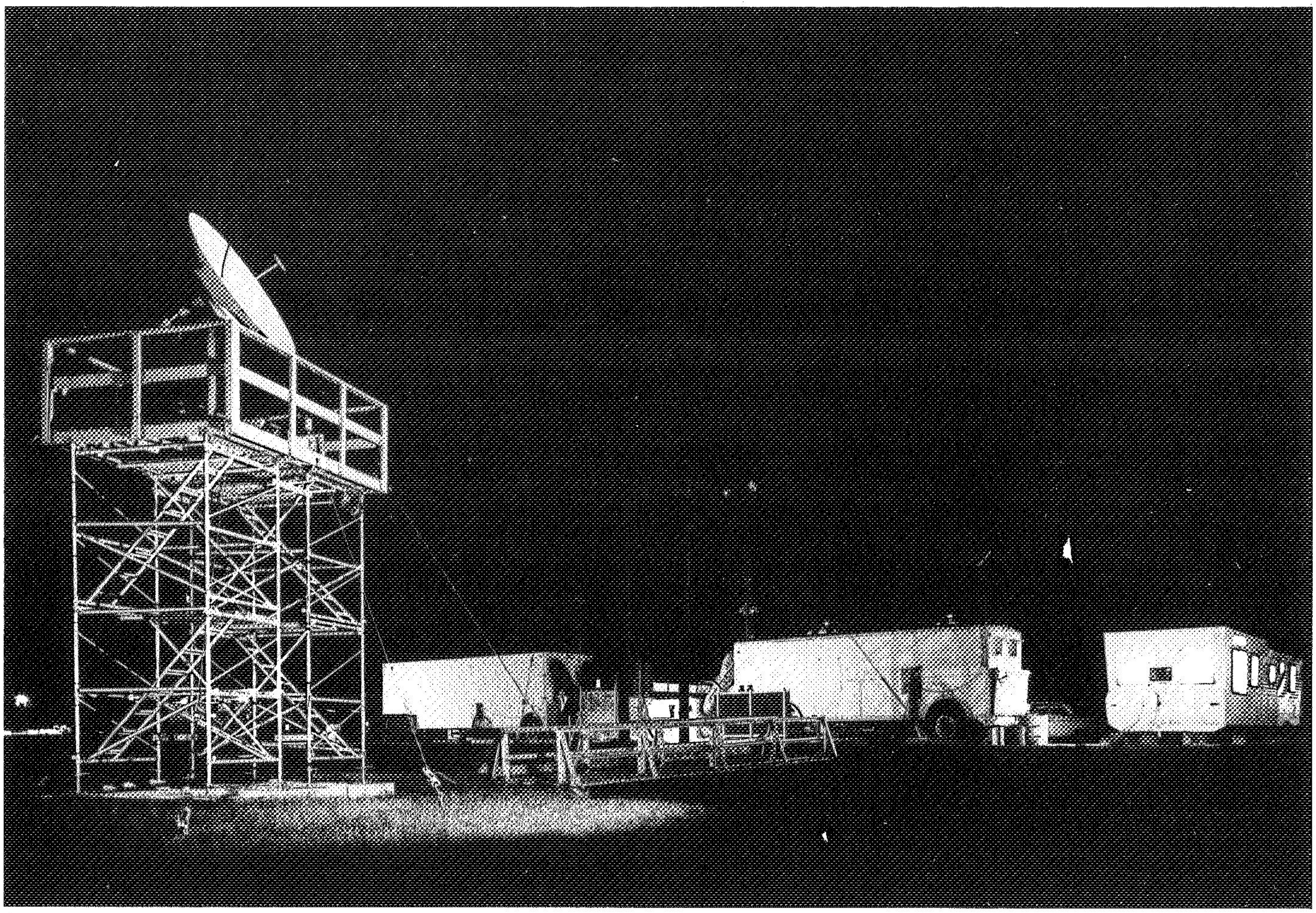

Fig. II-14. Trailer-mounted L-band equipment at Cape Kennedy (1964)

Chapter III
Milestones

The following is a chronological list of milestones outlining the development of the DSN. Appropriate references to the text will be added to events that are described in the continuity.

1954	JPL designed the original guidance system for the *Sergeant* missile. This system was of a combination radio-inertial type operated at X-band frequencies. Present unified S-band technology was developed from this system.
1956	JPL and the Army Ballistic Missile Agency developed the Microlock satellite tracking system for the Re-entry Test Vehicle Program.
1957	
October	Soviet Union launched *Sputnik I,* the first Earth-orbiting satellite.
November	Soviet Union launched *Sputnik II,* carrying a dog named Laika.
1958	
January	U.S. Army launched *Explorer I,* America's first successful Earth satellite. Van Allen radiation belt discovered.

1958

June	Construction began at Goldstone on the first 26-m-diameter antenna station, built initially to receive signals from *Pioneer* spacecraft; later named the JPL Pioneer Deep Space Station.
November	Construction of the Pioneer Deep Space Station was completed.
November	The first JPL communication network of voice circuits and teletype facilities was established to transmit digital data and maintain technical and administrative liaison between present and future tracking stations and computer and communication centers.
December	President Eisenhower issued Executive Order EO 10793, which transferred the functions and facilities of Caltech/JPL from the Department of the Army to NASA.
December	The first JPL 26-m-diameter antenna deep space station, Pioneer, became operational.
December	NASA/ABMA/JPL launched *Pioneer III*, the first lunar probe. It was unsuccessful in reaching the Moon, but the existence of a second Van Allen radiation belt was discovered.

1959

March	NASA/ABMA/JPL launched *Pioneer IV*, America's first successful Moon probe.
July	Construction began on a second JPL 26-m-diameter antenna deep space station at Goldstone. This station was to be equipped with a 10-kW transmitter.
December	Construction of the second Goldstone deep space station was completed. Built initially to support the *Echo II* Project, it became known as the Echo station.

1960

March	Construction began at Woomera, Australia, on the third JPL deep space station.
April	The JPL Goldstone Echo Deep Space Station became operational.
August	The first public demonstration was made of a two-way telephone call relayed by bouncing its signals off the surface of the Moon. In another experiment, President Eisenhower's voice was reflected from Goldstone, California, to Holmdel, N.J., through use of the *Echo I* satellite.

1960

September	A bilateral agreement with South Africa was ratified providing for construction of a 26-m-diameter antenna deep space station near the city of Johannesburg.
September	Construction of the third JPL 26-m-diameter antenna deep space station, at Woomera, Australia, was completed.
November	The Woomera Deep Space Station became operational.
—	Original Ground Communications System teletype and voice lines were procured for exclusive deep space use.

1961

January	Construction began on a fourth JPL 26-m-diameter antenna deep space station at Johannesburg, South Africa.
March	First use of Goldstone antenna for radar astronomy experiments; signals were bounced off Venus, providing a more accurate determination of the astronomical unit. Radar range to Venus was measured to within ± 500 km, permitting an accurate target designation for the upcoming *Mariner II* mission to Venus in 1962.
May	A mobile L-band compatibility test station was established by JPL at the Kennedy Space Center.
June	Construction of the fourth JPL 26-m-diameter antenna deep space station, at Johannesburg, South Africa, was completed.
July	The Johannesburg Deep Space Station became operational.
September	The Johannesburg Deep Space Station was officially dedicated by United States and South African officials. This completed a world-wide network of tracking stations later to be known as the Deep Space Network. JPL thus gained the capacity for continuous line-of-sight communication with lunar and interplanetary probes despite the Earth's rotation.
—	Development of real-time telemetry processing capability at JPL's Mission Control began and continued on into the succeeding year. This was the first real-time application for flight support at JPL using a general purpose computer and a teletype signal input.
—	The stand-alone IBM 704 computer became functional for analysis programs.
—	Through the use of a precision crystal oscillator in the ground system exciter and a new L-band two-way transponder on the *Ranger I* spacecraft, doppler accuracies were improved from tens of meters per second to tens of millimeters per second.

1962

—	A rubidium atomic frequency standard, characterized by 1×10^{-11} frequency stability performance, was installed at Goldstone and used for the *Mariner II* Project. Doppler quality was improved from 50 mm/s to 5 mm/s.
—	A method employing continuous-count doppler further improved the doppler quality by reducing round-off error from 5 to 2 mm/s.
—	A Deep Space Station Digital Recording and Instrumentation System was developed to support the *Ranger* Project.
—	A closed-circuit television system was introduced at JPL Mission Control.
—	Basic plans were developed for a new ground tracking receiver that was to operate at S-band frequencies. All spacecraft communication was soon to be restricted to the S-band.

1963

January	The first radar contact with the planet Mars was made by the 26-m-diameter antenna at the Goldstone Venus Station. Return echoes indicated both rough and smooth surfaces.
February	Selection of a suitable site in Spain for an S-band 26-m-diameter antenna station was completed. The site chosen was Robledo.
March	Agreement was reached with the Australian Government to establish a 26-m-diameter antenna deep space station near Canberra.
July	Construction was started on this, the second Australian 26-m antenna station. Known as Tidbinbilla, it was to become the first full S-band station of the Deep Space Network.
July	JPL agreed to a NASA/OTDA request to support the Manned Space Flight Network.
August	The Deep Space Network made a recommendation to NASA that L-band communication be continued until January 1966. At that time, conversion of all stations to S-band operation would be completed. NASA agreed to this recommendation in September.
October	Dr. Eberhardt Rechtin was appointed Assistant Director for Tracking and Data Acquisition; he was to be responsible for the deep space stations and for interstation communications.
October	Construction began at Goldstone on the Deep Space Network's first 64-m-diameter antenna deep space station, which was to be known as the Goldstone Mars station.

1963

October	Construction of the new Space Flight Operations Facility building was completed and the first Block I IBM 7094 computers were installed.
December	The Deep Space Network was officially established as an organizational entity to accommodate the increasing number of unmanned flight projects more efficiently.
December	Communications circuits between the JPL Space Flight Operations Facility and Woomera, Australia, were converted from high-frequency radio to submarine cable. Reliability was improved.
—	Tactical intercom equipment was installed at the deep space stations.
—	Development of real-time telemetry processing continued at the Space Flight Operations Facility in the support of the *Ranger* Block II series. Capabilities for engineering unit conversion and data suppression were provided. Essentially the same program provided spacecraft test and flight support.
—	The stand-alone IBM 7094 computer was made available for large computational programs at the Space Flight Operations Facility.

1964

January	The United States and Spain announced an agreement to construct and operate a deep space station 48 km (30 miles) west of Madrid. The station was to be used primarily as part of the Deep Space Network.
March	Construction began on the permanent Manned Space Flight Network S-band control room at the Pioneer Deep Space Station at Goldstone.
April	Construction began on an interim MSFN S-band control room at the Goldstone Pioneer Deep Space Station.
June	Construction was completed on the interim MSFN S-band control room at Goldstone Pioneer.
July	The first L-band-to-S-band conversion system was installed, checked out and ready for operation at the Woomera Deep Space Station.
August	Construction began on the planned 26-m-antenna deep space station near Robledo, Spain.

1964

August	The second L-band-to-S-band conversion system was installed, checked out, and ready for operation at the Johannesburg Deep Space Station.
September	Construction was completed on the permanent MSFN control room facilities at the Pioneer Deep Space Station.
October	Construction began on a permanent DSN spacecraft Compatibility Test Station at Cape Kennedy.
October	Construction of the S-band Tidbinbilla Deep Space Station was completed.
—	A microwave system became operational between the JPL Space Flight Operations Facility and Goldstone.
—	A new teletype switcher provided for improved distribution of messages and data.
—	A specialized JPL configuration for *Mariner 1964* was introduced at the Space Flight Operations Facility with the following characteristics: (1) Real-time input/output hardware was installed in conjunction with an IBM 7044 computer. (2) The 7044 computer was coupled to the IBM 7094 computer by large disk storage and direct data connection. (3) Input/output consoles and display devices from the user areas were connected to the 7044.
—	An advanced software operating system was installed at the Space Flight Operations Facility with the following characteristics: (1) Real-time processing in a large-scale, general-purpose computer. (2) Time sharing of programs in the 7094 computer. (3) Support of two missions simultaneously. (4) Remote input entry from user consoles. (5) Recovery capability via a four-way computer switch. (6) Data management capability, utilizing the shared disk concept, providing random and sequential access.
—	Complete conversion from L-band to S-band was accomplished by the Deep Space Network.

1964	
—	The rubidium atomic frequency standard was installed and operating at all deep space stations.
—	DSN doppler quality was improved to 1 mm/s.
1965	
—	Precision determination of the atmosphere of Mars was obtained by doppler data taken during a planetary occultation period.
January	Construction began on a DSN 9-m S-band antenna station on Ascension Island.
March	The first all new S-band station at Tidbinbilla became operational in support of *Mariner 1964*.
April	Construction of the permanent DSN Spacecraft Compatibility Test Station at Cape Kennedy was completed.
May	The DSN Cape Kennedy station was declared operational. Conversion from full L-band operation to full S-band operation was completed.
June	The Goldstone Echo station was converted from full L-band operation to full S-band operation.
July	Construction of the Robledo Deep Space Station was completed.
July	The Robledo Deep Space Station became operational.
—	Usage of the IBM 7044-7094 computer string in the Space Flight Operations Facility was expanded to include support of both the *Mariner 1964* and the *Surveyor* Projects.
—	The Deep Space Network initiated a high-speed data system employing a serial data stream.
1966	
January	Construction began on a 26-m-antenna deep space station near Cebreros, Spain.
February	Construction of the 64-m-antenna Mars Deep Space Station was completed at Goldstone.
March	Construction of the DSN 9-m S-band antenna station on Ascension Island was completed.
April	The DSN 9-m-diameter S-band antenna station on Ascension Island became operational.

1966

April — Construction began on separate control room facilities for the MSFN at the Tidbinbilla Deep Space Station.

May — The 64-m-antenna Mars Deep Space Station became operational at Goldstone. With this event, the operational range of Earth-to-spacecraft communication became immensely extended.

October — The MSFN S-band control room facilities at the Goldstone Pioneer Deep Space Station became operational.

December — Construction was completed on the Cebreros Deep Space Station.

— Lunar ranging capability was first demonstrated in conjunction with the *Lunar Orbiter* Project. Lunar range was measured to within ± 15 m. Time synchronization between the committed deep space stations was determined to within microseconds. Lunar ephemeris was determined to within ± 100 m.

— Doppler quality was improved to within 0.5 mm/s.

— A computer-based teletype communications switching system (Univac Communications (Comm) Processors) was used for the first time throughout the NASA Communications Network to support the *Mariner 1967* Project.

— The Space Flight Operations Facility computer string concept continued. Changes included deletion of the four-way computer switch and redesign of the IBM 7044 operating system for:

(1) Provision of a clear and well-defined interface between the DSN and Project portions of the system.

(2) Establishment of the first use of a high-speed data line directly into the IBM 7044.

(3) Development of a high-rate data link with the Comm Processor.

1967

— The Cebreros Deep Space Station became operational.

February — Construction of the MSFN control room facilities was completed at DSN's Tidbinbilla Deep Space Station.

March — The Johannesburg Deep Space Station was converted to full S-band operation.

November — Construction began at JPL on a compatibility test facility to conduct communication compatibility testing between the DSN and specific spacecraft.

1967

- The Deep Space Network planetary ranging capability was first demonstrated in conjunction with the *Mariner Venus 1967* Project. Venus range was determined to within ± 15 m.

- Discovery was made of lunar mass concentrations (mascons) using radio metric data obtained from *Lunar Orbiter* spacecraft.

- The high-speed data stream was upgraded to a 2400-bits/s data rate.

1968

- A demonstration of X-band lunar bounce time synchronization was conducted by the Deep Space Network. Time correlation between participating stations was shown to be better than 5 μs.

- The Deep Space Network Compatibility Test Facility became fully operational.

- The first operational use of encoder/decoder equipment for high-speed data was originated at the Space Flight Operations Facility.

- Improvements in the IBM 7044-7094 software system at the Space Flight Operations Facility were initiated during the support of the *Mariner 1969* Project to:

  (1) Improve input/output control.

  (2) Develop limited multiprogramming capability.

  (3) Simplify output formatting capability.

- A display buffer operating system, using Univac 3100 equipment, was developed at the Space Flight Operations Facility to:

  (1) Provide a hard-line link to the 7044 computer.

  (2) Collect and display DSN monitor data.

  (3) Establish computer-based operations control functions.

Chapter IV
DSN Support

The two main activities supported by the DSN have been space flight projects and Earth-based radio science. The primary activity has always been the support of space flight projects. No less important, however, has been the DSN support provided to radio science experiments which involve the use of radio frequency emission and propagation technology to probe a physical environment.

Flight Projects

The DSN support to flight projects began with the *Explorer I* satellite, which was launched into orbit on January 31, 1958. The successful *Explorer* series was followed by DSN support of the *Pioneer III* and *IV* lunar probes. The next program was the *Ranger* Project, whose most challenging objective was to obtain close-up television pictures of the Moon. Following *Ranger* came *Mariner* flybys of Venus and Mars, the *Atlas–Centaur* series of tests for the *Surveyor* launch vehicle, *Pioneers VI and VII, Surveyor, Lunar Orbiter,* and support for the *Apollo* Project.

Ranger

At the start of the *Ranger* Program in 1961, the DSN consisted of three 26-m-diameter L-band antennas and two trailer-mounted antennas, located in Florida and South Africa, which were used during the early, near-Earth portion of the trajectory.

During the months of June and July 1961, the 26-m stations at Goldstone, Woomera, and Johannesburg underwent a complete angle-pointing accuracy evaluation in preparation for the first *Ranger* launch in August. Star tracks, static boresight calibrations, and radio frequency dynamic tracking tests, using helicopters and balloons as L-band signal sources, were included in the test program. The three 26-m stations were equipped with narrow-band receivers using crystal mixers in the front end. These provided a system noise temperature of about 1500 K. Only the Goldstone Echo station had a command capability at that time. Using telephone and teletype data channels, telemetry and radiometric data were brought into the Communications Center at JPL and patched (switched) to teleprinters in the newly designed SFOF for monitoring purposes.

The objective of the *Ranger* series of flights was to make close-up scientific observations of the Moon. To accomplish this, the spacecraft were put on a trajectory ending in impact on the lunar surface. The close-up scientific observations, including approach television, were to be made and radioed back to Earth before impact destroyed the spacecraft. *Ranger* was a new generation of spacecraft incorporating many new and untried principles. Those directly relating to the evolution in design and operation of the DSN were:

(1) Spacecraft attitude stabilization, making possible communications and closed-loop tracking via high-gain, directional antennas on the spacecraft and the Earth.

(2) Launch toward the Moon from an Earth parking orbit.

(3) Midcourse trajectory correction to increase the accuracy of the trajectory, involving accurate Earth-based radio metric measurements before and after the correction.

The first two *Ranger* flights, called Block I of the Project, were to be placed in high, elliptical Earth orbits in order to functionally test the spacecraft and ground system design. The scientific payload for these flights was limited to an environment-sampling instrument package.

Ranger I was launched on August 23, 1961. The planned high elliptical trajectory was not obtained because of a failure in the second stage ignition of the *Atlas–Agena* launch vehicle. The spacecraft went into a short-lived, low-altitude, 90-min Earth orbit. The deep space stations were able to track the spacecraft successfully, although the high angular rates caused some stations to drop lock occasionally. Telemetry data were also recorded.

Ranger II was launched on November 18, 1961, and suffered a similar second-stage ignition failure. This presented the DSN with another Earth satellite tracking problem with station visibility limited to about ten minutes on each pass. The mobile station at Johannesburg, because of its higher angular rate capability and relatively low horizon, was the only station to obtain any effective data.

Rangers III, IV, and *V* (Block II) were designed to impact the lunar surface with a survivable lunar capsule which would subsequently transmit lunar surface data to Earth. For these missions, the deep space station receiver sensitivity was improved by the addition of a parametric amplifier to reduce the effective system temperature from 1500 K to 200 K, representing an 8-dB improvement in signal-to-noise ratio. An L-band maser was installed at the Goldstone Pioneer station in November 1961, to further reduce the system noise temperature to about 50 K. Other improvements included stable control of transmitter frequency and a high-power L-band antenna diplexer and feed. To aid in initial acquisition, the Johannesburg mobile station was provided with a wide-beam, helical antenna.

Ranger III was launched on January 26, 1962, and because of launch vehicle malfunction, went into a heliocentric orbit. It was, however, tracked by the DSN out to a distance of 896,000 km (560,000 miles).

Ranger IV, launched April 23, 1962, suffered a spacecraft malfunction which resulted in low power output, but was tracked during the entire 65-hour lunar transit period until lunar impact.

Ranger V, launched October 18, 1962, also experienced a spacecraft anomaly and went into a heliocentric orbit. The spacecraft transponder signal began falling rapidly and then disappeared entirely. The Goldstone station managed to lock onto the lunar capsule signal and continued tracking for 11 days until the end of October, by which time the signal strength had fallen to -169 dBmW.

The third phase of the *Ranger* Program (Block III Missions VI, VII, VIII, and IX) was designed to take closeup television pictures of the lunar surface during the final approach stages of the impact trajectory. In preparation for *Rangers VI* through *IX*, an L-band maser and special video equipment were installed at the Goldstone Echo station. Through December 1963 and January 1964, the entire network participated in a comprehensive series of integration tests and operational readiness tests to ensure the highest possible standard of readiness for *Ranger VI*.

Ranger VI, launched on January 30, was tracked flawlessly by all stations, but the spacecraft television system failed to operate prior to lunar impact. Between the end of the *Ranger VI* mission and the launch of *Ranger VII* in July, the entire L-band network was subjected to an intensive calibration program covering antenna, diplexer, feed lines, receivers, and transmitters. As a consequence, the DSN was well prepared for *Ranger VII*, the first successful *Ranger* mission, and all stations operated without incident during the 68 hours from injection to lunar impact.

Following the success of *Ranger VII* in July, 1964, no major changes were made in the network. Operations consisted mainly of tests necessary to ensure full operational readiness for *Ranger VIII*. This activity was necessitated by the fact that some of the stations had been supporting *Mariners III* and *IV* on S-band, and some reconversions to L-band were required.

Ranger VIII (February 1965) was successful, and good video was received by the Goldstone Pioneer station. As the DSN continued to gain experience in tracking and communications, the operational techniques in these areas improved, as did the ability of the personnel to react quickly to unexpected, anomalous situations. This preparedness was used to good effect in *Ranger IX* (March 1965), when transmitter failures within the last 30 min before impact were quickly rectified, or alternative measures taken, without affecting the retrieval of all the desired spacecraft video data. On March 24, 1965, the *Ranger IX* video mission, broadcast over commercial television, successfully ended the *Ranger* series by returning more than 5800 progressive, close-up pictures of the lunar surface before crashing into the crater Alphonsus.

Atlas–Centaur

The nine test flights of the *Atlas–Centaur* (AC) launch vehicle were directly related to the *Surveyor* Project. The second-stage *Centaur* used liquid hydrogen as a propellant and carried a simulated *Surveyor* payload which varied from a bulk weight version to a full, dynamic model of the *Surveyor* spacecraft. The early *Centaur* test flights carried an L-band beacon, while the later flights carried an S-band transponder to coincide with the introduction of the S-band capability into the DSN. The DSN supported AC flights 2, 3, 5, 6, 8, and 9. The AC Flight 1 suffered a vehicle destruct by the Range Safety Officer some 55 seconds after liftoff; AC flight 4 was not equipped with an L-band beacon to enable tracking by the DSN; and AC flight 7 carried a bulk-weight *Surveyor* model spacecraft. Flights 2 and 3, November 1963 and June 1964, each carried an L-band beacon with a battery life of 10 hours. The DSN generated one-way radio metric data during this 10-hour period whenever the *Centaur* was visible to one of the deep space stations; however, because of its low Earth orbit, each pass was limited to 10 minutes.

AC flight 5 (March 1965) exploded and burned on the launch pad. Flight 6 (August 1965) carried a *Surveyor* dynamic model with a battery life of 20 hours on a direct-ascent, variable-launch-azimuth trajectory targeted to impact the Moon. The dynamic model, equipped with an S-band transponder, was tracked by the DSN in two-way mode and generated two-way doppler data for the full 20 hours of battery life provided by the dynamic model.

AC flights 8 and 9 (October 1966) were launched into an Earth parking orbit; a second burn then injected the mass models on a simulated lunar transfer trajectory. The mass models were equipped with S-band transponders and 20-hour batteries. These flights successfully demonstrated the full operational capability of the *Centaur*, including its restart capability. The DSN provided two-way, S-band doppler and angle tracking, together with the desired spacecraft model telemetry. The operations training experience gained by the DSN during the *Atlas–Centaur* development program proved to be of significant value for the first *Surveyor* launch.

Mariner Mission to Venus (1962)

During the summer of 1962, two *Mariner* spacecraft were launched on an orbit toward the planet Venus. These spacecraft, whose design borrowed heavily from the *Ranger* Block III design, were launched aboard *Atlas–Agena* launch vehicles and carried a 3-W L-band radio transponder and telemetry and command equipment.

Mariner I was launched on July 22, 1962. Shortly afterward, problems developed in the launch vehicle guidance system, causing the vehicle to yaw off course. Just 6 seconds before separation, the Range Safety officer pressed the destruct button. What was left of the flight impacted the Atlantic Ocean 357 seconds after lift-off. *Mariner II* was launched on August 27, 1962, into a trajectory toward the planet Venus from an Earth parking orbit at an altitude of 184 km (115 miles). On December 14, 1962, the spacecraft passed within 35,200 km (22,000 miles) of Venus, at a range of 57,600,-000 km (36,000,000 miles) from Earth.

Throughout the 109 days of the *Mariner II* mission, the DSN stations maintained continuous 24-hour communication with the spacecraft, transmitting commands, recording telemetry, and generating radio metric data for orbit determination purposes. Two-way doppler was provided by the Goldstone Pioneer and Echo stations. The Echo station successfully transmitted commands to the spacecraft on December 14, 1962, at a range of 57,600,000 km from Earth.

Mariner Mission to Mars (1964)

By August 1964, a three-station network was equipped with the new S-band frequency system to support the first of the *Mariner* missions to Mars. The DSN Woomera and Johannesburg stations were provided with hybrid L/S receivers and the Goldstone Pioneer station was operating with the first pure S-band receiver. S-band masers and parametric amplifiers, 10-kW transmitters, a good communications network, and well-established data processing and mission control systems were available to support these missions.

During November 1964, two *Mariner* spacecraft were scheduled for launch and would encounter Mars in July 1965. The first, *Mariner III*, failed shortly after launch when a nose-fairing release mechanism failed to operate. On November 28, 1964, *Mariner IV* was successfully launched on a 7½-month flight that passed within 9789 km (6118 miles) of Mars. On July 14, 1965, *Mariner IV* telemetered to Earth the first closeup pictures of the Martian surface.

By the time *Mariner IV* was launched, the number of stations in the DSN had increased to eight. Rubidium frequency standards had been introduced throughout the DSN to replace the less stable, crystal-controlled oscillators used during the *Mariner II* mission. These rubidium frequency standards were the basis for the precision two-way doppler necessary for radio guidance and navigation of the spacecraft to a more accurate aiming point in the vicinity of Mars. Other improvements in the navigation area included (1) the use of a doppler multiplier to reduce resolution inaccuracies introduced by the digital counter and (2) the use of a computer facility at Goldstone for monitoring the quality of the two-way doppler data received from all the other stations. Goldstone was also equipped with an experimental open-loop S-band receiver for recording the *Mariner IV* occultation data, which provided experimenters with the first reliable information on the Martian atmosphere.

The Venus experimental station at Goldstone, normally used for DSN research and development, was used for command backup for the *Mariner IV* encounter with Mars. The station's 100-kW transmitter ensured that communication with the spacecraft could be maintained via its omnidirectional antenna should an unexpected change in the spacecraft's attitude cause its directional antenna to point away from the Earth.

The expansion of DSN capability during the time interval between *Mariners II* and *IV* diminished the need for special project-designed equipment to be added to the network for the *Mariner IV* mission. The two principal areas dependent on project-provided items were (1) the command and telemetry equipment (Fig. IV-1) installed at the deep space stations and (2) the mission-dependent software for the high-speed computers located in the Space Flight Operations Facility.

Pioneer

The second generation of *Pioneer* spacecraft, beginning with *Pioneer VI*, was designed to measure the interplanetary particles and fields environment along trajectories that placed the spacecraft in heliocentric orbits ranging between 0.7 and 1.2 AU.[17] The spacecraft were launched approximately 1 year apart, starting in December 1965 with *Pioneer VI* and followed in August 1966, December 1967, and November 1968 by *Pioneers VII, VIII* and *IX*, respectively. These spacecraft were completely successful and are still operating.

Since the start of this *Pioneer* generation in 1965, the DSN has introduced many modifications toward improving the threshold capability of the network for *Pioneer* telemetry support. Seven 26-m antenna stations were equipped with improved masers, more efficient microwave equipment, linear antenna polarizers, 3-Hz carrier tracking loops, advanced demodulation hardware, and sequential decoding software (for the support of *Pioneer IX*).

To provide for real-time telemetry data processing, the Canberra, Echo, Robledo, and Johannesburg Deep Space Stations were equipped with special ground operational equipment supplied by the *Pioneer* Project. The spacecraft monitoring station at Cape Kennedy was similarly outfitted to cover the prelaunch spacecraft compatibility testing. The ground operational equipment consisted of a command encoder, a computer buffer, and a demodulator/bit synchronizer. Associated test equipment, consisting of a test transponder and error rate tester, were also provided. The bulk of the support was furnished by the DSIF 26-m stations. The 64-m station at Goldstone was used to track *Pioneer* spacecraft which were beyond the threshold of the 26-m network. However, the systematic improvement of the 26-m network resulted in a significant enhancement of the carrier signal-to-noise ratio of *Pioneer* telemetry signals at the input of the S-band receivers. These improvements in the 26-m network have extended the threshold from 0.4 AU (1965) to approximately 1.5 AU (1969).

Frequently referred to as interplanetary weather stations, the *Pioneer* spacecraft carry instrumentation to

[17]Measured in astronomical units; 1 AU is the mean distance from the Earth to the Sun; nominally 148,800,000 km (93,000,000 miles).

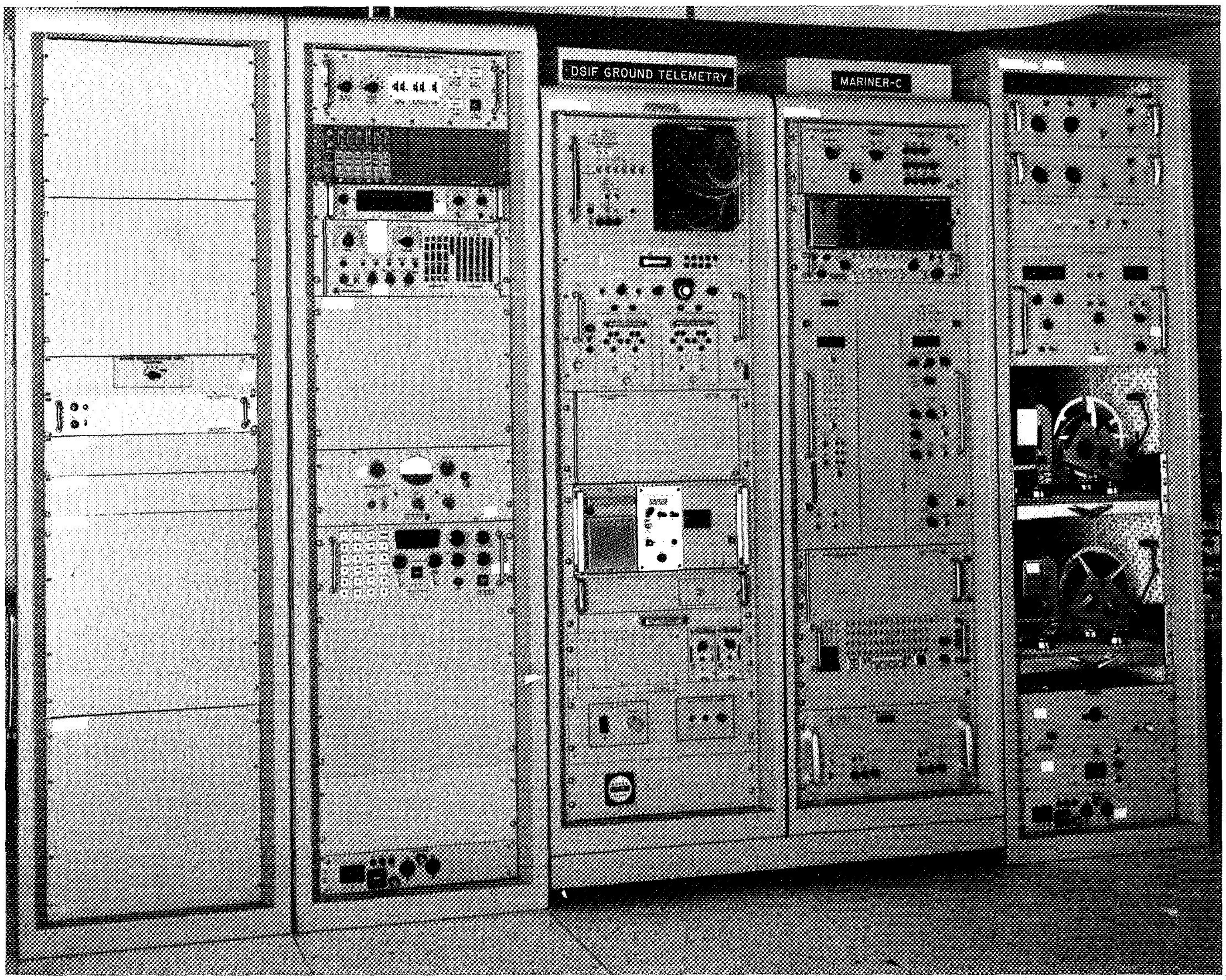

Fig. IV-1. Special *Mariner* command and telemetry equipment

measure such phenomena as energetic charged particles, magnetic and electric fields, the solar wind, cosmic dust, and infrared and ultraviolet emissions from the Sun. To take advantage of the scattered positions of these spacecraft in their orbits around the Sun, continuous surveillance by the DSN is necessary. Two experiments which require no on-board scientific instruments are the celestial mechanics investigation by JPL, which uses two-way doppler as its source of data, and the convolutional coding and sequential decoding experiment (*Pioneer IX* only).

Each of the *Pioneer* spacecraft is identical and carries low-gain and high-gain antennas, together with a 7-watt transmitter operating at S-band. A subcarrier can be modulated at bit rates of 512, 256, 64, 16 and 8 bits/s, as required by the varying demands placed on the telemetry link. Coherent spacecraft transponders provide for two-way doppler information and an FSK command system operating at 1 bit/s.

The almost continuous collection of *Pioneer* telemetry data over a 4-year period has given the DSN an opportunity to develop and extend its capabilities to track and return data over a sizable segment of our solar system. Regular and thorough analysis of the DSN's performance has led to the introduction of highly specialized and advanced telecommunications hardware.

During the 4 years of its support of the *Pioneer* program, the DSN has collected approximately 18 billion bits of telemetry data, provided 30,000 hours of telemetry support, and recorded these data on more than 14,000 7-channel magnetic tapes. In addition, approximately 28,000 commands have been sent to the various *Pioneer* spacecraft from the DSN stations during this time. Throughout this period, the DSN support of the *Pioneer* Program has been characterized by the long and substantially trouble-free life of all four spacecraft, by the need to be able to respond quickly to demands for increased coverage during significant solar events, and by a continuing incentive to enhance the data retrieval capabilities of the DSN.

Surveyor

The *Surveyor* Project planned and conducted seven unmanned lunar missions launched between May 1966 and January 1968. Each was successfully launched with the *Atlas–Centaur* vehicle, which utilized for the first time a high-specific-impulse, liquid hydrogen/liquid oxygen fuel stage. Five of the spacecraft successfully soft-landed on the lunar surface and returned a large quantity of engineering and scientific data during extensive postlanding operations, accomplishing all mission and project objectives. Four of the spacecraft soft-landed at selected lunar sites to provide data required to support the *Apollo* program. *Surveyor VII*, the final spacecraft, was then successfully used for scientific investigation of a contrasting site in the rugged lunar highland. Two of the spacecraft, *Surveyors II* and *IV*, failed to achieve successful lunar landings.

Surveyor mission-dependent equipment for sending commands and processing telemetry and video data was installed at each of the supporting deep space stations: Pioneer, Canberra, Robledo, Cape Kennedy, Ascension, and Johannesburg. The Project provided the station personnel to maintain and operate this mission-dependent equipment, pending the training and transfer of responsibilities to on-site DSN personnel. The Project also provided station personnel for spacecraft control and data analysis should there be a total failure in communications at any time between the station and the SFOF in Pasadena.

The development of the *Surveyor* spacecraft required the use of DSN equipment and facilities for compatibility testing, culminating in an extensive series of tests at Goldstone, California, with a telecommunications model of a *Surveyor* spacecraft. The availability of these DSN facilities and the model spacecraft also provided a basis for extensive training of DSN personnel.

Operations during the transit and postlanding phases required special command, control, and real-time display equipment at each of the deep space stations. This equipment was used (1) to control the spacecraft guidance system and the lunar scientific experiments and (2) to receive and record the data acquired from the spacecraft. The *Surveyor* spacecraft could operate with telemetry information bit rates from 17.2 through 4400 bits/s, together with several analog subcarriers and analog television, and had provision for handling 256 discrete commands.

The DSN provided its new 64-m antenna, the Mars Deep Space Station at Goldstone, California, in May 1966, to return the high-rate 4400-bits/s telemetry during the trajectory-correction maneuver of these spacecraft and to provide better magnetic tape recordings of the telemetry measurements during the critical soft landing on the lunar surface and the subsequent television transmissions. The *Surveyor* spacecraft, radiating from the Moon, provided an excellent far-field signal source for the antenna pattern measurement for this station.

The *Surveyor* Project introduced many innovations which had significant influence on the development of the DSN. In particular, video information was received, processed, and displayed in real time for operational decision-making. These video signals were converted simultaneously into television pictures for visual observations and photographs for a permanent record. Also, extensive use was made of real-time, high-speed data processing using the IBM 7044–7094 system in the SFOF. During prelaunch testing, DSN facilities for the simulation of spacecraft maneuvers and high-speed telemetry data provided the Mission Operations team with realistic and effective training of the mission operations team for the critical portions of the mission.

Postflight analysis of each of the seven *Surveyor* flights indicated that the support provided by the DSN to the Project was excellent. While the experience gained by the DSN in support of previous flight projects was invaluable, credit for this success must be given to the exhaustive premission training program necessitated by the complexity of the *Surveyor* mission design. During this training period, as well as during the missions themselves, *Surveyor* Project personnel worked side by side with DSN mission-independent personnel to form a homogeneous team that could react quickly to unforeseen circumstances. This training factor, plus the enhanced reliability of both the mission-dependent and mission-independent equipment and computer programs, contributed significantly to the program and to the support provided to it by the DSN.

Table IV-1 summarizes the *Surveyor* launches and the amount of data retrieval support provided by the DSN.

Table IV-1. *Surveyor launches*

Mission	Launch date	Result
1	5/30/66	Soft landing. Operated for 2 lunar days; 13,000 pictures, 108 commands.
2	9/20/66	Spacecraft became unstable in flight and destroyed itself.
3	4/17/67	Soft landing. Operated for 1 lunar day; 10,000 pictures, 63,000 commands.
4	7/14/67	Lost radio contact before touchdown.
5	9/11/67	Developed helium leak during flight but achieved soft landing. Operated for 2 lunar days; 27,000 pictures, 123,000 commands, 118 hours of alpha scatter measurements.
6	11/7/67	Soft landing. Operated for 1 lunar day; 30 h of alpha scatter measurements, re-fired vernier engines for second liftoff, 45,000 pictures, 170,000 commands.
7	1/7/68	Soft landing. Operated for 2 lunar days; 100 h of alpha scatter measurements, carried out surface sampler experiments, 28,000 pictures, 150,000 commands.

Lunar Orbiter

The objective of the *Lunar Orbiter* Project was to obtain high-resolution photographic data of potential *Apollo* landing sites on the Moon, together with detailed, wide-angle photographic lunar mapping data. To accomplish this, the spacecraft carried a complex optical camera and film processing package which employed facsimile transmission techniques to reduce the radio frequency bandwidth to a value compatible with the DSN channel assignment.

A standard S-band network of three deep space stations was used to support the five *Lunar Orbiter* missions; these stations were each augmented with special-purpose, mission-dependent equipment and operating personnel supplied by the Project.

The *Lunar Orbiter* Project consisted of five identical spacecraft, launched between August 1966 and August 1967, and placed in various high- and low-altitude orbits around the Moon. All five of the *Lunar Orbiter* missions were successful. Trajectories were varied to achieve orbits with different inclinations to the lunar equator, enabling the Project to survey approximately 99% of the lunar surface. The entire front surface of the Moon, together with most of the back surface, was photographed, requiring transmission of some 2,000 pictures. The *Lunar Orbiter* photographic resolution required that the equivalent of 5×10^{12} information bits per mission be transmitted in analog format to the DSN. Approximately 32,000 commands were transmitted during the mission series.

The *Lunar Orbiter* Project, managed by NASA's Langley Research Center, was conducted concurrently with the DSN support of the JPL-managed *Surveyor* and *Mariner-Venus 1967* Projects. This multiple-mission environment heavily taxed the resources of the DSN and required not only the precise scheduling of the activities of the three projects, but the cooperation and coordination of all involved. Thus, of necessity, better understanding of the relationships between the flight projects and the Earth-based supporting facilities of the DSN was achieved.

Lunar Orbiter was the first project to use the JPL-designed "turn-around" ranging transponder on board the flight spacecraft, which provided the DSN with its first opportunity to test the entire ranging system (which includes both the spacecraft and the Earth-based equipment components) under actual flight operations conditions. While this test was very important from a DSN developmental viewpoint, the ranging data obtained during the five missions were also extremely important to the project's second objective: obtaining geophysical data about the Moon that would be needed prior to the *Apollo* manned lunar activities. The ranging system performed exceedingly well, and, in addition, provided opportunities to experiment with new uses for the system. One was the improvement in the network's ability to synchronize the time standards at the various DSN stations throughout the world. This improvement in worldwide time synchronization between the stations provided a more accurate determination of the spacecraft's orbit about the Moon, which, in turn, yielded additional information regarding the physical properties of the Moon itself.

Postmission analysis of the *Lunar Orbiter* radio metric data yielded a greatly improved model of the Moon's gravitational potential, its ephemeris with respect to Earth, a confirmation of the true lunar radius that was first detected during the analysis of the *Surveyor* Project radio metric data, and, finally, the unexpected discovery of lunar gravitational potential anomalies, thought to be caused by subsurface mass concentrations which became known as "mascons."

The DSN support for the *Lunar Orbiter* Project met all mission requirements and, in addition, included some significant developments. Along with the first operational use of the DSN ranging system for orbit determination and deep space station time synchronization, the spacecraft were used for retransmission of voice communication from Earth and for conducting bistatic radar mapping of the lunar surface. *Lunar Orbiter* was the first continuous high-activity project supported by the DSN. During the 30-day photographic phase of each mission, the spacecraft had to be monitored and maneuvered, photo operations conducted, and navigation parameters determined on a round-the-clock, 24-hour schedule. During one period, three *Lunar Orbiter* spacecraft were simultaneously supported while orbiting the Moon.

Mariner Mission to Venus (1967)

NASA resumed its scientific investigation of the planet Venus with the initiation of the *Mariner V* Project in December 1965. The spacecraft was essentially the same as the one used for the *Mariner Mars* mission in 1964. Certain science instruments were replaced by new experiments more appropriate to the Venusian atmosphere and ionosphere. Because of significant advances in radio guidance technology, *Mariner V* was targeted to pass within 4020 km (2500 miles) of the surface of Venus, compared to the 34,600-km (21,500-mile) target distance achieved by *Mariner II* in 1962.

At the inception of the *Mariner V* Project in December 1965, teams were established to assist the Project in planning the technical and operational design of the mission. Since the same telecommunication system was carried aboard *Mariner V* as was used for *Mariner IV*, the mission-dependent equipment interfaces at the DSN station were basically unchanged between the two missions. However, new equipment such as the telemetry and command processor had been added to the network in the interval between *Mariners IV* and *V*; this, in turn, altered the Project/DSN interface, both physically and operationally. In addition, the *Mariner IV* spacecraft was still operating in its extended mission phase and was to be tracked in conjunction with the *Mariner V* mission to make concurrent measurements from two different vantage points of solar plasma and magnetic fields, as well as charged particle concentrations in interplanetary space.

Compatibility and readiness testing and operator training began approximately 6 months prior to launch. After launch, the DSN provided continuous 24-hours-a-day coverage during all critical phases of the mission and averaged one tracking pass per day during the cruise phase.

Mariner V was launched on June 14, 1967, and was successfully injected into an orbit toward Venus. During the cruise period, the DSN successfully made ranging measurements for the first time with a *Mariner* spacecraft. This, together with the normal radio metric data, greatly facilitated the orbit determination process. During the first 22 days of the flight, the ranging system was used to obtain data from the spacecraft out to a distance of 10,000,000 km. *Mariner V* thus became the first spacecraft to be ranged beyond lunar distances. Forty days after launch, the telemetry data rate was automatically switched from 33⅓ to 8⅓ bits/s to compensate for the decreasing signal power caused by the increased communications range. All spacecraft subsystems continued to operate normally. On September 19, 1967, the spacecraft detected an intense stream of solar particles which were associated with a small solar flare that occurred near the west limb of the Sun.

When the spacecraft was switched from its omnidirectional antenna to its high-gain antenna on October 1, the new, experimental planetary ranging system was tested and declared ready for use during the encounter sequence. The received telemetry signal levels throughout the mission were very close to nominal. To prevent a loss of telemetry data during the grayout period between omnidirectional to high-gain antenna switchover, a digital demodulation program was conceived which improved the telemetry threshold by approximately 5 dB and enabled retrieval of telemetry that would otherwise have been lost.

Encounter preparations proceeded smoothly, and the command to start the encounter sequence was transmitted by the DSN on October 18, 1967, 15 hours before encounter. The closest approach occurred on the following day at a distance of 4070 km (2544 miles) above the surface of the planet. Occultation, or loss of radio signal as the spacecraft passed behind the planet, was observed at 17:39:08 GMT, and exit occultation (signal reacquisition) occurred at 17:59:59 GMT on October 19.

Throughout the mission, operations within the DSN were normal and the spacecraft performed flawlessly.

After passing Venus, the *Mariner V* spacecraft continued in a heliocentric orbit while the DSN continued to track it on an intermittent basis until the communications range became too great to detect a usable signal. Radio contact was not re-established with *Mariner V* until October 14, 1968. The signal was weak and displaced from the expected frequency, and no further telemetry or command capability could be established with the spacecraft. On November 5, the mission was terminated.

Mariner V was the first project to use the redesigned 7044 computer system, which provided a two-mission processing capability. After midcourse, and throughout the mission, the 7044 successfully processed data simultaneously from both *Mariner IV* and *V* spacecraft. *Mariner V* was also the first project to use the newly installed communications processor in the SFOF, which automatically switched all teletype messages throughout the facilities of the DSN. In addition to the scientific data gathered by the instruments on board the spacecraft, valuable scientific measurements of the Venusian atmosphere were obtained by the DSN from the S-band occultation experiment, the bistatic radar astronomy experiment, and the research and development planetary ranging experiment.

Mariner Missions to Mars (1969)

Authorized in 1965, the *Mariner VI* and *VII* missions had as objectives (1) the further investigation of Mars, begun with *Mariner IV* (1964) experiments relevant to the search for extraterrestrial life and (2) the development of the technology required for future planetary exploration. The *Mariner VI* and *VII* spacecraft design differed from the *Mariner IV* design in that all of the scientific instruments were planet-oriented and mounted on a scan platform, and the communications, control, data handling, and storage features were modified to enhance the recovery of planetary data. Two investigations requiring no special spacecraft instrumentation, i.e., S-band occultation and celestial mechanics, were to provide information on the physical properties of the atmosphere and to extend the data on certain fundamental solar system parameters recovered from previous *Mariner* missions.

The objectives of the *Mariner Mars 1969* Project represented a significant step forward by comparison with previous planetary projects. The DSN committed to the project the use of its newly developed high-rate telemetry detection system and real-time digital television system which, although demonstrated in the laboratory, had not previously been used in support of an in-flight spacecraft. Considerable preflight testing was, therefore, necessary.

During the spacecraft development phase, and through the completion of construction and final compatibility testing with the DSN, the *Mariner 1969* Project made extensive use of the new DSN Compatibility Test Area at JPL. The area was used to demonstrate operational performance and to develop procedures for the use of the new equipment which was being integrated into the network for the support of *Mariner 1969*. This new mission-independent equipment included the multiple-mission telemetry system, capable of detecting and processing telemetry data for more than one class of spacecraft; the high-rate telemetry system, capable of detecting and processing telemetry data at rates of tens of thousands of bits per second; and the real-time, high-rate, digital television system which would be used at the Goldstone 64-m antenna to relay to the SFOF the television pictures that the *Mariner 1969* spacecraft would transmit while encountering the planet Mars. These mission-independent systems were all tested against actual spacecraft hardware prior to implementation into the DSN. The *Mariner VI* and *VII* missions fall beyond the scope of this history, but it can be reported that the missions were highly successful.

Apollo

The tracking and data acquisition responsibility for *Apollo* was assigned to the Manned Space Flight Network of the Goddard Space Flight Center, Greenbelt, Maryland. Because of its prior experience with unmanned lunar and planetary spacecraft tracking and communication assignments, JPL's DSN was assigned a supporting role to the MSFN in the operation of the *Apollo* Lunar Program. This supporting role ranged from providing the MSFN with S-band receiver-exciter-ranging subsystem equipment and lunar trajectory and orbit determination computer software programs to providing three of its own deep space stations as backup to the MSFN facilities during *Apollo* missions.

To provide redundancy, an MSFN control wing was added to the Goldstone Pioneer, the Canberra, and the Robledo Deep Space Stations. The MSFN wing housed the special *Apollo* transmitting and receiving equipment plus switching connections that allowed the single 26-m antenna to be switched between the DSN and MSFN. During *Apollo* mission operations, DSN personnel were operationally responsible to the MSFN Control Room Supervisor to ensure that all mission sequences were conducted properly. To further enhance the mission support, the MSFN provided a single coordinator to direct the operations at both the DSN/MSFN wing stations and the colocated MSFN 26-m station at each geographical area. This configuration was employed, starting with the *Apollo 4* test flight, up through the successful flight of *Apollo 8* in December, 1968. Because of the advantageous location of Cape Kennedy, that station was converted to the *Apollo* frequencies and provided monitoring support for *Apollo 4* and subsequent *Apollo* launches during the final countdown and liftoff, until the spacecraft disappeared over the horizon.

The DSN Ascension Island station was also outfitted with the equipment necessary to track and receive telemetry from the *Apollo* vehicles. Cross-training of the DSN and MSFN operations personnel was carried out on an accelerated basis because of the late development of this requirement. During *Apollo 4, 5,* and *6* missions, the two stations operated as a single team, and provided excellent support to the project. Since *Apollo 7* and subsequent *Apollo* flights did not require the use of two antennas at Ascension Island, and the future unmanned space flight projects to be supported by the DSN did not require a DSN station at Ascension Island, the DSN station was decommissioned following the *Apollo 6* mission.

The *Apollo 8* transmission broadcast over commercial television required the use of the spacecraft's high-gain antenna for the first time. To ensure receiving pictures, NASA Headquarters requested the services of the DSN 64-m antenna at Goldstone, which could receive the television signal via the *Apollo* spacecraft's low-gain omnidirectional antenna if the high-gain antenna system failed. A workable interface between the 64-m antenna and the 26-m MSFN prime *Apollo* station at Goldstone had to be developed to deliver the signals acquired by the 64-m antenna to the MSFN for processing and subsequent transmission to the *Apollo* mission control center at Houston. An *Apollo* signal data demodulator was borrowed from the MSFN prime *Apollo* station to provide a suitable interface between the 64-m antenna receivers and the DSN Goldstone intersite microwave system. The signal was routed from one Goldstone DSN station to another until it finally arrived at the DSN/MSFN wing station, where it could be transmitted to the MSFN prime *Apollo* station for processing.

This *Apollo 8* requirement also imposed two new operational interfaces. First, the 64-m antenna feed system did not have an automatic tracking capability. It was therefore necessary to make arrangements to have the MSFN and/or the Manned Spacecraft Center provide timely spacecraft state vectors to the DSN in order to generate tracking predictions and/or antenna drive tapes for each phase of the *Apollo 8* mission that required 64-m antenna station support. This support was required whenever the *Apollo 8* spacecraft was at a range of 80,000 km (50,000 miles) or more from the Earth. New state vectors were required after every engine burn by the *Apollo* spacecraft.

The second operational interface requirement resulted from the fact that the personnel working at the DSN's 64-m antenna had no previous operational experience with a manned mission, and there was not enough time for them to undergo formal training before launch. The DSN 64-m antenna station and the Apollo prime station exchanged selected personnel and conducted accelerated briefings on the operational techniques of their respective networks.

Despite the shortness of the preparation, the support provided by the 64-m antenna to the *Apollo 8* mission was excellent. *Apollo 8* was injected toward the Moon while in Earth orbit over the Hawaiian Islands in the Pacific Ocean; 8 minutes later, using nominal tracking predictions and antenna drive tapes, the 64-m antenna station acquired the *Apollo* signal. The signal was so strong, however, that it overloaded the receiver. Three to four hours passed before the correct pointing predictions could be provided for the station's control unit to locate the spacecraft accurately and obtain meaningful signal strength readings. During the rest of the mission, the Goldstone 64-m antenna continued to communicate with *Apollo 8* and supported all television broadcasts while the spacecraft was en route to the Moon, orbiting the Moon, and returning to Earth.

Earth-Based Radio Science

A precision, state-of-the-art, Earth-based spacecraft tracking and communications network such as the DSN has inherent RF system characteristics that are well suited to support radio science measurements. The emission characteristics and effects on RF radiation propagation are measured; the results provide information about the physical characteristics of the source and/or the propagation environment. The particular DSN characteristics, or performance, that are attractive to the radio science community include high-gain, low-noise S- and X-band antennas, relatively gain-stable, low-noise amplifiers and receivers, polarization diversity capability, precision time and frequency standards, and accurate and versatile recording instrumentation. In particular cases where long baselines or more than one deep space station is required, the DSN can provide ideal geometry for specific measurements. The opportunity to use these unique DSN facilities for radio science purposes is made available to the scientific community by NASA whenever the DSN is not supporting a space flight project. The allocation to radio science is a maximum of 5 percent of the available time of the Goldstone Mars 64-m antenna and an as-yet undetermined percentage for a 26-m antenna station, when more than one station is required.

The DSN support of radio science experiments falls into two general categories: (1) radio-astronomy oriented and (2) spacecraft-environment oriented. Spacecraft radio science is not normally coupled to primary spacecraft mission objectives, but, in some cases, it can be, as in measurements of occultation phenomena. Generally, when spacecraft primary missions were completed, the project managers allowed the spacecraft to be used in scientific and engineering experiments. An experiment evaluation panel, composed of membership from the radio science community, has been set up to allocate the use of these tracking facilities for radio astronomy purposes.

Experiments With Spacecraft

Several occultation experiments were supported by the DSN before 1969, notably on the *Mariner IV* Mars mission and the *Mariner V* Venus mission. These experiments provided significant information about the temperature-pressure profiles in the atmospheres of Venus and Mars. The DSN was instrumented with both open- and closed-loop receivers to measure doppler shift and signal attenuation characteristics resulting from signal passage through the planetary atmosphere and ionosphere during entrance and exit occultation. Measurements of the *Mariner V* signal during occultation of Venus in October 1967 showed large signal attenuation effects in addition to a large, atmosphere-caused doppler shift. Data were obtained down to within 5 km of the Venusian surface. Occultation of a spacecraft and radar time-delay measurements have improved our knowledge of the radius of Mercury, Venus, and Mars. Also, the knowledge of the oblateness of Venus and Mars has been enhanced by establishment of values that place limits on the oblateness.

In April 1966, during superior conjunction with the Earth, the *Mariner IV* spacecraft signals passed through the solar corona to within 0.9 deg of the Sun. This was the first opportunity to measure the effect of the solar corona on the propagation of an S-band radio signal. The signal was too weak at this time for direct phase lock because the spacecraft high-gain antenna was no longer pointed toward the Earth. It was necessary to employ spectrum analysis techniques wherein only the power spectrum of the received signal waveform was measured. The predicted spectral broadening of the received signal resulting from its passage through the solar corona was observed.

In November 1968, the *Pioneer VI* spacecraft passed behind the Sun. The design of the *Pioneer* antenna presented an opportunity to measure Faraday rotation of the spacecraft signal, in addition to collecting further data on the spectral broadening phenomena of solar plasma. The experiment provided both steady state and transient measurements of Faraday rotation phenomena.

The current accuracy of the radio doppler and ranging systems has opened the possibility of testing gravitational theories using planetary spacecraft. Knowledge of the gravity potential of the Moon has increased considerably from analysis of radiometric data generated during the *Lunar Orbiter* Project.

A bistatic radar mapping experiment was conducted in October 1966, by Stanford University, using the *Lunar Orbiter II* spacecraft, and again in December 1967, using the *Lunar Orbiter V* spacecraft. The spacecraft high-gain transmitting antenna was directed at the lunar surface, and both the direct beam (via the spacecraft side lobes) and the reflected signal from the lunar surface were received on Earth. The interference pattern was recorded and, when processed, resulted in an elementary radar map of several areas near the limb of the Moon.

A test of a convolutional coding technique for telemetry was made in February 1968 by JPL. A *Lunar Orbiter* ranging transponder was used to send back to Earth a coded data sequence which had been transmitted to the spacecraft. The purpose of the experiment was to demonstrate the performance of a convolutional coded telemetry system in an actual flight environment. The *Lunar Orbiter V* ranging channel was also used in a voice relay experiment. A voice-modulated subcarrier was transmitted from the Goldstone Deep Space station through the spacecraft transponder and received at an overseas

DSN station. It was used to demonstrate that such a system was practical and could be used for voice communications backup.

Lunar Orbiters II and *IV* were used to measure the delay stability of the on-board ranging transponder in an evaluation of ranging data versus doppler data differencing technique for calibration of charged particles. Because of the nature of the lunar orbit, with lunar Sun occultation occurring regularly, the delay drifts due to thermal effects obscured measurement of the desired effects.

Natural Radio Sources

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

In September 1967, the DSN was approached by Dr. David Robertson of the Australian Department of Supply, Space Research Group, who suggested that long-baseline interferometry measurements be made of a number of galactic radio sources using the baseline between the Goldstone and Canberra deep space stations. Such a baseline has a resolving power capability of about 2×10^{-3} arc-seconds. Dr. Alan Moffet of Caltech joined the effort as a co-experimenter. Observations were made in September 1967, November 1967, May 1968, and several times thereafter. Reasonable success in defining several radio sources was achieved after timing and computer program irregularities were resolved.

Early in 1968, after the discovery of pulsars (pulsating radio sources) was announced, several measurements of these objects were made, using DSN facilities. JPL made VHF measurements at 82–85 MHz in March 1968, using the 64-m Mars Deep Space Station at Goldstone. Dr. Moffet conducted a number of pulsar polarization measurements at S-band on the 64-m antenna, beginning in April 1968, and discovered that certain pulsars have a regular change in the polarization angle during each pulse.

JPL undertook the investigation of pulsar absolute timing and timing rate stability with the intent of possibly using pulsars for timing correlations between deep space stations. Investigations were carried out on the Venus Deep Space Station antenna at Goldstone, with a program of constant surveillance of a number of pulsars. It was verified that pulsars were steadily decreasing in rate with time, and abrupt changes in decay rate were discovered in several pulsars. These discoveries generated great interest among radio astronomers, but left pulsars of negligible interest as a timing standard for the DSN. In this regard, signals from Quasar 3C273 were used by JPL to measure the time difference between two deep space stations at Goldstone. The received noise-like signals were correlated, allowing for the time of flight difference between stations. The resulting additional time difference measured was the difference between the two clocks at each station. A time resolution of 30 μs was obtained.

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

The 9-m antenna at Goldstone, in addition to being used as the lunar time synchronization transmitting station, has also been used as a precision, 22- to 24-GHz planetary radiometer to determine absorptive and emissive properties of Venus at these frequencies.

Chapter V
DSN Development

Supporting Research and Advanced Development Program

The Supporting Research and Advanced Development Program at JPL has continuously contributed new technology to the DSN. Two major factors have been the Program's use of effective long-range planning and the recognition by the NASA Office of Tracking and Data Acquisition of new technology areas of particular benefit to flight projects. After a new concept is investigated and verified through research and appears to have significant value for future missions, it is funded and further developed in advanced engineering. This phase provides a prototype design that is used for a system demonstration to DSN and flight project managers. Such demonstrations are usually dynamic, using spacecraft already in flight. After this phase is successfully completed, the concept is considered to be a proved design. At this point, if approved future missions require this capability, the system is funded, developed, and procured as an operational element for the entire DSN. To provide assurance that the system is field-reliable, is operable, and is accompanied by the necessary documentation and spare parts, the discipline for a formalized transfer of the system from development to operations is required to complete the cycle. The result has been new technology ready for use when needed to meet flight project objectives.

Developments in Tracking and Communications

After the *Pioneer III* and *IV* missions, and prior to the launching of *Ranger I* in August 1961, a major communications research program, designated *Project ECHO*, was established at JPL. This project extended the *Pioneer* telecommunications technology to the point where the resulting ground station design would be directly applicable for use in tracking and communication on up- and down-links with space probes.

An antenna was installed for *Project Echo* (Fig. V-1) about 11 km (7 miles) from the *Pioneer* site, so that it could be used in a bistatic radar configuration with the *Pioneer* antenna. This antenna was a 26-m azimuth–elevation design, with a much higher angular tracking rate than the 26-m equatorial mount antenna. A secondary purpose for using this type of antenna was to evaluate it as a candidate for installation in the then proposed Deep Space Network. The *Echo* Project was a joint effort with the Bell Telephone Laboratories at Holmdel, N. J., to demonstrate the feasibility of communicating from the east to the west coast of the United States via an orbiting reflecting balloon 30.5 m (100 ft) in diameter at an altitude of 9000 km (5000 nautical miles). A 960-MHz link was established from Holmdel to Goldstone, and a 2388-MHz link from Goldstone to Holmdel.

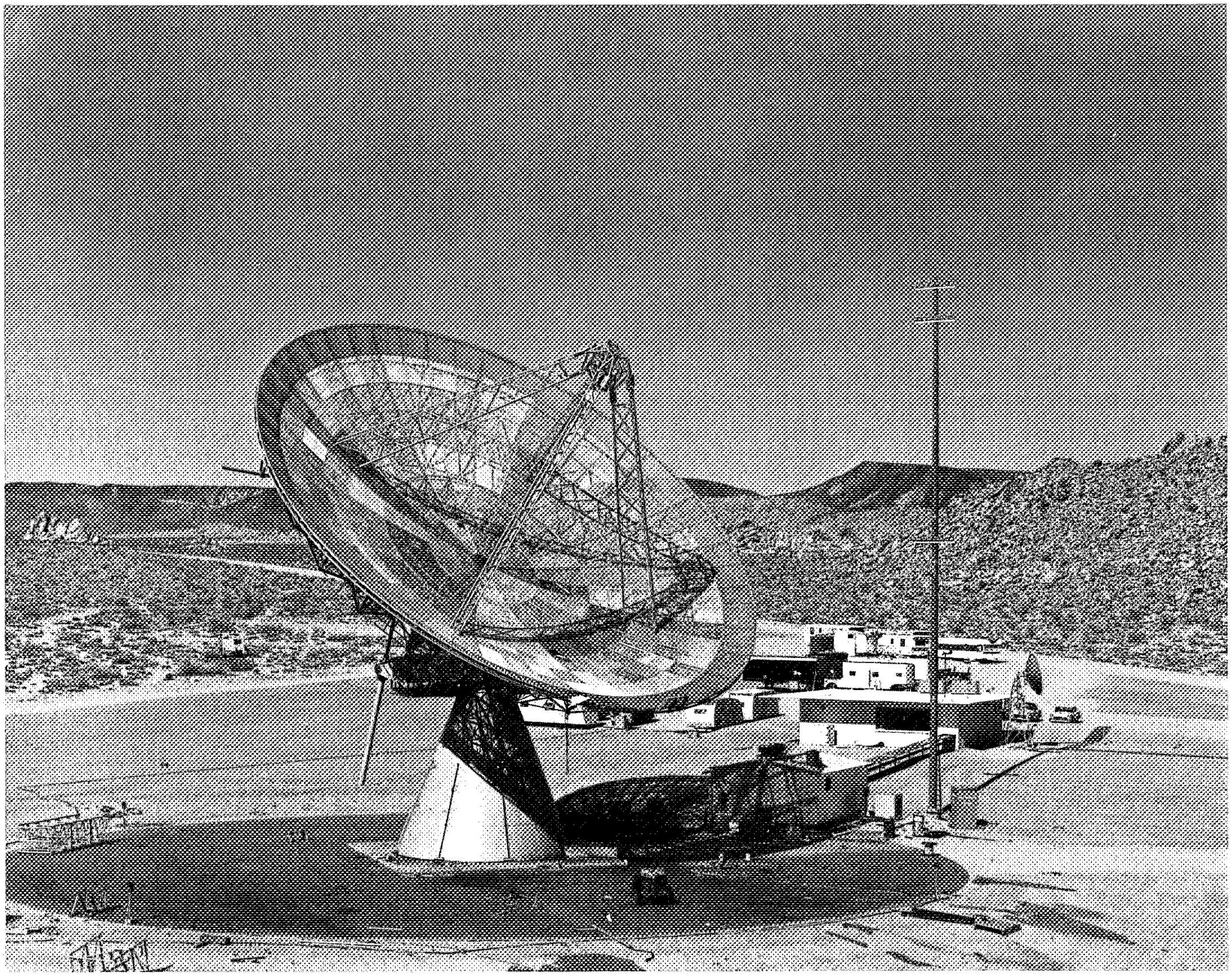

Fig. V-1. Transmitting antenna located at Goldstone

JPL used a modified version of the 960-MHz receiving system designed for *Pioneers III* and *IV* at Goldstone. In addition, these stations were equipped with low-noise amplifiers. A 10-kW, 2388-MHz S-band transmitter was installed at the *Echo* station for the link to Holmdel. A passive tracking doppler radar was also implemented at Goldstone, using the 10-kW transmitter at the *Echo* station, and a 2388-MHz angle-tracking S-band receiver at the *Pioneer* station. The *Pioneer* antenna thus had a dual-simultaneous frequency capability for receiving radio communications at 960 MHz and for receiving angle-tracking radar at 2388 MHz. The S-band was chosen for these advanced development activities, both because of the availability of the spectrum and its application to future deep space communication design.

The Deep Space Network was first implemented with receivers and exciter/transmitters for operation at 960 and 890 MHz, respectively, using much of the *Echo* technology. When these frequencies were originally selected, it was known that the assignment would not be permanent. First, the band had been previously allocated for Tactical Air Navigation purposes, and second, the band was not optimum from a space communications design standpoint. Two major factors were (1) galactic background noise was still high at 960 MHz and (2) because the 26-m antenna was far from its gain limit design, higher frequencies could provide more link capability by the increased gain of spacecraft antennas, which were constrained in area. From these considerations, S-band appeared to be a near-optimum frequency.

JPL, acting as an agent for NASA Headquarters at the 1961 Geneva International Frequency Allocation Conference, was instrumental in establishing the present S-band deep space frequency allocation. The uplink/downlink frequency ratio remained close to the same value used at L-band, its value being constrained to not less than 7 percent, nor greater than 15 percent, between the uplink and the downlink. This provided optimum performance of the feed at both frequencies, but would still provide enough separation so that diplex filtering could be accomplished efficiently.

In 1962, the DSN began implementing the S-band equipment design. By early 1963, much of the engineering was complete and a major contract was let to industry for production. At this same time, the Manned Space Flight Network was being implemented, and, to maximize cross support capabilities between the DSN and the MSFN, NASA Headquarters decided to install the same or similar S-band receiver/exciter ranging equipment in both networks. JPL was tasked to design and procure the necessary receiver/exciter ranging equipment for both the DSN and the MSFN.

In late 1963, the Deep Space Network was formally established, comprising the Deep Space Instrumentation Facility, the Ground Communications Facility, and the Space Flight Operations Facility.

The Planetary Radar Program

Early in 1960, plans were being made at JPL for space flight missions to the near planets. Communication system requirements, such as data rates and microwave design representing the state of the art, were being considered. For instance, doppler tracking accuracy requirements for planetary missions made it mandatory to use atomic oscillators for the DSN ground transmitters. It was also recognized that to obtain sufficient navigation accuracy, an accurate determination of the astronomical unit and planetary ephemerides was necessary.

Feasibility plans were developed for extending the Goldstone Echo station radar capability with state-of-the-art experimental technology that would permit the indirect measurement of the astronomical unit by measuring the radar range to the planet Venus. The planet ephemeris would also be improved significantly by this method. In order to use the Echo radar for the 1961 Venus conjunction opportunity, it was necessary to add a low-noise maser amplifier to the receiver and to provide a filter for detecting the return echo. The distance to Venus was determined to within 500 km. The optical determination of the astronomical unit was found to be in error by about 10,000 km. If the optical value had been used to navigate the *Mariner II* spacecraft to Venus, there would have been no encounter with the planet.

Although the major justification for the planetary radar program was to provide the necessary technology for the DSN, planetary radar work in determining and refining astronomical constants and contributing to planetary science through radar mapping proved to be of great value in supporting NASA's scientific planetary exploration program. The effort continued with repeat observations of Venus, Mars, and Mercury. Planetary radar doppler and time delay measurements from Mercury, Venus, and Mars have produced significant improvements in the accuracies of the ephemerides of these planets. The value of the astronomical unit has been improved by three orders of magnitude and is known today to an accuracy of 3 parts in 10^8. The position of Venus relative to the Earth is known to within 10 km. A similar improvement in the knowledge of the position of Mars relative to the Earth has been accomplished. In addition, variations in elevation on Mars (topography) amounting to 12 km have been found. A figure of merit C for planetary radar was established, which provided a measure of the ability to detect and track distant targets:

$$C = PGA/T\ F^{1/2}$$

where

P = transmitter power, W

G = antenna gain

A = receiver aperture

T = system temperature, K

F = frequency, MHz

Table V-1 lists the basic planetary radar performance, beginning with the 1961 Venus contact. Table V-2 is a summary of the significant scientific results derived from the DSN planetary radar effort.

Improvements in planetary radar capability required the development of components and systems technology that related directly to improvements in the Deep Space Network that were necessary to meet flight project requirements for deep space tracking and communications. A high-efficiency, low-noise antenna feed, very low-noise amplifiers, very high-power transmitters, signal processing technology, and ranging systems designed and first used

Table V-1. Planetary radar figure of merit

Year	New Capability	C Factor ($C = PGA/T\ F^{1/2}$)
1961	64 K temperature, 9-kW transmitter, power spectrum analyzer.	3×10^{8}
1962	Range gate, rubidium oscillator, 12.5-kW transmitter.	6×10^{8}
1963	100-kW transmitter, improved shaped pattern feed.	6×10^{9}
1964	35 K temperature.	1.2×10^{10}
1966	9-channel correlator, improved range gate.	1.2×10^{10}
1967	64-m antenna for reception, 25 K temperature.	1.2×10^{11}
1968	450-kW transmitter on 26-m antenna.	5.4×10^{11}
1969	32-channel correlator, 17 K temperature.	8×10^{11}
1970	400 kW on 64-m antenna, hydrogen frequency reference.	4.8×10^{12}

Table V-2. Planetary radar program milestones

Year	Opportunity	Results
1961	Venus	First Venus detection; determination of the AU within 500 km; refinement of ephemerides.
1962	Venus	Determination of slow retrograde rotation.
1963	Mars	First Mars detection; measurement of albedo vs longitude at 13 deg latitude.
1963	Mercury	First Mercury detection; measurement of albedo and range.
1963	Jupiter	Statistically significant detection; not repeated.
1964	Venus	Discovery of large bright surface features.
1965	Mars	Measurement of albedo and roughness vs longitude. *Mariner IV* camera directed to photograph Trivium Charontis, a very bright, smooth radar target.
1966	Venus	Location of a number of new surface features. Rotation found to be ~243.0 days, at, or very near, Earth synchronous.
1967	Venus	±0.5-km ranging data obtained, leading to improvements in the orbit, planet radius, and AU.
1968	Icarus	Detection, verification of ephemeris, estimation of size and roughness.
1969	Venus	Ranging, large map, highest resolution, north-south ambiguity resolved.
1969	Mars	±0.2-km altitude profile of equatorial region.
1969	Mercury	Surface features detected (not Venus-like).
1970/71	Mars	Detail surface mapping.
(Future)	Venus	4×4-km Venus mapping.
	Mercury	Altitude profile to 2 km.
	Jupiter	Detection of Jupiter moons.

in the experimental planetary radar operations have all had direct application to the development of the Deep Space Network.

The JPL planetary radar effort has served to focus the attention of JPL management on research and development activities which affect the long-range future. It has been possible to establish a small number of limited scientific objectives toward which many individual lines of applied research contribute. *Project Echo* was the first use of this principle. The planetary radar work provides a research and development environment that is closely analogous to the needs of the DSN in its communication and tracking support of deep space automatic spacecraft.

Digital Communications

Many of the early JPL tracking and communications designs of the middle and late 1940s incorporated analog techniques for signal processing functions. Typical of these early systems were FM/FM and FM/PM[18] telemetry, automatic range tracking by radar, and early doppler guidance systems. For the most part, up through the early 1950s, analog designs were far simpler and more reliable than vacuum tube digital circuitry. Also, the introduction of optimum filtering techniques at that time provided an acceptable increase in performance, which tended to perpetuate the use of analog circuitry for data transmission and processing. Analog circuits usually depend on electrical or mechanical signals to represent physical quantities, and thus, in analog computing and other processing, these signals are subject to absolute accuracy limitations and calibration stability inherent with such systems. Usually the maximum accuracy obtainable even in individual computing circuits is typically from 0.1% to 1.0%.

With the introduction of small, low-cost, reliable solid-state digital circuitry in the mid-1950s, the advantages of applying digital technology for communications and tracking purposes became clear. Many of the techniques for approaching the theoretical limits of communication channel efficiency are most readily implemented with digital-type coding, especially at high speed. Further, more complex guidance and telemetry systems produced a volume of data that was most efficiently processed by high-speed digital data processors. Consequently, it was necessary that the raw data be in a convenient digital form. Emphasis on the development of digital communications technology increased at JPL in early 1954 and reached early success in 1955 with the first digital tracking system designed for the *Sergeant* missile doppler ranging system.

[18]FM/FM = A frequency-modulated subcarrier which in turn frequency modulates the RF carrier.
FM/PM = A frequency-modulated subcarrier which in turn phase modulates the RF carrier.

Because of the multiplicity of existing and proposed methods for digital transmission, a central problem in telemetry system design in the late 1950s was to establish performance comparisons of the various designs. An additional important factor in selecting digital design was the ease (simplicity, hence reliability) with which they could be mechanized. The two digital communication methods chosen by the DSN for general application were the PCM/FSK system (where the pulsed modulation shifts the output frequency between predetermined discrete values) and the PCM/PSK system (where the pulsed modulation shifts the instantaneous phase of the modulated wave between predetermined discrete values). In the late 1950s, this was an effective compromise of efficiency and simplicity. The advantage of the PCM/PSK system was a 3-dB improvement in performance over the PCM/FSK because of the retention of phase information in the communications process. This technique was used for the *Mariner Venus 1962* telemetry and command systems.

By 1967, the technology of channel coding was advanced enough to be implemented in an operational system. The baseline figure of merit of a communications channel is the channel capacity as defined by Shannon,[19] and is the maximum error-free data rate. The theorem states that for all transmission rates less than a given value, it is possible to process the data at the transmitter so that it can be recovered from the noisy received signal with a probability of error which approaches zero as the length of the data sequence becomes infinitely long. Investigation was initiated in 1967 to compare convolutional coded telemetry systems with the established coding method. The conclusions were that modified, short-length, convolutional coding techniques were competitive with block coding.

Large Earth-Based Antennas

During the 1960 implementation of the DSN's 26-m antenna network, studies were begun to determine the essential characteristics and optimum size for an antenna specifically designed for advanced deep space tracking and communications. These studies culminated in the "Advanced Antenna System." Tradeoff studies of the spacecraft–Earth-based link indicated that diameters from 55-75 m were near optimum and the most cost-effective.

[19]Shannon, C. E., *Mathematical Theory of Communication*, Ph.D. thesis, Massachusetts Institute of Technology, 1940.

NASA/OTDA was particularly sensitive to the requirements for large-diameter antennas for supporting planetary exploration; several large antenna programs had run into trouble because of basic design inadequacies and lack of proper planning. NASA, then, along with JPL, wanted to assure success by thoroughly studying the system designs and by staying close to the proved state-of-the-art design techniques.

Late in 1962, JPL released to industry for proposal a specification and conceptual design for a 64-m-diameter antenna. Contractor selection was made and construction begun in late 1963. The 64-m deep space station (Fig. V-2) was completed in May 1966 and provided operational support for *Pioneer VII*, which was launched in August 1966.

New Capability

The DSN introduced a considerable amount of new capability in response to flight project requirements. In most cases, this capability was a direct application of previous DSN supporting research and advanced development. The following paragraphs summarize these capability improvements in the uplink, downlink, and doppler capability, the ranging capability, and the telemetry and command system efficiency.

The key parameters that influence the system performance of an Earth-based deep space station are antenna gain, transmitter power, receiver noise temperature, and tracking loop bandwidth. The Earth-based station radio link capability can be expressed by combinations of these parameters into two fundamental figures of merit: (1) The uplink effective radiated power, which is the product of antenna gain and transmitter power, and (2) downlink receiving system sensitivity, which is the quotient for antenna gain and the product of noise spectral density and tracking loop bandwidth. Figure V-3 is a graph of the capability improvement of the uplink, and Fig. V-4 is a graph of like improvements for the downlink. The method of specifying the figure of merit for the doppler system involves computing the differences between doppler observable and the doppler derived from orbit computation. Figure V-5 depicts the improvement in this factor over the past 10 years. Also shown is the corresponding increase in guidance accuracy resulting from doppler improvement. The effect of specific improvements are annotated. The ranging capability, as shown in Fig. V-6, is a plot of geocentric range residual of several bodies in the solar system, resulting from the introduction of planetary radar ranging and spacecraft ranging.

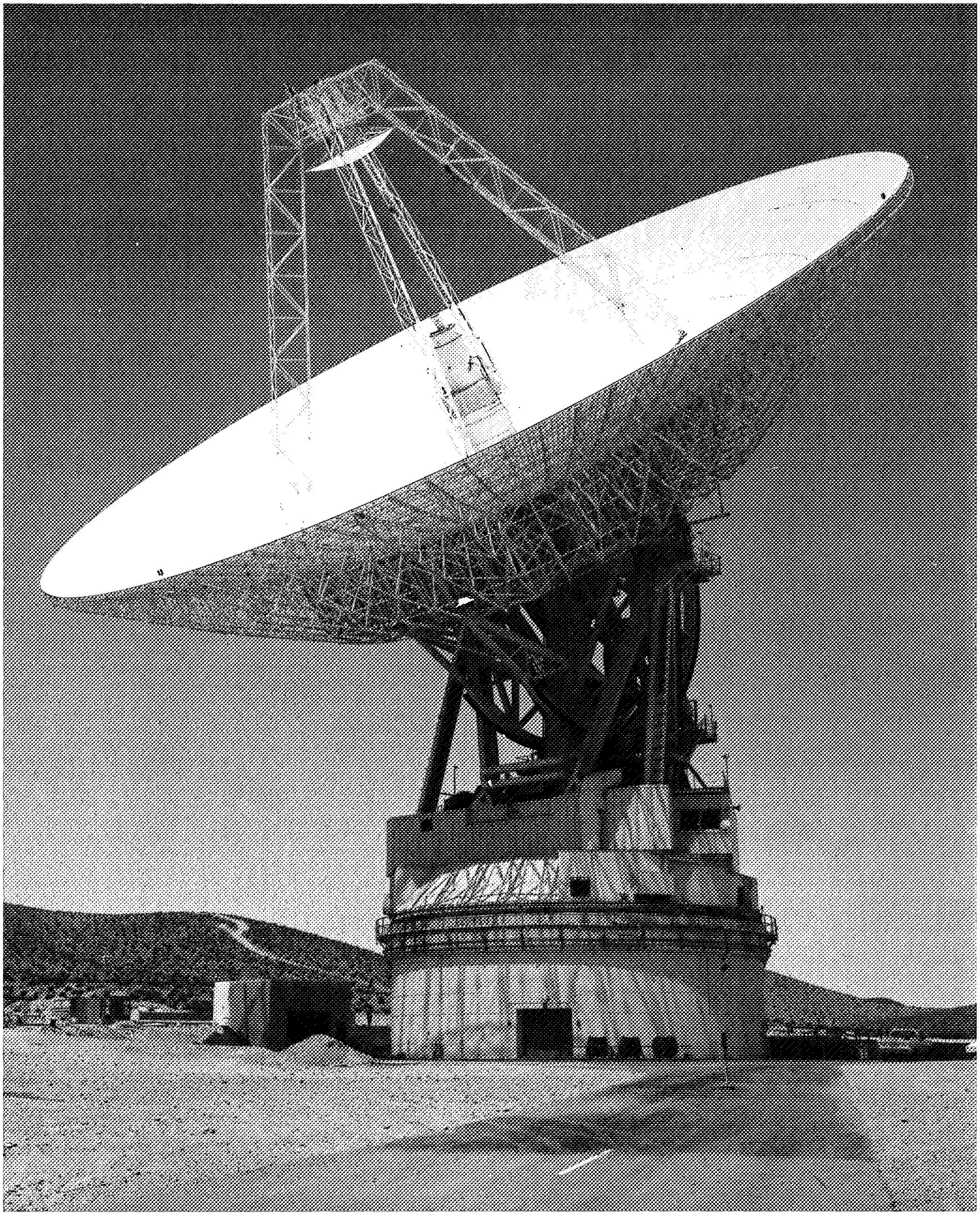

Fig. V-2. The 64-m-diameter Mars antenna at Goldstone

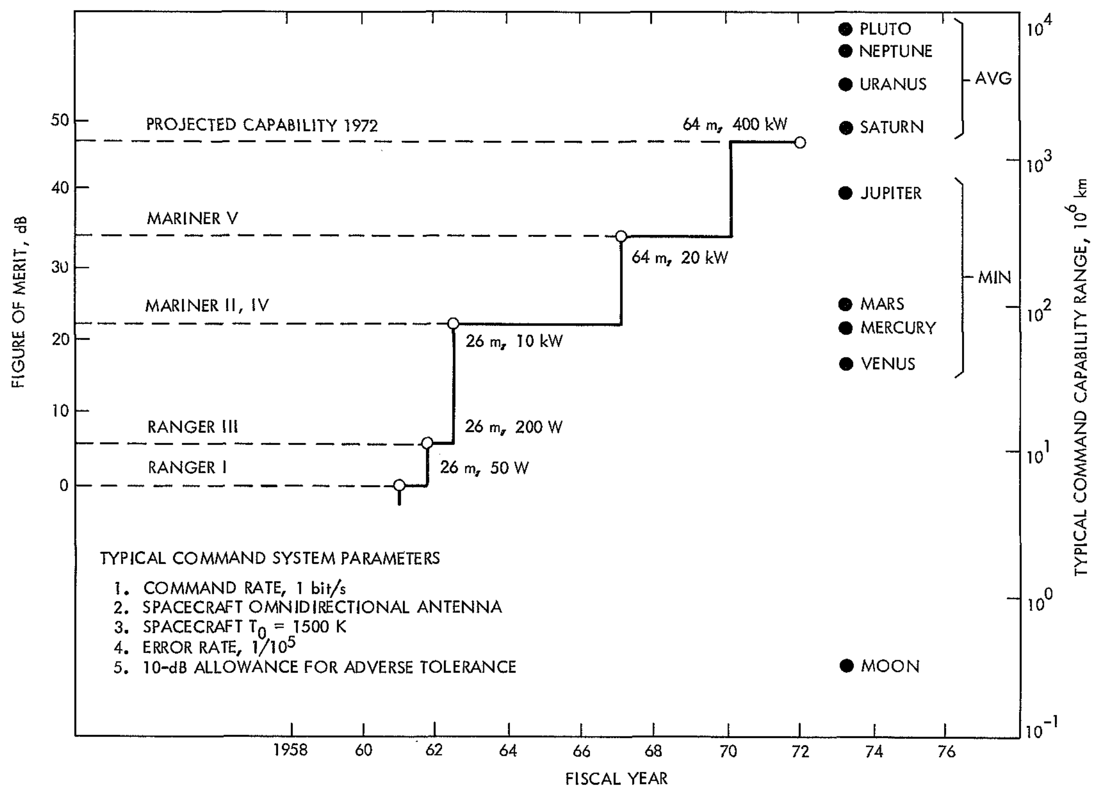

Fig. V-3. DSN uplink figure of merit

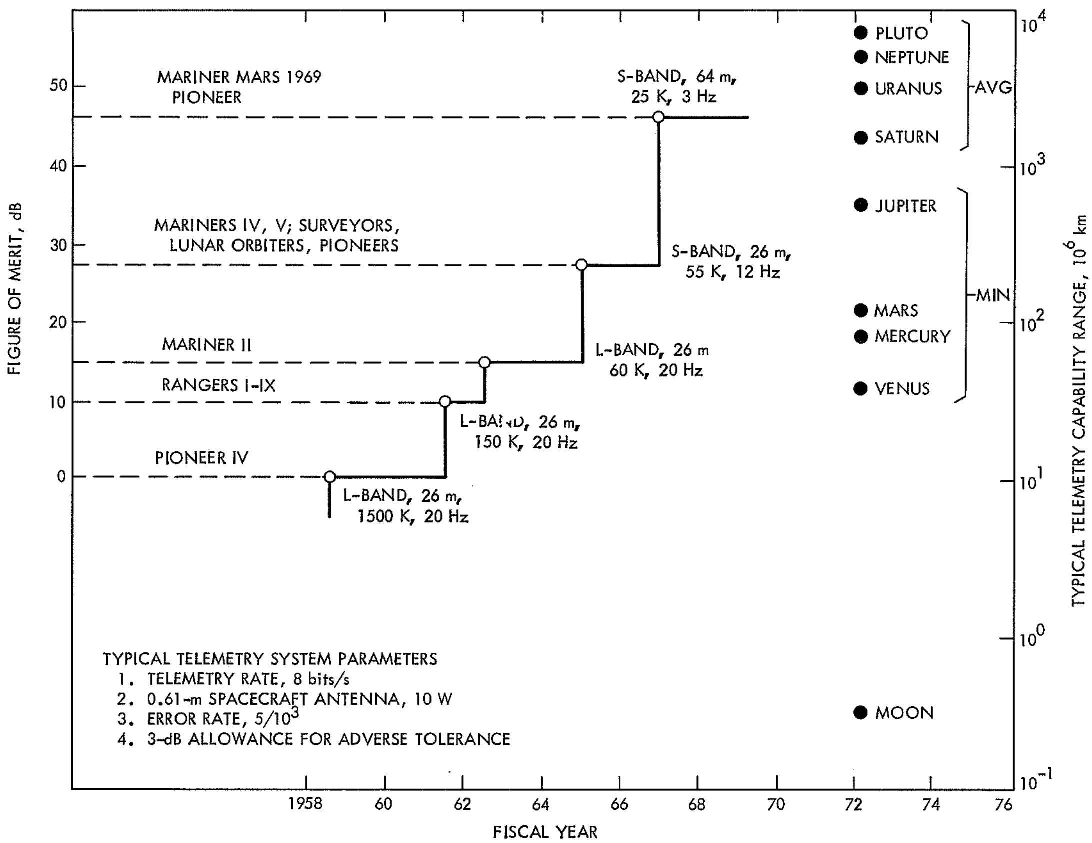

Fig. V-4. DSN downlink figure of merit

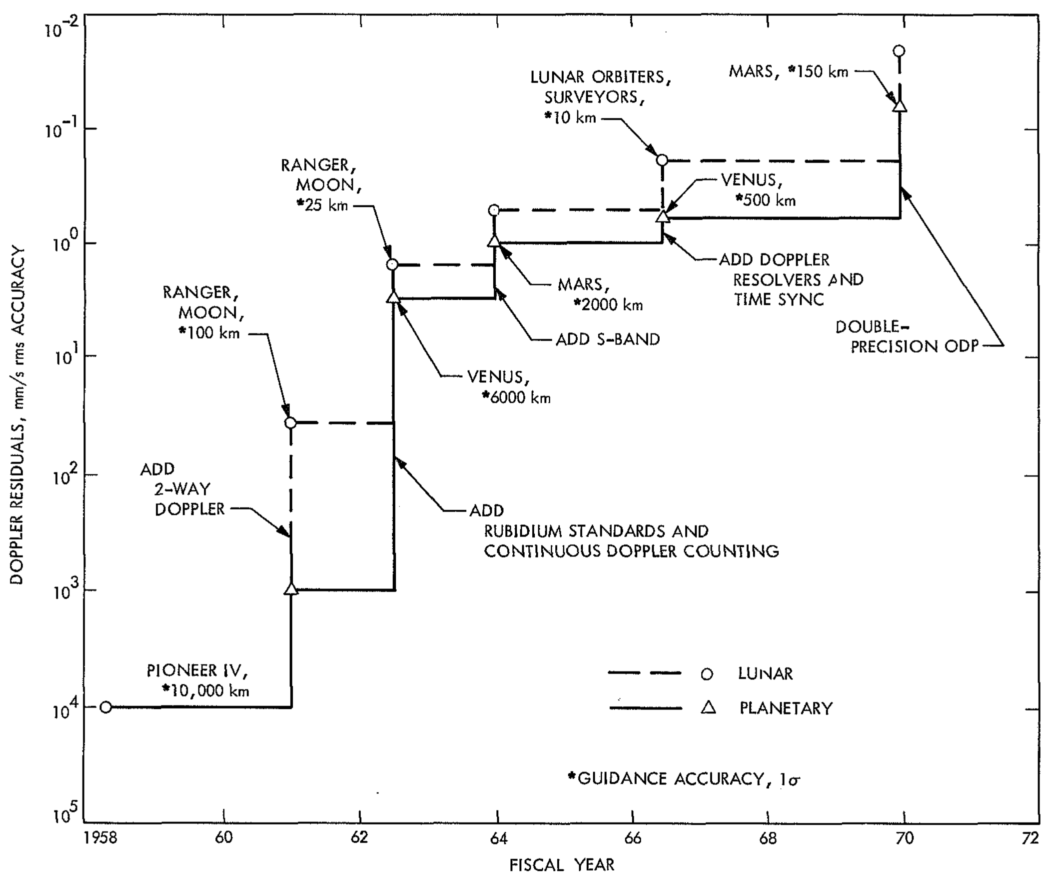

Fig. V-5. Doppler residuals (observables minus computed doppler)

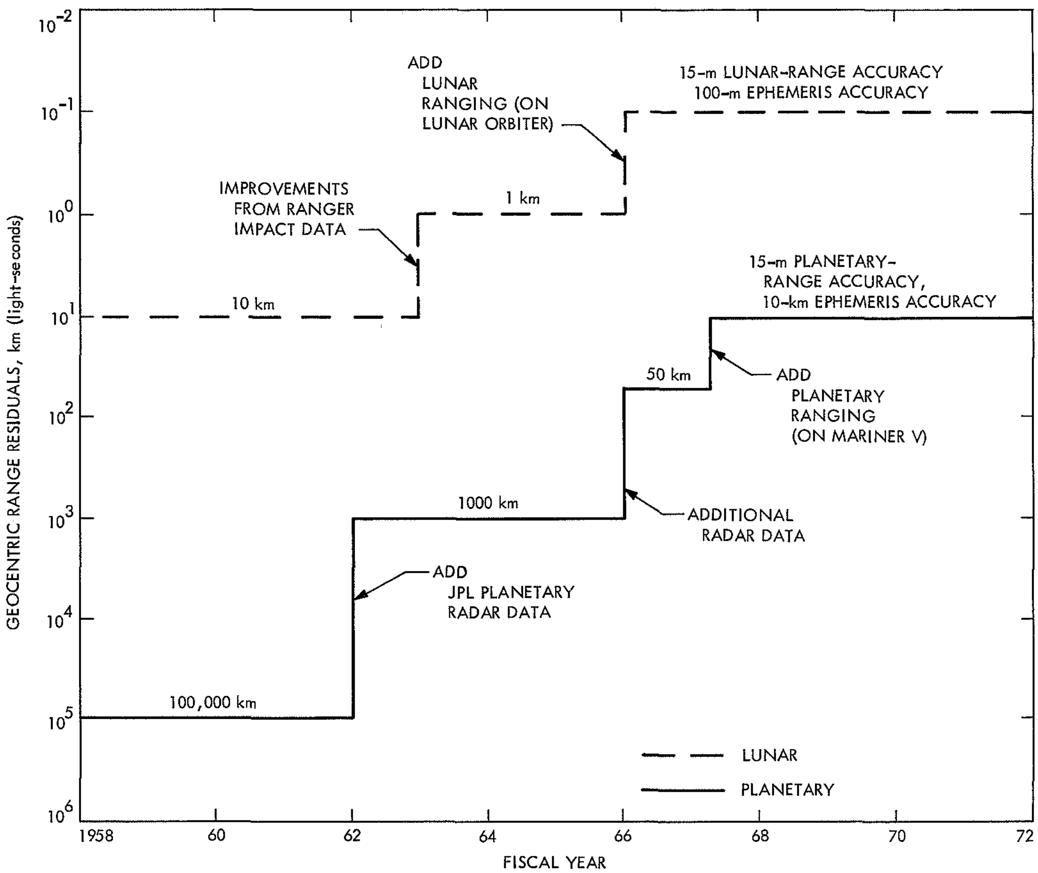

Fig. V-6. Ranging system residuals

Accurate time correlation between deep space stations was found to be necessary in determining the precise orbits of accelerating spacecraft. The *Lunar Orbiter* Program required knowledge of this difference to within 50 μs. This capability was achieved as a temporary expedient by a convenient reconfiguration of the unified S-band Mark I ranging system. In 1968, an advanced engineering version of an X-band lunar bounce time correlation system was developed and tested successfully. The system uses a 10-kW X-band transmitter at Goldstone and small receiving stations at each deep space station for reception of a synchronized range modulation code. The accuracy of time correlation for this technique is better than 20 μs.

Efficient modulation encoding methods have been introduced into the network as a result of activity by the Supporting Research and Advanced Development Program. A plot of system efficiency, in terms of energy per bit over the noise spectral density for a given error rate, is shown in Fig. V-7.

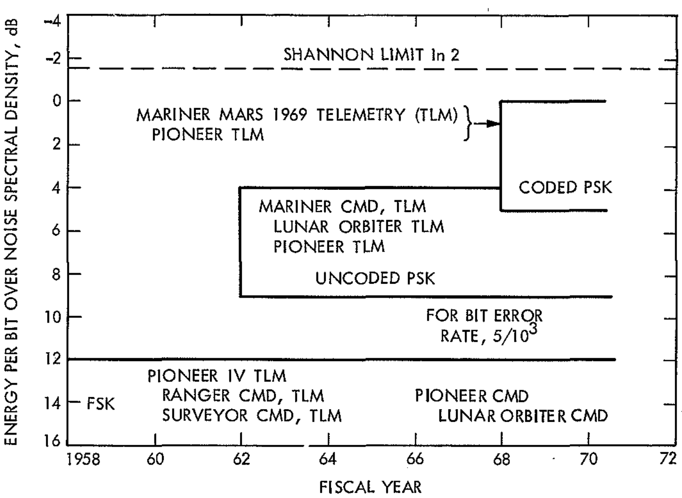

Fig. V-7. Communications system efficiency figure of merit. (TLM denotes telemetry; CMD, command.)

Radio Navigation

Fundamental Radiometric Concepts and History

In the observation of any system to determine the state, the first step is to make a set of observations whose values will allow a unique deduction of what the state is. The dimensions of the observation, then, must be at least as large as the dimension of the system being observed. In the case of a space probe, that dimension is 6 plus time (the three components of position and velocity). If more observations than this are made, the excess can be used to produce an "averaged" answer, one that will be more accurate in the presence of random errors in the measurements themselves.

Because there are measurement errors, it is desirable that the observations strongly relate to the state being observed. For example, trying to determine the number of automobiles in Los Angeles County by measuring the total effluent levels would not be a very good scheme—a relationship exists, but it is very indirect and the link between the two is established via a complex physical model incorporating many imperfect assumptions. It would be better to count automobile registrations directly.

There are analogous principles in space navigation. It would be ideal to have direct, independent measurements of the position and velocity of the probe. Since these are not possible, alternative measurements are sought that quickly establish the relationship with the probe state. The basic high-precision Deep Space Network measurements of topocentric range and doppler meet these criteria rather well in all phases of space flight. These criteria directly measure radial distance and speed and depend on changing geometry to afford a six-dimensional view of the state. In the case of translunar missions, the changing geometry of the probe with respect to the Earth establishes the desired "multi-aspect" views of the orbit over the period of a day or so. In lunar and planetary orbit, the strong gravitational field influencing the probe produces a strong temporal signature on the doppler data which allows the deduction of what the state must be in a single revolution or less about the primary body. In interplanetary cruise (that is, for most current deep space tracking), the slow arc of the spacecraft orbit around the Sun suggests that the spacecraft might have to be tracked for a significant portion of a full revolution in order that a solid deduction be made as to the six state components. This is not really the case, however, because we observe from a station located on the Earth's surface rather than the center, and the diurnal motion of the Earth produces a sinusoidal modulation on the geocentric range-rate (the doppler measures range-rate directly) whose amplitude and phase give nearly direct measurements as to the spacecraft's declination and right ascension. Classical astronomers have had no such aid in their optical observations of the heavenly bodies, and indeed have sometimes been obliged to observe their targets over many years before the desired orbit could be clearly discerned.

Figure V-8 depicts the basic geometry and the principle described. The doppler first measures the geocentric

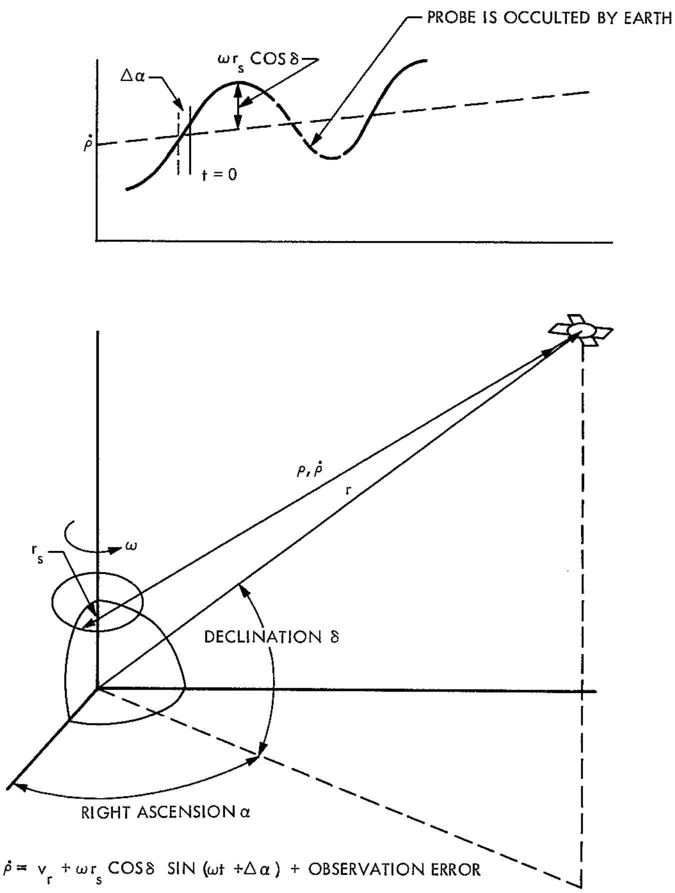

Fig. V-8. Basic geometry for doppler tracking

range-rate directly (this can be viewed as one of the state components). Second, by observing the amplitude of the sinusoidal modulation, and knowing the distance of the tracker off the Earth's spin axis and the Earth's rotation rate, one can measure cos δ. Third, the modulation crosses zero when the spacecraft crosses the meridian of the deep space station—if the longitude of the tracker is known, this establishes the probe's right ascension. Thus, in a single pass of doppler tracking, three of the requisite six components are (nearly) directly observed.

Later, perhaps in a day or so, the characteristics of this modulation will have changed, both in amplitude and phase (Fig. V-9). These changes are related to right ascension rate and declination rate, two of the three remaining state components. Finally, the change in the geocentric range-rate can be related to the geocentric range of the spacecraft, but only indirectly through the solar gravitation, and suffers from the disadvantages of that indirectness. It is much more accurate to supply the sixth component with a direct measurement—this is accomplished with the DSN ranging system. Thus, in the span of a few days' tracking, the range and doppler system can observe, rather directly, all the primary system states—satisfying the original criterion for an attractive measurement scheme.

This simple interpretation of the fundamental geometry of deep space tracking was not understood when interplanetary flight was first undertaken early in the 1960s—the problem was viewed in the same manner as classical astronomers viewed theirs. Its discovery in 1965 and subsequent development has led to a great (and proper) reliance on short-term tracking for orbit estimation in critical mission time periods, and it is the major paradigm employed to isolate the critical error factors influencing navigation accuracy. The following paragraphs present a historical account of the handling and reduction of these errors.

Fundamental Accuracy Limitations of Radio Observables

The preceding paragraphs characterized the sensitivity of the measurement geometry to errors in the radio metric observables. The critical parameters are the target ephemeris, the station location on a rotating Earth, the doppler count, and round-trip light time. The error contribution of the radio system to each of these parameters will be briefly discussed in turn, with

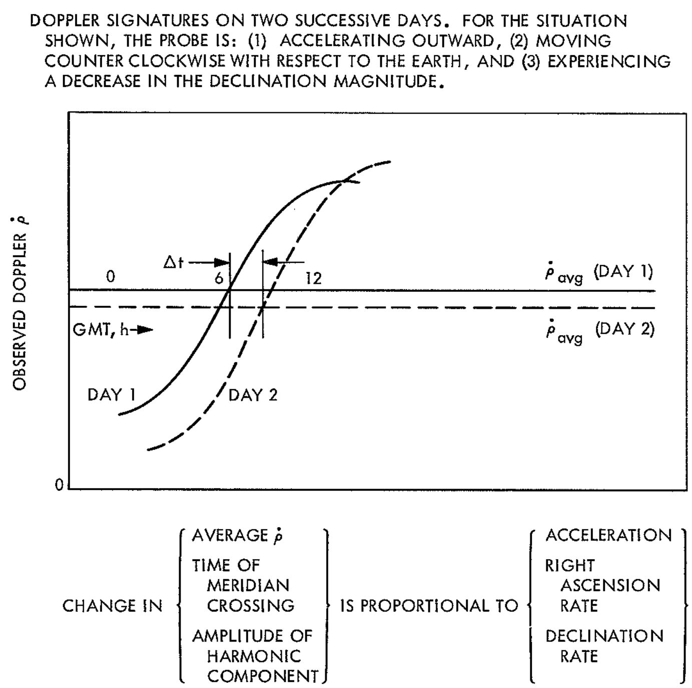

Fig. V-9. Doppler signature on two successive days

emphasis on fundamental limitations. Each parameter will be elaborated on and historically developed in succeeding sections.

The Moon and planetary ephemerides have been refined through the use of Earth-based radar measurements; however, accurate determination of tangential and out-of-plane components are not possible with this type of instrumentation. Accurate ephemeris data become a critical navigation requirement, particularly for Grand Tour outer-planet flyby missions. The use of approach guidance techniques in conjunction with Earth-based measurements provides a far more optimum geometry and, as an example, in the case of Saturn missions, will reduce targeting errors from over 5000 km to probably less than 500 km.

Errors in station location (longitude, distance from the Earth's spin axis, and errors due to pole motion and estimates of universal time), while they affect the final accuracy of right ascension and declination determinations using radio metric data, do not affect the radio metric data directly. In 1963, the value for station location accuracy was about 40 m, and the present nominal value, considering all these factors, is from 2 to 5 m. For a *Mariner Mars 71* orbit, a 2-m station location error will enlarge into a target error of about 50 km. It is expected that the DSN will approach an accuracy of from 0.2 to 0.5 m in station location within the next 5 years, but probably not much better than this in the near future.

The accuracy of doppler information depends fundamentally on the frequency and phase stability of the measurement system and the external factors which change the medium's velocity of propagation such as tropospheric and charged-particle effects. The introduction of the hydrogen frequency standard will reduce contributions of doppler count error to almost negligible values. The dominant equipment error will then be the phase drift in the ground and spacecraft RF systems. Typical uncalibrated phase drifts in the system over an 8-hour pass are probably less than ± 0.5 m (4 Hz) and probably can be reduced to less than ± 0.1 m.

The accuracy of ranging information depends on the uncalibrated time delay stability in the ranging system. Present system performance is from ± 5 to ± 15 m, with the present (1969) delay errors both in the spacecraft and ground equipment. It seems reasonable to predict that within the next 5 years the spacecraft transponder delay stability will be better than 10 nanoseconds (calibrated to better than 1 ns) and the ground system better than 1 ns. This will provide a measurement accuracy to better than ± 1.5 m.

The accuracy to which charged-particle effects can be removed from the tracking data depends on performing accurate differential group vs phase velocity measurements ($c = \sqrt{V_g V_p}$) or differential phase delay measurements vs frequency, or both. The equivalent station location error resulting from correcting for charged particles using Differenced Range vs Integrated Doppler (DRVID) for a Mars mission is about 1 m; using the two-frequency method (X- and S-band) it is about 0.1 m, provided stable coherency between the X- and S-band spacecraft transmitter can be maintained. The important parameter in charged-particle calibration is the measurement of the changes in the charged-particle content during a pass; this is the factor that results in errors in the estimation of velocity and direction. The DRVID technique is not useful unless range (time delay) stability can be determined to better than 1.5 m over a pass.

The equivalent station location error resulting from use of a tropospheric model is from 1 to 3 m. In the future, with improved models and local atmospheric measurement, this error can be reduced to less than ± 0.2 m.

Development of Accuracy Models

It is of fundamental importance to the development of the DSN that error sources in tracking data be identified and their size measured. By so doing, it is possible to predict performance under new conditions such as going from lunar to planetary distances, going from L-band to S-band tracking, or tracking near the Sun. Using such predictions provides the necessary guidance for DSN accuracy improvements that will most efficiently provide the required performance.

How are these errors identified and measured? While many of the errors are identified and controlled as the DSN design evolves, the complete demonstration requires flight performance and evaluation. Here the actual performance is compared with the predicted performance. Postflight analysis of mission tracking data has proved to be a powerful way of locating the "culprits" (errors) which control the accuracy of DSN tracking data for navigational and other purposes. The "culprits" are found by analyzing the "wiggles" they cause in the tracking data residuals. As indicated in Fig. V-10, the

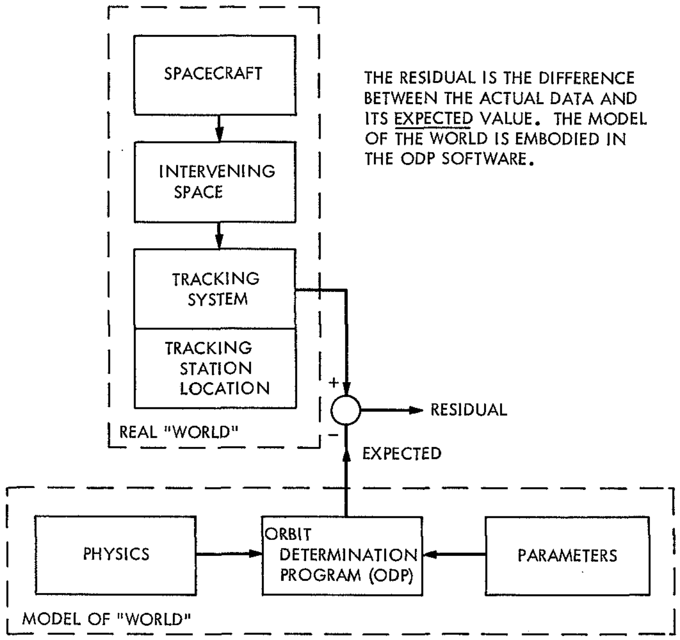

Fig. V-10. Generation of tracking data residuals

residual is the difference between the actual data output and the expectation of its value.

A simple example of this error-finding process is the analysis of the relatively high-frequency noise found on the *Ranger* mission doppler residuals. As the spacecraft distance increased or as the sample spacing was decreased, the highly "visible" fluctuations in the residuals increased. After the effects of quantizing the doppler counts were removed, it was evident that the culprit was instability in the reference oscillator. A more difficult case is tropospheric refraction. Here the inadequacies of the theoretical model predicting the effect are most evident at low elevation angles. By analysis of the "signature" at low elevation angles at rise and set of the spacecraft, more accurate models and approaches have evolved.

Probably the most important signatures found in tracking data residuals are those of a diurnal nature, particularly those caused by errors in our knowledge of the location of the stations in space. The signatures corresponding to an error of 2 m in longitude or distance off the Earth's spin axis have an amplitude of only 0.14 mm/s (0.002 Hz at S-band) and are 90 deg out of phase with each other. Such relatively small and slowly varying wiggles were initially detected by careful analysis of spans of tracking data as long as several months. By such analyses, our knowledge of station locations has been dramatically improved and this once-dominant error source is being controlled. Recognition of the dominant nature of even small diurnal error sources has led to the design of experiments to detect and measure ground station and propagation errors.

A vital step in the orderly pursuit of DSN error sources was the formation of the DSN Inherent Accuracy Project in 1965. The project leader reported to the DSN Executive Committee, whose members are on the JPL senior staff level and are concerned with overall DSN effectiveness. The project's goals are:

(1) To determine and verify the inherent accuracy of the DSN as a radio navigation instrument for lunar and planetary missions.

(2) To formulate designs and plans for refining this accuracy to its practical limits.

Activities of the Project have been reported regularly in the DSN volume of the JPL Space Program Summaries since January 1966. Meeting these goals is a cooperative task of two JPL technical divisions. To accomplish these goals, the project holds regular monthly meetings to coordinate and to initiate activities that are relevant. The project leader is authorized to task project members to conduct analyses of proposed experiments, prepare reports on current work, and write descriptions of proposed experiments. Further, the Inherent Accuracy Project is authorized to deal directly with flight projects, utilizing the DSN regarding data-gathering procedures which bear on inherent accuracy.

One of the functions of the Inherent Accuracy Project was to establish accuracy goals on a consistent basis so that effort was directed toward perfecting the system elements whose error contribution was controlling overall performance. Within the DSN, a "balanced" design was sought. However, as DSN accuracy continued to improve by about 2 dB per year, it was found that the controlling errors could lie outside the tracking system and that changes in the spacecraft and project navigation software would be required to achieve the project's desired accuracy. In recognition of the importance of coordinating the goals of the overall spacecraft navigation system with the DSN measurement goals, the JPL Navigation Program (JNP) was established in December 1968. The JNP is the organizational means by which the various research and development activities influencing navigational capabilities for future missions are coordinated. At the JNP level it is possible to deal with tradeoffs involving such factors as:

(1) Improved DSN accuracy.

(2) Spacecraft transponder accuracy.

(3) Reliance on on-board navigation measurements to supplement radio tracking.

(4) Tighter tolerances on control or measurement of spacecraft nongravitational forces (e.g., variation of solar radiation force, gas leaks, etc.).

(5) Charged-particle calibration requiring new spacecraft elements such as dual-frequency downlinks or wider-bandwidth ranging.

(6) Project navigation software accuracy and sophistication of estimation techniques.

Thus the natural outgrowth of the efforts to develop an efficient balance of DSN errors has been a program wherein logically balanced goals are set for the DSN and the other elements contributing to navigation performance.

In the next Section, the result of feedback of postflight analysis on the performance of the DSN elements is described. Next are documented some of the incidental, but very valuable, byproducts of the careful analysis of flight data. Scientifically significant results quickly became such a valuable output of such analyses that Radio Science Experiment Teams are now considered essential parts of NASA flight project science teams. The first formally recognized science experiment based on tracking data analysis was the *Mariner Mars 1964* occultation experiment. The technical feasibility of this demanding experiment was based on DSN-sponsored postflight analysis of atomic-oscillator-derived radio metric data from the *Mariner II* Venus spacecraft.[20]

Doppler Critical Parameters

Doppler count accuracy. Figure V-11 indicates the improvement in resolution of the integrated doppler observable. The first tracking systems used L-band frequencies (960 MHz). By converting to an S-band system (2.3 GHz), the DSN achieved greater resolution and, at the same time, reduced charged-particle and tropospheric effects.

Following the conversion to S-band, the doppler system was improved further by counting both positive-going zero crossings and negative-going crossings. This permitted resolution to the half-cycle level. Another improvement was the adaptation of the "times 8" subsystem, which again improved resolution by a factor of 4.

The most dramatic improvement resulted from the incorporation of the doppler resolver, which enabled resolutions to within 1/100th of a cycle. It is anticipated that a two-way X-band system will enhance resolution by a factor of 4 and may result in even greater accuracies by reducing the transmission media effects.

Frequency system performance. Figure V-12 indicates the performance of frequency systems employing crystal oscillators, rubidium vapor oscillators, and hydrogen masers. The baseline frequency system that was

[20]Kliore, A., Cain, D. L., and Hamilton, T. W., *Determination of Some Physical Properties of the Atmosphere of Mars From Changes in the Doppler Signal of a Spacecraft on an Earth-Occultation Trajectory*, Technical Report 32-674. Jet Propulsion Laboratory, Pasadena, Calif., Oct. 15, 1964.

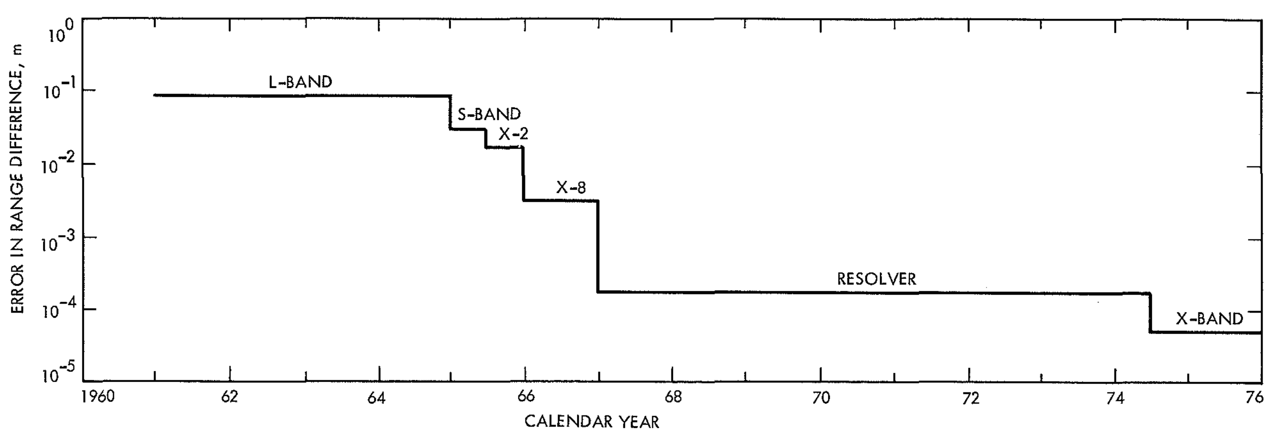

Fig. V-11. Integrated doppler resolution

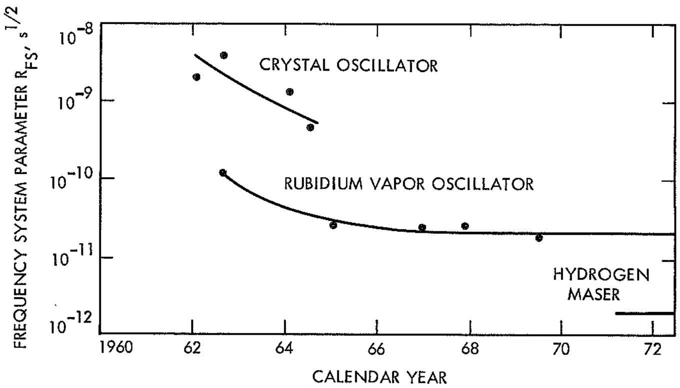

Fig. V-12. DSIF frequency standard performance

employed in the early 1960s used crystal oscillators as a timing standard. By converting to the rubidium vapor standard in the mid-1960s, an improvement of nearly two orders of magnitude was realized. The rubidium standard has been gradually improved and constitutes present DSN frequency stability. It is anticipated that by converting to hydrogen masers as a frequency standard, the Deep Space Network can obtain an improvement of nearly an order of magnitude.

The ordinate in Fig. V-12 is the figure-of-merit of two-way oscillators and is related to the $\Delta f/f$ stability and the two-way transmission time.

Charged-particle calibration. Figure V-13 indicates the improvement in charged-particle calibration techniques achieved by the DSN. The effect of charged particles on the L-band system is indicated in Fig. V-13. A dramatic improvement was achieved by conversion to the S-band system, since the charged-particle effect is inversely proportional to the square of the transmitted frequency.

The first calibration techniques employed were used to calibrate the *Mariner 1969* in-flight data. These were (1) the use of Faraday rotation measurements of the Earth's ionosphere obtained from geostationary satellites and (2) ionosonde measurements of the lower ionosphere. These techniques were also used to calibrate past missions to improve the station locations used by the *Mariner 1969* mission.

Presently, the DSN is using the DRVID technique to calibrate charged particles in the Earth's ionosphere and the interplanetary medium. This technique is based on the essentially equal and opposite effect of charged particles on phase and group velocity.

For missions which employ S/X downlink transmission, dual-frequency measurements of charged particles can be employed as a calibration technique.

Troposphere calibration. Early flights employed no tropospheric calibration, as indicated by Fig. V-14. In the early 1960s, a model for the entire DSN was used to provide estimates of the tropospheric effect within the Orbit Determination Program. This model remained in use until the mid-1960s, when an individual model for

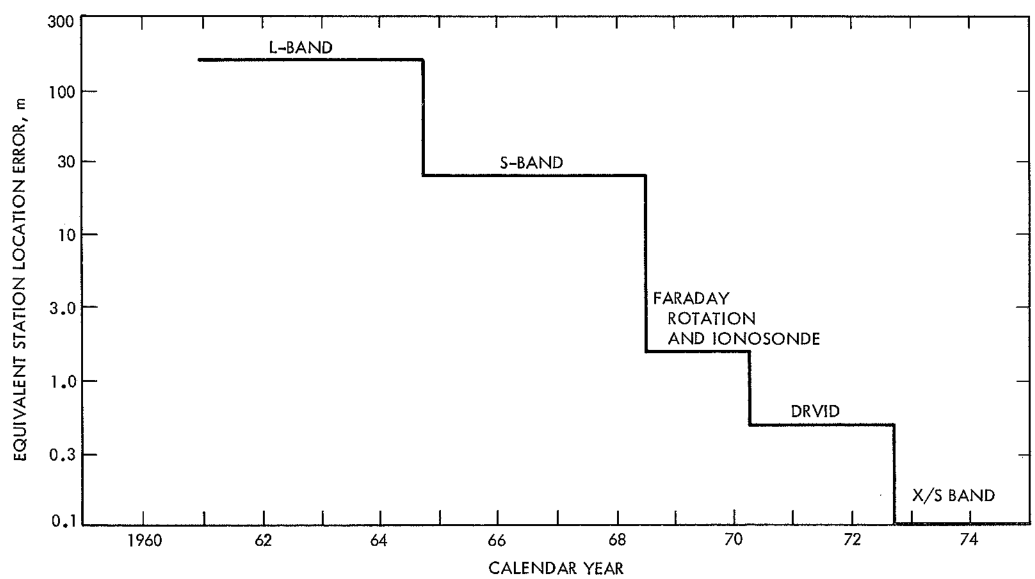

Fig. V-13. Charged-particle calibration

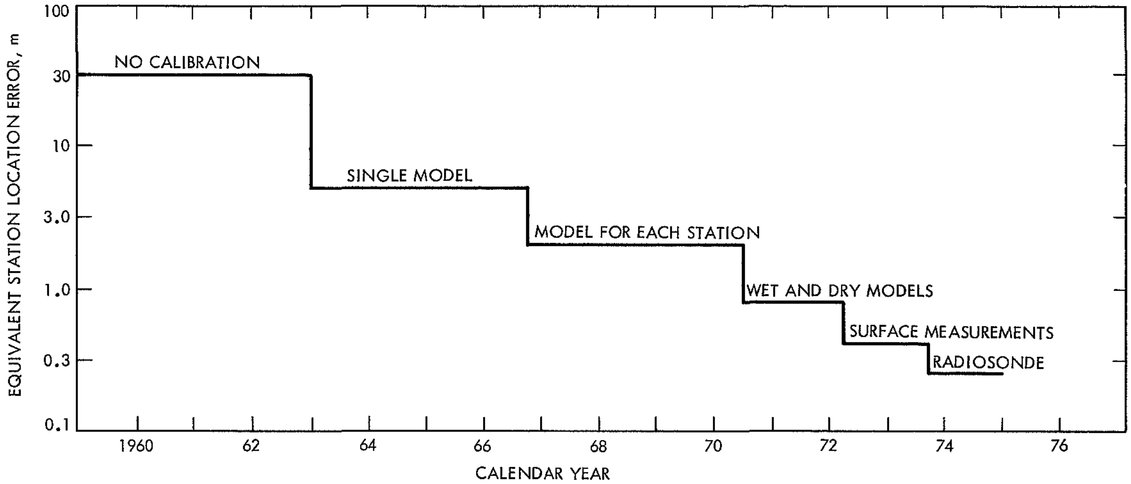

Fig. V-14. Tropospheric calibration

each deep space station was employed, improving the estimation.

Presently, two models of the troposphere are being developed to estimate the tropospheric effect, one model based on a dry component, accounting for the effect of the dry gases in the lower atmosphere, and a second model that accounts for the water vapor in the atmosphere. These wet and dry models will be individually scaled for each deep space station.

It is anticipated that even greater accuracy can be obtained by making a limited number of surface measurements at each deep space station and adjusting the model to employ these data. Further improvement could possibly be obtained by employing radiosonde or radiometry to measure the tropospheric effect along the ray path.

Special uses of doppler data. In addition to its navigation role, doppler data have had a number of additional uses. Among these are the determination of astronomical constants, deep space station locations, masses of the target planets, and scientific data on the atmospheres of Venus and Mars.

Special or unusual motion of the spacecraft can also be detected in the doppler data. For example, orbit trim maneuvers employ a small rocket engine. The performance of the midcourse maneuver, beginning with *Ranger III,* has been evaluated in this manner. Spacecraft motion is also visible when the spacecraft antenna moves with respect to the spacecraft center of mass. The Orbit Determination Program estimates the trajectory of the spacecraft center of mass. When the spacecraft rotates about its center of mass, the doppler counter will be in error by the amount that the antenna has rotated with respect to the ground station. The spin rates of *Pioneer* interplanetary probes have been determined in this manner. Doppler data has not only been used to guide spacecraft to the Moon; it has also provided significant physical data about the Moon. The discovery of the lunar mass concentrations (mascons) from analysis of *Lunar Orbiter* data was an unexpected bonus and a significant contribution to science.

The measurements of the atmospheres of Mars and Venus have significantly improved the knowledge of these planets' environments. Besides being important from a scientific standpoint, such knowledge has great effect on the design of planetary landers.

Spacecraft Ranging Critical Parameters

Historically, DSN ranging systems have divided themselves into two classes: those intended for operation out to lunar distances and those designed for spacecraft ranging at planetary distances. The lunar systems are Mark I and Mark IA, while the planetary ranging systems are known by the name of their principal designer, Tau for R. C. Tausworthe, and Mu for W. L. Martin. The basic differences between these systems is in the method of range coding and received code detection. As illustrated in Fig. V-15, the history of DSN spacecraft ranging begins with the series of *Lunar Orbiter* spacecraft using Mark I and IA ranging systems. These early systems were designed for operation at lunar distances; however, their operational distance limits were actually a factor of 10 greater than minimally required, as demonstrated early in the *Mariner V* mission in 1967. The delay instability of the Mark I ground system was under 5 m in an 8-h period.

Ranging of *Mariner V* beyond the limit of the Mark IA capability ushered in the era of spacecraft ranging to planetary distances and was accomplished with the Tau ranging system to approximately the distance of Venus at *Mariner V* encounter (0.5 AU). An improved Tau ranging system was used to support the *Mariner 1969* mission and succeeded in ranging *Mariner VI* and *VII* beyond their Mars encounter to a distance of 0.8 AU. This improved Tau ranging system had a much increased internal stability compared with its performance during the *Mariner V* mission and this stability afforded an opportunity to exploit ranging data to measure charged particle dynamical effects. The technique used is Differenced Range Versus Integrated Doppler and depends strongly on the stability in range and doppler systems over several hours. The doppler system has typically been more stable (1.0 m over 8 h) than the ranging systems (3.0 m over 8 h for the Tau system of *Mariner Mars 1969*).

With the advent of the *Mariner Mars 1969* extended mission, the Mu ranging system, a planetary spacecraft ranging system developed by W. L. Martin and R. Goldstein, was installed. The Mu ranging system differs in several respects from the Tau system, the main differences being the sequential binary coding of the Mu system, compared with the pseudorandom coding of the Tau system. The Mu system also employs RF doppler rate-aiding for range decoding. This rate-aiding method also automatically produces DRVID information. Because of the high-speed digital logic used in the Mu system, the ranging instrumentation itself has approached a negligible drift level such that the 10 ns (1.5 m) of drift measured over 8 h is the result of the remaining tracking station equipment. The Mu ranging system has demonstrated ranging performance to a distance of 2.6 AU, making the *Mariner Mars 1969* relativity experiment possible.

The future of ranging in the DSN appears very promising. The DRVID charged-particle calibration technique will provide near-real-time support for *Mariner Mars 1971* navigation and be a complementary calibration method for the S- and X-band experiments on *Venus Mercury 73* and *Viking 75*. With the S- and X-band experiments will come the ability to calibrate range data for total columnar charged-particle effects giving increased navigation accuracy and offering important radio science data. It is only with these calibrations that the submeter inherent accuracy of ranging can be realized.

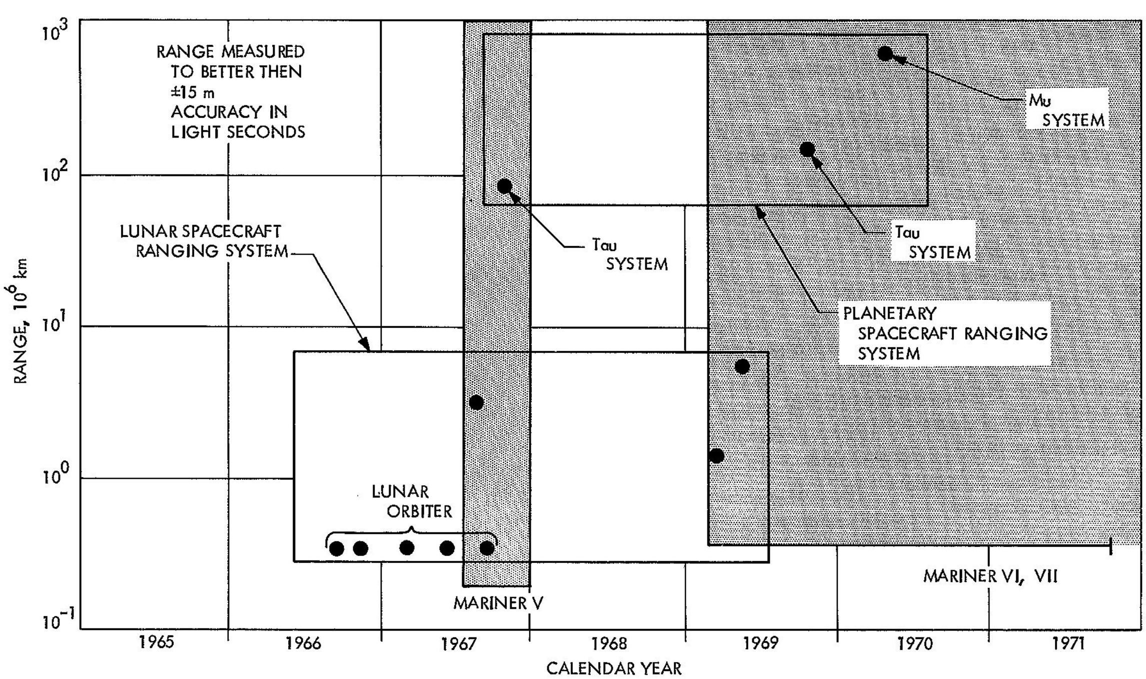

Fig. V-15. Demonstrated spacecraft ranging performance

For the era of outer-planet missions, ranging code regeneration at the spacecraft will extend ranging performance to the limits of the solar system.

Station Locations

Figure V-16 indicates the improvement in knowledge of the station location of the Deep Space Network. The improvements result from postflight analysis of the radio metric data. Each mission is "re-flown" by processing the radio metric data obtained from the mission; however, the location of the spacecraft is assumed to be known and the locations of the stations are solved for as unknowns.

Figure V-16 also illustrates the reduction in the uncertainty of the station longitude using this technique. The uncertainty in Earth spin radius, the second component of station locations, has shown a similar improvement and is generally more accurately known than longitude. As previously discussed, the station longitude is affected by errors in universal time, polar motion, and spacecraft right ascension, as well as errors introduced by the transmission media. Spin radius, on the other hand, is not affected by timing errors (UT1 errors).

Lunar flights have provided estimates of relative station longitudes; however, to obtain accurate absolute longitudes, interplanetary flights are required. To establish the spacecraft's right ascension with sufficient accuracy requires the use of planetary encounters, so that the right ascension of the spacecraft can be coupled into the ephemeris. The spin radius is determined by obtaining solutions for station locations during periods when the spacecraft was at zero declination, since the uncertainty of the spin radius solution is at a minimum for this condition. Earth spin radius solutions for station locations have been obtained from lunar flights and for zero declinations on the *Mariner* and *Pioneer* missions. Hence, there are many of these solutions available. To obtain absolute longitudes, *Mariner II* and *IV* tracking data have been very valuable and have provided much-improved solutions.

Figure V-16 shows the most dramatic improvement in station longitude. This improvement resulted from the use of 1965 *Mariner IV* Mars encounter data. It is anticipated that *Mariner Mars 1971*, when in orbit about Mars, may provide a significant advancement in station longitude solutions. In addition to this, more accurate calibration techniques will improve knowledge of the station locations.

DSN Timing and Time Synchronization

Universal time is a basic observable for use in the orbit determination process. Since doppler and range observables are measured in a rotating Earth coordinate

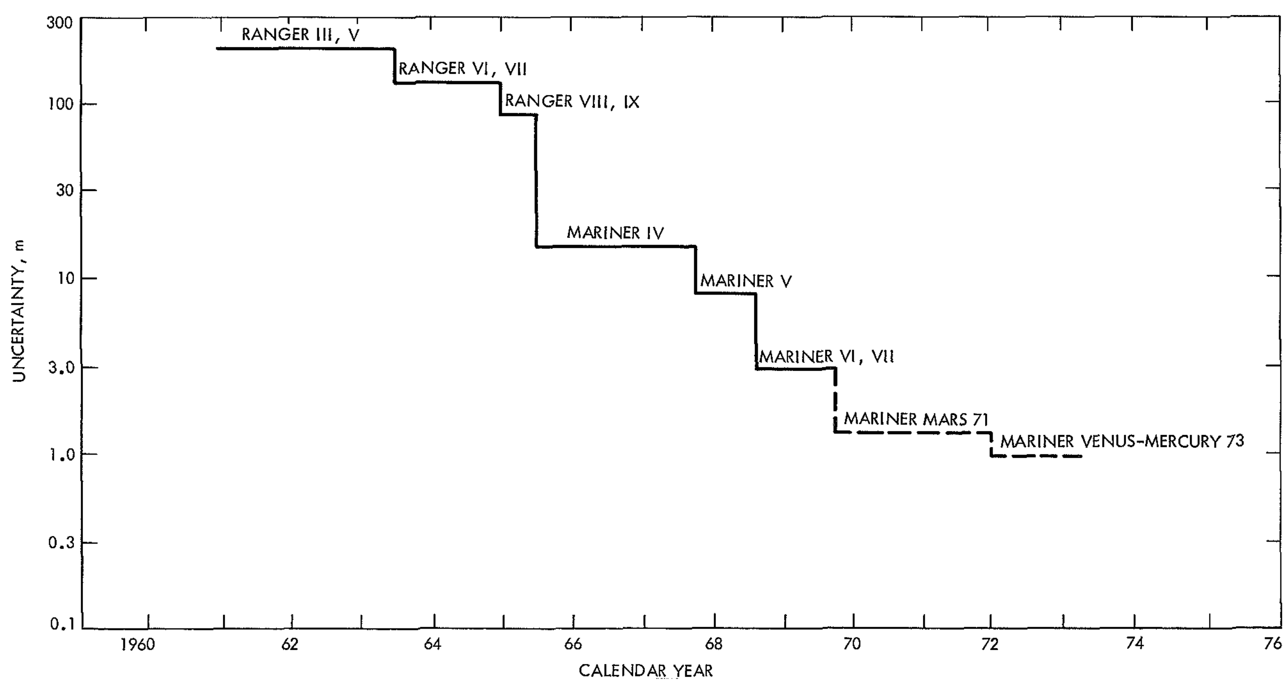

Fig. V-16. Deep space station longitude uncertainty

system, the phase of the Earth's angular position in inertial space is of first-order interest. This timing parameter is tagged on all metric data originating from the DSS. Not only is its absolute accuracy important, but the accuracy in transferring this parameter (time synchronization) to the various stations is equally critical.

Before the spring of 1965, the method of time tagging doppler observations involved the use of a precision clock at each deep space station. This clock was synchronized to the National Bureau of Standards (NBS) station WWV on high-frequency radio. Station WWV used the Universal Time Coordinated (UTC) timing base. This provided a synchronization accuracy between stations of about 3 ms to WWV. The orbit determination program accepted this time tag as indicating the true, instantaneous, rotational position of the Earth in inertial space (UT1). Unfortunately, this was not the case, as UTC was only an approximation to UT1 with a precision of 100 ms. The UTC was derived by the US A1 time scale and had to be corrected periodically by 100-ms steps. This accuracy was sufficient for ocean navigation purposes, for which it was intended.

The discovery of the incorrect use of these data occurred during April 1965. There was a persistent 40-m difference in "solved for" longitudes of all deep space stations between the values determined in using *Ranger VII* and *Ranger VIII* radio metric data. An intensive search had eliminated all known or previously experienced error sources by late April 1965, but the discrepancy remained. It was clear that a new problem or systematic error in the Orbit Determination Model was trying desperately to reveal itself through the doppler data taken from these lunar probes. A unique probing of the obvious by an astronomically trained newcomer turned up the fact that a 100-ms UTC change had been made between the two *Ranger* flights.

The solving of this timing problem was important, however, for several reasons. The timing corrections (and later polar motion as well) were the first of a long series of "platform and medium calibrations." These now comprise a substantial area of effort in their own right and have been an essential ingredient in the continuing series of deep space missions. This was another example of the inherent quality of the doppler tracking data both for "self calibration" and scientific application.

Timing polynomials reflecting corrections from UTC to UT1 were introduced on a crash basis for *Mariner IV* encounter in July 1965. Polar motion and timing were improved for *Mariner V*, with continuing research and development for each mission cycle. Fundamental potential improvements for determination of time and pole are under consideration, among them very long baseline interferometry and the lunar laser retroflector. If we can maintain a Mars orbiter in good health for a long period, the spacecraft itself can be used to determine these quantities for future missions. Timing, polar motion, and the station location determinations which they support are a critical parameter in the high-precision spacecraft navigation required for mission support. Figure V-17 depicts the improvement in universal time from 1965. The present absolute accuracy of UT1 is about 2 ms.

Deep space station time synchronization with UT1 has had a similar history of evolution and improvement. The earliest system used to transfer time to the deep space stations was HF radio. Even with all corrections applied, the accuracy was no better than 2 to 4 ms, and often it was not possible to receive WWV transmissions throughout the network in a consistent fashion. The use of very-low-frequency (20-KHz) WWV transmissions provided some improvement in synchronization accuracy, because it involved propagation delay variations in the characteristically more stable ground wave transmission. Even with calibration, however, the accuracy of the synchronization could only be monitored, as no specific timing pulse is transmitted. Again, propagation characteristics did not make these data available to all stations. In 1966, *Lunar Orbiter* required synchronization of stations to better than 50 μs to provide accurate tracking observables for determination of lunar gravitational harmonics. Clearly, a quantum jump in performance was necessary.

Two methods were proposed, one using a transportable cesium standard from NBS and the other using the DSN ranging system in conjunction with the *Lunar Orbiter* spacecraft. The transportable standard was the most accurate, providing timing accuracies to better than 5 μs; it was also a very expensive operation, as this would have to be repeated at least monthly. The DSN ranging system mode, which was finally selected, provided inexpensive synchronization to better than 20 μs.

A DSN operational time synchronization system was developed in 1968 that did not require a spacecraft transponder. It depended upon the propagation delay of a precision-timed X-band signal from Goldstone to overseas stations during the mutual lunar view periods. The accuracy of this system is approximately 5 μs. It is in the process of being installed throughout the network.

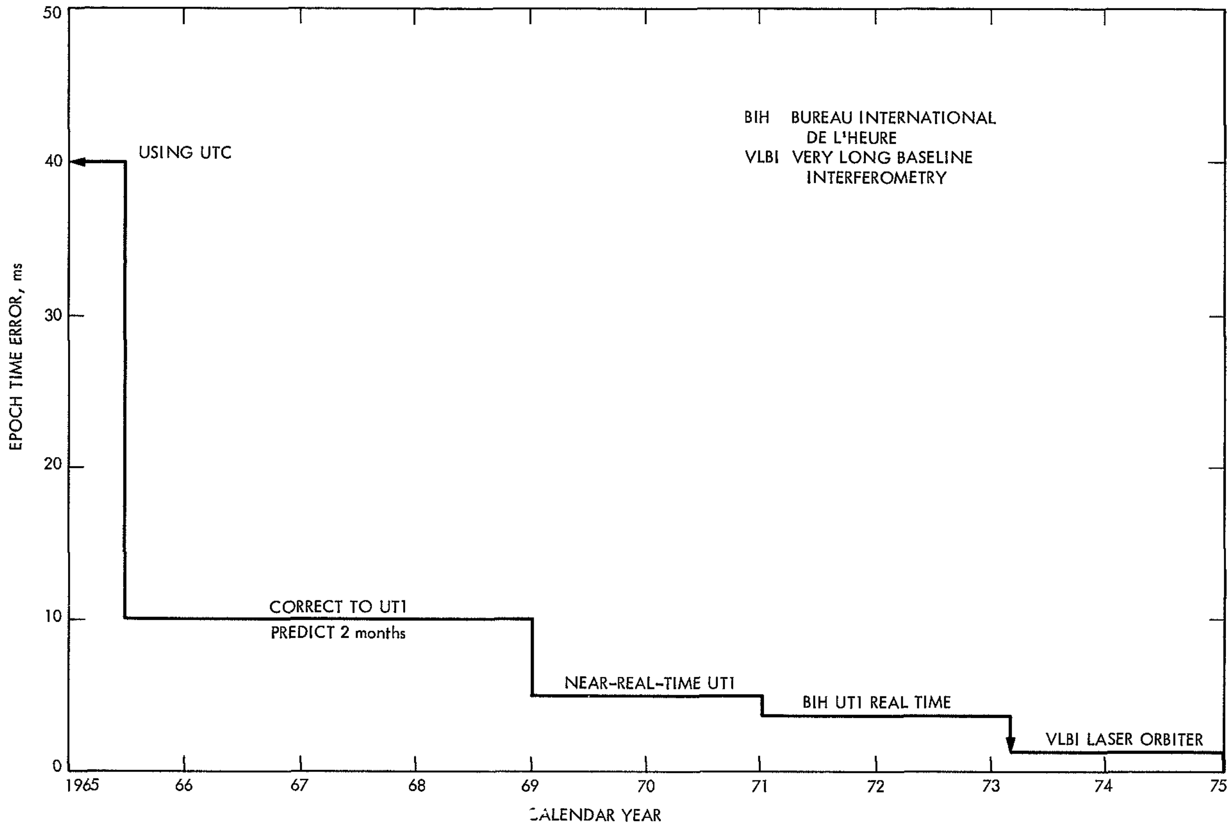

Fig. V-17. Station longitude accuracy based on Universal Time

Spacecraft Transponder Design

The doppler and ranging characteristics of the spacecraft radio system have first-order impact on the radio metric system accuracy and, because of this, have to be considered and improved along with the ground system parameters. Over the past 12 years the spacecraft radio system has evolved from a single crystal-controlled transmitter to the present two-way ranging and doppler transponder. The design development of the transponder has been characterized by a conservative approach to technology innovation. Spacecraft projects, for obvious reasons, have historically pressed for minimum changes between launchings, as long as designs were adequate. The ground system has experienced continuous improvement and updating. JPL is now mounting an effort to design significant improvements in the spacecraft transponder, especially in the phase and time delay stability characteristics, to maintain the proper balance between spacecraft and ground tracking system performance.

Pioneer IV was equipped with a simple one-way transmitter for telemetry and doppler measurements. State-of-the-art spacecraft crystal oscillators (1 part in 10^6) were used. The oscillator temperature was telemetered to allow correction for temperature variations. Even under these conditions it was not possible to measure velocity to much better than 10 to 30 m/s because of residual unknown drifts. This level of performance turned out to be nearly useless for even rough lunar navigation purposes. This forced much dependence on early postinjection angle and angle rate measurements for orbit determination purposes.

The two-way L-band transponder was introduced with the *Ranger I* mission in 1961. This design, in conjunction with the Earth-based station, provided a two-way doppler accuracy over a 15-min tracking period (at lunar distance) of about 10 to 50 mm/s. Most of the accuracy limitations were inherent in the ground system design. The temperature and signal level phase stability of the transponder was not considered critical when compared with the ground system inaccuracies.

In 1963, an S-band transponder was developed for the *Mariner IV* mission. The S-band design was based on much of the L-band technology and also incorporated a turnaround ranging channel. Variations of this S-band transponder were used on the five *Lunar Orbiter* spacecraft and on *Mariners V, VI,* and *VII.*

The time delay stability over the design temperature and signal level range was nominally 50 ns; however, with telemetered temperature and signal level data, this value could be determined to better than 10 ns. The phase shift variation through the transponder over the design signal level and temperature range was greater than ± 15 S-band cycles, but again this effect could be calibrated to better than 5 Hz over a tracking pass (assuming no major temperature or signal level changes during the pass). System doppler accuracy during this period improved to 1 to 0.5 mm/s over a 15-min data arc. In 1967, an attempt was made to measure charged-particle effects on *Lunar Orbiter IV* tracking data, using the DRVID technique. Uncorrelated time delay variation ($> \pm 15$ m) in the spacecraft transponder, caused by lunar eclipse temperature variations, rendered the experiment useless. Clearly, it was necessary to provide improved transponder phase and time delay performance to maintain the usefulness of radio metric data for the missions of the 1970s.

This new transponder is now under development with an improved ranging channel and incorporating a coherent dual-frequency S/X band downlink. The design objectives are (1) to provide time delay stability over the range of operating temperature and signal levels to better than 10 ns and (2) to be able to calibrate the change to less than 1 ns. Differential phase shift between S and X band over the expected daily temperature and signal level will be less than 1 cycle at X-band. This performance will result in about an order of magnitude improvement over the *Mariner IV* transponder.

Radio Metric Data Preprocessing

Since the earliest flight projects, the DSN has performed quality control and some level of data validation on the radio metric data provided to flight projects for orbit determination, celestial mechanics, or radio science purposes. This function maximizes high-quality data and assists in rapid location of system failures. The orbit determination process itself is superior to any other method in establishing the quality of the data, and thus the process of data quality control and validation requires the participation of the flight projects in providing the final error detector mechanism. Data random noise and format accuracy, however, can be evaluated without trajectory modeling assistance.

DSN radio metric data generated at the deep space stations are transmitted by teletype to the SFOF for validation prior to their delivery to the projects. Radio metric data contain time, counted doppler, range, and angles. In addition, peripheral information such as the spacecraft identifier, format identifier, doppler mode, receiver status, servo status, reference frequency status, and range data status are interlaced as a data condition code.

Data editing consists of checking for proper formats with appropriate field lengths and legal numeric teletype codes, selecting data by spacecraft identifier, data type, and data condition codes. Prior to 1962, data editing and selection were performed manually and were primarily project functions. From 1962 to 1967, data editing and selection were performed by computer but still remained primarily project functions. From 1967 to the present, data editing and system data record generation by computer have been performed by the DSN.

Chapter VI
Development of Multiple-Mission Capability in the DSN

Ranger IX impacted the Moon in the Crater Alphonsus at 14:08:21 on March 24, 1965, thus ending the series of *Ranger* missions. This event also marked a turning point in the history of the DSN; from this point on, the network began a transition from its hitherto single-mission supporting role to the role of a multimission supporting network. This change permeated every aspect of the Network, not only the technical facilities of the DSIF, GCF, and SFOF, but also the management, coordination, and scheduling of the limited DSN resources to meet the heavy and, in many cases, conflicting demands of the flight projects. In this environment were born the concepts that subsequently evolved into the multimission telemetry and command systems; the mission-independent software programs; standardization in engineering, operations, and documentation; interface management and control; and compatibility testing.

The impact of the transition from single-mission support to multiple-mission support first became apparent in the number and complexity of the interfaces between the flight projects and the DSN. This was true particularly with respect to the flight projects not managed by JPL. The need for precise interface specifications and a viable method of interface control provided some of the motivation for establishing the DSN documentation system. This system provided for specifications that controlled the Project and DSN interfaces. For the *Lunar Orbiter*, *Pioneer*, and *Surveyor* Projects this interface control assured compatibility between the equipment of the spacecraft and the deep space stations.

Multiple-Mission Telemetry

In the years preceding 1967, the deep space stations received telemetry from spacecraft at a wide range of subcarrier frequencies, data rates, and types of modulation. Each flight project selected its own parameters for its telemetry requirements, and because each project was different, the ground demodulation equipment differed. This necessitated equipping the ground station assigned to a particular mission with "mission-dependent" demodulation equipment. While providing maximum design freedom, this "mission-dependent" operation proved costly in equipment, installation time, and training time. In addition, it limited the flexibility of the DSN, since only those stations having the mission-dependent equipment could support that particular mission.

It became apparent that most of the future flight projects planned to use PCM-PM-PM as their standard modulation mode. On this basis, it was decided to begin developing a multiple-mission telemetry system consisting of general-purpose, mission-independent equipment capable of meeting the requirements of all projects at any DSN station.

Conceptually, this multiple-mission telemetry system consisted of a flexible and efficient subcarrier receiver, tunable from 20 KHz to 1.5 MHz. It contained a subcarrier demodulation loop that accepted 10-MHz signals from the receiver, phase-modulated with one or more square wave subcarriers which, in turn, were phase-modulated with data. Demodulation was accomplished in a manner that did not lose the power in the square-wave harmonics. Bit synchronization was accomplished by a computer operating in conjunction with special-purpose digital equipment by using the transitions in the telemetry data stream. To change from one spacecraft to another, it was necessary to change the computer program and reset the subcarrier voltage-controlled oscillator, certain bandwidths, and time constants.

A separate channel for subcarrier and bit synchronization was not required from the spacecraft. Therefore, this power could be used to increase the power in the information channels. The fixed-phase relationship between subcarrier and bit timing was contained in the original data and could be recovered without the use of a separate synchronization channel. This removed the requirement for rigid bit timing in the various spacecraft data sources and resulted in simplification of the spacecraft subsystem interfaces. This simplification of spacecraft electronics contributed to increased reliability.

In late 1966, the multiple-mission telemetry system concept was one of the major objectives planned by JPL for the DSN as a network; the concept was a specific goal for *Mariner Mars 1969.*

In April 1967, the DSN established an advanced engineering project called "High Rate Telemetry" which had three objectives:

(1) To meet the requirements of the *Mariner Mars 1969* Project by providing equipment at the Goldstone Mars Deep Space Station to receive data from the *Mariner Mars 1969* spacecraft at 16,200 bits/s.

(2) To develop prototype, high-rate ground telemetry equipment with multiple-mission capability for the DSN.

(3) To advance the technology of deep space communication.

The high-rate telemetry was a modification of the basic digital telemetry system used on *Mariners IV* and *V*. It differed from that system, however, in that the data were block-coded, there was no synchronization channel, and the detection process was more efficient. The spacecraft data were encoded into blocks of binary symbols and transmitted to the ground receiving station, where they were recorded in a usable format for the data user.

By July 1967, the basic engineering design for the multiple-mission telemetry system had been completed, and the prototype system was designed and constructed. Checkout began during the first week in October. By the end of 1967, numerous changes had been introduced into the basic design in order to extend the range of capability, simplify operator control, and improve performance. By January 1968, the prototype had been installed at JPL for compatibility testing between the DSN and the spacecraft. Development, production, and testing continued almost simultaneously through the first half of 1968. By July of that year, installation and checkout of the new multiple-mission telemetry had been completed on schedule at JPL, as well as at the Goldstone Echo; Cape Kennedy; Johannesburg; Cebreros; and Woomera Deep Space Stations. In March and April of 1968, detailed performance tests were run, and the results indicated that the design goals had been achieved. In May, June, and July 1968, the *Mariner* flight spacecraft were delivered and supported in a test program by JPL. To provide that support, field sets were installed and tested. These tests demonstrated that the multiple-mission telemetry design goal had been reached. In November 1968, the prelaunch operations began at Cape Kennedy and, to support this activity, one field set was installed there, while a second field set remained at JPL.

Mission-Dependent Command System

Prior to 1969, no DSN Multiple-Mission Command System existed. Instead, each flight project had its own mission-dependent command system. Each system had a different configuration, separate procedures, mission-dependent equipment at the deep space stations, and mission-dependent software in the SFOF computers. The SFOF typically used subsystems for data processing, display, computer input/output and mission-dependent software. The DSIF typically used subsystems for transmitting, recording, telemetry and command data handling, mission-dependent equipment, and mission-dependent software.

The following procedures were used to command the spacecraft. Mission-dependent user programs in the IBM 7094 main processor generated a set of commands which were written on magnetic tape. IBM cards or a hard copy printout from the IBM 1301 disk memory were then generated by using the IBM 7044 input-output computer. Commands were transmitted from the SFOF to each DSS by one (or a combination) of the following methods:

(1) The IBM 7044 computer read command data from the disk memory or from the cards and formatted the data for teletype transmission to the DSS. (The IBM 7044 formatting software was mission-independent.)

(2) Command data were converted from IBM 7094 digital magnetic tape to punched paper tape, which was then mailed to the DSS for storage in a command library for later transmission to the spacecraft.

(3) Punched paper tape was read in the SFOF and transmitted by teletype to the DSS.

(4) Commands were transmitted by voice circuit to the operator at the DSS.

(5) Commands were sent by teletype to the DSS to be punched on paper tape or transmitted to the DSS by means of the DSN's mission-dependent software capability.

The command verification procedures were primarily done manually. At each transfer point, the data were checked for errors and verified. The command data at the deep space stations were displayed and checked by the command operator. The operator notified the SFOF of the verification by using teletype, voice, or high-speed data lines. Some sets of mission-dependent equipment contained logic for bit-by-bit comparison of the transmitted command with the stored command as it was returned from the radio frequency subsystem. This type of equipment provided a command inhibit capability (manual or automatic) if an error was detected. Final verification of the transmitted command was obtained by analysis of the spacecraft telemetry stream.

Operations and Support Standardization

The change from the single-mission concept to a multiple-mission concept for the DSN introduced a variety of procedures. It was therefore necessary to standardize the network in such a way that the functions of the network were not impaired through rigidity of controls and at the same time were enhanced by a better flow of information.

Engineering Standards

The network provides a standards laboratory charged with maintaining equipment evaluation, testing to criteria such as National Bureau of Standards calibrations, and certification of equipment.

The various types of tapes (analog, digital, and video) undergo data verification prior to being sent from the various deep space stations to the user.

Operations Standardization

Toward the latter part of 1965, increased demand for station time by the ever-multiplying number of flight projects raised a need for standardization of the functions of the deep space stations. One such problem was the time needed to check out and calibrate the equipment at each deep space station before each mission and spacecraft view period. Both time and procedures varied from mission to mission and between stations; since mission-dependent equipment was involved, the station checkout varied also with the criticality of the various phases of each mission. Thus, three classes (A, B, C) of checkout activity were established. The time assigned to each of the three classes varied from 6 to 8 hours (Class A) to less than 1 hour (Class C). The degree of complexity of the procedures varied correspondingly. By mid-1966, these standards were adopted by all DSN stations for operational use.

Another problem was the state of engineering development, or change to the equipment at the deep space station. This involved identifying precisely what equipment was at the station and whether it was operating. This was solved by placing each station under engineering change control. The design of the deep space station is "frozen" at a specified time prior to the mission, and only documented, authorized changes to station equipment are allowed.

Finally, the timing of the interface between the development and operation of the deep space station was solved by a transfer agreement. This agreement, signed by all responsible organizations, established the terms and conditions for turning over the deep space station to the operating personnel.

Documentation Standardization

The foundation of any standardization program is proper documentation. As an outgrowth of the rising complexity of the DSN support for flight projects, there was a need for some uniform system of documentation, to cover such things as Project-to-DSN interface agreements, DSN facility and systems descriptions, operating procedures, test procedures, and reporting.

Starting in 1965, attempts were made to coordinate the then individual approaches to this problem into a cohesive and logical documentation system. The wide range of activities to be covered, together with the conflicting viewpoints of the individuals responsible, made this a difficult task, and it was not until January 1968 that a documentation system was formulated. Since that time, many documents have been created which record all phases of DSN functions.

Scheduling

The DSN Scheduling Office was created to schedule the allocation of appropriate facilities and equipment for the effective support of each flight mission at the proper times and geographic locations. This resource allocation service simultaneously supports several missions in varying stages of progress. Further, the DSN facilities and equipment require varying amounts of time for routine maintenance, major repairs, and the installation of newly developed hardware systems and subsystems.

Chapter VII
Summary

Looking Backward

We have seen, in the evolution of the DSN, the development of the concept of close support between the network and the flight projects, particularly through the telecommunication system interface. The strength of the supporting research and advanced development program made it possible to implement new capabilities quickly, as soon as it became clear that flight project success would be enhanced by such capability. We have seen that the concept of continuous surveillance of the spacecraft has contributed significantly to the success of these missions in the ability to respond quickly to unforeseen operational situations by

(1) Applying radio commands as a backup to onboard navigation systems.

(2) Designing the flight/ground interface in such a way that if the flight system is degraded, increased capability is available from the earth-based facilities.

(3) Enhancing science return from long-duration missions such as the *Pioneers* by increasing the capability in the network during the flight.

The supporting research and advanced development program has kept the network essentially at the state of the art of deep space communications. The network successfully supported all the lunar, planetary, and interplanetary missions of the 1960s, returning all science data of the primary missions and considerable secondary science data from the extended missions. From these considerations, it would seem that the correct amount of redundancy has been built into the network for the type of deep space missions contemplated by NASA. Toward the end of this decade, the network was commissioned to concentrate on close support of interplanetary and planetary missions while future lunar missions (which were to be primarily manned) were assigned to the Manned Space Flight Network of the Goddard Space Flight Center (GSFC).

Originally, the network used teletype to transmit data acquired at the deep space stations to both network and mission control functions in the control center at JPL. As NASA developed a worldwide ground communication network through a central organization at GSFC (NASCOM), the capability for data transmission increased rapidly, so that by the end of the decade the primary mode for data transmission from the deep space stations was by high-speed data line at 2400 bits/s. Throughout this period, voice communications improved markedly as high-frequency radio circuits, particularly between ground terminals, were replaced by cable circuits. In the middle of this decade more efficient use of communications circuits was made through the introduction of communications processors at key points in the worldwide network, which brought into being message-type switching centers for teletype transmissions.

Looking Forward—DSN 1979

Deep Space Network development during the next 10 years will essentially be in the same environment of change and will follow the same state-of-the-art objectives that have characterized the preceding years. The DSN will continue to be modified and upgraded in the process of adapting to new flight project requirements and will continue to maintain the proper balance between spacecraft system performance and ground system performance.

Performance improvements will appear in two somewhat related areas: (1) within the DSN systems and (2) in response to DSN systems requirements, by the Deep Space Network facilities themselves. Increased DSN systems performance will probably be most apparent at the flight project/mission operations interface, wherein increased data quality and reliability will be effected. Increased performance in the Deep Space Instrumentation Facility will influence the spacecraft link design performance. Changes in the Ground Communication Facility and Space Flight Operations Facility will be made to increase efficiency and reliability in performing the DSN systems functions. The DSN systems performance prognosis for 1979 will be described first.

Tracking

Nearly an order-of-magnitude improvement in the performance of the Tracking and Data System will be attained within the next 10 years. Charged-particle calibration of radio metric data, using both the doppler and ranging observables and the two-frequency doppler observable, should reduce integrated doppler tracking errors over an 8-h pass to something under 0.2 m. Hydrogen frequency standards with stabilities of one part in 10^{13} will be utilized for support of the Outer Planet Missions in all of the 64-m antennas in the network. Programmed oscillators will be used to provide accurate doppler recovery during planet flyby and for occultation measurements. Through the use of a sequential ranging system, it is a much simpler task to provide regenerative ranging on board the spacecraft. If flight projects provide this regeneration capability, it will be possible to incorporate a planetary ranging capability with 26-m antennas.

To assist in the accurate measurement of the Deep Space Network station locations on the Earth's surface, very-long-baseline interferometry, using radio noise sources, will be employed. It is expected that position location errors will be well under 1 meter. For planets beyond Jupiter, earth-based radio guidance will be supplemented with terminal guidance using optical sensors on board the spacecraft. This type of guidance will permit accurate pre-encounter corrections of planetary ephemeris errors. This technique will result in far less consumption of midcourse fuel and thus allow larger science payloads aboard the spacecraft.

Telemetry and Command

The DSN Telemetry and Command Systems will continue to be multiple-mission in nature and will be responsive to new project requirements as they appear. The major changes expected in the telemetry and command subsystems will perhaps be the updating of the processing computers, which have been operating in the network for approximately 8 years and are becoming somewhat obsolete. A time-sharing computer with far greater capability will probably replace the present computer in the Multiple-Mission Telemetry and Command Subsystems by 1979. Consistent with the availability of a wide-frequency spectrum at X-band, very-high-rate telemetry with its attendant wide-bandwidth requirement will be feasible, and it is projected that rates from 250×10^3 to 1×10^6 bits/s will be quite common. Standard types of decoding will be available, including block decoding and sequential decoding of convolutional codes. New decoding methods, including maximum likelihood decoding of convolutional codes and algebraic concatenated decoding, will be available in the telemetry and command subsystem design. Coding techniques will provide signal-to-noise ratio performance within 1 to 2 dB of that theoretically possible. Perhaps with the advent of economical high-bit-rate data transmission lines, it may be practical to provide decoding of telemetry signals at a central point rather than at the deep space stations. This concept has yet, however, to be proved feasible. Multiple-level frequency-shift-keying (MFSK) signal processors and recording capability will be necessary to support low-power planet probes, especially those Outer Planet Mission entry probes that will land on the surface. The data rates in the MFSK designs will be from 1/100 to 1 bit/s. As more stable oscillators are available on board the spacecraft, phase-coherent telemetry systems with bit rates as low as 1 bit/s will become practical.

The Outer Planets Missions spacecraft will have, as an integral part of the design for long spacecraft life, programmable computers on board for controlling the spacecraft functions. To initialize these computers rapidly and often with the latest operational information, high-rate command systems will be required. The present rate of 100 bits/s maximum is expected to expand to 1,000 and maybe 10,000 bits/s. At these bit rates, perhaps command encoding and decoding may become a requirement. A direct command capability to the spacecraft via the SFOF will be available from many locations at remote information centers.

Simulation

The Deep Space Network Simulation Data System will continue to evolve and provide the support for simultaneous mission simulation requirements of the tracking, telemetry, and command systems. Larger and faster computers will be necessary to generate and process multiple data streams and to accommodate more complex spacecraft models.

Operations Control

The DSN Operations Control System will be characterized by a number of DSN data systems analysis teams interfacing directly with the spacecraft projects on a multiple-mission basis. The DSN will probably be tasked to support, at least during the cruise phases, the mission operations of the Outer Planet Mission spacecraft. As DSIF subsystems become more reliable, it is expected that more automatic control of the deep space stations will be possible. Wide-band data lines will be required to support the high data rates required for communication between computers to make this operational technique feasible.

Monitor

The Monitor System will continue to be developed with its objective of (1) recovering rapidly from communication interruptions and (2) making available alternative resources when stations or other DSN facilities are not operational. It is expected that all NASA network facilities will continue to be shared among the NASA projects, especially for support during critical periods.

Deep Space Instrumentation Facility

The Deep Space Instrumentation Facility will most likely consist of two 64-m subnets and at least two 26-m subnets. Combinations of signals from 64-m antennas will be utilized for enhancement of signal-to-noise ratio. There may be the beginning of a large antenna program with aperture sizes greater than 120 m.

In addition to the S-band and X-band allocations recently provided, it is expected that new technology developments will provide an operational capability in the K_μ-band region near the gain limit frequency of the 64-m antenna. At this time, it appears that optical communications techniques for deep space communications support will still not be practical within the next 10 years. The X- and K_μ-band frequencies will probably have their greatest applications where non-time-critical wide-band high-data-rate transmission from spacecraft to Earth is required.

DSIF technology in antenna gain and noise temperature is probably approaching a practical limitation of about 75 to 80 dBi (decibels relative to an istotropic radiator) and 10 to 15 kelvins, respectively. It may be possible to achieve a high power capability transmission at S-band up to several megawatts, and it may be appropriate to provide X-band transmitters to advantage, especially for the Outer Planets Missions, where a constant-area uplink antenna on the spacecraft appears to be a standard mode of communications.

The Deep Space Network will continue to support radio science activities and will probably expand its support to the radio astronomy community. It is appropriate to make these facilities available to radio science activities because it appears that fiscal resources for these instruments will probably not, at least in the near future, be available for purely radio science purposes. The high-gain apertures, the low system temperature, and the geometry of the Deep Space Network stations make them particularly attractive for radio science purposes. The tricone capability recently installed at Goldstone will be provided on all of the 64-m antennas, and it is expected that support to radio science experiments will be facilitated by the rapid switchover capability of these tricones from one feed to another.

Ground Communications Facility

The Ground Communications Facility will have a significantly greater capability in the late 1970s. The standard data transmission system—the high-speed data lines—will probably be upgraded to at least 7,200 bits/s as a standard capability. In addition to this, the wide-band data line (50×10^3 bits/s) will have wide application and use at all deep space stations for transmission of high-rate telemetry signals and will also support the DSIF remote initialization and monitoring function if this proves feasible. To support the data rates of missions in the late 1970s (100×10^3 to 1×10^6 bits/s), the NASCOM supergroup transmission capability will be utilized when high-rate real-time mission operations must be supported with video data.

Space Flight Operations Facility

The Space Flight Operations Facility will be characterized both by mission control areas within the facility, as are now available, and by a communications interface for transmitting data to remote information centers. It will probably be possible for spacecraft projects to operate from their home facilities during the major portion of the mission cruise phase. Fourth-generation central processors will probably be available, along with small peripheral buffers to be used by the project for their own mission-dependent programs.

Planning—DSN and Flight Projects

Flight project interfaces with internal and external projects will become more efficient, and more complete documentation will be available earlier for description of flight project–DSN hardware and software interfaces. The coordination of flight project Tracking and Data System standards will continue, and it is expected that most projects will utilize similar near-optimum telecommunication system designs. The Planetary Program Tracking and Data System Integration Working Group type of activity will continue and will maintain an active interface between the Tracking Data System and new projects to focus on necessary additional capability or requirements for new telecommunications standards.

The development of a number of management information systems, such as scheduling, flight project requirements on the DSN, monitoring support summaries, DSN development plans, and the Deep Space Network budgets, will be typical of the up-to-date data bases available for management purposes in the late 1970s. Indeed, the beginnings of such systems with these types of data bases residing in a computer are now well under way.

DSN–Spacecraft Interfaces

Spacecraft designs will be updated in a number of areas to incorporate new technology appropriate to maintaining the necessary balance between the spacecraft and the DSN. Typical of these spacecraft improvements will be an increase in the spectral purity of transmitted signals from the spacecraft, so that very narrow bandwidths at the ground station can be used to an advantage. It will probably be possible to provide phase-coherent bit rates of the order of 1 bit/s and tracking bandwidths as narrow as 1 Hz. Other areas where improvements are expected are the S-band/X-band coherence stability for the generation of precision doppler data, the availability of a wider transponder tuning range for high doppler shift tracking by the transponder, the design of highly stable time delay characteristics in the spacecraft transponder ranging system, and the incorporation of ranging regeneration on the spacecraft to increase the distance capability of the ranging system. This will permit planetary ranging on a 26-m antenna. Spacecraft will be designed to accommodate the DSN enhancement possibilities such as 120-m antennas and 2-mW transmitters, and spacecraft will continue to be mechanized to be compatible with 26-m-antenna backup capability where possible.

The development of more automatic spacecraft in the late 1970s will probably mean that continuous tracking of spacecraft will not be necessary. As a result, it is expected that more spacecraft missions can be accommodated with a given number of deep space stations.

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NASA — JPL — Coml., L.A., Calif.