Chapter 7

The Advance of Technology in the Deep Space Network

THE DSN TECHNOLOGY PROGRAM

No history of the DSN would be complete without a full appreciation of its contribution of advanced technology to the successful development of the Network. The wellspring of new and innovative ideas for increasing the existing capability of the Network; for improving reliability, operability, or cost effectiveness; or for enabling recovery from potential mission-threatening situations has resided, from the very beginning of the Network's history, in a strong program of advanced technology, research, and development. Known by various names through the years, the numerous elements of the advanced technology program were formally identified as a complete entity and placed under the direction of the newly established Technology Office of the Telecommunications and Mission Operations Directorate (TMOD) in 1997. It was known as the TMOD Technology Program. The program scope was further expanded to include technologies relevant to the full end-to-end Deep Space Mission System (DSMS). This expansion included flight components of the physical communications links (data services) and added mission services activities like protocol developments, mission planning and execution tools, science data visualization, and the merging of tools and autonomy.

These disciplines covered almost every aspect of DSN-related technology. Theoretical work in any of them could always be complemented with experimental work in well-equipped laboratories and machine shops at JPL and verified with field measurements at DSS 13, which was maintained primarily for research and development (R&D) purposes.

Prior to 1997, the program was known most generally as the DSN Advanced Systems Program and covered antennas, low-noise amplifiers, Network signal processing, frequency and timing, radio metric tracking, navigation, Network automation, atmospheric propagation. It also involved the evolution of the program research and development tracking station, DSS 13, at Goldstone. These were all elements of ground-based systems. In 1985, a second Systems Development Program was added to cover telecommunications systems analysis, spacecraft radio communication systems, and inflight demonstrations of new uplink and downlink communications systems.

Due in no small part to the unremitting efforts of Nicholas A. Renzetti to ensure that the results of these efforts were properly documented, a continuous record of the early work carried out under the DSN Technology Program was published by JPL in a series of progress reports. Starting in 1969 as Volume II of the JPL Space Programs Summary 37-XX series, it became the DSN Progress Reports in 1971, TDA-PRs in 1980, and the TMO-PRs in 1998. In August 1994 the series began publication on the World Wide

Web. An index of all articles published after 1970 also became available online at that time. (See the appendix at the back of the book.)

The technology underlying many of the major engineering changes, discussed earlier in the context of DSN operations support for flight missions, was described by James W. Layland and Lawrence L. Rauch in 1997 (see section 1 of the appendix). As those authors made clear, most of the progress in antenna design; uplink and downlink performance improvement; and the application of radio metric techniques to spacecraft navigation, radio science, radio astronomy, and radar astronomy originated in the DSN program of advanced research. These new technologies were later made available to the DSN engineering groups for implementation into the operational Network.

This phase of DSN endeavor is illustrated by tracing the advancement of technology in those key areas. The material that follows is derived from the work of Layland and Rauch and is intended for the general reader. The technical reader is referred to the appendix at the back of the book, which cites significant publications associated with each topic.

The Great Antennas of the DSN

A photograph of the NASA Deep Space Communications Complex near Canberra, Australia, is shown in Figure 7-1. The largest antennas in the photo are quasi-parabolic reflector antennas, one with a diameter of 70 meters; the others, 34 meters. These were used for deep space mission support, while the other, smaller antennas, 26-meter or 9-meter antennas, provided tracking support for Earth-orbiting missions.

Each of the antennas has what is termed a Cassegrain configuration with a secondary reflector mounted on the center axis just below the focal point of the primary reflector "dish." The secondary reflector serves to relocate the focal point closer to the surface of the main dish and thus establish a more convenient location for the low-noise amplifiers, receivers, and powerful transmitters.

The efficiency with which parabolic antennas collect radio signals from distant spacecraft is degraded to some extent by radio noise radiated by the Earth terrain surrounding the antenna. This form of radio noise is known scientifically as "black body radiation" and is a physical characteristic of all material with a temperature above absolute zero (-273 degrees Celsius or 0 kelvin). The magnitude of noise power radiated by a material body depends on its temperature. While it is incredibly small at the temperature of typical Earth surfaces, it is enormous at the temperature of the Sun, for instance. All parabolic

Figure 7-1. The Deep Space Communications Complex in Canberra, Australia

radio antennas have sidelobes in the beam pattern, and the magnitudes of those sidelobes can increase as the antennas deviate from the ideal shape. The shape of the beam and its sidelobes is essentially the same whether the antenna is used for transmitting or receiving signals. The sidelobes are analogous to the circles of light surrounding the main beam of a flashlight when it is held close to a reflecting surface.

When an antenna is used for transmitting a strong signal to a spacecraft, the sidelobes are of no great consequence. However, when the antenna is receiving a weak signal from a distant spacecraft, particularly at or near the horizon, the “Earth noise” picked up by the sidelobes is sufficient to obscure the spacecraft signal in the extremely sensitive receivers used on the DSN antennas. This interference produces errors in the data stream being delivered to the spacecraft engineers and scientists, and it may cause the DSN receivers and antennas to lose the spacecraft signal altogether, in which case the data stream is completely lost.

The earliest antennas in the DSN (Figure 7-2) were of commercial design and were parabolic in shape. Then, as now, the actual efficiency of the antenna represented a compromise between maximum signal-gathering capability and minimum susceptibility to radio noise picked up from the surrounding Earth.

Figure 7-2. An early parabolic design of a DSN antenna.

Improved technology that could reduce the sidelobes and increase the signal collection capability (gain) of future DSN antennas appeared in the Advanced Systems Program in the early 1970s. The new technology was based on a "dual-shape" design wherein the surface shapes of both the primary and secondary reflectors were modified to illuminate the slightly reshaped "quasi-parabolic" surface of the main reflector more uniformly. However, it was not until the 1980s, when the first 34-meter high-efficiency antennas were built, that the new "dual-shape" design saw operational service in the Network (Figure 7-3).

These antennas were needed by the DSN for support of the Voyager spacecraft in their tour of the outer planets. At the time, the DSN was in transition from the lower, less capable S-band (2.3 GHz) operating frequency, for which the early spacecraft and antennas were designed, to X-band (8.4 GHz), a higher, more capable operating frequency. When X-band technology became available in the DSN, largely as a result of work in the Advanced Systems Program, all the later spacecraft and DSN antennas were designed to operate at X-band frequencies. These antennas were therefore the first to be optimized for performance at X-band.

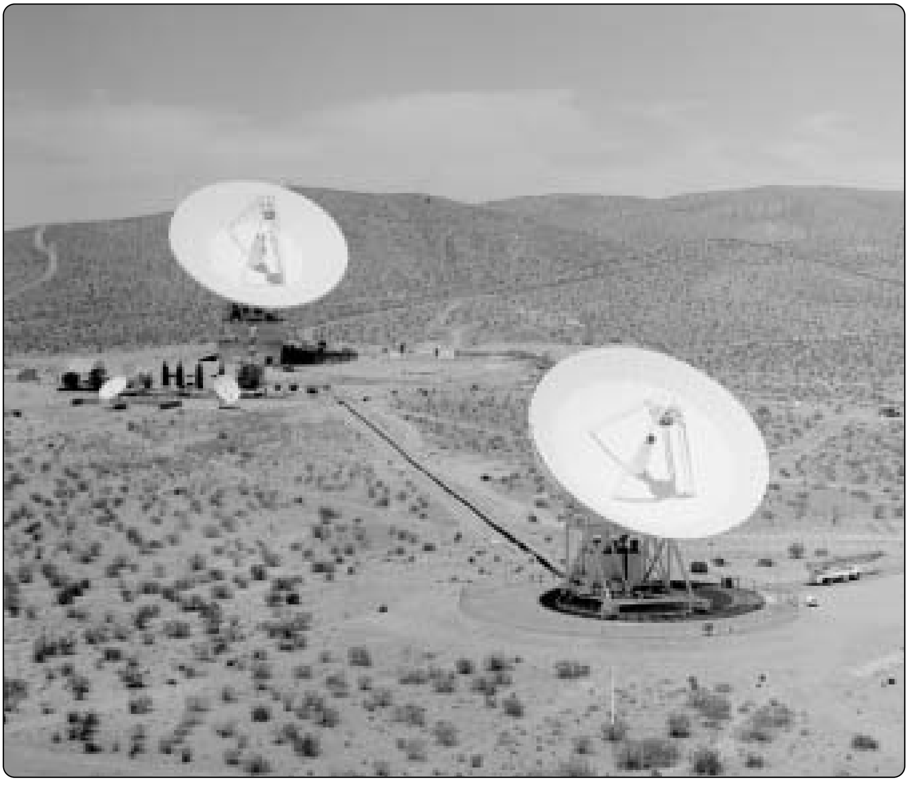

Figure 7-3. The quasi-parabolic 34-m high-efficiency (HEF) antenna, DSS 15.

As the *Voyager 2* spacecraft headed outward toward Neptune, it was recognized that an increased signal-collecting area was needed on Earth to effectively support this unique science opportunity. The DSN's largest antennas at the time were 64-m parabolas of the original design. Calculations showed that the best investment of scarce construction funds would be to modify these antennas, using the dual-shape design, to expand their diameter to 70 m. It was also apparent that the upgraded large antennas would benefit the planned Galileo and Magellan missions.

Completed in time for support of *Voyager 2* at Neptune, the 70-m enhancement project (Figure 7-4) resulted in an increase of more than 60 percent in the effective collecting area of these large antennas. Fully half of the increase was attributed to the dual-shape design, a product of the DSN Advanced Systems Program.

Figure 7-4. A 70-meter antenna with dual-shape reflector design.

By the end of the century, several new 34-m antennas employing the dual-shaped reflector design in conjunction with beam waveguide (BWG) techniques had been constructed for operational use in the Network. The dual-shaped reflector design enhanced the radio performance of the antenna, while the beam waveguide configuration greatly facilitated maintenance and operation of the microwave receivers and transmitters. Using a series of additional secondary reflectors to relocate the focal point into a stationary room below the main dish, the BWG design feature enabled these critical components to be mounted in a fixed environment rather than in the more conventional type of moving and tipping enclosure mounted on the antenna itself.

Beam waveguide antennas had been used for many years in Earth communications satellite terminals where ease of maintenance and operation outweighed the consideration of losses introduced into the microwave signal path by the additional microwave-reflecting mirrors. For deep space applications, however, where received signal power levels were orders of magnitude smaller, any losses in the signal path were a matter of great concern, and the losses associated with BWG designs kept such antennas out of consideration for DSN purposes for many years. Researchers in the DSN Advanced Systems Program nevertheless pursued the idea of BWG antennas for the DSN and, by 1985, were ready to conduct a collaborative experiment with the Japanese Institute for Space and Aeronautical Sciences (ISAS) using its new 64-m beam waveguide antenna at Usuda, Japan. Using one of the DSN's low-noise microwave receivers installed on the Usuda antenna to receive a signal from the *International Cometary Explorer* (ICE) spacecraft, the researchers made very precise measurements of the microwave losses, or degradation, of the downlink signal.

The results of the experiment were very surprising. The measured losses, attributable to the BWG design, were much smaller than expected, exhibiting similar performance at zenith and better performance at low-elevation angles; they confirmed the efficacy of the BWG configuration.

Encouraged by this field demonstration, researchers sponsored by the Advanced Systems Program moved forward with the construction of a prototype BWG antenna for potential application in the Network.

This new prototype BWG antenna was built at the Venus site at Goldstone and replaced the aging 26-m antenna that had served for many years as a field test site for technology research and development (R&D) programs. The designers used microwave optics analysis software, an evolving product of the Advanced Systems Program, to optimize the antenna for operation over a wide range of current and future DSN operating fre-

Figure 7-5. A 34-meter beam waveguide antenna at Goldstone Technology Development Site, DSS 13.

quency bands. When completed, the antenna successfully demonstrated its ability to operate effectively at S-band, X-band, and Ka-band (approximately 2, 8, and 32 GHz, respectively). Figure 7-5 shows the completed BWG antenna, and Figure 7-6 shows the interior of the equipment room below the antenna structure.

Figure 7-6. Stationary equipment room below the BWG antenna.

The various frequencies and modes of operation for the BWG antenna were selected by rotating the single microwave mirror at the center of this room. Lessons learned by Advanced Systems Program personnel in the construction and evaluation of this antenna were incorporated into the design of the operational BWG antennas for the Network, with the result that the performance of these somewhat exceeded that of the prototype, especially at the lower frequencies. A selection of technical references related to great antennas of the DSN can be found in section 2 of the appendix at the end of the book.

Forward Command/Data Link (Uplink)

The large antennas of the DSN are used for transmission of radio signals carrying instructions and data to the spacecraft, as well as for reception of signals. Getting data to distant spacecraft safely and successfully requires that substantial power be transmitted from the ground and directed in a narrow beam at the spacecraft. For most "normal" situations, the compatible design of spacecraft and the DSN is such that power of about 2 kW to 20 kW is adequate. However, situations in space are not always normal. Unexpected events can redirect a spacecraft's main antenna away from Earth, leaving only a low-gain or omnidirectional antenna capable of receiving anything from Earth. Transmitter power of up to 400 kW at S-band can be sent from the 70-m antenna during attempts to regain contact with a spacecraft in such an emergency situation.

The initial design and evaluation of R&D models of the high-power transmitters and their associated instrumentation was carried out under the Advanced Systems Program. Much of the essential field testing was carried out as part of the planetary radar experiments. This cooperative and productive arrangement provided a realistic environment for testing without exposing an inflight spacecraft to an operational unqualified uplink transmission. Later, DSN engineers implemented fully qualified operational versions of these transmitters in the Network at all sites.

The pointing of the narrow forward link signal to the spacecraft is critical, especially when making initial contact without having received a signal for reference, as is typical in emergency situations. The beamwidth of the signal from the 70-m antenna at S-band is about 0.030 degrees, while that of the 34-m antenna at X-band is about 0.017 degrees. Achieving blind pointing to that precision requires a thorough understanding of the mechanics of the antenna, including the effects of gravity and wind on the dish and specifics of the antenna bearing and positioning mechanisms, as well as knowledge of the spacecraft and antenna positions, atmospheric refraction, and other interferences.

Forward link data delivered to a spacecraft, if incorrectly interpreted, have the potential for causing that spacecraft to take undesirable actions, including some that could result in an emergency situation for the spacecraft. To guard against that possibility, the forward link signal is coded with additional redundant data that allow the spacecraft data system to detect or correct any corruption in that signal. Operating on the presumption that it is always better to take no action than to take an erroneous one, the forward link decoding accepts only data sets for which the probability of error is extremely small, and it discards those that cannot be trusted. A selection of technical references related to the forward command/data link (uplink) can be found in the section 3 of the appendix at the end of the book.

Return Telemetry/Data Link (Downlink)

Throughout the Network, the stations use the same antennas for both the forward link and the return data-link signals. Because the strength of a signal decreases as the square of the distance it must travel, these two signals may differ in strength by a factor of 10^{24} in a single DSN antenna. Isolating the return signal path from interference by the

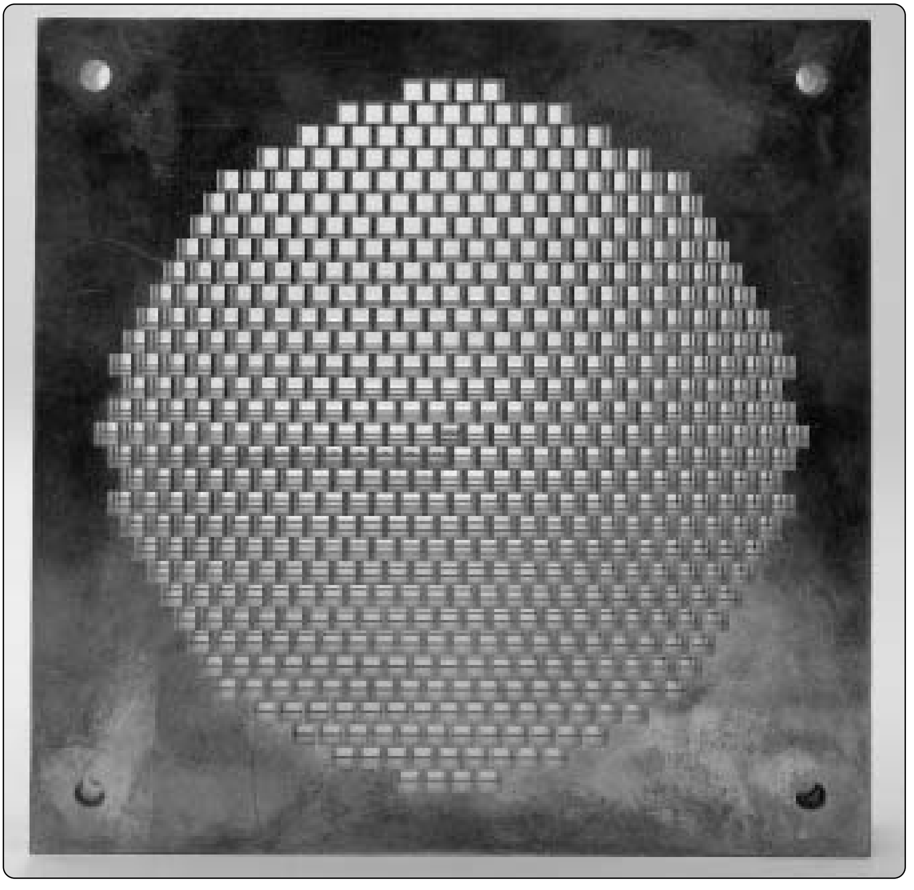

Figure 7-7. Dichroic (frequency-selective) reflector developed under Advanced Systems Program.

much stronger forward signal poses a significant technical challenge. Normally, these two signals differ somewhat in frequency, so at least a part of this isolation can be accomplished via dichroic or frequency-selective reflectors. These reflectors (Figure 7-7) consist of periodic arrays of metallic/dielectric elements tuned for the specific frequencies that either reflect or pass the incident radiation. These devices must not only be frequency-selective, but they must also be designed to minimize the addition of extraneous radio noise picked up from the antenna and its surroundings, which would corrupt the incredibly weak signals collected by the antenna from the desired radio source in deep space.

The DSN Advanced Systems Program developed the prototypes for almost all the reflectors of this type in current use in the Network. As an adjunct to this work, powerful microwave analytical tools that can be used to affix design details for almost any conceivable dichroic reflector applicable to the frequency bands of the DSN were also developed under the Program.

Low-Noise Amplifiers

The typical return data link signal is incredibly small and must be amplified before it can be processed and the data itself reconstructed. The low-noise amplifiers that reside in the antennas of the DSN are the most sophisticated in the world and provide this amplification while adding the least amount of noise of any such devices.

Known as traveling-wave masers (TWMs), the quietest (in terms of adding radio noise) of these operational devices amplify signals that are propagated along the length of a tuned ruby crystal. Noise in a TWM depends upon the physical temperature of the crystal, and those in operation in the DSN operate in a liquid helium bath at 4.2 kelvin. (Zero kelvin is equivalent to a temperature of minus 273.18 Celsius. Therefore, the temperature of the helium bath is equivalent to approximately minus 269 Celsius.) The practical amplifiers for the DSN were invented by researchers at the University of Michigan, and early development of these amplifiers was carried out under the DSN Advanced Systems Program, as were many improvements throughout the Network's history. The quietest amplifiers in the world today (Figure 7-8), which operate at a physical temperature of 1.2 kelvin, were developed by the DSN Advanced Systems Program and demonstrated at the Technology Development Field Test Site, DSS 13.


Figure 7-8. Ultra-low-noise amplifier (ULNA) at DSS 13.

Some of the low-noise amplifiers in the DSN today are not TWMs, but a special kind of transistor amplifier (Figure 7-9) using high-electron mobility transistors (HEMTs) in amplifiers cooled to a physical temperature of about 15 kelvin.

Developed initially at the University of California at Berkeley, such amplifiers were quickly adopted by the scientific community for radio astronomy applications. This, in turn, spawned the JPL development work that was carried out via collaboration involving JPL and the DSN Advanced Systems Program, radio astronomers at the National Radio Astronomy Observatory (NRAO), and device developers at General Electric. This work built upon progress in the commercial sector with uncooled transistor amplifiers. In the 2-GHz DSN band, the cooled HEMT amplifiers are almost as noise-free as the corresponding TWMs, and the refrigeration equipment needed to cool the HEMTs to 15 kelvin is much less troublesome than that for the TWMs. Primarily for this reason, current development efforts in the DSN Advanced Technology area are focused on improving the noise performance of the HEMT amplifiers for the higher DSN frequency bands.

The first DSN application of the cooled HEMT amplifiers came with the outfitting of the NRAO Very Large Array (VLA) in Socorro, New Mexico, for collaborative support of the Voyager-Neptune Encounter. The VLA was designed for mapping radio emissions from distant stars and galaxies and consists of 27 antennas, each 25 meters in diame-

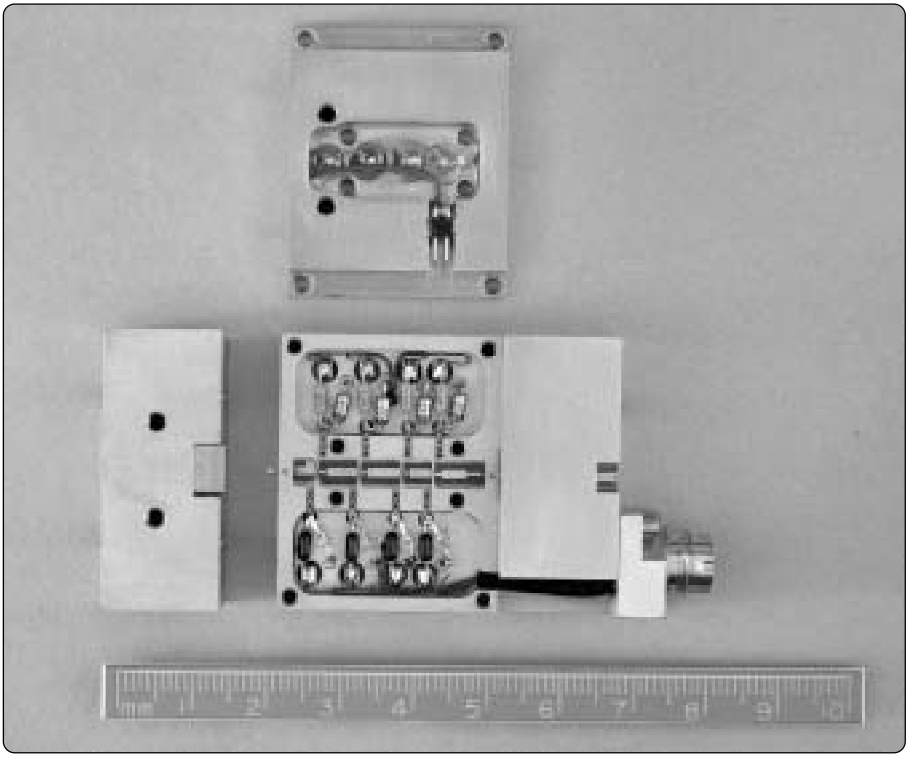

Figure 7-9. High-electron mobility transistor (HEMT) low-noise microwave amplifier.

ter, arranged in a tri-axial configuration. Within the funding constraints, only a small part of the VLA could be outfitted with TWMs, whereas HEMTs for the entire array were affordable and were expected to give an equivalent sensitivity for the combined full array. In actuality, technical progress with the HEMTs under the Advanced Systems Program during the several years taken to build and deploy the needed X-band (8-GHz) amplifiers resulted in better performance for the fully equipped VLA than would have been possible with the VLA partially equipped with the more expensive TWMs. Since that time, many of the DSN operational antennas have had cooled HEMT amplifiers installed for the 2-GHz and 8-GHz bands. A selection of technical references related to return telemetry (downlink) can be found in section 4 of the appendix at the end of the book.

Phase-Lock Tracking

Once the first stages of processing in the low-noise amplifiers are completed, there are still many transformations needed to convert the radio signal sent from a spacecraft into a replica of the data stream originating on that spacecraft. Some of these transformations are by nature analog and linear; others are digital with discrete quantification. All must be performed with virtually no loss in fidelity in order for the resultant data stream to be of practical use.

Typically, the downlink signal consists of a narrow-band "residual carrier" sine wave, together with a symmetric pair of modulation sidebands, each of which carries a replica of the spacecraft data. (Specifics of the signal values vary greatly, but are not essential for this general discussion.) If this signal is cross-correlated with a pure identical copy of the residual carrier, the two sidebands will fold together, creating a low-frequency signal that contains a cleaner replica of the spacecraft data than either sideband alone. Of course, such a pure copy of the carrier signal does not already exist; it must be created, typically via an adaptive narrow-band filter known as a phase-locked loop. The recreated carrier reference is thus used to extract the sidebands. The strength of the resultant data signal is diminished to the extent that this local carrier reference fails to be an identical copy of the received residual carrier. Noise in the spectral neighborhood of the received residual carrier and dynamic variations in the phase of the carrier itself limit the ability to phase-lock the local reference to it.

These dynamic variations are due predominantly to the Doppler effect in play between a distant spacecraft and the DSN antenna on the surface of a spinning Earth. The variations interfere with the return data link process, but they themselves provide for a radio location function. Over the years, the DSN Advanced Systems Program has contributed significantly to the design for the phase-locked loops and to the knowledge of phase-coherent communications, and thus to the performance of the operational DSN. A selection of technical references related to phase-lock tracking can be found in section 5 of the appendix at the end of the book.

Synchronization and Detection

Further steps in converting a spacecraft signal into a replica of the spacecraft data stream are accomplished by averaging the signal over brief intervals of time that correspond to each symbol (or bit) transmitted from the spacecraft and by sampling these averages to create a sequence of numbers, often referred to as a "symbol stream." These averages must be precisely synchronized with the transitions in the signal as sent from the spacecraft so that each contains as much as possible of the desired symbol and as little as possible of the adjacent ones. Usually, a subcarrier, or secondary carrier, is employed to shape the spectrum of the spacecraft signal, and it must be phase-tracked and removed prior to the final processing of the data itself. The Network contains several different generations of equipment that perform this stage of processing. Designs for all of these have their roots in the products of the DSN Advanced Systems Program. The oldest current equipment is of a design developed in the late 1960s by a partnership between the DSN Advanced Systems Program and the DSN implementation programs. This equipment is mostly analog in nature and, while still effective, is subject to component value shifts with time and temperature, and thus requires periodic tending and adjustments to maintain desired performance.

As digital devices became faster and more complex, it became possible to develop digital equipment that could perform this stage of signal processing. Digital demodulation techniques were demonstrated by the Advanced Systems Program in the early 1970s in an all-digital ranging system. Similar techniques were subsequently employed for data detection in the second generation of the Demodulator-Synchronizer Assembly. A selection of technical references related to data synchronization and detection can be found in section 6 of the appendix at the end of the book.

A Digital Receiver

Rapid evolution of digital technology in the 1980s led researchers to explore the application of digital techniques to various complex processes found in receiving systems such as those used in the Network. The processes of filtering, detection, and phase-lock carrier tracking, formerly based on analog techniques, were prime candidates for the new digital technology.

In this context, the Advanced Systems Program supported the development of an all-digital receiver for Network use. Known as the Advanced Receiver (ARX), the developmental model embodied most of these new ideas and demonstrated capabilities far exceeding those of the conventional analog receivers then installed throughout the Network.

Encouraged by the performance of the laboratory model, an engineering prototype was built and installed for evaluation in an operational environment at the Canberra, Australia, Complex. Tests with the very weak signal from the *Pioneer 10* spacecraft, then approaching the limits of the current DSN receiving capability, confirmed the designer's

Figure 7-10. The Advanced Receiver (ARX) as used to track the *Pioneer 10* spacecraft.

performance and, incidentally, significantly extended the working life of that spacecraft.

As a result of these tests, the DSN decided to proceed with the implementation of a new operational receiver for the Network that would be based on the design techniques demonstrated by the ARX. The new operational equipment, designated the Block V receiver (BVR), would include all of the functions of the existing receiver in addition to several other data processing functions, such as demodulation and synchronization, formerly carried out in separate units.

As the older generation receivers were replaced with the all-digital BVR equipment, the Network observed a general improvement in weak signal tracking performance and operational reliability. The receiver replacement program was completed throughout the Network by 1998. A selection of technical references related to digital receivers can be found in section 7 of the appendix at the end of the book.

Encoding and Decoding

The data generated by science instruments must be reliably communicated from the spacecraft to the ground, despite the fact that the signal received is extremely weak and that the ground receiver corrupts the signal with additive noise. Even with optimum integration and threshold detection, individual bits usually do not have adequate signal energy to ensure error-free decisions. To overcome this problem, structured redundancy (channel encoding) is added to the data bit-stream at the spacecraft. Despite the fact that the individual "symbols" resulting from this encoding have even less energy at the receiver, the overall contextual information, used properly in the decoding process on the ground, results in more reliable detection of the original data stream.

High-performance codes to be used for reliable data transfer from spacecraft to DSN were identified by research performed under the Advanced Systems Program and adopted for standard use in the Network while the search for even more powerful and efficient codes continued. New, more efficient block codes, which made better use of the limited spacecraft transmitter power by avoiding the need to transmit separate synchronizing signals, were developed under the DSN Advanced Systems Program and first demonstrated on the *Mariner 6* and *7* spacecraft in 1969. By putting the extra available spacecraft transmitter power into the data-carrying signal, the new block code enabled the return of the Mars imaging data at the astonishing (for the time) rate of 16,200 bits per second, an enormous improvement over the 270-bps data rate for which the basic mission had been designed. Of course, conversion of the encoded data stream back to its original error-free form required a special decoder. The experimental block decoder, developed under the same program for this purpose, formed the basis for the operational block-decoders implemented in the Network as part of the Multimission Telemetry System shortly thereafter.

While the JPL designers of the Mariner spacecraft were pursuing the advantages of block-coded data, the designers of the *Pioneer 9* spacecraft at the Ames Research Center (ARC) were looking to very complex convolutional codes to satisfy their scientists. The scientists agreed to accept intermittent gaps in the data caused by decoding failure in exchange for the knowledge that successfully decoded data would be virtually error-free. In theory, a convolutional code of length $k = 25$ would meet the requirement, but it had a most significant drawback. The decoding process was (at the time) extraordinarily difficult. Known technically as "sequential decoding," this was a continuous decoding operation rather than the "one block at a time" process used by the DSN for decoding the *Voyager* data.

The original plan was to perform the decoding operation for *Pioneer 9* in non-real-time at ARC, using tape-recorded data provided by the DSN. However, Pioneer engineers working in conjunction with the DSN Advanced Systems Program explored and demonstrated the potential for decoding this code in real time via a very-high-speed engineering model sequential decoder. With the rapid evolution in capability of small computers, it became apparent that decoding Pioneer's data in such computers was both feasible and economical. Subsequent implementation of sequential decoding in the Network was done via microprogramming of a small computer, guided by the knowledge gained via the efforts of the Advanced Systems Program. The subsequent *Pioneer 10* and *11* spacecraft flew with a related code of length k = 32 and were supported by the DSN in a computer-based decoder.

The DSN standard code, flown on *Voyager* and *Galileo*, consisted of a short convolutional code that was combined with a large block-size Reed-Solomon code. The standard algorithm for the decoding of convolutional codes was devised in consultation with JPL researchers and demonstrated by simulations performed under the Advanced Systems Program. Prototypes of the decoding equipment were fabricated and demonstrated at JPL, also with the support of the Advanced Systems Program.

The application of coding and decoding technology in the DSN was paced by the evolution of digital processing capability. At the time of the Voyager design, a convolutional code of length k = 7 was chosen as a compromise between performance and decoding complexity, which would grow exponentially with code length. Equipment was implemented around the DSN to handle this code from *Voyager* and subsequently from *Magellan*, *Galileo*, and others. Modern digital technology has permitted the construction of much more complex decoders, and a code of length k = 15 was devised with the support of the Advanced Systems Program. This code was installed as an experiment on the *Galileo* spacecraft shortly before its launch. The corresponding prototype decoder was completed soon afterward. Though not used for *Galileo* because of its antenna problem, the more complex decoder was implemented around the Network for support of the Cassini and subsequent missions.

Efforts of the Advanced Systems Program provided the understanding of telemetry performance to be expected with the use of these codes. Figure 7-11 displays the reliability of the communication (actually, the probability of erroneous data bits) as it depends upon the spacecraft signal energy allocated to each data bit for uncoded communication and three different codes.

Research on new and even more powerful coding schemes, such as turbo codes, continued to occupy an important place in the Advanced Systems Program. Turbo codes are composite codes made up of short-constraint-length convolutional codes and a data stream interleaver. The decoding likewise consists of decoders for the simple component codes, but with an iterative sharing of information between them. These codes, which push hard on the fundamental theoretical limits to signal detection, can result in almost a full decibel of performance gain over the best previous concatenated coding systems. A selection of technical references related to data encoding and decoding can be found in section 8 of the appendix at the end of the book.

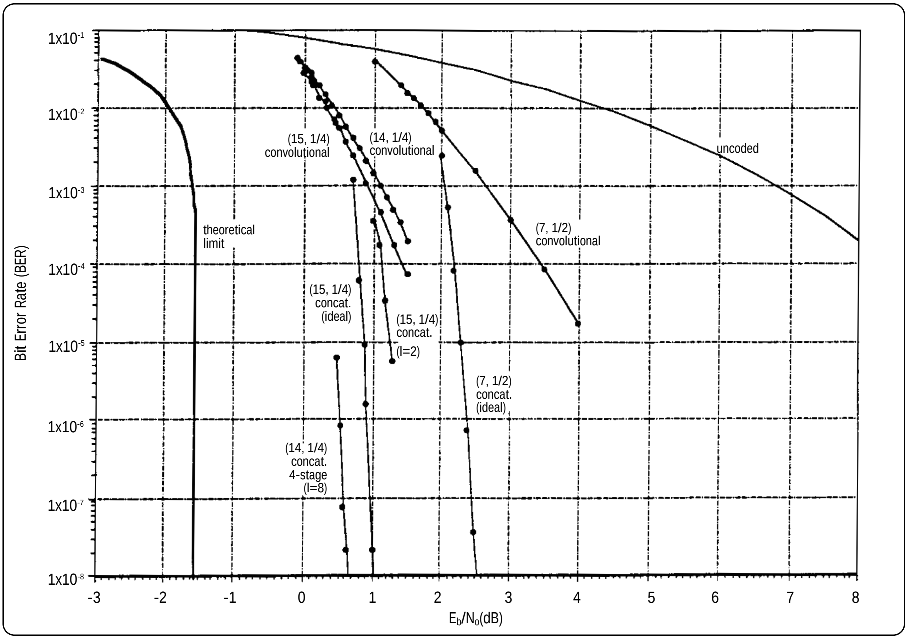

Figure 7-11. Telemetry communication channel performance for various coding schemes. The first set of curves shows the *Voyager* k = code, both alone and in combination with the Reed-Solomon code. The second set of codes illustrates the k = 15 code, which was to be demonstrated with Galileo's original high-rate channel, shown alone and in combination with the Reed-Solomon code, either as constrained by the *Galileo* spacecraft data system (I = 2) or in ideal combination. The third set shows the k = 14 code, devised by the Advanced Systems Program researchers for the actual Galileo low-rate mission, both alone and in combination with the selected variable-redundancy Reed-Solomon code and a complex four-stage decoder. The added complexity of the codes, which has its greatest effect in the size of the ground decoder, clearly provides increased reliability for correct communication.

Data Compression

Source encoding and data compression are not typically considered a part of the DSN's downlink functions, but the mathematics that underlie coding and decoding are a counterpart of those that guide the development of data compression. Simply stated, channel encoding is the insertion of structured redundancy into a data stream, while data compression is the finding and removal of intrinsic redundancy. Imaging data are often highly redundant and can be compressed by factors of at least two, and often four or more, without loss in quality. For *Voyager*, two influences led to a factor-of-two increase in the number of images returned from Uranus and Neptune. The first was the effecting of a very simplified image-compression process constrained to fit into available onboard memory. The second improvement involved corresponding changes to the channel coding.

The success of data compression technology in enhancing the data return from the *Voyager* missions firmly established the technique as an important consideration in the design of all future planetary downlinks. The original telecommunication link design for the *Galileo* spacecraft used data compression to almost double the amount of imaging data that the spacecraft could transmit from its orbital mission around Jupiter. The failure of the spacecraft's high-gain antenna prior to *Galileo*'s arrival at Jupiter prompted an intense effort to find even more complex data compression schemes that would recover some of the Jupiter imaging data that otherwise could not have been returned. A selection of technical references related to data compression can be found in section 9 of the appendix at the end of the book.

Arraying of Antennas

The technique of antenna arraying, as practiced in the Deep Space Network, made use of the physical fact that a weak radio signal from a distant spacecraft that is received simultaneously by several antennas at different locations is degraded by a component of radio noise that is independent of each receiving station. By contrast, the spacecraft signal itself is dependent, or coherent, at each receiving site. In theory, therefore, the power of the signal, relative to the power of the noise, or signal to noise ratio, (SNR) could be improved by combining the individual antennas in such a way that the coherent spacecraft signals were reinforced, while the independent or non-coherent noise components were canceled out.

In practice, this involved a complex digital process for compensating for the time, or phase, delays caused by the different distances between each station and the spacecraft. It also called for compensating for differing distances between the various antenna locations and the common station where the combining function was carried out. This technique became known as antenna arraying, and the digital processing function that realized the theoretical "gain" of the entire process was called "signal combining."

By 1970, conceptual studies had described and analyzed the performance of several levels of signal combining and two of these schemes, carrier and baseband combining, were of potential interest to the Network. Both techniques involved compensation for the phase delays caused by the various locations of the arrayed antennas. The difference lay in the frequency at which the combining function was performed. “Carrier” combining was done at the carrier frequency of the received signal, while “baseband” combining was carried out at the frequencies of the subcarrier and data signal that modulated it. Each had its advantages and disadvantages, but baseband combining proved easier to implement and was, obviously, tried first.

The “arraying and signal combining” concept was first developed and demonstrated in 1969 and 1970 by J. Urech, a Spanish engineer working at the Madrid tracking station. Using signals from the *Pioneer 8* spacecraft and a microwave link to connect two 26-m stations located 20 km apart (DSS 61 and DSS 62), he succeeded in demonstrating the practical application of the principle of baseband combining in the Network for the first time. Because of the low baseband frequency of the *Pioneer 8* data stream (8 bits per second), as well as the close proximity of the antennas, no time-delay compensation was necessary.

Within the bounds of experimental error, this demonstration confirmed the R&D theoretical estimates of performance gain and encouraged the Advanced Systems researchers to press forward with a more complex form of baseband combining at a much higher data rate (117 kilobits per second) in real time.

The demonstration took place at Goldstone in September 1974, using the downlink signals from the *Mariner-Venus-Mercury* (MVM) spacecraft during its second encounter with the planet Mercury. Spacecraft signals from the two 26-m antennas, DSS 12 and DSS 13, were combined in an R&D combiner with signals from the DSS 14 64-m antenna in real time at 117 kbps. The less-than-predicted arraying gain obtained in this demonstration (9 percent versus 17 percent) was attributed to small differences in performance between key elements of the several data-processing systems involved in the test. Although this experience demonstrated both the practical difficulty of achieving full theoretical gain of an antenna arrayed system and the critical effect of very small variations in the performance of its components, it also established the technical feasibility of baseband arraying of very weak high-rate signals.

In 1977, with the lessons learned from these demonstrations as background, the DSN started to develop an operational arraying capability for the Network. The *Voyager 1* and *2* Encounters with Saturn in 1980 and 1981 would be the first to use the arraying in the Network. A prototype baseband real-time combiner (RTC), based on the analysis and design techniques developed by the earlier R&D activity, was completed in the fall of 1978. Designed to combine the signals from DSS 12 and DSS 14 at Goldstone, it was used with varying degrees of success to enhance the signals from the *Voyagers* at Jupiter in March and July of 1979 and the *Pioneer 11* Encounter of Saturn in August and September of that year.

Like the previous demonstration, this experience emphasized the critical importance of having all elements of the array-receivers, antennas, and instrumentation operating precisely according to their specified performance capabilities. With this very much in mind, the DSN proceeded to the design for operational versions of the RTC for use at all three complexes to support the *Voyager 1* and *2* Encounters of Saturn. The operational versions of the RTC embodied many improvements derived from the experience with the R&D prototype version. By mid-August 1980, they were installed and being used to array the 64-m and 34-m antennas at all three complexes as *Voyager 1* began its far-Encounter operations. During this period, the average arraying gain was 0.62 dB, about 15 percent greater than that of the 64-m antenna alone. While this was good, improvement came slowly as more rigorous control and calibration measures for the array elements were instituted throughout the Network. By the time *Voyager 2* reached Saturn in August 1981, these measures, supplemented with additional training and calibration procedures, had paid off. The average arraying gain around the Network increased to 0.8 dB (approximately 20 percent), relative to the 64-m antenna alone. This was clearly a most satisfactory result and the best up to that time. Antenna arraying had become a permanent addition to the capability of the Network.

While researchers working within the Advanced Systems Program continued to explore new processes for arraying antennas, engineers within the DSN took advantage of the long flight time between the Voyager Saturn and Uranus Encounters to refine the existing RTC configuration. Over the next five years, the formerly separate data-processing functions of combining, demodulation, and synchronization were integrated into a single assembly. This integration facilitated improvements in performance, stability, and operational convenience. By the time *Voyager 2* approached Uranus in 1985, the new Baseband Assemblies (BBAs), as they were called, had been installed at all three Complexes. In addition, a special version of the basic four-antenna BBA was installed at the Canberra Complex. This provided for combining the Canberra array of one 64-m and two 34-m antennas with signals from the 64-m Parkes Radio Telescope, 200 km distant (Figure 7-12).

In January 1986, this arrangement was a key factor in the successful return of Voyager imaging data from the unprecedented range of Uranus. But even greater achievements in antenna arraying lay ahead.

Figure 7-12. The 64-m antenna of the Radio Astronomy Observatory, Parkes, Australia.

In 1989, the DSN used a similar arrangement with great success to capture the Voyager imaging data at a still greater range—from Neptune. This time the Goldstone 70-m and 34-m antennas were arrayed with the 27 antennas of the Very Large Array (VLA) (Figure 7-13) of the National Radio Astronomy Observatory at Socorro, New Mexico.

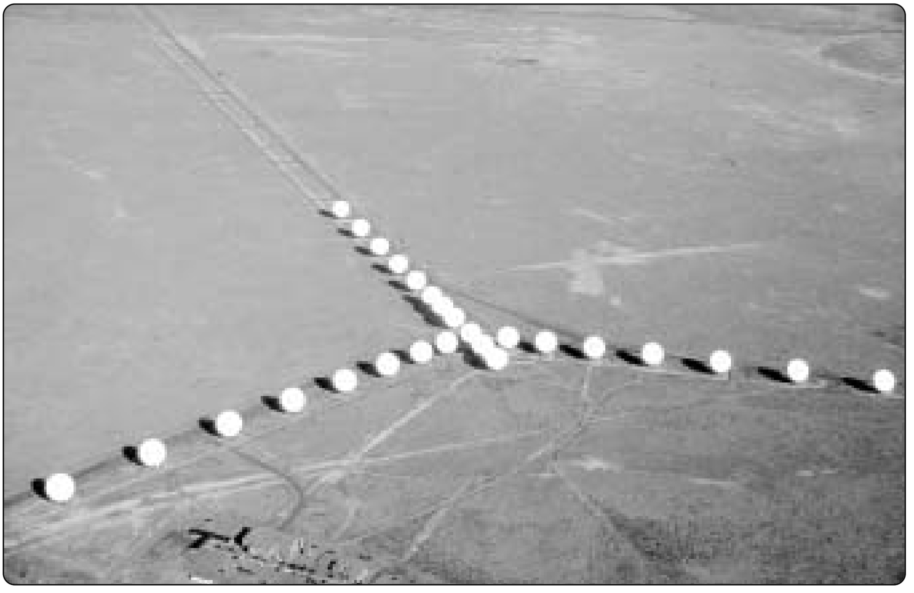

Figure 7-13. The Very Large Array (VLA) of the National Radio Astronomy Observatory (NRAO) at Socorro, New Mexico.

DSN support for the Voyager Encounter of Uranus was further augmented by the Canberra-Parkes array in Australia, which the DSN had reinstated with the addition of new BBAs, new 34-m antennas, and the upgraded 70-m antenna.

The success of these applications of the multiple-antenna arraying technique provided the DSN with a solid background of operational experience. The DSN drew heavily on this experience a few years later, when it was called upon to recover the science data from *Galileo* after the failure of the spacecraft's high-gain antenna in 1991. Together with the data compression and coding techniques discussed earlier, the Network's Canberra/Parkes/Goldstone antenna arrays succeeded in recovering a volume of data that, according to the Galileo project, was equivalent to about seventy percent of the original mission.

With time, arraying of multiple antennas within Complexes, between Complexes, or between international space agencies came into general use as a means to enhance the downlink capability of the Network. In the latter years of the century, most of the enhancements to the arraying in the DSN were driven by implementation and operational considerations rather than by new technology, although the Advanced Systems Program continued to explore the boundaries of performance for various alternative arraying architectures and combining techniques. A selection of technical references related to antenna arraying can be found in section 10 of the appendix at the end of the book.

Radio Metric Techniques

In addition to being able to exchange forward and return link data with an exploring spacecraft, it is equally important to know the precise location of the spacecraft and its velocity (speed and direction). Information about the position and velocity of the spacecraft can be extracted from the one-way or two-way radio signals passing between the spacecraft and the DSN. When these data are extracted by appropriate processing and further refined to remove aberrations introduced by the propagation medium along the radio path between spacecraft and Earth, it can be used for spacecraft navigation.

Radio metric techniques similar to those used for spacecraft navigation can also be used for more explicit scientific purposes, notably radio science, radio astronomy, and radio interferometry on very long baselines (VLBI).

Since its inception, the DSN Advanced Systems Program has worked to develop effective radio metric tools, techniques, observing strategies, and analysis techniques that furthered the DSN pre-eminence in these unique fields of science. In more recent times, the Advanced Systems program demonstrated the application of Global Positioning System technology to further refinement of radio metric data generated by the DSN. A selection of technical references on radio metric tools can be found in section 11 of the appendix at the end of the book.

Doppler and Range Data

If the Earth and the spacecraft were standing still, the time taken for a radio signal to travel from the Earth to the spacecraft and back would be a measurement of the distance between them. This is referred to as the round-trip light time (RTLT). However, since the Earth and the spacecraft are both in motion, the RTLT contains both position and velocity information, which must be disentangled through multiple measurements and suitable analysis. The precision at which such measurements can be obtained is limited by the precision of the time-tag marker to the radio signals, and by the strength of the signal in proportion to the noise mixed with it, or by the signal-to-noise ratio (SNR).

Precise measurements of changes to this light time are far easier to obtain via observing the Doppler effect resulting from the relative motions. Such measurements are mechanized via the phase-locked loops in both spacecraft and ground receivers using the spacecraft's replica of the forward link residual carrier signal to generate the return link signal, and counting the local replica of the return link residual carrier against the original carrier for the forward link signal. The raw precision of these measurements is comparable to the wavelength of the residual carrier signal, e.g., a few centimeters for an X-band signal (8 GHz). Numerous interesting error sources tend to corrupt the accuracy of the measurement and the inferred position and velocity of the spacecraft, and they have provided significant technical challenge for work under the Advanced Systems Program.

The observed Doppler contains numerous distinct components, including the very significant rotation of Earth. As Earth turns, the position of any specific site on the surface describes a circle, centered at the spin axis of the Earth, falling in a plane defined by the latitude of that site. The resultant Doppler component varies in a diurnal fashion with a sinusoidal variation, which is at its maximum positive value when the spacecraft is first observable over the eastern horizon. Its corresponding negative value occurs at approach to the western horizon. A full-pass Doppler observation from horizon to horizon can be analyzed to extract the apparent spacecraft position in the sky, although the determination is somewhat weak near the equatorial plane. Direct measurements of the RTLT are useful for resolving this difficulty.

Three distinct generations of instruments designed to measure the RTLT were developed by the Advanced Systems Program and used in an ad hoc fashion for spacecraft support before a hybrid version was designed and implemented around the DSN. The third instrument designed, the Mu-II Ranging Machine, was used with the Viking Landers in a celestial mechanics experiment, which provided the most precise test, up to that time, of the general theory of relativity.

These devices function by imposing an additional "ranging" modulation signal on the forward link, which is copied on the spacecraft (within the limits imposed by noise) and then imposed on the return link. The ranging signal is actually a very long period-coded sequence that provides the effect of a discrete time tag. The bandwidth of the signal is on the order of 1 MHz, giving the measurement a raw precision of a few hundred meters, resolvable with care to a few meters. Among other features, the Mu-II Ranging Machine included the first demonstrated application of the digital detection techniques that would figure strongly in future developments for the DSN.

Timing Standards

The basic units of measurement for all radio metric observations, Doppler or range, derive from the wavelength of the transmitted signal. Uncertainties or errors in knowledge of that wavelength are equivalent to errors in the derived spacecraft position. The need for accurate radio metrics has motivated the DSN Advanced Systems Program to develop some of the most precise, most stable frequency standards in the world. While the current suite of hydrogen maser frequency standards in the DSN field sites was built outside of JPL, the design is the end product of a long collaboration in technology development, with research units being built at JPL under the DSN Advanced Systems Program and elsewhere.

Continued research under the Advanced Systems Program for improved frequency standards resulted in the development of a new linear ion trap standard (Figure 7-14) that

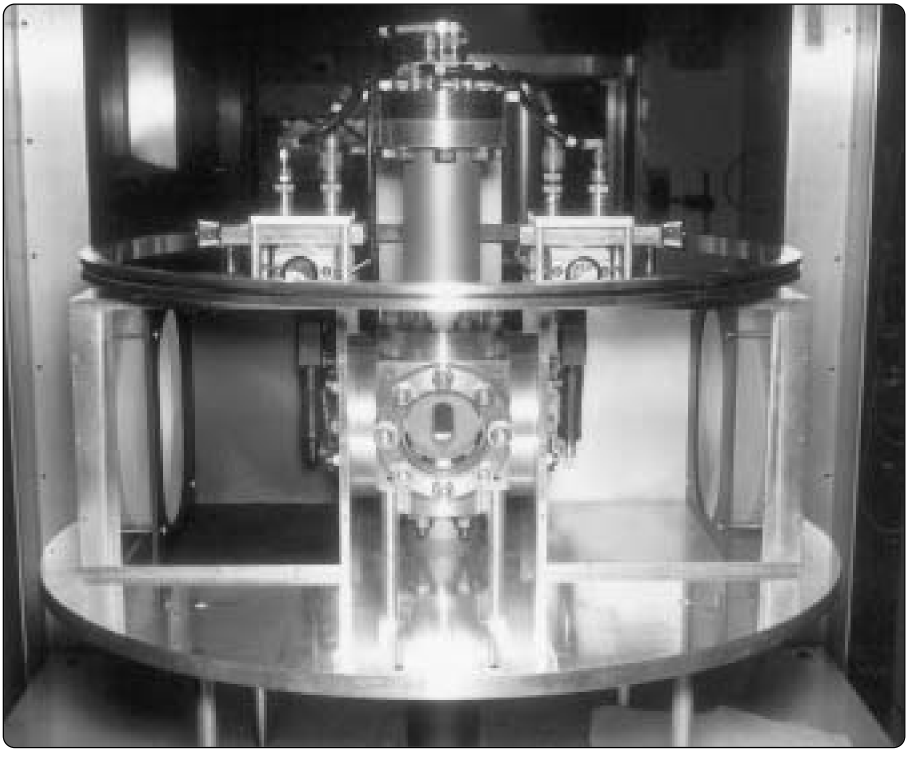

Figure 7-14. The new linear ion trap (LIT) standard.

offered improved long-term stability of a few parts in 10^{16}, as well as simpler and easier maintenance than that required by the hydrogen masers.

Work was under way to implement the LIT standard in the DSN, while research efforts continued for improvements that could be transferred to field operation in the future. A selection of technical references related to timing standards can be found in section 12 of the appendix at the end of the book.

Earth Rotation and Propagation Media

Radio metric Doppler and range data enable the determination of the apparent location of a spacecraft relative to the position and attitude of the rotating Earth. Earth, however, is not a perfectly rigid body with constant rotation, but contains fluid components as well, which slosh about and induce variations in rotation of perhaps a few milliseconds per day. Calibration of Earth's attitude is necessary so that the spacecraft's position in inertial space can be determined—a necessary factor in navigating the spacecraft toward a target planet. Such calibration is available via the world's optical observatories and, with greater precision, via radio techniques, which will be discussed further in the sections entitled "VLBI and Radio Astronomy" and "Global Positioning System."

The interplanetary media along the signal path between Earth and the spacecraft affect the accuracy of the Doppler and range observations. The charged ions in the tenuous plasma spreading out from the Sun, known as the solar wind, bend and delay the radio signal. Likewise, the charged ions in Earth's own ionosphere and the water vapor and other gases of the denser lower atmosphere bend and delay the radio signal. All of these factors are highly variable because of other factors, such as intensity of solar activity, season, time of day, and weather. All factors must be calibrated, modeled, or measured to achieve the needed accuracy; over the years, the DSN Advanced Systems Program has devised an increasingly accurate series of tools and techniques for these calibrations. A selection of technical references related to Earth rotation and propagation can be found in section 13 of the appendix at the end of the book.

Radio Science

Radio science is the term used to describe the scientific information obtained from the intervening pathway between Earth and a spacecraft by the use of radio links. The effects of the solar wind on the radio signal path interfere with our efforts to determine the location of the spacecraft, but if the relative motions of Earth and the spacecraft are modeled and removed from the radio metric data, much of what remains is information about the solar wind and, thus, about the Sun itself. Other interfering factors are also of scientific interest.

In some situations, the signal path passes close by a planet or other object, and the signal itself is bent, delayed, obscured, or reflected by that object and its surrounding atmosphere. These situations provide a unique opportunity for scientists to extract information from the signal about object size, atmospheric density profiles, and other factors not otherwise observable. Algorithms and other tools devised to help calibrate and remove interfering signatures from radio metric data for use in locating a spacecraft often become part of the process for extracting scientific information from the same radio metric data stream. The precision frequency standards, low-noise amplifiers, and other elements of the DSN derived from the Technology Program are key factors in the ability to extract this information with a scientifically interesting accuracy. Occasionally, engineering models developed by the Program are placed in the Network in parallel with operational instrumentation for ad hoc support of metric data-gathering for some unique event.

The effects of gravity can also be observed by means of the radio link. Several situations are of interest. If the spacecraft is passing by or in orbit about an object that has a lumpy, uneven density, that unevenness will cause a variation in the spacecraft's pathway that will be observable via the radio metric data. If the radio signal passes near a massive object such as the Sun, the radio signal's path will be bent by the intense gravity field, according to the theories of general relativity. And in concept, gravitational waves (a yet-to-be-observed aspect of gravity field theory) should be observable in the Doppler data from a distant spacecraft. All of these possibilities depend upon the stability of the DSN's precision frequency standards for the data to be scientifically interesting. A selection of references related to radio science can be found in section 14 of the appendix at the end of the book.

VLBI and Radio Astronomy

The technical excellence of the current DSN is, at least in part, a result of a long and fruitful collaboration with an active radio astronomy community at the California Institute of Technology (Caltech) and elsewhere. Many distant stars, galaxies, and quasars are detectable by the DSN at radio frequencies. The furthest of these are virtually motionless and can be viewed as a fixed-coordinate system to which spacecraft and other observations can be referenced. Observations relative to this coordinate set help to reduce the distorting effects of intervening material in the radio signal path and uncertainties in the exact rotational attitude of Earth during spacecraft observations.

Little precise information can be extracted by observing these objects one at a time and from a single site, but concurrent observation at a pair of sites will determine the relative position of the two sites referenced to the distant object. The observing technique is known as very long baseline interferometry (VLBI) and was developed by the research of many contributors, including substantial work by the DSN's Advanced Systems Program. If three sites are used in VLBI pairs and multiple objects are observed, the positional attitude of Earth and the relative positions of the observed objects can be determined. If one of the observed is a spacecraft transmitting a suitable signal, its position and velocity in the sky can be very accurately defined. A demonstration of this technique via the Advanced Systems Program led to operational use for spacecraft such as *Voyager* and *Magellan*.

VLBI can also be used in conjunction with conventional radio metric data types to provide the calibration for the positional attitude of Earth. Such observations can be made without interfering with spacecraft communication except for the time utilization of the DSN antennas. In addition to determining Earth's attitude, the observations measure the relative behavior of the frequency standards at the widely separated DSN sites, and thus help to maintain their precision performance. Again, demonstration of this capability via the Advanced Systems Program led to routine operational use in the DSN.

Design and development of the DSN equipment and software needed for VLBI signal acquisition and signal processing (correlation) was carried out in a collaboration involving the Advanced Systems Program, the operational DSN, and the Caltech radio astronomy community. Tools needed to produce VLBI metric observations for the DSN were essentially the same as those for interferometric radio astronomy. Caltech received funding from the National Science Foundation for this activity, and both Caltech and the DSN shared in the efforts of the design while obtaining products that were substantially better than any that they could have been obtained independently.

Another area of common interest between the DSN and the radio astronomy community is that of precision wideband spectral analysis. Development efforts of the Advanced Systems Program produced spectral analysis tools that have been employed by the DSN in spacecraft emergency situations and in examining the DSN's radio interference environment, and they have served as pre-prototype models for equipment for the DSN. Demonstration of the technical feasibility of the very-wide-band spectral analysis and preliminary observations by a megachannel spectrum analyzer fielded by the Advanced Systems Program helped establish the sky survey planned as part of the former SETI (Search for Extraterrestrial Intelligence) Program.

Another technique (one similar to the use of VLBI for a radio metric reference) is used if two spacecraft are flown to the same target; the second can be observed relative to the first, providing better target-relative guidance once the first has arrived at the target. Techniques for acquiring and analyzing such observations have been devised by the Advanced Systems Program. A selection of technical references related to VLBI and radio astronomy can be found in section 15 of the appendix at the end of the book.

The Global Positioning System

The Global Positioning System (GPS) is a constellation of Earth-orbiting satellites designed (initially) to provide for military navigation on Earth's surface. Research under the Advanced Systems Program showed that these satellites could provide an excellent tool to calibrate and assist in the radio metric observation of distant spacecraft. GPS satellites fly above the Earth's atmosphere and ionosphere in well-defined orbits so that their signals can be used to measure the delay through these media in a number of directions. With suitable modeling and analysis, these measurements can be used to develop the atmospheric and ionospheric calibrations for the radio path to a distant spacecraft.

Additionally, since the GPS satellites are in free orbit about Earth, their positions are defined relative to the center of mass of Earth, and not its surface. They provide another method to observe the uneven rotation of Earth.

GPS techniques can also be used to determine the position of an Earth-orbiting spacecraft relative to the GPS satellites, as long as the spacecraft carries a receiver for the GPS signals. The potential of this technique was initially demonstrated by the Advanced Systems Program. GPS was subsequently used by the TOPEX/POSEIDON Project for precise orbit determination and a consequent enhancement of its scientific return. A selection of technical references related to the GPS can be found in section 16 of the appendix at the end of the book.

Goldstone Solar System Radar

The Goldstone Solar System Radar (GSSR) is a unique scientific instrument for making observations of nearby asteroids, the surfaces of Venus or Mars, the satellites of Jupiter, and other objects in the solar system. Although the GSSR makes use of the DSN 70-m antenna for its scheduled observing sessions, its receiving, transmitting, and data-processing equipment is unique to the radar program. The GSSR is a product of many years of development by the DSN Advanced Systems Program. In the early days of the DSN, the Advanced Systems Program took ownership of the radar capability at the DSN's Goldstone, California, site and evolved and nurtured it as a vehicle for developing and demonstrating many of the capabilities that eventually would be needed by the Network.

Scientific results abounded as well, but they were not its primary product. Timely development of DSN capabilities was the major result. Preparations for a radar observation at the DSN Technology Development Field Site bore many resemblances to those for a spacecraft planetary encounter, since the radar observations could only be successful during the few days when Earth and the radar target were closest together.

In the conventional formulation of the radar sensitivity equations, that sensitivity depends upon the aperture, temperature, power, and gain of the system elements. Here, aperture refers to the effective size, or collecting area and efficiency, of the receiving antenna; temperature is a way of referring to the noise in the receiving system, where a lower temperature means a lesser noise; power refers to the raw power level from the transmitter; and gain is the effective gain of the transmitting antenna, which depends in turn upon its size, its surface efficiency, and the frequency of the transmitted signal. Where the same antenna is used both to transmit and to receive, the antenna size and efficiency appear twice in the radar equations.

Significant improvements to the DSN's capability for telemetry reception were to come from the move upward in frequency from S-band (2 GHz) to X-band (8 GHz) on the large 64-m antennas. Performance of these antennas at the higher frequencies and the ability to successfully point them were uncertain, however, and these uncertainties would best be removed by radar observations before spacecraft with X-band capabilities were launched. The radar had obvious benefit from the large antenna and the higher frequency. The first flight experiment for X-band communication was carried out on the 1973 Mariner Venus Mars mission. Successful radar observations from the Goldstone 64-m antenna demonstrated that the challenge of operating the large antennas at the higher X-band frequency could be surmounted.

High-power transmitters were needed by the DSN for its emergency forward link functions but were plagued by problems such as arcing in the waveguide path when power densities became too high. High-power transmitters were essential for the radar to "see" at increased distances and with increased resolution. Intense development efforts at the DSN Technology Development Field Site could take place without interference or risk to spacecraft support in the Network. Successful resolution of the high-power problems for the radar under the Advanced Systems Program became the successful implementation of the high-power capability needed by the Network for uplink communications.

Low-noise amplifiers were needed by the DSN to increase data return from distant spacecraft. Low-noise amplifiers were essential for the radar to enable it to detect echoes from increasingly distant targets or to provide for increased resolution of already detectable targets. The synergistic needs of both the radar system and the Network led to the development of the extremely low-noise maser amplifiers that became part of the standard operational inventory of the DSN.

Digital systems technology was rapidly evolving during this period and would play an increasing role in the developing DSN. Equipment developed by the Advanced Systems Program for its radar application included 1) digital encoders to provide for spatial resolution of parts of the radar echo, 2) computer-driven programmable oscillators to accommodate Doppler effects on the signal path from Earth to target to Earth, and 3) complex, high-speed digital signal processing and spectrum analysis equipment. Much of the digital technology learned this way would transfer quickly to other parts of the signal processing work under the Advanced Systems Program and eventually into the operational DSN. Some of the elements would find direct application, such as the programmable oscillators, which became essential for maintaining contact with the *Voyager 2* spacecraft following a partial failure in its receiver soon after launch. And the signal analysis tools would be called on many times over the years to help respond to spacecraft emergencies.

Some of the products of the early radar observations (see Figure 7-15) were both scientific in nature and essential for providing information for the planning and execution of NASA's missions.

One notable "first" was the direct measurement of the astronomical unit. (One astronomical unit (AU) is equal to 1.5 x 108 km, the mean distance between Earth and the Sun.) It sets the scale size for describing distances in the solar system. The measurement was made in support of preparations for sending *Mariner 2* to Venus and provided a correction of 66,000 km from conventional belief at that time. It also enabled corrections that brought the mission into the desired trajectory for its close flyby of the planet. The GSSR was also used in qualifying potential Mars landing sites for the Viking Landers, and it continues to provide information about the position and motion of the planets, which is used to update the predicted orbits for the planets of the solar system. A selection of technical references related to the Goldstone solar system radar can be found in section 17 of the appendix at the end of the book.

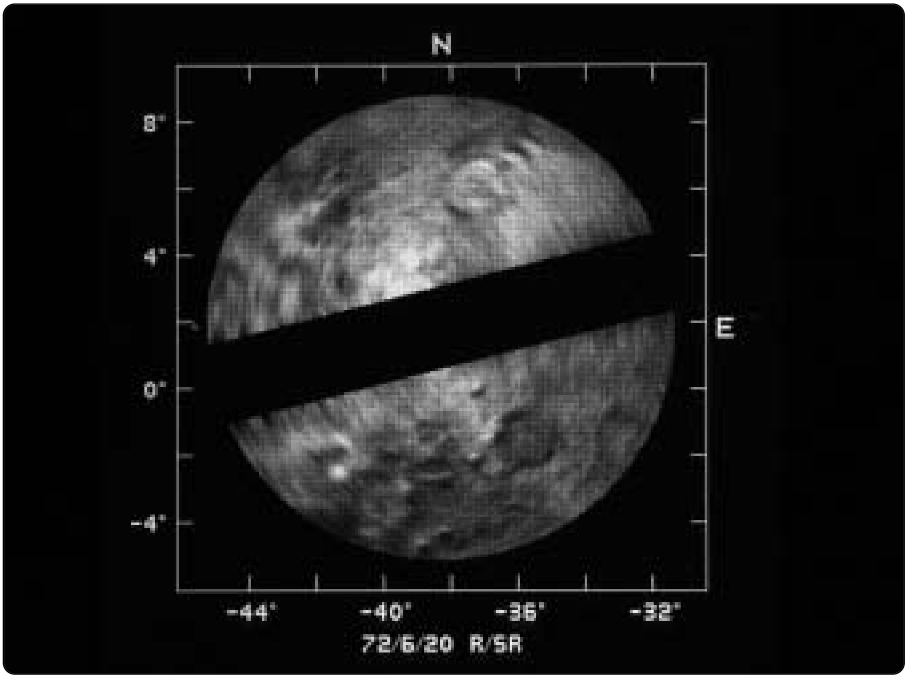

Figure 7-15. First high-resolution radar image of Venus.

Telecommunications Performance of the Network

The progress of deep space communications capability over the period of forty years since the inception of the Network is illustrated in Figure 7-16.

In interpreting the data presented in Figure 7-16, it will be observed that the logarithmic scale that displays the data rate gives an impression that the early improvements are more significant than the later improvements. This is because the steps represent fractional or percentage increases, rather than incremental increases. The latter would show the actual data rate increases, which are much larger in the later improvements. If the value was proportional to the amount of data, then the display of the incremental increases would be more meaningful than the logarithmic display.

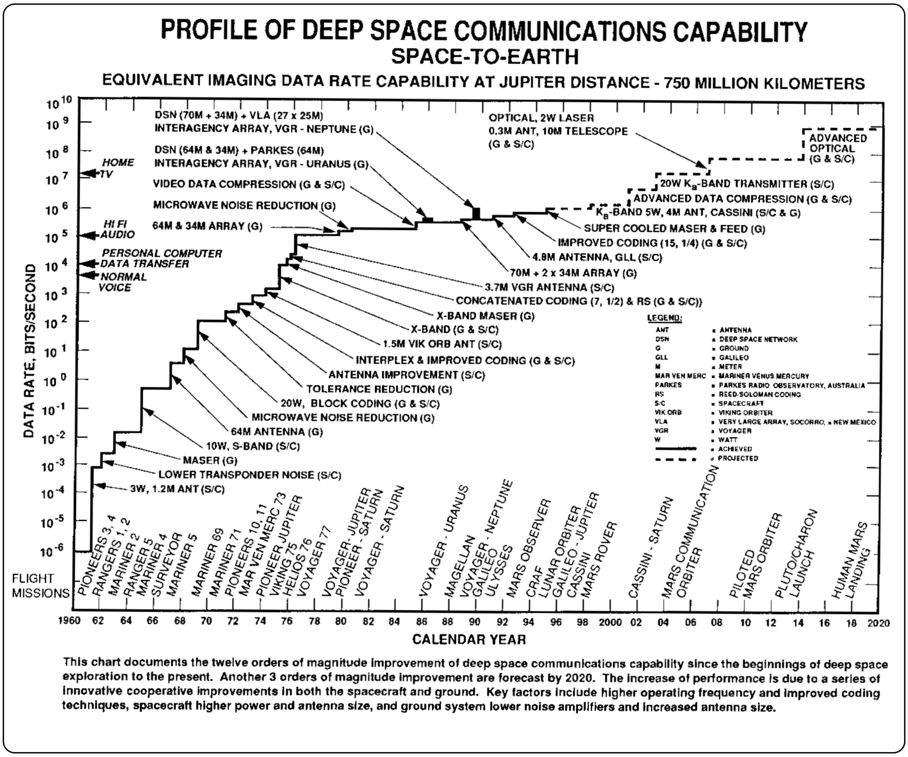

Figure 7-16. Profile of deep space communications capability. The timeline on the horizontal axis of the figure covers the first forty years of actual Network operational experience through the close of the century and extends for a further twenty years to forecast the potential for future improvements through the year 2020. The vertical axis displays the growth in space-to-Earth downlink capability of the Network. The downlink capability is given in units of telemetry data rate (bits per second) on a logarithmic scale and represents the equivalent imaging data rate capability for a typical spacecraft at Jupiter distance (750 million kilometers). Significant events in the history of deep space telecommunications and deep space exploration are appropriately annotated on both axes.

Presented this way, however, the figure clearly shows that, from inception though 1997, the downlink capability of the Network grew from 10^{-6} to 10^{6} bits per second, equivalent to twelve orders of magnitude.

This remarkable progress is not, of course, solely due to improvements in the Network. Many of the steps result from "cooperative" changes on the part of both the DSN and the spacecraft. Coding, for example, is applied to the data on the spacecraft and removed on Earth. A change in frequency has resulted in some of the larger steps shown by causing the radio beam from the spacecraft to be more narrowly focused. Such change necessitates equipment changes on both the spacecraft and Earth.

Other steps represent advances that are strictly spacecraft-related, such as increases in return-link transmitter power or increases in spacecraft antenna size, which improves performance by more narrowly focusing the radio beam from the spacecraft.

Still other steps depict improvements strictly resulting from the DSN, such as reduction in receiving system temperature, increase in the size of the ground antennas, or use of arrays of antennas to increase the effective surface area available for collecting signal power. A selection of technical references related to telecommunications performance can be found in section 18 of the appendix at the end of the book.

Cost-Reduction Initiatives

With one exception, the program continued to pursue the same broad themes in this period, December 1994 to December 1997, that had characterized its earlier work. The new theme that began to appear in the program in 1994 was directed at the reduction of Network operations costs.

A Network automation work area was set up to develop automated procedures to replace the extremely operator-intensive work of running a spacecraft "pass" over a DSN tracking station. This effort soon produced demonstrable results. A fully automated satellite tracking terminal that could reduce operations costs for near-Earth satellites was demonstrated in 1994. A software prototype that reduced the number of manual inputs for a typical 8-hour track from 900 to 3 was installed at DSS 13 and used to support Ka-band operations at that site. Eventually this technology would find its way into the operational Network. A contract for a new, small deep space transponder offering lower size and power needs, and most importantly lower production costs, was initiated with Motorola in July 1995. This became an element in JPL's future low-cost micro-spacecraft. Development of a space-borne micro-GPS receiver, which offered the promise of low-cost orbit determination for most low-Earth orbiting spacecraft, was also initiated in 1995.

Prototypes of a new class of low-cost, fully automated, autonomous ground stations that would simplify implementation and operation and reduce the life-cycle cost of tracking stations in the DSN were introduced in 1995, 1996, and 1997. The first of these terminals was designed for tracking spacecraft in low-Earth orbit and was named LEO-T. It was enclosed in a radome and mounted on the roof of a building at JPL, where it accumulated over two years of unattended satellite tracking operations without problems. Prompted by the success of LEO-T, the program undertook a fast-track effort to develop a similar automated terminal for deep space applications. It would be called DS-T. The prototype DS-T was to be implemented at the 26-m BWG antenna at Goldstone. Automation technology was carried one step further into the area of Network operations in 1997 with the introduction of Automated Real-time Spacecraft Navigation (ARTSN). In addition to the antenna system, the DS-T included an X-band microwave system, a 4-kW transmitter, and an electronics rack containing commercial-off-the-shelf equipment to carry out all baseband telemetry downlink, command uplink, and Doppler and ranging functions. It was planned to demonstrate DS-T with *Mars Global Surveyor* early in 1998 and to use this technology (autonomous uplink and downlink) in the Network with the New Millennium DS-1 spacecraft later that year. A selection of technology references related to cost-reduction initiatives can be found in section 19 of the appendix at the end of the book.

KA-BAND DEVELOPMENT

In the past, the major improvements in the Network's deep space communications capabilities were made by moving the operating frequency to the higher frequency bands. Recognizing this, research and development at Ka-band (32 GHz) was started in 1980. Initial efforts were directed toward low-noise amplifier development and system benefit studies. However, it was also clear that the performance of existing antennas (which were designed for much lower frequencies) would severely limit the improvement in performance that could be realized from the higher operating frequency. Accordingly, in 1991, a new antenna specifically designed for research and development at Ka-band was installed at the DSS 13 Venus site at Goldstone. It would be used as the pathfinder for development of large-aperture beam waveguide antennas that would, in due course, be implemented throughout the Network.

Small imperfections in the surface of an antenna cause larger degradations at Ka-band than at lower frequencies, and, because of the narrower beam width, small pointing errors have a much larger effect. In 1994, improvements in antenna efficiency and in antenna pointing were made on the research and development Ka-band antenna at DSS 13 and on the new operational antenna at DSS 24. These improvements were effected by the use of microwave holography for precise determination of antenna efficiency, along with a special gravity-compensation system to counteract the effect of gravitational sag as a function of antenna elevation angle. In a search for further downlink improvement, a new feed system consisting of a maximally compact array of seven circular Ka-band horns was designed and tested at DSS 13. Each horn was connected to a cryogenically cooled low-noise amplifier, a frequency down-converter, an analog-to-digital converter, and a digital signal processor. The signals from each horn were optimally combined in a signal processor and presented as a single output with a quality equivalent to that of a signal from an undistorted antenna. The measured gain in downlink performance was 0.7 dB.

The technology program continued to develop operational concepts that would eventually lead to the adoption of Ka-band for deep space missions. Tradeoff studies between X-band and Ka-band showed the overall advantage of Ka-band, taking due account of the negative effects inherent in its use, to be about a factor of four, or 6 dB, in data return capability. Obviously, end-to-end system demonstrations were needed to instill confidence in the new technology. In 1993, the *Mars Observer* spacecraft carried a nonlinear element in its transmission feed to produce a fourth harmonic of the X-band signal. The demonstration (called KABLE for Ka-band Link Experiment) provided a weak Ka-band signal for the tracking antenna at DSS 13. A second demonstration

(KABLE II) was conducted using the Mars Global Surveyor mission in 1996. This experiment would be used to characterize Ka-band link performance under real flight conditions and validate the theoretical models derived from the studies mentioned above.

KABLE-II required additions to the MGS spacecraft radio-transponder to generate a modulated Ka-band downlink from which the improvements that had been made to the DSS 13 antenna to reduce pointing errors and improve performance while tracking a spacecraft at Ka-band could be evaluated. While the main objective of KABLE-II was to evaluate Ka-band for future operational use, it also served as a testbed for new Ka-band technology applications in both the flight systems and the ground systems.

In the course of transition to simultaneous X-/Ka-band operation, the DSN needed the capability to support various combinations of X- and Ka-band uplinks and downlinks. These included Ka-band receive only; X-/Ka-band simultaneous receive, with or without X-band transmit; and full X-band transmit/receive simultaneously with Ka-band receive/transmit. The technology program developed new microwave techniques using frequency-selective surfaces and feed junction diplexers to provide the frequency and power isolation necessary to realize the performance required by a practical device. In late 1996, a demonstration at DSS 13 succeeded in showing that these four different modes of operation could coexist on a single beam waveguide antenna within acceptable performance limits. This work provided a viable solution to the problem of simultaneous X-/Ka-band operation on a single antenna; this solution would be needed by the operational network to support the Cassini radio science experiment (search for gravitational waves) in 2000.

Recognizing the need for a cheaper, smaller, less power-consuming radio-transponder to replace the existing device on future deep space missions, the advanced development program embarked on a joint program with other JPL organizations to develop the Small Deep Space Transponder (SDST). The concept employed Microwave Monolithic Integrated Circuits in the RF circuits and Application Specific Integrated Circuit techniques to perform digital signal-processing functions, with a RISC microprocessor to orchestrate overall transponder operation. The transponder would transmit coherent X-band and Ka-band downlinks and receive an X-band uplink. Besides minimizing production costs, the principal design drivers were reduction in mass, power consumption, and volume. The Small Deep Space Transponder was flown in space for the first time aboard the DS-1 New Millennium spacecraft in July 1998.

With a view to providing a better understanding of the performance of Ka-band links relative to X-band links from the vantage point of a spaceborne radio source, the DSN technology program engaged in the development of a small low-Earth-orbiting spacecraft called SURFSAT-1. Launched in 1995, the experiment provided an end-to-end test of Ka-band signals under all weather conditions and DSS 13 antenna elevation angles as the spacecraft passed over Goldstone. The SURFSAT data was also used for comparison with the KABLE data received from MGS. Later, the SURFSAT X-band and Ka-band downlinks were used to great advantage to test and calibrate the DSN's new 11-meter antennas prior to their support of the VSOP (HALCA) Orbiting VLBI mission in 1996. A selection of technical references related to Ka-band development can be found in section 20 of the appendix at the end of the book.

Other Technologies

While reduction of Network operating costs and the introduction of Ka-band into the Network were important features of the Technology Program in the late 1990s, they were not the only areas of activity. Interagency agreements allowed Wide-Area Differential GPS techniques, originally developed under the technology program for NASA spacecraft orbit determination and DSN Earth platform calibrations, to be made available for applications within the Department of Transportation and Federal Aviation Administration.

In addition to these other technologies, further advances were made in the areas of photonics and optical communications. A selection of technical references related to other technologies can be found in section 21 of the appendix at the end of the book.

Optical Communications Development

Beginning in 1980, the Technology Program supported theoretical analyses that predicted, under certain system and background light conditions typical of deep space applications, the ability to communicate at more than 2.5 bits of information per detected photon at the receiver. Laboratory tests later confirmed these theoretical predictions. However, detection power efficiency was only one of the many factors that needed to be studied to bring optical communications to reality. Others included laser transmitter efficiency, spatial beam acquisition, tracking and pointing, link performance tools, flight terminal systems design, definition of cost-effective ground stations, and mitigation of Earth's atmospheric effects on ground stations.

Several system-level demonstrations were carried out as this work progressed. The first, carried out in December 1992, involved the detection of a ground-based pulsed laser transmission by the *Galileo* spacecraft during its second Earth fly-by. The second demonstration was carried out over the period November 1995 to May 1996 with the Japanese Earth-orbiting satellite ETS VI.

Both experiments yielded important observational data in support of theoretical studies and encouraged the further development of optical communications technology with supportive flight demonstrations. A selection of technical references related to optical communications development can be found in section 22 of the appendix at the end of the book.

DSN Science

Science and technology have always been closely coupled in the DSN. Since the very beginnings of the DSN, its radio telescopes had provided world-class instruments for radio astronomy, planetary radar, and radio science. Many technology program achievements were of direct benefit to these scientific endeavors, and DSN science activities frequently resulted in new techniques that eventually found their way into the operational Network.

In the period reported here, the program supported radio astronomy investigations related to the formation of the stars and to the study of microwave radio emissions from Jupiter, as well as radio science measurements of the electron density in the solar plasma outside the plane of the ecliptic (Ulysses). It also supported a program of tropospheric delay measurements which would be of direct benefit to the Cassini gravitational waves experiment. The Goldstone Solar System Radar (GSSR) continued its highly successful series of Earth Crossing Asteroid (ECA) observations, which began with images of Toutatis (asteroid 4179) in 1992 and continued with Geographos (asteroid 1620) in 1994 and Golevka (asteroid 6489) in 1995. This work was expected to increase in the years ahead as new and improved optical search programs enabled the discovery of more ECAs. A selection of technical references related to DSN science can be found in section 23 of the appendix at the end of the book.