The Evolution of Technology in the Deep Space Network: A History of the Advanced Systems Program

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This article presents a survey of the principal efforts of the DSN Advanced Systems Program and its impact upon the operational Deep Space Network from about 1960 to 1995. The article is structured along two main themes. First is a tour of the fundamental services provided by the Network and the physical elements and technologies that support these services. The second theme is presented as a series of focused case histories of changes inspired by specific missions, such as Galileo, Voyager, or Mariner–Venus–Mercury, or by specific technologies, such as the application of fiber optics. A bibliographic entrée to a substantial body of other reading material also is provided.

I. Introduction

The Deep Space Network (DSN) of 1995 might be described as the evolutionary result of 45 years of deep-space communication and navigation, together with the synergistic activities of radio science and radar and radio astronomy. But the evolution of the DSN did not just *happen*—it was carefully planned and created. The evolution of the DSN has been an ongoing engineering activity, and engineering is a process of problem solving under constraints, one of which is technology. In turn, technology is the knowledge base providing the capability and experience for practical application of various areas of science, when needed.

The best engineering solutions result from optimization under the fewest constraints, and if technology needs are well anticipated (ready when needed), then the most effective engineering solution is possible. Throughout the history of the DSN, it has been the goal and function of DSN advanced technology development (designated the DSN Advanced Systems Program from 1963 through 1994) to supply the technology needs of the DSN when needed, and thus to minimize this constraint on DSN engineering.

Technology often takes considerable time to develop, and when that happens, it is important to have anticipated engineering needs; at times, this anticipation has been by as much as 15 years. Also, on a number of occasions, mission malfunctions or emergencies have resulted in unplanned needs for technology

that has, in fact, been available from the reservoir of advanced technology provided by the DSN Advanced Systems Program. Sometimes, even DSN engineering personnel fail to realize that the organization of JPL permits an overlap of DSN advanced technology activities with subsequent engineering activities. This can result in the flow of advanced technology into DSN engineering in a natural and sometimes almost unnoticed way.

In the following pages, we will explore some of the many contributions of the DSN Advanced Systems Program that were provided to DSN Engineering and Implementation. These contributions are, for the most part, unique capabilities that have met the requirements of flight projects for 45 years. These unique capabilities include not only the world's best deep-space communications system, but also outstanding competency in the fields of radio metric measurement, radar and radio astronomy, and radio science.

II. A Functional View of the Deep Space Network

Viewed from outer space, the DSN looks like a cluster of antennas; one large quasi-parabolic dish (70 m) and several smaller ones (34 m), each of which could be the source of radio signals carrying commands and data to guide the actions of an exploring spacecraft. As the Earth turns, the cluster begins to disappear over one edge, to be replaced by another at the opposite edge, which continues as the source of radio signals to the spacecraft. (Three such clusters of antennas currently exist, and they are distributed about the surface of the Earth to provide a nearly continuous view to observers at the Mission Control Center.)

Not so obvious, but equally true, is the fact that these same antennas are listening to any signal sent Earthward by our spacecraft. The very tiny amount of radio energy from the spacecraft is collected and focused by the precision quasi-parabolic dish antennas into microwave equipment that amplifies it in special low-noise amplifiers that operate at temperatures near absolute zero. From these amplifiers, the signal passes on to other equipment that eventually transforms it into a replica of the data that originated on the spacecraft.

Looking outward from the Mission Control Center, which operates the distant spacecraft, the DSN appears to be a data communication service that accepts a stream of data to be transported to our exploring spacecraft and delivers another stream of data that originated on the spacecraft. We expect that both streams will be delivered with near-absolute certainty and near-perfect precision. We know that it is possible to be in constant contact with the spacecraft; however, when we consider the Earth's rotation, we know that the actual contact with the spacecraft must be commutating among several sites on Earth, but this commutation is (in concept at least) transparent to earthbound viewers. In addition to a data communication service, the DSN also provides a location service referred to as radio metrics, which enables us to understand from Earth-based measurements exactly where that spacecraft is and where it is going.

The details of how the DSN's services are provided depend upon the precision instruments and the algorithms that comprise the operational DSN. In addition to the very visible large antennas, the following types of equipment are part of the DSN: (1) high-power transmitters and their support equipment; (2) low-noise amplifiers, phase-coherent receivers, and synchronous detectors that transform the radio signal into a stream of numbers (symbols); (3) encoders for the forward signal path and decoders in the return path that operate on the detected symbol stream to help ensure the fidelity of the data communicated via the DSN; and (4) Doppler extractors and range-finding devices that provide the data for the location service. Most of these devices, the algorithms by which they operate, and our understanding of how well they operate, derive from products of the DSN's Advanced Systems Program.

A. The Antennas of the DSN

Figure 1 depicts the DSN antenna complex in Australia. The largest antennas in the photo are quasi-parabolic reflector antennas, one with a diameter of 70 m. Smaller antennas used for deep-space mission

Fig. 1. The DSN antenna complex in Australia.

support are 34 m in diameter, while 26- or 9-m antennas provide support to 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 dish. The secondary reflector serves to relocate the focal point to near the surface of the main dish and establishes a more convenient location for the low-noise amplifiers, receivers, and powerful transmitters.

The earliest antennas in the DSN (Fig. 2) were of commercial design and were parabolic in shape. Then, as now, the exact efficiency of the antenna represented a compromise between gathering as much as possible of the radio signal from the distant source and picking up little spill-over noise from the surrounding Earth. By the 1970s, researchers of the DSN Advanced Systems Program recognized that the overall antenna performance could be improved substantially by what was termed a "dual-shape" design in which the shape of the secondary reflector could be modified to more uniformly illuminate the main reflector, while the main reflector was slightly reshaped into a quasi-parabolic form. It was not until the 34-m high-efficiency (HEF) antennas (Fig. 3) were being built in the early 1980s that the new design could be put into practice.

These antennas were optimized for performance at X-band (8.4 GHz) and were needed by the DSN for support of the Voyager spacecraft in their tours of the outer planets. As the Voyager 2 spacecraft headed outward toward Neptune, it was recognized that 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 and expand their diameter to 70 m. It was also apparent that the upgraded large antennas would benefit the planned Galileo and Magellan Missions as well. The 70-m enhancement project (Fig. 4) was completed in time for support of Voyager 2 at Neptune and represented a more than 60-percent increase in the effective collecting area of these antennas. Fully half of this is attributable to the dual-shape design, a product of the DSN Advanced Systems Program.

Fig. 2. An early parabolic design of a DSN antenna.

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

Fig. 4. The 70-m antenna with "dual-shape" reflector design.

At the time of this writing, construction projects are under way that will build new 34-m antennas for the operational DSN and will eventually eliminate the oldest ones. These new antennas incorporate the dual-shape design as well as a beam waveguide (BWG), which uses a series of additional secondary reflectors to relocate the focal point into a stationary room below the dish. The BWG design feature had been used for years for communications satellite terminals where ease of service outweighed any added noise. Concern for noise from the additional mirrors kept such antennas out of contention for DSN usage. In 1985, a team of JPL researchers from the DSN Advanced Systems Program worked in collaboration with Japan's Institute for Space and Astronautic Sciences (ISAS) to install one of JPL's experimental low-noise amplifiers into the ISAS 64-m BWG antenna in Usuda, Japan. The configuration was demonstrated with S-band (2-GHz) signals from the International Cometary Explorer (ICE) en route to the comet Giacobini–Zinner, achieving surprisingly good performance with no detectable noise penalty.

Moving from this demonstration to application of the BWG technology in the DSN took the building of a prototype antenna, which was outfitted and evaluated by the DSN Advanced Systems Program. This antenna was in fact a replacement for the aging 26-m antenna that had been for many years the field laboratory for technology development. The antenna design was optimized using microwave optics analysis software, itself an evolving product of the Advanced Systems Program. The completed antenna has been demonstrated to operate effectively at S-, X-, and Ka-bands (2, 8, and 32 GHz, respectively).

Figure 5 shows the completed BWG antenna, and Fig. 6 shows the interior of the equipment room below. Rotation of the single mirror at the center of this room can select among the various frequencies and modes of operation. 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 now in use and under construction, making their performance exceed that of the prototype, especially at the lower frequencies.

Fig. 5. The 34-m beam-waveguide (BWG) antenna at Goldstone (Technology Development Site).

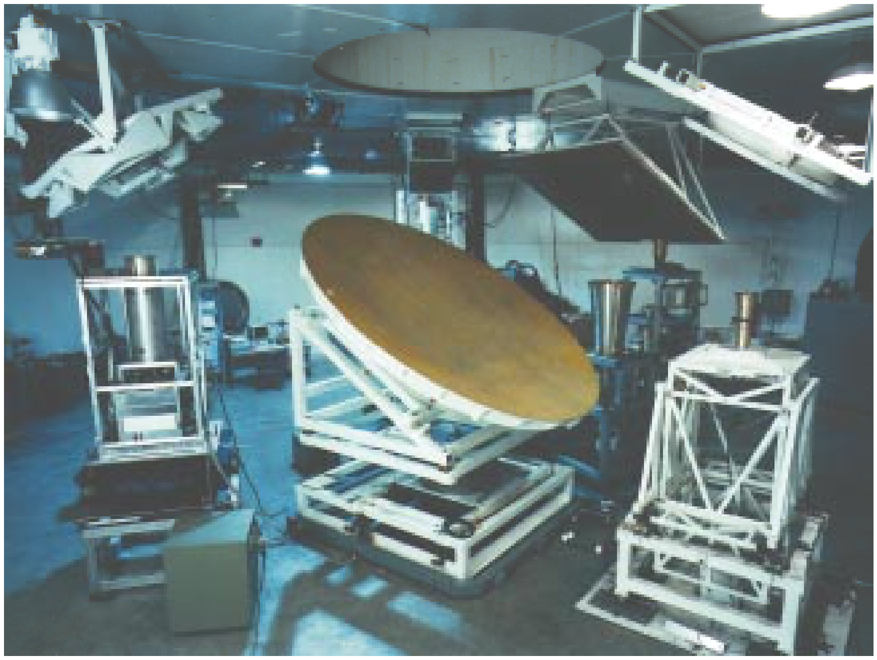

Fig. 6. The stationary equipment room below the BWG antenna.

B. Forward Command/Data Link

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 safely and successfully to distant spacecraft 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 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 can be sent from the 70-m antenna during attempts to regain contact with a spacecraft in such an emergency situation.

Although development of the current generation of transmitter systems has been carried out in a purely implementational engineering mode, initial design and evaluation of these high-power transmitters and their associated instrumentation were carried out under the Advanced Systems Program. Much of the needed field testing was done via planetary radar, which provided a realistic environment without risking unexpected side effects on a spacecraft.

Pointing of the narrow forward link signal to the spacecraft is critical, especially when making initial contact without having a received signal for reference, as is typical for emergency situations. The beamwidth of the signal from the 70-m antenna at S-band is about 0.030 deg, while that of the 34-m antenna at X-band is about 0.017 deg. 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 of causing that spacecraft to take undesirable actions, including some that could result in an emergency situation for that 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 discards those that cannot be trusted.

C. Return Data Link

Throughout the DSN, the same antennas are used 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 DSN antenna. Isolating the return signal path from interference by the much stronger forward signal has posed a significant technical challenge. These two signals differ somewhat in frequency, so at least a part of this isolation is accomplished via dichroic or frequency-selective reflectors. These reflectors (Fig. 7) consist of periodic arrays of metallic/dielectric elements tuned for the specific frequencies that are to be either reflected or passed through.

One of the strongest design constraints is that noise added to the received signal must be minimized. Prototypes of almost all of this type of reflector currently in use in the DSN, as well as microwave analytical design tools that can be used to affix design details for almost any conceivable dichroic reflector applicable to the frequency bands of the DSN, were developed under the DSN Advanced Systems Program.

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

The quietest of the operational devices are known as traveling-wave masers (TWMs), which amplify signals that are propagating 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 K. Invented by University of Michigan researchers, early development of practical amplifiers for the DSN 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 (Fig. 8), which operate at a physical temperature of 1.2 K, were developed by the DSN Advanced Systems Program and demonstrated at the Technology Development Field Test Site, Deep Space Station 13 (DSS 13).

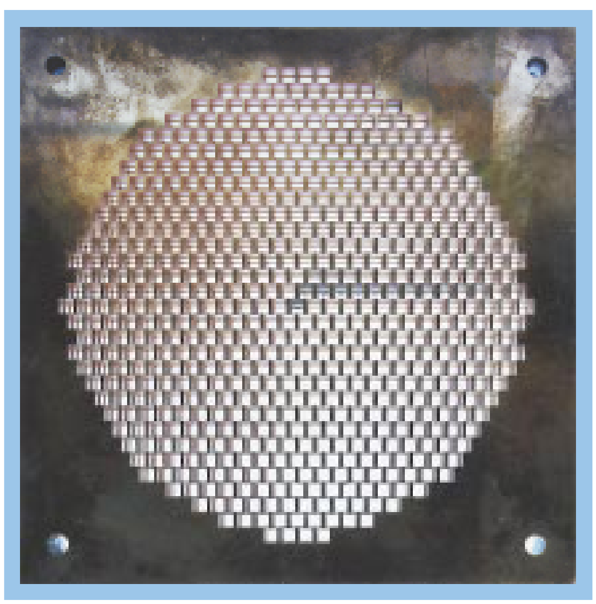

Fig. 7. The dichroic (frequency-selective) reflector developed under the Advanced Systems Program.

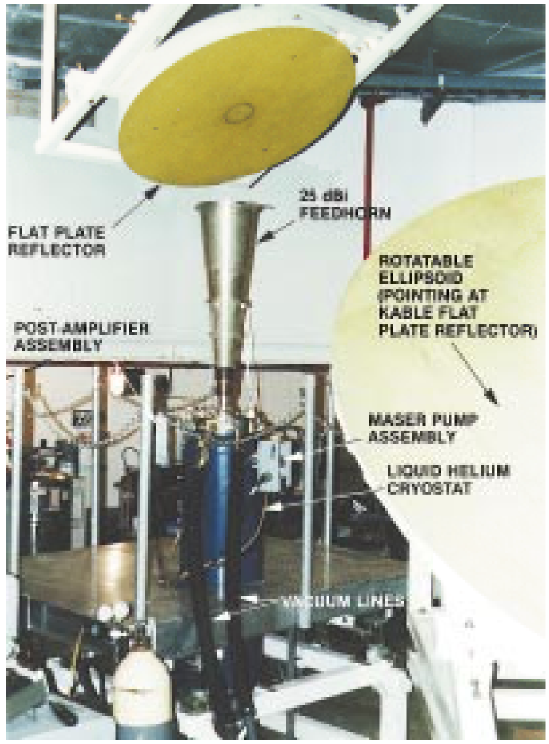

Fig. 8. The ultralow-noise amplifier (ULNA) at DSS 13.

Some of the low-noise amplifiers in the DSN today are not TWMs, but are a special kind of transistor amplifier (Fig. 9) using high-electron mobility transistors (HEMTs) in amplifiers cooled to a physical temperature of about 15 K. Initial development of such amplifiers occurred at the University of California at Berkeley, leading to their adoption by the radio astronomy community. 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 K 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 m in diameter, arranged in a triaxial 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 the cooled HEMT amplifiers installed for the 2- and 8-GHz bands.

2. Phase-Lock Tracking. Once through the first stages of processing in the low-noise amplifiers, there are still many transformations needed to convert the radio signal from a spacecraft into a replica

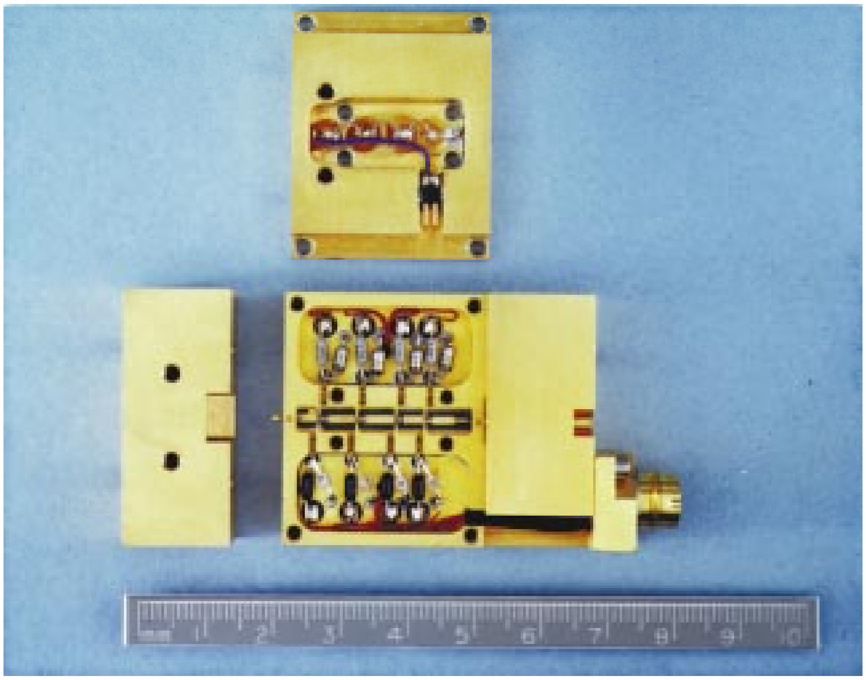

Fig. 9. The high-electron mobility transistor (HEMT) low-noise amplifier.

of the data stream originating on that spacecraft. Some of these transformations are by nature analog and linear, and others digital with discrete quantization. All must be performed with virtually no loss in fidelity for the resultant data stream.

The signal typically consists of a narrowband "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 exist, but must be created, typically via an adaptive narrowband filter known as a phase-locked loop. The recreated carrier reference thus is 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 predominantly the Doppler effect of the relative motion between the distant spacecraft and the DSN antenna on the surface of a spinning Earth; they interfere with the return data link process, but 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.

3. 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 associated symbol and as little as possible of the adjacent ones. In usual cases, a subcarrier, or secondary carrier, is employed to shape the spectrum of the spacecraft signal, and it

will be phase-tracked and removed at this stage. There are several different generations of equipment in the current DSN 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 derived from the Multimission Telemetry Demonstration, done in the late 1960s by a partnership of 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 subsequently were employed for data detection in the second generation of the Demodulator–Synchronizer Assembly.

4. A Digital Receiver. More recently, the ongoing evolution of the capabilities of digital devices has made possible the migration of digital techniques into the filtering, detection, and phase-lock processes of the receiving systems. Because of this, the Advanced Receiver (ARX) (Fig. 10) developed under the Advanced Systems Program has a demonstrated precision of performance that is almost inconceivable for conventional analog signal-handling methods. A copy of the ARX was constructed and deployed to the DSN Australian site for ad hoc support of the Pioneer 10 spacecraft on its way out of the solar system, thus delaying the date at which the signal became too weak to be received reliably.

Fig. 10. The Advanced Receiver (ARX) used in support of Pioneer 10.

Current implementation efforts have been concluded on a new operational receiver (the Block V) for the DSN, which builds upon the design techniques of the ARX and incorporates all of the functions of the current receivers and the demodulator–synchronizer equipment. By 1998, all of the older generations of this equipment should be out of the DSN, replaced by the new digital Block V Receiver, which offers improved technical signal-handling performance, as well as improved maintainability.

5. Codes and Decoding. The sequence of numbers from the demodulator–synchronizer equipment is still not the replica of the mission data stream on the spacecraft because, in most circumstances, special codes have been applied to that data stream to improve the reliability of communications. These codes transform the data before they leave the spacecraft, adding carefully designed redundancy and complexity, and the resultant coded stream is reverse transformed by decoding equipment at the DSN site in order to recover the original data stream. The best codes to be used for reliable data transfer have been identified by research performed under the Advanced Systems Program; that work is still making progress. The present accepted standard, flown on Voyager and Galileo, consists of a short convolutional code that is 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 have been fabricated and demonstrated at JPL, also with the support of the Advanced Systems Program.

Evolution of the use of codes and decoding equipment has been 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 needed for Galileo because of its antenna problem, the more complex decoder will be implemented around the DSN for support of 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 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. One of these is the Voyager $k = 7$ code, shown both alone and in combination with the Reed–Solomon code. Second is the $k = 15$ code, which was to be demonstrated with Galileo's high-rate channel, shown alone and in combination with the Reed–Solomon code, either as constrained by Galileo's data system ($I = 2$) or in ideal combination. Third, and finally, is the $k = 14$ code devised by the Advanced Systems Program researchers for the Galileo low-rate mission, shown both alone and in combination with the selected unbalanced 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 decoder, clearly provides increased reliability of correct communication. Research on new and improved codes continues to provide amazing improvements in performance, as can be seen later in our case study on the Galileo Mission to Jupiter and in recent articles in *The TDA Progress Report.*

Other types of codes have been used in the past and continue to be active on some of the older spacecraft. The DSN Advanced Systems Program has played a part in each. The imaging data of Mariner'69 were encoded using short block codes with a self-synchronizing feature devised by the Advanced Systems Program researchers. A decoder for this code was constructed and used experimentally to provide a substantial increase in the data volume returned from the mission. At about the same time, Pioneer 9 was launched with a very complex code of length $k = 25$, which could be decoded by an iterative approximation technique known as "sequential decoding." The code was chosen to satisfy the needs of Pioneer's experimenters, who would accept intermittent gaps in their data caused by decoding failure in exchange for knowledge that successfully decoded data would be virtually error-free.

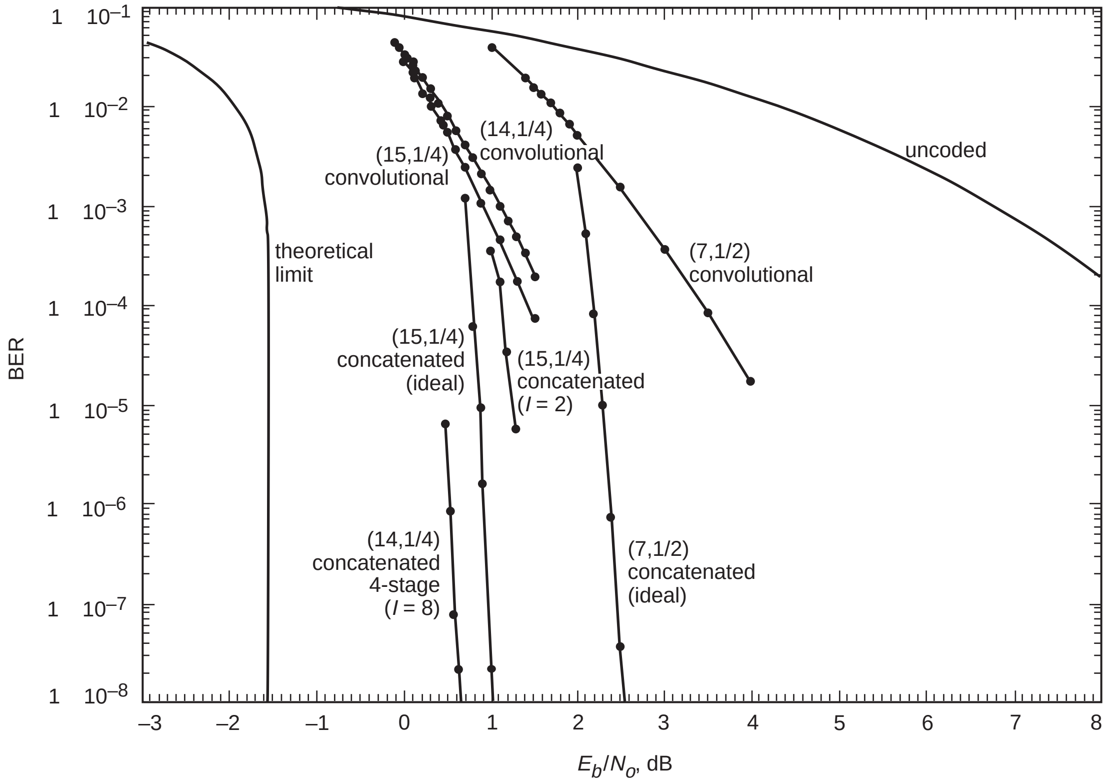

Fig. 11. The probability of erroneous data bits.

Decoding was planned to be performed by mission operations at Ames Research Center using a recorded symbol stream delivered from the DSN. In conjunction with Pioneer, 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 DSN 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 are still supported by the DSN in a computer-based decoder.

6. Data Compression—A Mathemagical Twin of Coding. Source encoding and data compression are not typically considered a part of the DSN's downlink functions, but the mathemagics 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 often are highly redundant and can be compressed by factors of at least two, and often four or more, without loss in quality. For Voyager, the combined effect of a very simplified image compression process, which was constrained to fit into available onboard memory, and the corresponding changes to the channel coding was about a factor-of-two increase in the number of images returned from Uranus and Neptune.

As with many other items of technology, properly crediting this end result is difficult. There is an active international community with interests in data compression for many purposes. Researchers under the DSN Advanced Systems Program have contributed significantly to the current state of the art. However, it remained for others to actually establish data compression on Voyager in flight and on subsequent missions. By the time of the design of the Galileo data system, data compression had become a regular option for about a factor of two in the imaging data system. The failure of Galileo's high-gain antenna

(HGA) prompted an intense effort to find compression schemes that would recover some of the Galileo imaging data that otherwise could not be returned.

D. Arraying of Antennas

Arraying of DSN antennas is a network capability that has been employed whenever the required receiving sensitivity significantly exceeded that which could be established on a single aperture with the best efficiency and lowest practical system temperature. The overall architecture of the future DSN, as currently understood, depends upon the ability for an array of several 34-m antennas to mimic the functionality of a single 70-m antenna whenever needed.

The Galileo Mission to Jupiter, with its broken large antenna, is the current motivating factor for arraying; the Voyager Mission to the outer planets spurred the development of the current arraying tools, as well as many other changes to the network through the 1980s. The current arraying or signal-combining subsystem, the Baseband Assembly (BBA), was developed incorporating digital signal-processing techniques first employed in the experimental ranging machine (designated the Mu-II Ranging Machine), built by the Advanced Systems Program.

Other network changes included the construction of the 34-m HEF antennas, the expansion of the 34-m standard (STD) antennas from their prior 26-m size, and the rebuilding of the 64-m antennas to become the dual-shape, high-efficiency 70-m antennas. For these antennas, the high-efficiency illumination patterns are a product of the radio frequency "optics" analysis software tool kit developed with support from the Advanced Systems Program.

Several radio astronomy observatories outside the DSN also collaborated in the arraying for the Voyager encounters. Signals received at the Parkes Radio Telescope in Australia (Fig. 12) were arrayed into the Canberra DSN site, and signals at the NRAO VLA (Fig. 13) in New Mexico were arrayed into the DSN site at Goldstone, California. The low-noise receiving amplifiers for the VLA were developed in collaboration with the DSN technology development efforts.

Arraying for Voyager could not have been approached with confidence and commitment were it not for significant prior efforts supported by the DSN Advanced Systems Program. In [1], R. Stevens states that, in 1970, early analyses led to experimentation by the DSN Spanish Complex personnel, who used the two 26-m antennas receiving signals from Pioneer 8. Simple baseband and bit-stream combining were employed. No special time alignment of the signals was required due to the low data rate and short distance between antennas. A similar simplistic approach was applied operationally in combining signals within each complex in support of the ICE spacecraft during the Giacobini–Zinner Comet encounter in 1985. Another significant effort supported by the Advanced Systems Program was the combining of high data rate signals where time alignment of the signals from the several antennas was essential for performance. The site was Goldstone, and the occasion was the 1974 second Mercury encounter of the Mariner–Venus–Mercury (MVM) spacecraft. The successful demonstration showed an appropriate 0.7-dB improvement in sensitivity due to arraying of the two 26-m antennas at DSS 12 and DSS 13 with the 64-m antenna at DSS 14. This improvement in sensitivity was consistent with predictions, but also demonstrated a unit-to-unit variation in performance of the then-current analog Subcarrier Demodulator Assembly (SDA).

The function of the SDA has since been incorporated into the current generation of arraying equipment for improved and more consistent performance. The next follow-on arraying activity was the development of a prototype operational baseband Real-Time Combiner (RTC), which would be demonstrated with the support of Voyager at Jupiter and Pioneer 11 at Saturn. Lessons from these early demonstrations were incorporated into the operational RTC configuration that was committed for support of Voyager at Saturn with a combined 64-/34-m array.

Fig. 12. The Parkes Radio Telescope, Australia.

Fig. 13. The National Radio Astronomy Observatory (NRAO) Very Large Array (VLA), New Mexico.

The flight time for Voyager from Saturn to Uranus (1986) was long enough to permit development and implementation of improved arraying in the form of the BBA, which combined the functions of the RTC and the demodulation/detection equipment into one digital processor. Experience gained via the Advanced Systems Program in both arraying and digital detection processes helped establish the design of the BBA with a tolerance of about 0.1 dB.

Several additional antennas were constructed during this period, and the BBA was designed to handle up to four independent baseband signal inputs. In addition, a special variant of the BBA provided for the combining of signals from the Parkes Radio Telescope into the array at the DSN Canberra Complex, 200-km distant. A similar device was used to combine the signals from the NRAO VLA in New Mexico into the Goldstone array for the 1989 Neptune encounter.

Meanwhile, the Advanced Systems Program continued to explore the arraying process to develop methods that might provide greater operational simplicity, improved performance, or both. Combining at the symbol-stream stage of processing is feasible for signals like those from Voyager and requires a lower information-transfer rate between the antenna sites; it also simplifies the time-alignment process for signals from widely separated antennas. Symbol-stream combining was demonstrated for intercontinental arrays first with the Giacobini–Zinner comet encounter in 1985 and later with Voyager. It was considered for a time to be a backup to the development of the remote baseband arraying with the radio observatories, but was released when that development was demonstrated successfully.

Arraying has now been an operational part of the DSN for the better part of a decade, and most of the effort recently applied to it has been via the Implementation or Operations Programs. Modest efforts via the Advanced Systems Program continue to explore the boundaries of performance for various alternative arraying architectures, including forms of carrier combining or full-spectrum as well as baseband and (complex) symbol-stream techniques.

E. Radio Metrics—Tools and Techniques

In addition to being able to exchange forward and return link data with an exploring spacecraft, it is equally important that we understand where the spacecraft is and where it is going. The radio signal exchanged with the spacecraft conveys some of the necessary information, which can be extracted and refined by appropriate processing and analysis, about the position and motion of that spacecraft. Since its inception, the DSN Advanced Systems Program has worked to develop effective instrumentation, observing strategies, and analysis techniques that enable the DSN to provide an increasingly capable radio location service to distant spacecraft.

1. Conventional Doppler and Range. 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 can be disentangled through multiple measurements and suitable analysis. The precision with which such measurements can be obtained is limited by the precision with which one can attach a time-tag marker to the radio signals.

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, i.e., 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 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 the Earth. As the 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 and its corresponding negative value as it approaches 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 to date 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, which is 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.

2. Timing Standards. Whether for Doppler or range, the measurement unit for the radio metric observations derives 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 has resulted in the development of a new linear ion trap (LIT) standard (Fig. 14) that offers 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 currently is under way to implement the LIT standard in the field in the DSN, while research efforts continue for improvements that can be transferred to field operation in the future.

3. Earth Rotation and Propagation Media. The transformation from a stream of Doppler (and range) data into the apparent position of a spacecraft in flight defines that position relative to the position and attitude of the rotating Earth. The 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 the Earth's attitude is necessary so that the spacecraft's position in inertial space can be determined, which is a necessary factor in navigating it 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 Sections II.E.5 and II.E.6, "VLBI and Radio Astronomy" and "Global Positioning System."

Material in the signal path between the Earth and the spacecraft affects the accuracy with which the Doppler and range can be determined. The charged ions in the tenuous plasma spreading out from the Sun, known as the solar wind, will bend and delay the radio signal. Likewise, the charged ions in the Earth's own ionosphere and the water vapor and other gasses of the denser lower atmosphere will bend and delay the radio signal. All of these factors are highly variable because of other factors, such as

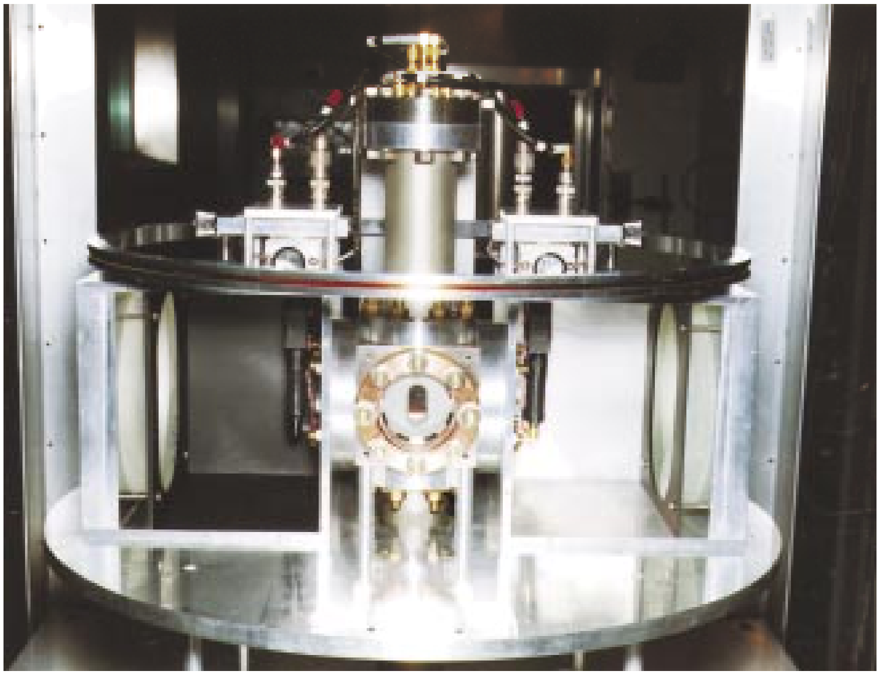

Fig. 14. The new linear ion trap (LIT) standard.

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.

4. Radio Science. Radio science is the term used to describe the scientific information obtained from the intervening pathway between the 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 the Earth and 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 can be similarly of scientific interest to other investigators.

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 us 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 Advanced Systems Program are key factors in the ability to extract this information with a scientifically interesting accuracy. And, on the occasion of some unique events, the engineering models developed by the Advanced Systems Program will be placed into the field for ad hoc support of the metric data gathering, perhaps in parallel with operational instrumentation.

The effects of gravity also can 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.

5. 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 the 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 the 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 also can be used in conjunction with conventional radio metric data types to provide calibration for the positional attitude of the Earth. Such observations can be made without interfering with spacecraft communication, except for the time utilization of the DSN antennas. In addition to determining the attitude of the Earth, 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) were 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 was funded by the National Science Foundation for this activity, and both Caltech and the DSN shared in the efforts for the design, while obtaining products that were substantially better than any that they could have 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 have served as pre-prototype models for equipment for the DSN. Demonstration of the technical feasibility of very wideband 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 Search for Extraterrestrial Intelligence (SETI) 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.

6. Global Positioning System. The Global Positioning System (GPS) is a constellation of Earth-orbiting satellites designed (initially) to provide for military navigation on the Earth's surface. As has been shown by research under the Advanced Systems Program, these satellites 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. Research by the Advanced Systems Program is continuing on this process.

Additionally, since the GPS satellites are in free orbit about the Earth, their positions are defined relative to the center of mass of the Earth and not its surface. They thus provide another method to observe the uneven rotation of the Earth. This method can supplement or in part replace the VLBI technique currently used. Position of a spacecraft in Earth orbit also can be determined relative to the GPS satellites as long as that spacecraft carries a receiver for the GPS signals. The potential of this technique was initially demonstrated by the Advanced Systems Program. GPS subsequently was used by the TOPEX/POSEIDON Project for precise orbit determination and a consequent enhancement of its scientific return.

F. The Goldstone Solar System Radar

The Goldstone Solar System Radar has become a NASA-sponsored facility science instrument for performing scientific observations of nearby asteroids, the surfaces of Venus or Mars, the satellites of Jupiter, and other objects in the solar system. The current instrument is sustained by the resources of the DSN Implementation and Operations Program, but its form 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 would be needed by the Network.

Scientific results abounded as well, but 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 be successful only during the few days when the 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, and 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 to both transmit and 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 the first 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 was scheduled to be on MVM 73. 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.

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 appetite of the radar system for increasingly lower noise levels provided a motivator for the Advanced Systems Program to develop the extremely low-noise TWM amplifiers that would be transferred for implementation throughout the DSN.

Digital systems technology was evolving rapidly 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 knowledge gained 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, e.g., Fig. 15, were both scientific in nature and essential for providing information for the planning and execution of NASA's missions. One notable "first" is the direct measurement of the astronomical unit (AU), which is the mean orbital radius of the Earth and which sets the scale size for the distances in the solar system. The measurement was made in support of preparations for Mariner 2 to Venus and provided a correction of 66,000 km from conventional belief at that time. It also allowed corrections that brought the mission into the desired trajectory for its close flyby of the planet. The radar system was also used in qualifying potential Mars landing sites for the Viking landers and continues to provide information about the position and motion of the planets that is used to update the predicted orbits for the planets of the solar system.

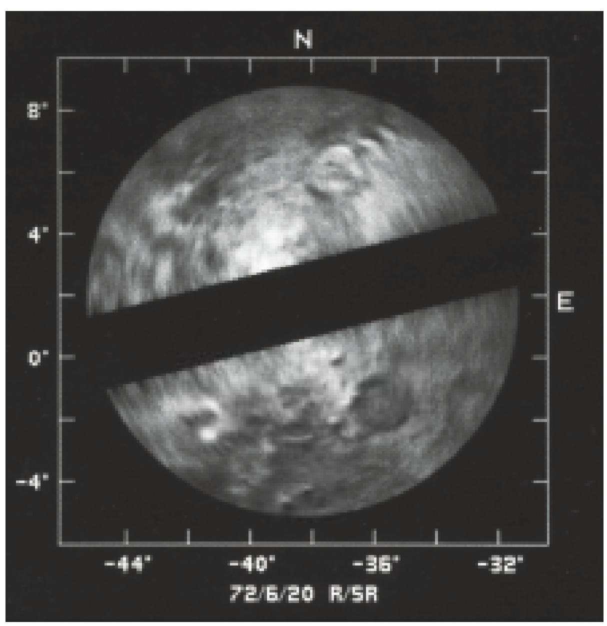

Fig. 15. The first high-resolution radar image of Venus.

G. Concluding Observations

Now that the discussion of the key features of the form and function of the DSN is concluded, it is well to note that the Network is also a business that exists, quite simply, to provide services to its customers. Customers of the DSN range from the currently operating and in-flight missions to those that are in their early planning stages. DSN customers also include both the flight missions (e.g., Voyager) and ground-based observations (e.g., those of the Goldstone Solar System Radar).

Interaction between the DSN and its customers begins early, as soon as mission concepts are defined and the potential support is identified. The ensemble of potential needs of all of these becomes the inspiration for many of the research and development efforts of the dedicated DSN Advanced Systems Program. As described earlier, products of the Advanced Systems Program range from theoretical concepts to physical models, and include demonstrations of devices and subsystems that could in the future become a part of the operating DSN and its technology base, which is applied as needed to benefit the DSN's customers.

Under appropriate circumstances, the engineering models produced by the Advanced Systems Program may be used to directly support a customer on a "best-effort" basis, but more often, they become the starting point for the design of equipment to be implemented in the Network. The implementors use the technological products of the Advanced Systems Program and other sources, as appropriate, to design subsystems in a form suitable for installation in the Network for long-term effective support of the DSN's customers. The implementors typically work in close coordination with staff participating in the Advanced Systems Program; their products are the hardware and software of the operational DSN.

Although the configuration and capabilities of the operational DSN are kept relatively stable, they are not static. Both the Network and the planning for it evolve in response to the needs of its customers, whenever those needs arise. Customer requirements can be stated formally as the outcome of a long-recognized planning process or appear in the form of a problem to be solved or an opportunity to enhance a customer's data return. Ready examples can be found in the support to Voyager and elsewhere. Early failures in the receivers on Voyager 2 necessitated precompensating the forward-link Doppler, which was accomplished by applying the programmable local oscillators developed and demonstrated under the Advanced Systems Program via Goldstone radar. And the extensive use of arraying, which was first demonstrated by the Advanced Systems Program in 1973, was initiated operationally with the Voyager's Saturn passage, and subsequently became the key to significant enhancement of the mission return from Uranus and Neptune.

In summary, the needs of the DSN's customers have been the driving force for all activities, including not only the active operational support, but also the early planning in concert with the mission planners and supporting research and technology development efforts. A strong technology development program motivated by the needs of the Network's customers has been an essential element in providing effective support to the customer base. An effective and flexible, yet needs-driven, implementation program also is essential to providing the quality of support that the DSN's customers can and do expect.

III. Case Studies of Technology in the DSN

A. Advanced Systems Program and the Galileo Mission to Jupiter

A NASA mission to Jupiter first was discussed by the scientific community in the middle 1960s, and in early 1976 a scientific working group headed by James Van Allen formulated the Jupiter Orbiter Probe (JOP) Mission. The official start of the project was in October 1977, with the name being changed to Galileo in February 1978.

The Probe was designed to carry seven instruments whose measurements during descent through the upper reaches of the Jovian atmosphere are transmitted by radio to the Orbiter, with the microwave signal

itself providing additional science information. The Orbiter was designed to carry some 11 instruments whose measurements, along with those received from the Probe, are transmitted by radio to the DSN on Earth. The Orbiter–Earth two-way microwave signals also provide additional science information. It is evident that the entire success of the mission depends on the radio signals connecting the Orbiter to Earth and Earth to the Orbiter.

After the start of the Galileo Project, there followed what has been described as a twisted tale of politics, technology, and science. Launch was to be in January 1982 with arrival at Jupiter in 1985. The Space Transportation System (STS), called the space shuttle, had been approved for development in 1972, and it was chosen as the (only) launch platform for Galileo. Galileo thus became the first deep-space mission to use the shuttle. The space shuttle fell behind schedule with many problems. The choice of the Galileo upper stage flip-flopped several times between the Inertial (Interim) Upper Stage (IUS) and the more powerful Centaur. The launch date slipped from 1982 to 1984 to 1985 and finally firmed on May 20, 1986, with the use of the Centaur G upper stage providing a flight time to Jupiter of about two and one-half years. In December 1985, damaged memory chips were discovered in the finished spacecraft, and a maximum effort had the spacecraft ready again in early 1986, with delivery to the launch site shortly thereafter.

On January 28, 1986, the Challenger disaster occurred. The space shuttle program was suspended, the Galileo May 20, 1986, launch date was cancelled, and Galileo was trapped in the delay of the shuttle reevaluation process. Also, as a fallout of the Challenger disaster, it was determined that a Centaur upper stage would not be used in future shuttle operations. The Galileo upper stage once more became the less powerful IUS. This resulted in an increase of Galileo flight time to Jupiter from two and one-half years to six years, requiring three gravity assists (one at Venus and two at Earth) with a thermally undesirable close approach to the Sun. The launch date again slipped more than three years to October 18, 1989, with arrival at Jupiter in December 1995, some 18 years after the beginning of the project. As one of the Project leaders has said, "One of the more unique aspects of Galileo has been its very rocky history." James Van Allen has referred to the Galileo Project as "the perils of Pauline."

After the October 1989 launch, Galileo's early cruise phase was nominal, with data retrieved over the shorter distances via S-band signals from the low-gain spacecraft antennas. The high-gain "umbrella" antenna with X-band capability remained furled for about the first year and one-half of cruise while the spacecraft was subject to the Venus and first Earth gravity-assist encounters involving the close solar approach.

On April 11, 1991, the Galileo Mission suffered a grave mishap. The command was sent for the spacecraft high-gain antenna to unfurl. The antenna unfurled part way and the mechanism jammed, leaving the antenna in a useless condition. At first there were expectations that the mechanical problem could be solved, but following attempts extending over more than a year to overcome the problem, it became evident that the high-gain antenna and X-band downlink would be unavailable. Without further remedies, the planned downlink data rate from Jupiter of over 100,000 bits per second (b/s) would be reduced to about 10 b/s using a spacecraft low-gain antenna at S-band. Such a four-orders-of-magnitude decrease in data return would be disastrous for the scientific goals of the mission.

Not long after the initial failure of the high-gain antenna, the DSN Advanced Systems Program, against the possibility that the problem could not be solved, reviewed the reservoir of its advanced technologies to see what might be applied to materially increase the 10 b/s provided by the spacecraft S-band low-gain antenna. This reservoir of advanced technologies included not only devices, but also the outstanding people who had developed the technology over an extended period. Four of the advanced technology areas had evident promise, as follows:

(1) Increase the S-band signal-to-noise ratio of the DSN S-band antennas; that is, increase A_e/T_{op}, where A_e is the effective area of the antenna(s) and T_{op} is the operating noise temperature of the antenna/receiver system. A_e can be increased by antenna arraying, and T_{op} can be decreased with ultralow noise amplifiers and feeds.

(2) Improve the efficiency of the modulation of the radio signal, such as with a suppressed carrier. The new Block V Receiver (BVR) has fully suppressed carrier capability.

(3) Use improved channel codes so that the desired bit-error probability requires less energy per bit; that is, reduce E_b/N_o. New high-performance concatenated codes and hardware have been designed and tested.

(4) Aggressively apply data compression techniques to the various science, engineering, and optical navigation data from the spacecraft to Earth to provide an increase in the effective data rate. This requires reduced bit-error probabilities for the compressed data, which also can be provided by the improved codes of (3).

These considerations were described in a report prepared by Telecommunications and Data Acquisition (TDA) Technology Development.[1] It was estimated that the combination of (1), (2), and (3) above would increase the 10-b/s data rate by an order of magnitude, and the application of (4) would provide at least another order-of-magnitude increase. The resulting equivalent data rate of at least 1000 b/s coupled with careful editing and choice of science and other data could provide a viable mission fulfilling much of the original Galileo science objectives.

However, it is one thing to discuss technology capabilities and quite another to move the technology into a constrained engineering application in a relatively short time. The improvements of (1) and (2) would involve mainly DSN systems with little interaction with the spacecraft. However, the improvements of (3) and (4) would strongly interact with the spacecraft, requiring reprogramming and reallocating of spacecraft computer resources within the constraints of spacecraft operability and safety. Also, the compression of science data would extensively involve science team members in evaluating and choosing data compression algorithms. The November 5, 1991, early report was conducted primarily by ground systems people with small participation from Galileo engineers and science team members, who were busy with the high-gain antenna problem, the Gaspra encounter, etc.

With the positive results of the TDA Technology Development early report and the probability of repairing the high-gain antenna fading, a major Galileo S-band Mission study was jointly chartered by TDA and the Flight Projects Office (FPO), with the report issued on March 2, 1992.[2] The study was divided into four subtasks: science/mission design; telecommunication systems; ground systems; and spacecraft systems. The basic conclusion of this more detailed study was that by using the technology from the Advanced Systems Program a viable Galileo S-band Mission would be feasible. A design was provided that would meet a somewhat reduced, but very palatable, set of science objectives.

On January 7, 1993, the Galileo S-band Mission was formally approved and funded. Some details of the technologies used in this rescue follow.

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[1] L. J. Deutsch et al., *Galileo Options Study*, internal document, Jet Propulsion Laboratory, Pasadena, California, November 5, 1991.

[2] L. J. Deutsch et al.,*Galileo S-Band Mission Study*, internal document, Jet Propulsion Laboratory, Pasadena, California, March 2, 1992.

(1) Antenna Arraying and Noise Temperature Reduction. The antenna-arraying capability developed by the Advanced Systems Program was made available for up to six antennas—the 70-m and three 34-m antennas at Canberra, the 64-m antenna at Parkes, and the 70-m antenna at Goldstone. This increases the effective area, A_E, for Galileo signal reception to the sum of the effective areas of the antennas, which can exceed that of three 70-m antennas.

    The antenna that could make the greatest contribution from reduction in operating noise temperature was the 70-m antenna at Canberra. Its southern hemisphere location gives it more time at higher elevation (less atmosphere noise contribution) when tracking Galileo, and none of the other antennas has a higher A_e. When arraying antennas, the contribution to the overall array signal-to-noise ratio is greatest by the antenna with the greatest A_e/T_{op}. Accordingly, the Canberra 70-m antenna was equipped with the receive-only "ultracone" feed and low-noise amplifier that previously had been developed by the Advanced Systems Program. It provides a receive-only very low T_{op} of 11.8 K, compared to a receive-only T_{op} of 15.6 K provided by the regular operational system.

(2) Improved Modulation Efficiency. Once the Block V Receiver (BVR) was available with its capability of tracking and processing fully suppressed carrier signals, the increase in modulation efficiency is essentially without cost. It is only necessary to program the spacecraft transmitter for an appropriate increase in phase modulation to obtain the increased efficiency. An increase of modulation index from 43 deg to 90 deg (fully suppressed carrier) approximately doubles the available data power. The BVR is based on the prototype Advanced Receiver (ARX) developed by the Advanced Systems Program over the better part of a decade. This prototype utilizes flexible digital implementation of carrier, subcarrier, and symbol tracking loops, which allows very narrow loop bandwidth. A Costas loop allows recovery and tracking of a fully suppressed carrier.

(3) The built-in channel coding available to the Galileo S-band transmitter was a hardware (7,1/2) convolutional code, primitive by today's standards—particularly for highly compressed data. By programming a software (11,1/2) convolutional code on a Galileo computer (possible because of low bit rates) and concatenating it with the hardware (7,1/2) code, a (14,1/4) code is produced. This is used with a software Viterbi decoder (permitted by low bit rates) as the inner code of a novel concatenated (255,k) variable redundancy Reed–Solomon (RS) coding scheme. The redundancy profile is (94,10,30,10,60,10,30,10), and the interleaving depth is 8. The staggered redundancy profile is designed to facilitate the novel feedback concatenated decoding strategy that allows multiple passes of channel symbols through the Viterbi decoder. During each pass, the decoder uses the decoding information from the RS outer code to facilitate the Viterbi decoding of the inner code in a progressively refined manner. The feedback concatenated decoder is implemented in software and provides a bit-error rate of 10×10^{-7} at an exceptionally low signal-to-noise ratio of $E_b/N_o = 0.65$ dB. The original (7,1/2) convolutional code would provide a bit-error rate of 10×10^{-3} at $E_b/N_o = 2.3$ dB. This error rate is acceptable for uncompressed image data but much greater than the 10×10^{-7} error rate required for compressed image data.

    In addition to this code based on research in the Advanced Systems Program, the processing of the received signals includes predetection recording and noncausal processing to eliminate acquisition delay and minimize dropout intervals. At each antenna, the S-band signal from the spacecraft is downconverted to 300 MHz and fed simultaneously to the BVR for real-time processing and to the Full Spectrum Recorder (FSR) for subsequent nonreal-time and noncausal processing. Noncausal processing involves using future as well as past values of the signal for estimation at a given time instead of being

limited to the use of past and present values, as required by real-time (without delay) processing. For example, noncausal processing can eliminate the usual acquisition delay by phase-lock and symbol loops (and the resulting loss of data) by processing the signal in reverse time, where the beginning of the signal becomes the end of the signal and future signal becomes past signal. Further, once the signal becomes available over an extended interval of time via the FSR, computer programs can make near-optimum estimates of the data by using the signal over the entire interval. Among other things, this permits maintaining synchronization during discontinuous changes in data rate used to take advantage of the predictable varying signal-to-noise ratio resulting from changing tracking antenna elevations and arraying combinations of DSN receiving antennas. (The spacecraft is not able to change data rate in continuous fashion.) This prevents loss of data at each change of rate while tracking loops reestablish lock.

(4) In a mission like Galileo, the majority of the downlink data is assigned to images and, thus, the maximum acceptable compression of image data is most important. The Galileo solid-state imaging camera provides 800 × 800 pixel images with 8-bit digitization of each pixel, thus producing 5.12 megabits per full image. In order to obtain a large factor of data compression for images, it is necessary to use compression algorithms, which introduce error. This error increases with the factor of compression. In order to determine the maximum acceptable error in images, the scientists and the Galileo solid-state imaging team conducted an extensive investigator-in-the-loop evaluation of compression algorithms. It was determined that an integer approximation of the discrete cosine transform, previously studied by the Advanced Systems Program, would provide generally acceptable images. The acceptable compression factor may vary from image to image, but on the average, a compression factor of at least 10 results. The integer approximation does not significantly degrade the compression and makes it possible to carry out the discrete cosine transform on a spacecraft computer of limited capability. The decompression operation includes postprocessing techniques in the frequency and spatial domains to remove compression artifacts without increasing distortion.

With the improved S-band downlink having a maximum data rate in the neighborhood of 100 b/s, the spacecraft tape recorder has an additional critical function. In addition to storing data for later transmission, the recorder must "convert" high-rate data produced by some of the instruments to low-rate data for subsequent playback over the improved S-band downlink, which still is a factor of about 1000 slower than the failed original X-band downlink around which the mission was designed. Some further recovery of Galileo's data volume was accomplished by simply allocating a large amount of DSN antenna time to the mission.

The early accomplishments of the Galileo Mission after arrival at Jupiter indicate that application of the Advanced Systems Program technology for the Galileo S-Band Mission has been entirely successful.

On December 7, 1995, the Galileo Probe entered the Jupiter atmosphere and functioned as planned. The Probe data were received and stored on the Orbiter just prior to its Jupiter orbit insertion. The stored Probe data were transmitted to Earth over an extended period via the S-band downlink. The advanced coding and other improvements of the Galileo S-Band Mission were activated later in 1996.

The first satellite encounter after Jupiter orbit insertion was that of Ganymede on June 27, 1996, at a distance of 832 km. All of the enhancements provided by the Advanced Systems Program (except for antenna arraying, scheduled for later) functioned as planned for imaging and other data. On September 6, 1996, there was a second Ganymede encounter at a distance of 262 km.

On November 4, 1996, there was the first encounter with Callisto, at a distance of 1104 km. At this encounter, the spacecraft was at one of its most distant points from Earth, and the DSN antenna arraying

capability was used for the first time on the mission. The array included the 70-m and 34-m antennas at Canberra, the 64-m antenna at Parkes, and the 70-m antenna at Goldstone. At this maximum distance, the spacecraft downlink data rate was programmed among 120, 80, 40, 32, and 20 b/s, depending on the combination of arrayed antennas and their tracking elevation angles. This arraying capability had been tested successfully in September at spacecraft telemetry bit rates up to 160 b/s.

On December 18, 1996, the Europa encounter occurred at a distance of 692 km. All communication enhancements continued to operate as planned. There is every indication these vital technology contributions from the Advanced Systems Program will continue to contribute to the success of the Galileo Mission during the remainder of its operation.

B. Advanced Systems Program and the Voyager Mission

Like other outstandingly successful deep-space missions before and after, the Voyager Mission to Jupiter, Saturn, Uranus, and Neptune and their moons and rings depended on the unique capabilities of the DSN, including the capability of arraying with non-DSN facilities at Parkes (Australia), the VLA (New Mexico), and Usuda (Japan). Many of these capabilities using technology previously provided by the Advanced Systems Program were in place at the time of the two Voyager spacecraft launches in 1977. However, other capabilities needed for the Uranus and Neptune encounters 9 and 12 years later were not available in the DSN in 1977 and, subsequently, came from technology provided by the Advanced Systems Program.

The amount of data that can be returned from the spacecraft, both in the form of telemetry from onboard instruments and radio science data from the microwave signals, is determined to a large extent by the capabilities of the DSN. Likewise, the accuracy of spacecraft navigation depends largely on DSN capabilities.

For the Voyager Mission, there were at least 17 first-time performance achievements by the DSN not accomplished anywhere before, and all strongly dependent on technology from the Advanced Systems Program. These first-time achievements are briefly described in the following paragraphs.

(1) The largest data rate (21,600 b/s) from the greatest distance (2.75 billion miles from Neptune); this achievement was made possible by the following accomplishments.

(2) The first use of an X-band downlink from deep space; this was made possible by antenna multifeed concepts and dual-frequency feeds using work in high-precision microwave measurement (errors below 0.001 dB) and low-loss, low-noise microwave systems.

(3) The lowest X-band operational receiving system noise temperature (SNT) of 20.9 K for the three DSN 70-m antennas at zenith, and an SNT of 25.5 K at 30-deg elevation (in clear dry weather). This was due in part to the specially shaped surfaces of the 70-m upgrade reflectors and subreflectors, based on design analyses from the Advanced Systems Program, which provided higher efficiency while maintaining low noise temperature; another contributing factor was the use of X-band low-noise ruby maser amplifiers developed by the Advanced Systems Program.

(4) The arraying of 29 antennas (70- and 34-m antennas at Goldstone, with 27 antennas [25 m] at the VLA) to provide the largest fully steerable equivalent aperture (151 m). This arraying (and DSN arraying) was possible only because of earlier research by the Advanced Systems Program on signal-combining algorithms and techniques for arraying. This was also the longest real-time aperture separation array (1,900 km via a communication satellite).

(5) The use of VLA antennas for the Voyager–Neptune encounter was made possible by the first X-band operational use of HEMT low-noise amplifiers (at each of the 27 VLA antennas). For some years prior, the Advanced Systems Program had been supporting HEMT development for cryogenic low-noise applications in the DSN.

(6) The outstanding first-time accomplishment reported in (1), above, could not have happened without the exceptionally high-performance channel coding technology using a concatenated Viterbi-decoded $K = 7, R = 1/2$ convolutional inner code with a 16-symbol error-correcting 8-bit (255,223) Reed–Solomon outer code (with interleaving depth 4). This provided a bit-error probability of 1×10^{-6} (for 2.5-ratio compressed image data from Neptune) at a theoretical signal-to-noise ratio (SNR) of $E_b/N_o = 2.43$ dB. Without coding, the required SNR would be increased by about 8 dB. To achieve this 8 dB by additional antennas instead of coding would require the 29-antenna array to be increased by 104 additional 34-m antennas. Coding is a bargain! The DSN coding algorithms and technology are the result of some 30 years of world-class research and development in this area supported by the Advanced Systems Program.

(7) The result of the first-time achievements described in paragraphs (2) through (6) above was to make the DSN, configured for the Voyager–Neptune encounter, the world's most sensitive digital radio receiving system, requiring an energy-per-bit flux density of only 2.4×10^{-25} (J/b)/m^2 at the receiving system (the 29-antenna array).

The Voyager Mission required other unique capabilities of the DSN, also depending on technology from the Advanced Systems Program, as follows:

(8) Receiving a downlink signal with fully suppressed carrier for VLBI use. This was based on research and development of advanced tracking loops.

(9) The DSN provided the highest power operational coherent uplink for spacecraft with a capability of 400 kW continuous wave (CW) at S-band [giving an effective isotropic radiated power (EIRP) of about 400 GW]. The technology for this capability came from the Solar System Radar, supported over the years by the Advanced Systems Program.

(10) The first continuous frequency-programmable uplink was used to "rescue" the only operative Voyager 2 receiver after its carrier loop lost most of the acquisition range due to a failed capacitor.

(11) The longest distance ranging at 4.42×10^9 km (at Neptune) with an accuracy of about 1 m, the most accurate space distance measurement (percentage-wise) ever made. This used the first three-way ranging system, made necessary by a round-trip light-time too long for a pass over a single deep-space receiving station. (The sequential ranging system used was developed by the Advanced Systems Program.)

(12) A Doppler accuracy of about 1 mm per second at Neptune distance, using Doppler extraction technology.

(13) The first operational use of delta VLBI, giving an angular accuracy of 150 nrad. (Over many years, VLBI technologies, including tropospheric measurement and system calibration, have been supported by the Advanced Systems Program.)

(14) Voyager was the first mission designed specifically to obtain radio science data by having very exacting requirements for radio system stability at S- and X-bands. The area of measuring and improving ground radio system stability has been supported by the Advanced Systems Program.

(15) The preceding four first-time achievements depended completely on the ultrastability of the DSN hydrogen maser frequency standards, which provided for first deep-space use a long-term timing stability Allan deviation of 1×10^{-14} over several hours and a short-term timing stability phase noise of -54 dBc at 1 Hz and -60 dBc from 10 to 10,000 Hz. Hydrogen maser and advanced frequency standards technology have been supported by the Advanced Systems Program for some 25 years.

(16) The first arrays of ground antennas for radio science used the Canberra 70-m antenna with the Parkes antenna at X-band and the Usuda antenna at S-band in a nonreal-time mode.

(17) As a result of the superb DSN downlink performance referenced above, the Voyager Mission yielded the largest amount of data (about 200 Gb) from deep space up to that time.

C. Advanced Systems Program and the Mariner 10 Mission to Venus and Mercury (1973–1975)

The Mariner 10 Mission by design and, seemingly by afterthought and accident, pushed the capabilities of the DSN to its limits. Some of these capabilities were achieved only with developmental hardware and systems from the Advanced Systems Program—sometimes on rather short notice. Mariner 10, launched on November 3, 1973, and completed shortly after the third Mercury encounter on March 16, 1975, had many significant achievements, some of which are listed here.

Mariner 10 was the first JPL spacecraft

(1) To transmit full-resolution images in real time from planetary distances.

(2) To photograph Venus.

(3) To encounter and photograph Mercury (three times).

And the Mariner 10 Mission was the first JPL mission to use

(1) Multiplanet gravity assist.

(2) Arrayed ground station antennas to improve SNR.

(3) Simultaneous coherent dual-frequency radio transmission (S- and X-band downlinks for radio science and radio metrics).

The design of the spacecraft's imaging data system (at S-band) provided a choice of just two uncoded data rates: 117.6 kb/s or 22.05 kb/s. The higher rate (117.6 kb/s) was determined to give effectively noise-free images [with a bit-error rate (BER) of 5×10^{-3}] from Venus distance using the standard 64-m antenna feeds and masers, with a comfortable SNR margin. With this configuration, the greater distance to Mercury would result in a decrease of 3.5 dB in SNR and would not permit use of the 117.6-kb/s rate for that encounter. The 22.05-kb/s rate, however, would permit the imaging of only a small portion of the visible part of Mercury rather than the entire visible part. (The Mercury encounter was scheduled for late March 1974, following the Venus encounter in early February 1974.)

So, in June 1973, the Mariner 10 Project Office requested the DSN to evaluate its capabilities to support a Mercury encounter with imaging data at 117.6 kb/s. The resulting evaluation determined that a reduction in antenna operating noise temperature would improve the SNR enough for the higher data rate to be used at the Mercury encounter (with an increased BER that was near 0.02). And it was found that the antenna operating noise temperature could be reduced to 13.2 K (at zenith) if new 2.1-K super-low-noise masers (from the Advanced Systems Program) were installed in a receive-only configuration at the Goldstone and Canberra 64-m antennas. In addition, the operating noise temperature of the

Canberra 64-m antenna could be reduced to 12.5 K (at zenith), if an ultracone with a specially designed feed (previously developed by the Advanced Systems Program) could be equipped with the new low-noise maser and installed on the Canberra antenna.

The Mariner 10 Project accepted this improvement of the DSN's capabilities on a best-effort, mission-enhancement basis. Unfortunately, a major spacecraft emergency occurred in 1973 on Christmas day, 7 weeks after launch and 6 weeks before Venus encounter, when the spacecraft antenna feed developed a problem that decreased the power output by 3 dB and changed the polarization from circular to essentially linear. The resulting mismatch with the DSN circularly polarized feeds caused an additional 3-dB loss in signal, for a total loss of 6 dB. Without correction, only the 22.05-kb/s rate could be supported at Venus, with a loss of over 80 percent of the imaging data. However, by using the antenna lower-noise capability (as just described for the Mercury encounter) and by installing emergency polarization equipment (from previous Advanced Systems Program work) at all three of the 64-m antennas to eliminate the 3-dB polarization loss, enough SNR was regained to yield very good results at the Venus encounter on February 5, 1974.

In the meantime, the spacecraft antenna problem was going through fail–heal–fail cycles. On March 4, 1974, 25 days before the Mercury encounter, the spacecraft antenna problem disappeared and did not return. This allowed the two 64-m antennas with super-low-noise masers and the ultracone to carry out the original purpose of supporting the 117.6-kb/s rate at Mercury. (The entire illuminated disk thus could be imaged rather than a small part of it at the 22.05-kb/s rate.)

It was decided to extend the mission to include a second Mercury encounter (to occur on September 21, 1974). The range for this encounter was greater than for the first, and this caused an additional SNR reduction of 1 dB. The increased BER at 117.6 kb/s resulting from this reduced SNR put imaging at this rate in doubt. The Advanced Systems Program had been developing a process of signal combining for antenna arraying, and this process was quickly brought into the DSN on a best-effort basis during the months before the second Mercury encounter. At that encounter, one 64-m and two 26-m antennas were arrayed to increase the SNR by about 0.6 dB, which was enough to allow (at an acceptable error rate) the full imaging provided by the 117.6-kb/s rate.

About 5 weeks before the second Mercury encounter (August 14, 1974), the Mariner 10 spacecraft tape recorder failed. From then on, all of the engineering and nonimaging science data had to be transmitted as it occurred, instead of being recorded for later playback, and this caused a considerable increase in workload for the DSN.

It was decided to extend the mission to include a third Mercury encounter, which was to take place on March 16, 1975. The primary purpose of this encounter was to gather more nonimaging science data. However, these data, transmitted at 2450 b/s simultaneously with the imaging data, took priority over imaging data. For instance, there were spacecraft attitude control problems that required additional DSN uplink activity, and more frequent radio metric data activities were needed for orbit corrections. Fortunately, improved radio metric data for the mission were provided by the Mu-II Ranging Machine that was developed by the Advanced Systems Program.

The research and development masers and ultracone installed on a best-effort, mission-enhancement basis had made possible the 117.6-kb/s imaging data for the first two Mercury encounters. Just before the third encounter, the ultracone maser cryogenic system at Canberra failed and the 22.05-kb/s imaging data rate had to be used; fortunately, the primary nonimaging science data were not impacted.

The highly successful MVM 73 Mission depended very significantly on both established and "last minute" contributions of the Advanced Systems Program.

D. Fiber-Optic/Photonics Technology

The introduction of fiber-optic technology into the DSN has resulted in cost savings and performance improvements that continue year after year. The addition of new fiber-optic/photonics technology in overall systems design will further increase cost savings and performance.

Significant cost savings have resulted from the use of less expensive optical fibers that replaced microwave links, coaxial cables, and expensive equipment that was used to mitigate degradation of signals by the replaced links and cables. The virtual lack of signal degradation by the fibers also reduces the number of required expensive items throughout a DSN complex, like hydrogen-maser or trapped-ion standards. Further important cost savings can be achieved by transmitting nearly all microwave signals through highly stable optical fibers. For the downlink signals, all of the equipment following the cryogenic low-noise amplifier module at every antenna could be moved to the signal processing center (SPC) of the DSN complex. Likewise, for the uplink signals, all equipment up to and including the exciter could be moved from every antenna to the SPC. Such a configuration would permit multiple cost savings (including elimination of antenna and/or station control rooms) and performance improvements.

1. Development of Optical Fiber Use in the DSN. The Advanced Systems Program began to monitor the development of fiber-optic technology in 1970, after Bell Telephone Laboratories announced that it had developed an optical fiber with low-enough loss for practical telecommunications applications. In the next years, the field of fiber-optic technology developed rapidly, resulting in lower-loss fibers and reliable semiconductor lasers that could furnish practical levels of optical input to fibers.

By 1978, the Frequency and Timing Systems (FTS) Research Group believed fiber-optic technology had reached a sufficiently practical level to propose a program for developing fiber-optic distribution of frequency and timing signals throughout DSN complexes. With fiber-optic technology, the number of expensive hydrogen masers in a complex could be reduced to one plus spares. Also, from a central location such as Goldstone, frequency and timing could be provided at an unlimited number of antennas and at other locations in the complex. Fiber optics could supply frequency and timing at least as well as a hydrogen maser at each location could, and with better interstation stability. In addition, fiber-optic links easily could carry all the interstation communications and eliminate the need for microwave links, which suffer from frequency allocation, reliability, and stability problems. Also, fiber-optic links consume much less energy than microwave links do, and they require no frequency allocations.

In 1979, the Advanced Systems Program provided initial funding for an in-depth study of state-of-the-art fiber-optic technology, which included the procurement of a laser diode, photodiode, and optical fiber cable to fabricate a basic system. Thermal coefficients of delay were determined for prototype single-mode fiber cable. The results of this study were promising, and in 1980 the Advanced Systems Program began long-term funding of fiber-optic research and development to meet future DSN needs. Over the first 9 years, the funding averaged approximately $250k per year, but has declined to half that as the technology has matured.

2. Fiber-Optic Research at JPL. Initial funding by the Advanced Systems Program provided for installation and testing of a 3-km fiber link at JPL, and in 1980, this link demonstrated its suitability for transmission of hydrogen-maser signals.

In 1981, the FTS Research Group designed and fabricated the first single-mode 1300-nm analog fiber-optic link using the first such lasers produced in the United States. Multimode fibers are not suitable for wideband signals because of velocity dispersion among the different modes. This link demonstrated the first fiber-optic transmission of a 1.25-GHz bandwidth analog signal to duplicate the function of a microwave link.

In 1982, the FTS Group installed the first fiber-optic link in the DSN, connecting DSS 13 with DSS 12, a distance of 7 km. The plowed-in buried cable contained six fibers, two of which were among the first

single-mode fibers produced by Corning Glass—the other fibers were multimode. The FTS Group also worked with the Telecommunications and Data Acquisition (TDA) Office and the Quality Assurance Section to develop fiber-optic cable specifications so such systems could be deployed in the DSN.

In 1984, a measurement of the frequency stability of the round-trip fiber-optic link between DSS 12 and DSS 13 gave the result of 1×10^{-14} for a 1000-second averaging time without the expense of active cable stabilization (which can provide orders of magnitude of additional improvement in stability). In the absence of any available microwave-link frequency allocation, and to meet a spacecraft project deadline for a link between Goddard Spaceflight Tracking and Data Network (GSTDN) and SPC 10, a fiber-optic link was installed and made operational in 90 days. This illustrated the rapid maturing of fiber-optic technology in the DSN with the support of the Advanced Systems Program. Also in 1984, the FTS Group implemented several fiber-optic links to meet unique requirements at the JPL Oak Grove facility. These links included two matched-delay 45-Mb/s fiber-optic links to support synthetic aperture radar work, another 45-Mb/s link to support image processing, and several fiber-optic video links in the Space Flight Operations Facility (SFOF) to provide improved performance with cost savings.

In 1986, the frequency stability of the link between DSS 12 and DSS 13 was improved to 1×10^{-15} over 1000 seconds to meet the needs of connected-element interferometry. This improvement was achieved without cable stabilizers by controlling reflections in the fiber. During 1986, the FTS Group planned and established the fiber-optic backbone system for the Goldstone complex. This system was based on a multifiber cable running from the Venus Station to the Mars Station (29 km) via the Echo and Apollo Stations and involved a total cost of $500k (not provided by Advanced Systems Program funding).

In 1987, the Goldstone fiber-optic backbone installation was completed and an additional 12-single-mode-fiber cable was installed between DSS 12 and DSS 13. The FTS Group designed, fabricated, and tested fiber-optic terminals for frequency distribution between SPC 10, DSS 13, and DSS 12. An improved cable stabilizer was designed, fabricated, and tested. Theoretical work was completed on the cause-of-delay change in fiber-optic cable under flexure (as in an antenna "wrap-up"). It was found that most of the change in delay was due to reflections into the transmitter laser and not due to the fiber directly, as previously had been believed.

Subsequently, based on the new understanding of delay change resulting from fiber flexure, a commercial optical isolator was developed. A transmitter using the isolator was designed, fabricated, and tested at Goldstone, where fiber-optic cable delay variation due to flexure was virtually eliminated, thus opening the way to the use of fiber optics in antenna wrap-ups and other moving environments. Based on a frequency and timing study under the Advanced Systems Program, it was decided that hydrogen masers would be installed only at SPC 10 rather than at several locations. Also, frequency and timing reference would be distributed throughout the Goldstone complex by fiber-optic technology. This new technology also eliminated the need for moving radio-frequency equipment (e.g., the radio frequency interference trailer) to various locations at the Goldstone facility. Essentially, the interference signal was transmitted over an optical fiber to the trailer, rather than the trailer being moved to the location experiencing interference.

Also, in 1988, the Advanced Systems Program, through the FTS Group, funded a private company with $30k for a best-effort development of a commercial, isolated laser-diode transmitter. Although considerable work was done, the funding was not adequate to finish the task. Fortunately, money from another sponsor allowed the development to be completed, and the product made the company, Ortel, the world's leader in commercial analog fiber-optic systems, which are now used extensively in cable television.

In 1989, the FTS Group solved the problem of direct transmission of microwave signals over optical fibers by modulating the amplitude of the optical signal. This solution made it possible for all radio receiving equipment except the radio-frequency amplifiers to be removed from the antenna site, thereby

enabling a future redesign of the radio system in DSN complexes. The initial work resulted in high-dynamic-range ultralow-noise fiber-optic links for microwave signal transmission at frequencies up to 20 GHz, with virtually no degradation. With later improvement in optical modulators, the range has been extended to include Ka-band.

In 1991, a method was developed using a fiber-optic link to measure the stability of a 34-m BWG antenna. The 14-GHz signal from a small adjacent reference antenna was carried over a fiber-optic link to the area of the feed of the large antenna, where the two signals were compared in phase. The 45-m fiber-optic link had a nighttime stability of about 1×10^{-16} over 1000 seconds. The system was able to measure and verify antenna phase stability to the 1×10^{-15} level.

In 1993, a study of fiber-optic code-division multiple-access systems for potential use in the DSN was completed. A significant contribution also was made to a study of large antenna arrays. Also, a 12-km optical-fiber link was placed between the X-band output of the low-noise amplifier at DSS 13 and the downconverter. Station personnel measured the receiving system parameters and could not tell the link was there. The Magellan spacecraft was tracked with the link in place.

Fiber-optics and laser technology continue to evolve and open new options for DSN instrumentation. In 1994, a high-stability all-photonic microwave/millimeter-wave oscillator was developed. Photonic mixing can now be achieved by heterodyning a pair of lasers and using electro-optic modulators and fast photodiodes with responses into the millimeter-wave region. This technology has supported the demonstration of one-step up- or down-conversion between microwave or millimeter-wave frequencies and conventional IF frequencies, where the converter inputs and the outputs can be either optical or electrical signals.

As a result of the long-term support of fiber-optic/photonic technology by the Advanced Systems Program (described in part above), there is now available for the DSN a technology that affords important cost savings and improved performance. The cost savings apply to both implementation and operation. By the nature of technology development and proof, the early applications in the DSN tended to be on a piecemeal basis—for example, merely replacing existing coaxial cables and microwave links with optical fiber. For the future DSN to fully realize the benefits of this technology, fiber-optic/photonics technology must be an integral part of DSN systems design. The resulting new design may well look quite different from that of the present DSN.

E. Telecommunications Performance

One measure of the technological progress in deep-space communications may be seen clearly in the accompanying chart, Fig. 16, which is informally identified as the "stair-step chart of telecommunications performance." The chart shows the growth in potential data rate through the years for a space-to-Earth return link from Jupiter and has appeared in a number of publications. The timeline begins in 1960 and attempts to forecast up to the year 2020. Actual growth through 1995 is more than 12 orders of magnitude and includes contributions from both ground and spacecraft technology evolution.

Many of the steps on this chart 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 on 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 improve performance by more narrowly focusing the radio beam from the spacecraft.

Still other steps depict improvements resulting strictly from the DSN, such as reductions in receiving system temperature, increases in the size of the ground antennas, or the use of arrays of antennas, which increases the effective surface area for collecting signal.

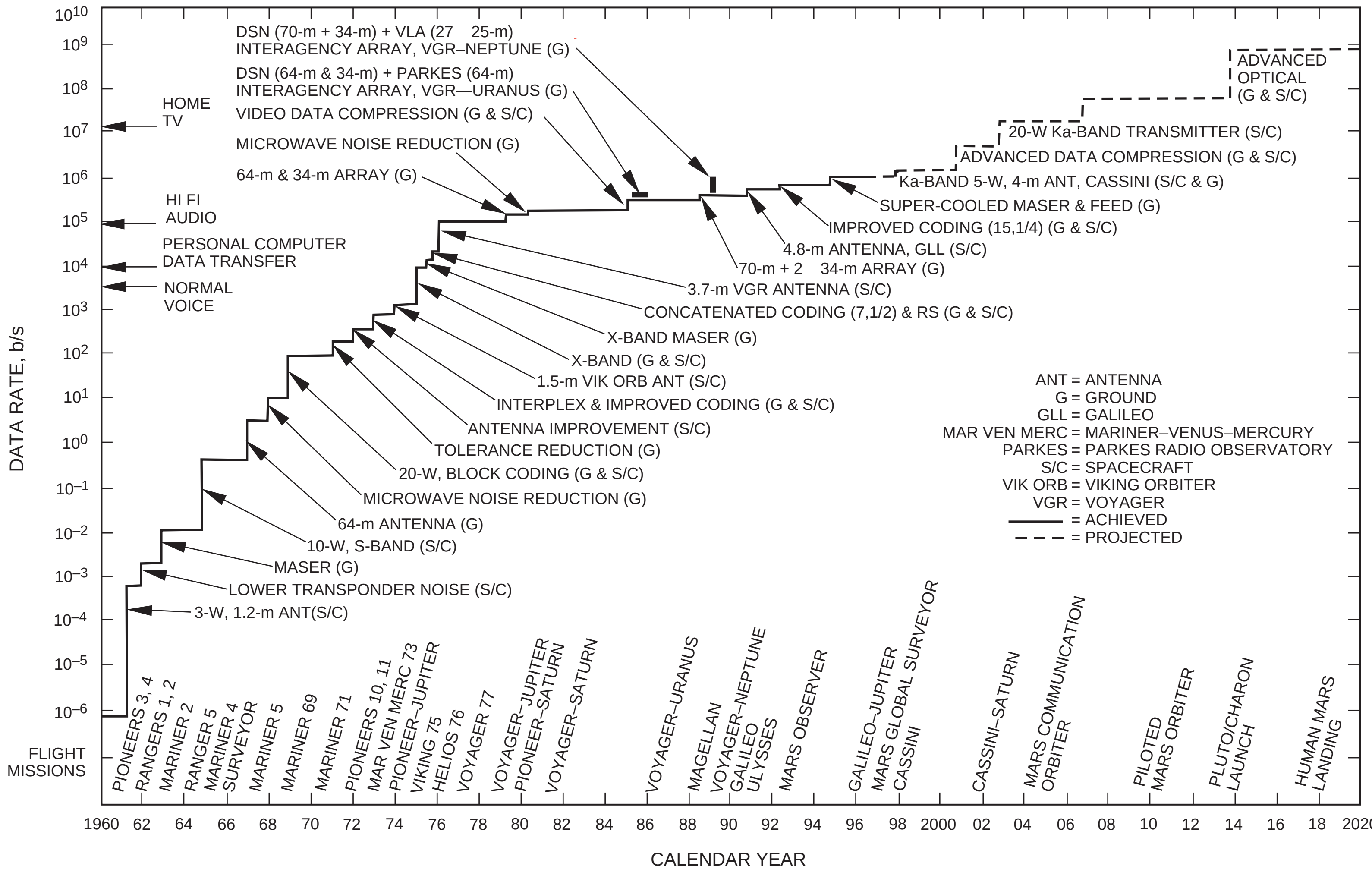

Fig. 16. Stair step chart of telecommunications performance: profile of deep-space communications capability, space-to-Earth (equivalent imaging data rate capability at Jupiter distance—750 million kilometers).

The DSN Advanced Systems Program has contributed directly to all of the changes that are DSN-only in nature and has made possible the DSN contributions to the cooperative steps. If one considers coding developments as a contribution from the DSN arena, since all the coding work has been led by the DSN Advanced Systems Program researchers, then the technologies of the DSN have contributed 3.5 decades of the 12 decades of the growth shown. The remaining 8.5 decades have resulted from a combination of purely spacecraft developments and the cooperative frequency increases.

The logarithmic scale used to display the data rate gives the 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 of the data were proportional to the amount of data, then the display of the incremental increases would be more meaningful than the logarithmic display.

Acknowledgments

The majority of this article appeared previously in JPL Publication 95-20, *The Evolution of Technology in the Deep Space Network, A History of the Advanced Systems Program*, by J. W. Layland and L. L. Rauch, Jet Propulsion Laboratory, Pasadena, California, 1995. That publication has been expanded in this article to include as a case study the role of the DSN ASP in the success of the Galileo Mission to Jupiter.

The original *Evolution of Technology in the Deep Space Network* was produced under the editorial leadership of Dr. N. A. Renzetti of the Jet Propulsion Laboratory (JPL), Pasadena, California. But the real authors of this story are many: first and foremost is Mr. Hugh Fosque, who nurtured, defended, and guided the Deep Space Network (DSN) Advanced Systems Program from National Aeronautics and Space Administration (NASA) Headquarters; next, are the dozen JPL Program Managers who supported Hugh over the years; and finally, the several hundred technologists who worked within the program and added their contributions, some large and some small, throughout the lifetime of the DSN Advanced Systems Program.

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Appendix A

Bibliography—Some Selections for Further Reading

The story of the technological development of the DSN was also documented through articles published in the JPL *Space Program Summaries* (see the next paragraph) and its successor journals, and also in external refereed journals. The following pages contain references to a sampling of that literature, intended to provide the interested reader with an entrée to the available reading. Many of the citations to follow were extracted from the on-line index to *The Deep Space Network Progress Report* and *The Telecommunications and Data Acquisition Progress Report* for issues from 1970 on, or from the author index to the earlier reports. There has been an attempt to keep the overall list manageable in size, but still include (most) key developments. Articles catalogued in the following pages (almost) exclusively describe work that was funded by the DSN Advanced Systems Program; known exceptions represent partnerships with the Implementation Program or ad hoc Operations usage of Advanced Systems Program products.

Please note that the early *JPL Space Programs Summary* was published as a five-volume set, designated as SPS 37-nn. One of these, vol. IV, was for all Supporting Research and Advanced Development activities, including the DSN Advanced Systems Program. The designation was SPS 37-nn, vol. III, for Deep Space Instrumentation Facility (DSIF) Implementation and Operations activities. The volume structure changed with SPS 37-47 to become a four-volume set, with vol. III containing all Supporting Research and Advanced Development and vol. II describing the DSN. Publication of the JPL SPS ended in 1970 with SPS 37-66. Reporting for the DSN, including the Advanced Systems Program, continued in a JPL Technical Report, JPL TR 32-1526, vol. I (February 15, 1971) through vol. XIX (February 1974). This series continued as *The Deep Space Network Progress Report* (DSN PR 42-nn) beginning with DSN PR 42-20 in April 1974, and except for a name change (to *The Telecommunications and Data Acquisition Progress Report*) in June 1980 (TDA PR 42-57), the series continues today. When the bibliography refers to these publications, they will be identified as JPL SPS, JPL TR, and TDA PR. Copies of these documents may be obtained from the Jet Propulsion Laboratory, Pasadena, California. TDA PR articles referenced from issues 42-118 forward may be accessed on-line through http://tda.jpl.nasa.gov/progress_report/

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Appendix B
Acronyms and Abbreviations

ARX	Advanced Receiver
AU	astronomical unit
BBA	Baseband Assembly
BER	bit-error rate
BWG	beam-waveguide (antenna)
Caltech	California Institute of Technology
CW	continuous wave
DSN	Deep Space Network
EIRP	effective isotropic radiated power
FTS	Frequency and Timing Systems
GPS	Global Positioning System
GSTDN	Goddard Spaceflight Tracking and Data Network
HEF	high-efficiency (antenna)
HEMT	high-electron mobility transistor
HGA	high-gain antenna
ICE	International Cometary Explorer
ISAS	Institute for Space and Astronautic Sciences
JPL	Jet Propulsion Laboratory
LIT	linear ion trap
MVM	Mariner–Venus–Mercury
NASA	National Aeronautics and Space Administration
NRAO	National Radio Astronomy Observatory
RTC	real-time combiner
RTLT	round-trip light-time

SDA	Subcarrier Demodulator Assembly
SETI	Search for Extraterrestrial Intelligence
SFOF	Space Flight Operations Facility
SNR	signal-to-noise ratio
SNT	system noise temperature
SPC	Signal Processing Center
STD	standard (34-m antenna)
TDA	Telecommunications and Data Acquisition
TWM	traveling-wave maser
ULNA	ultralow-noise amplifier
VLA	Very Large Array (at Socorro, New Mexico)
VLBI	very long baseline interferometry