

The Deep Space Network at 50

Joseph Lazio and Les Deutsch

From rovers on the surface of Mars to *Voyager 1* near the edge of the solar system, spacecraft regularly call home to Earth. For five decades, the Deep Space Network has been at the other end of the line.

NASA/JPL-CALTECH

The Deep Space Network (DSN) is the communications lifeline to spacecraft exploring the solar system and the universe beyond. From its three ground complexes—Canberra, Australia; Goldstone, California; and Madrid, Spain—the DSN transmits commands to spacecraft, tracks them on their journeys through the solar system, receives their data, and conducts its own scientific investigations. In addition, several of the technologies developed at the DSN have been incorporated into everyday life. It is the largest and most sensitive scientific telecommunications system in the world; it makes deep-space exploration possible.

Establishment of the network

A spacecraft launch is a highly visible event, but it is only the start of a mission. Scientists and engineers on the ground still have to track, potentially command, and receive data or telemetry from the spacecraft. *Explorer 1*, which became the first successful US satellite in January 1958, was significant not only because it rose off the launch pad but because data received from it led to the identification of the Van Allen radiation belts.

By the late 1950s, the Jet Propulsion Laboratory (JPL) had developed the Microlock tracking and telemetry system as part of its missile testing for the US Army. Key to future developments, the Microlock system paired a ground-based radio antenna with a transmitter on the missile that incorporated a phase-lock loop. That setup kept the transmitted and received signals in phase and allowed for precise positional information. To track

Explorer 1 during its entire orbit, JPL installed additional Microlock stations, including ones in Singapore and Nigeria. When *Explorer 1* transmitted its science data, the Microlock stations received them.

Following the success of *Explorer 1*, the US Air Force established the Pioneer lunar program with the goal of impacting or landing a spacecraft on the Moon. The Department of Defense's Advanced Research Projects Agency (ARPA), in charge of all US space programs for a brief interval in 1958, had already envisioned a "World Net"—a global network of spacecraft-tracking ground stations—that was well received at JPL, given its experience with international Microlock stations. With the World Net concept in mind, JPL personnel identified an area near the Goldstone Dry Lake in the Mojave Desert suitable for one ground station to track Pioneer lunar and future spacecraft.

For World Net, ARPA had taken the risk of purchasing three 26-meter-diameter antennas. With the Pioneer lunar launch dates approaching quickly, JPL constructed one of the antennas at the Goldstone site. Meanwhile, all JPL facilities, including the antenna, were transferred in October 1958 to the National Aeronautics and Space Administration, the newly established civilian space agency. Named Deep Space Instrumentation Facility 11 (DSIF 11), the antenna provided key diagnostic information

Joseph Lazio is chief scientist and **Les Deutsch** is deputy director of the Interplanetary Network Directorate at the Jet Propulsion Laboratory, California Institute of Technology, in Pasadena.



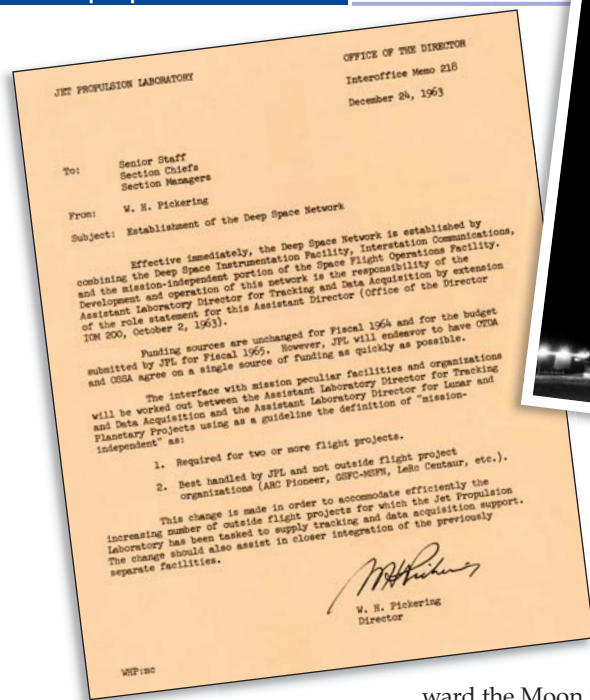


Figure 1. Deep Space Instrumentation Facility (DSIF) 41, a 26-m-diameter antenna, located at Woomera, Australia, was one of the first three antennas in what would become the Deep Space Network (DSN). To the left is the 24 December 1963 memo written by William Pickering, then director of the Jet Propulsion Laboratory, that established the DSN. (Courtesy of NASA/JPL-Caltech.)

after *Pioneer 3* failed to make it to the Moon in December 1958, and then tracked *Pioneer 4* as it traveled to-

ward the Moon in March 1959.

Continuous tracking and communication with deep-space spacecraft requires a network of at least three antennas, located approximately 120° apart in longitude. The initial World Net concept envisioned additional ground stations in the Philippines and Nigeria, but DOD personnel doubted whether stations at those latitudes could track the full suite of future spacecraft, especially given the likely orbits and trajectories of piloted spacecraft. After additional study, JPL proposed shifting the locations from Nigeria to Portugal or Spain and from the Philippines to Australia.

By 1960 the second 26-m antenna originally purchased by ARPA had been transferred to NASA, and JPL had identified a site at Woomera north of the Australian city of Adelaide. DSIF 41, shown in figure 1, was formally inaugurated on 10 February 1961 in a ceremony during which a congratulatory message was passed from Washington, DC, to Woomera by bouncing the transmission off the Moon.

The technical requirement of three stations located 120° apart in longitude means that international cooperation is an integral aspect of any deep-space communications network. The construction of DSIF 41 was the first example of such cooperation, with NASA providing the antenna and Australia's Weapons Research Establishment developing the local infrastructure. In contrast, difficulties in establishing a treaty with either Portugal or Spain led to considerations of an alternate location for the third DSIF site.

South Africa is located at approximately the same longitude, and it offered the additional benefit that a rocket's trajectory after launch from Cape Canaveral would typically pass over southern Africa. Additionally, the South African government was eager to work with NASA. By late 1960 NASA had acquired ARPA's third 26-m antenna, and installation of DSIF 51 at Hartebeesthoek, north of Johannesburg, began in January 1961. But in a harbinger of future events, diplomatic concerns over the South

African policy of apartheid prevented NASA's participation in the opening ceremony for DSIF 51.

In two years, the essential elements of the modern DSN had been put in place. Three ground stations, separated by approximately 120° in longitude, allowed nearly continuous contact with deep-space craft. Two factors combined to change the DSIF into the DSN.

First, NASA planned an increased suite of missions during the 1960s. Rather than a single spacecraft targeting a single destination as in the Pioneer lunar program, NASA envisioned robotic spacecraft traveling to multiple, more distant destinations and human spaceflight to the Moon. Commanding those spacecraft and retrieving their data would require larger, more sensitive, and more numerous antennas. Another aspect of having more missions was that scheduling became more complicated. DSIF personnel had to begin addressing questions such as which mission should use which antenna for how long.

Second, NASA centers other than JPL began to manage missions. Ensuring that the communications antennas could command and retrieve data, regardless of who was responsible for the spacecraft, required changes in and formalization of policies and procedures for multimission operations.

Recognizing all those factors, William Pickering, then JPL director, formally established the Deep Space Network on 24 December 1963 (see figure 1). The newly established DSN initially consisted of three sites—Goldstone, Hartebeesthoek, and Woomera—and, at JPL, a mission control center known as the Space Flight Operations Facility.

The modern DSN retains essential aspects of the original DSIF—notably the multiple locations—but with significant changes. To communicate with spacecraft deeper in the solar system, much larger antennas were constructed within a decade of the DSN's establishment. Based on the design of Australia's 64-m Parkes Radio Telescope, the new antennas provided significantly greater signal-to-noise ratio and greater range into the solar system than the original 26-m antennas. The first of the antennas went up at Goldstone, followed by an antenna at a new site outside Canberra and then an antenna at the new site of Robledo de Chavela near Madrid. The DSN site in South Africa was closed in 1974, for diplomatic reasons associated with apartheid. Operations in Australia were consolidated to the Canberra site; the Woomera site was shut down for economic reasons. The geographical configuration of the DSN today is shown in figure 2.

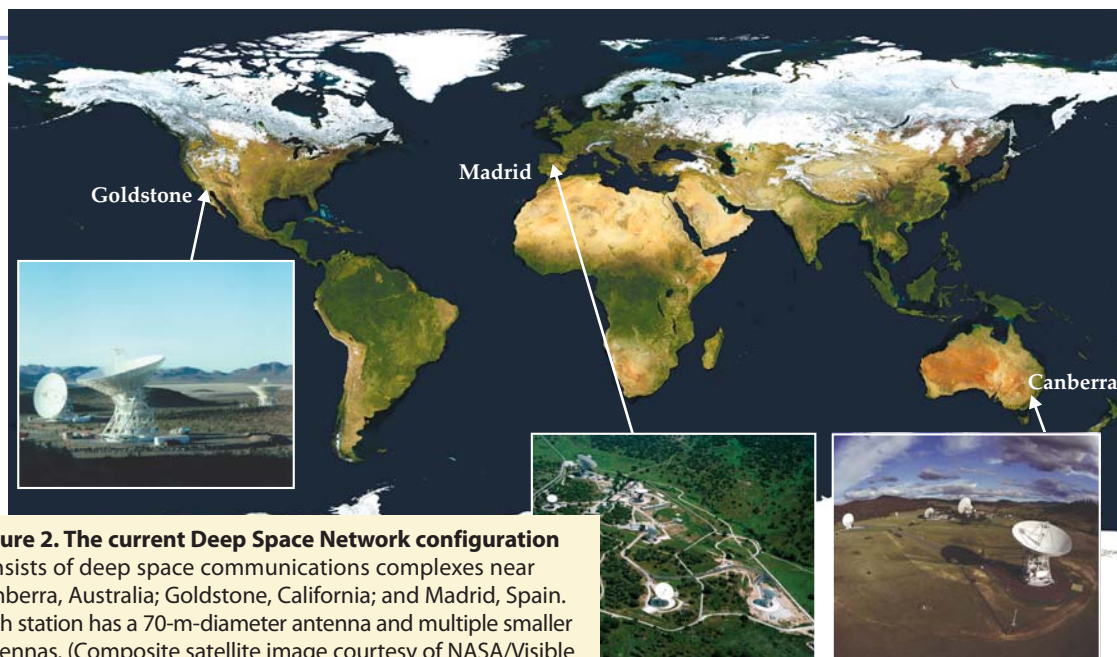


Figure 2. The current Deep Space Network configuration consists of deep space communications complexes near Canberra, Australia; Goldstone, California; and Madrid, Spain. Each station has a 70-m-diameter antenna and multiple smaller antennas. (Composite satellite image courtesy of NASA/Visible Earth. Inset photos courtesy of NASA/JPL-Caltech.)

The DSN and two Voyager spacecraft

Interplanetary communications is a dramatic demonstration of the inverse square law. The DSN was established when the goal was to reach the Moon, but it has since been used to communicate with spacecraft at all of the planets and now, with *Voyager 1*, a spacecraft arguably entering interstellar space. The table on this page illustrates how the signal flux from a spacecraft falls with increasing distance as it travels away from Earth.

All measurement systems contribute some level of noise. As a spacecraft moves farther away, the decreasing flux results in a decrease in the signal-to-noise ratio and increases the risk that noise fluctuations will obscure the transmission. Of course, once a spacecraft is launched, the onboard transmitter power is fixed, and the only way to address the flux decrease is with improvements to the ground communications system.

The Voyager program arose from an ambitious “grand tour” plan in the early 1960s that involved two spacecraft flying by the then-recognized five planets of the outer solar system. Although the plan was never realized, *Voyager 1* flew by Jupiter and Saturn and *Voyager 2* took a “mini-grand tour” of Jupiter, Saturn, Uranus, and Neptune. The two spacecraft have continued well past their initial goals, with *Voyager 1*, by many accounts, now outside the solar system.

The ever-increasing distances to *Voyager 1* and *Voyager 2* have required dramatic increases in DSN capability. Two approaches increased the effective aperture of the DSN to intercept a larger fraction of the spherical wavefront transmitted by the spacecraft. First, the diameters of the three flagship antennas were increased in the 1980s from 64 m to 70 m (see figure 3). Second, the DSN used aperture arraying to obtain synthetic increases during planetary encounters.

Aperture arraying builds on the concept of interferometry, particularly as developed in radio as-

tronomy. Individual antennas can record the signal independently to be played back later and correlated or summed. Adding appropriate time delays compensates for the geometrical time lags between the wavefronts reaching the different antennas. The result is to increase the effective aperture of the DSN and increase the signal-to-noise ratio. The aperture-arraying technique has been used between DSN antennas and also between DSN antennas and the Parkes Radio Telescope or the Very Large Array in New Mexico. The VLA is itself employed as an aperture array with an effective aperture equivalent to a 130-m antenna.

The resulting increases in the available aperture, and therefore the signal-to-noise ratio, ranged from 20%, simply from the diameter increase, to more than double by using the aperture-arraying technique.

An interplanetary fix-it tool

In multiple instances, the exquisite DSN antenna sensitivity coupled with new technology developed by DSN personnel have enabled spacecraft problems to be solved on the fly; in some cases the fixes saved complete missions. Two dramatic instances involve the *Galileo* mission after the failure of its

Signal strength and the inverse square law

Target	Distance (astronomical units)	Relative flux
Moon	0.0026	1
Mars	≈0.6	1.7×10^{-5}
Jupiter	4.2	3.8×10^{-7}
Neptune	30	7.5×10^{-9}
<i>Voyager 1</i>	≈125	4.3×10^{-10}

Distances to Mars and Jupiter are given at opposition, when they are on the opposite side of the sky from the Sun.

high-gain antenna and the *Cassini–Huygens* probe communications relay.

Launched in 1989, *Galileo* was a flagship mission to Jupiter that combined an orbiter and an atmospheric probe. The orbiter would acquire data from the probe as it fell into the Jovian atmosphere and later relay the data to the DSN. Then it would orbit Jupiter to study the planet and its moons.

The orbiter carried a deployable high-gain antenna designed to provide a data rate of 134 kilobits per second (kbps). Most likely due to long delays prior to launch, the high-gain antenna never deployed. Without it, the spacecraft had to communicate using smaller, low-gain antennas. It appeared as if communications would fall to about 10 bps, at least 10^4 smaller than the original mission design. To achieve as many of the original science goals as possible, DSN personnel worked with the *Galileo* team to improve the spacecraft software and the DSN facilities and increase the communications rate. In addition, operational improvements reduced the amount of returned data required to reach the science goals.

By the time *Galileo* arrived at Jupiter in 1995, two significant changes had been made to the DSN facilities to increase the instantaneous data rate. Jupiter was in the southern sky for *Galileo's* prime mission, so most of the DSN improvements were concentrated at the Australian complex. First, the 70-m antenna was equipped with a new ultralow-noise amplifier to reduce the noise level contributed by the antenna systems. Second, building on the experience from aperture arraying for the two Voyager spacecraft, the 70-m antenna was arrayed with the Parkes Radio Telescope and smaller DSN antennas.

Galileo itself was reprogrammed to adjust its data rate to compensate for changes in the expected signal-to-noise ratio, in a precursor to modern concepts of variable coding and modulation. As a simple illustration, consider a 1-bit data stream consisting of 0s and 1s, with additive Gaussian white noise—a reasonable approximation for deep-space communications. The energy needed to represent a bit is E_b , and the spectral energy density of the noise is N_0 . The probability P that the energy in a bit is entirely from noise is

$$P = \frac{\operatorname{erfc}(\sqrt{E_b/N_0})}{2},$$

where $\operatorname{erfc}(\sqrt{E_b/N_0})$ is the complementary error function and E_b/N_0 is the signal-to-noise ratio.

The signal-to-noise ratio for *Galileo* could vary depending on different factors. For example, when Jupiter was on the opposite side of the sky from the Sun or the spacecraft was at a high elevation as seen from the DSN, the signal-to-noise ratio might be higher. For those situations, the spacecraft was programmed to transmit more data, which could be sustained with no increase in the bit error rate. Similarly, in situations expected to decrease the signal-to-noise ratio—for example, when Jupiter was in the same part of the sky as the Sun or the spacecraft was at a low elevation—the spacecraft was programmed to transmit fewer bits. That technique effectively kept the data rate as high as it could be at all times.

In actual operations, error-correcting codes provide comparable bit error rates at lower signal-to-noise ratios, but the concept remains valid. Akin to how the internet works, the DSN and *Galileo* team also implemented packetized telemetry: The spacecraft sent data segments from instruments when they became available rather than according to a fixed schedule.

Two additional software changes designed to achieve a higher data rate were uploaded to the spacecraft. First, additional error-correction capabilities were added to the spacecraft transmissions. Typically, error correction is achieved by adding redundancy to the transmitted signal; if the expected redundancy in the encoded signal is not present, the signal can be recognized as corrupted and often can be corrected. Better error correction allows more errors to be tolerated at the receiving end of the link while maintaining overall data quality—effectively allowing a lower signal-to-noise level. For *Galileo*, the standard DSN error-correcting code had been implemented in hardware. DSN personnel developed a new, more powerful error-correcting code that could still be passed through the hardware encoder. Second, image data compression using an integer cosine transform, similar to that used for the internet, was added by reprogramming the onboard guidance computer—*Galileo's* images could be transmitted to Earth using only about 1/10 as many bits.

Together, the improvements brought the typical effective data rate up to thousands of bits per second, which regained two of the four lost orders of magnitude. They enabled the *Galileo* mission to meet 75% of its original science objectives and make a myriad of new discoveries.

The *Cassini–Huygens* mission to Saturn involved both an orbiter, NASA's *Cassini* spacecraft, and a probe for Saturn's moon Titan, the European Space Agency's (ESA's) *Huygens*. After being released toward Titan, the *Huygens* probe was to transmit data to *Cassini*, which would then relay them to the DSN.

During *Cassini's* cruise to Saturn, engineers at the European Space Operations Centre tested the relay by using a DSN antenna to transmit to the spacecraft's relay radio, mimicking the amplitude and Doppler signature of the signals that would eventually come from *Huygens*. Surprisingly, the relay through *Cassini* failed. Repeated testing indicated an anomaly in *Cassini's* relay radio system.

A team of mathematicians and engineers from the DSN, the *Cassini* project, and the ESA used the DSN to further diagnose the anomaly and construct a solution. They determined that the relay would not operate properly at the expected rates of change in the Doppler shift of the signal from *Huygens*. The team developed a new trajectory for *Cassini's* 2004 arrival at Saturn and the *Huygens* probe's release toward Titan that kept the communication within the relay radio's working range.

As a result, the *Huygens* probe's approach and descent through Titan's atmosphere was a complete success. *Huygens* produced the first photographs of the eerie surface of Titan and a plethora of other discoveries about the only other body in the solar system known to have a stable liquid on its surface.

Radar astronomy with the DSN

From the start, the DSIF was engaged in tests that would lead to its radar-astronomy capability. The first test was part of the 1960 Echo experiment, in which radio signals were transmitted from an antenna on one coast of the US, reflected off an inflatable satellite called the Echo balloon, and received by an antenna on the other coast.

The recently completed DSIF 11 antenna was quickly identified as the West Coast receiving antenna, but it had no transmitting capabilities. A second antenna, the Echo antenna, was accordingly built at Goldstone. The two antennas were successful as the west coast component of the Echo experiment, transmitting to and receiving from complementary antennas at Bell Labs in Holmdel, New Jersey. The Echo antenna was used shortly thereafter for the moon-bounce inauguration of DSIF 41 in Australia.

As *Mariner 2*, the first interplanetary spacecraft, was being readied for a 1962 launch date, absolute distances within the solar system were not known with sufficient accuracy for robust navigation. The separations of planets relative to the mean Earth–Sun distance of 1 astronomical unit (AU) were well known; for example, the semimajor axis of Venus’s orbit is 0.7 AU and that of Mars is 1.5 AU. However, to know when to fire onboard thrusters for the final course correction prior to a planetary flyby or orbital injection maneuver, it is necessary to know absolute distances.

In early 1961, Venus was between the Sun and Earth at its inferior conjunction, when it was only about 0.3 AU from Earth. In a series of experiments, the Echo antenna, equipped with a new, higher-power 10-kW transmitter, sent radar signals that would be reflected by Venus and received back on Earth by DSIF 11. Taking into account the motions of Earth and Venus during the course of the transmissions, DSN researchers analyzed the roundtrip travel times from Earth to Venus and back. The results gave a value of $1 \text{ AU} = 149\,598\,640 \pm 200 \text{ km}$, an improvement by a factor of two over the best determinations available at the time.

Radar techniques have advanced significantly beyond simply using time delays to find distances. Consider the idealized case of a transmitter on an antenna of diameter d producing nearly monochromatic radar pulses at a wavelength λ . Simple diffraction optics indicates that the transmitted beam will have an angular spread λ/d . Over interplanetary distances, the transmitted beam expands to dimensions comparable to or larger than a planet.

If the target body has a dimension R , the initial pulse will be reflected over a time comparable to the duration for the pulse to sweep over the target body, R/c (about 3 ms for a target of order 1000 km), where c is the speed of light. If the receiving system is capable of sampling with a time resolution $\Delta t < R/c$, the radar return will consist of a series of echoes as the pulse sweeps across the target.

Further, if the body is rotating, the echo will be Doppler shifted. For a target rotating with period T and rotational velocity v , the maximal Doppler shift,

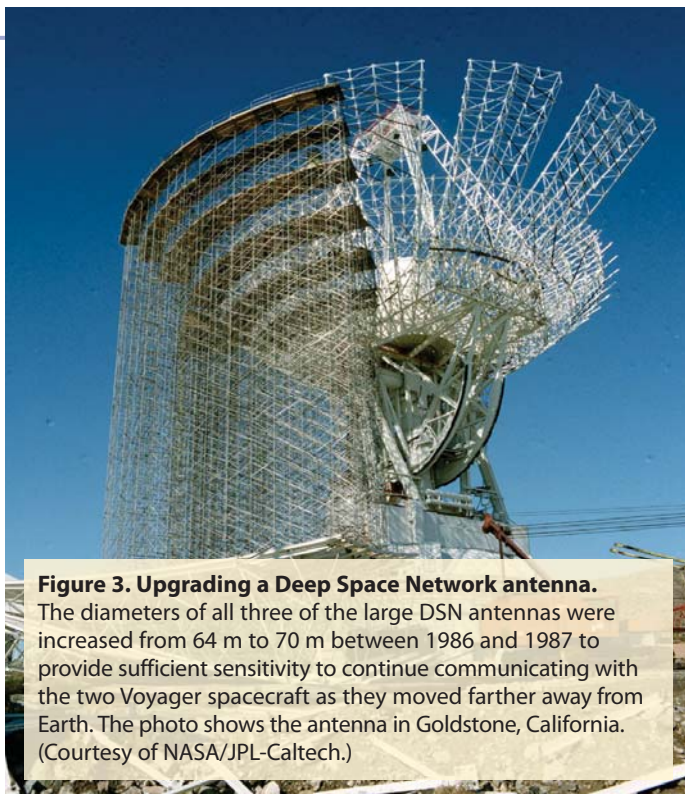


Figure 3. Upgrading a Deep Space Network antenna.

The diameters of all three of the large DSN antennas were increased from 64 m to 70 m between 1986 and 1987 to provide sufficient sensitivity to continue communicating with the two Voyager spacecraft as they moved farther away from Earth. The photo shows the antenna in Goldstone, California. (Courtesy of NASA/JPL-Caltech.)

which occurs at the target’s approaching and receding edges, is $v(v/c) \sim (R/T)(1/\lambda)$, for a signal transmitted at an original frequency ν . If the frequency resolution $\Delta\nu$ of the receiving system is finer than the maximal Doppler shift, the reflections will be a series of Doppler-shifted echoes. For the case of a uniformly rotating sphere, the regions of constant Doppler shift on the target consist of meridional lines. The received echoes, $P(\Delta t, \Delta\nu)$, which combine both the time delays and the frequency shifts, will be the delay-Doppler image of the target.

Once the astronomical unit was determined, a series of successive technical improvements to the DSN led to more distant and smaller objects being studied. Mars and Mercury were next, and the Galilean satellites of Jupiter, numerous asteroids, the rings of Saturn, Saturn’s moon Titan, and various comets now all have been imaged with delay-Doppler techniques. Figure 4 is a delay-Doppler image of near-Earth asteroid 1998 QE2 made with the DSN.

The radar astronomy results have been of interest not only to the scientific community but also to mission planners. Surprisingly strong reflections from Saturn’s rings were used to place bounds on the particle size and composition in the rings to assess the navigational hazard for the two Voyager spacecraft. The radar techniques developed by DSN personnel were used in the radar system aboard the *Magellan* spacecraft in 1990–94 to map the surface of Venus.

A solar-system-scale instrument

Scientists can investigate a host of effects by looking at the propagation of the signal from a spacecraft to the antenna. A medium with a potentially frequency-dependent optical depth $\tau(\nu)$, such as a planetary atmosphere, affects the amplitude of a signal that passes through it. Accelerations of the spacecraft

Figure 4. The Goldstone 70-m antenna captured this radar delay-Doppler image of asteroid 1998 QE2 on 29 May 2013 when it was about 6 million kilometers from Earth. The image clearly shows not only the asteroid itself but a previously unknown moon. The orbital period of the asteroid's moon was comparable to the duration of the radar imaging. Application of Kepler's laws allows the mass of the asteroid to be determined. Given the size of the asteroid, its density can also be estimated. (Courtesy of NASA/JPL-Caltech.)



will shift the instantaneous received frequency via the Doppler shift. The dispersion relation $\omega = \omega(k)$ between the frequency ω and wave number k in any medium can be used to infer properties of the medium. All those possibilities have been exploited by spacecraft-antenna communications links; they have effectively turned the combination of spacecraft and the DSN into a solar-system-scale instrument.

Starting with the first planetary missions, measurements of the Doppler shift of the spacecraft signal yielded order-of-magnitude improvements in our knowledge about the masses of the planets. Beyond simple measurements of the total mass, tracking the Doppler shift of a spacecraft, either during a flyby or in orbit, coupled with information about the densities of possible constituents, such as ices or rocks, provides constraints on the interior structure of a body. Initially used to discover mass concentrations on the Moon, the technique has since been exploited to infer the presence of subsurface oceans on Jupiter's moon Europa and Saturn's moon Enceladus.

If a spacecraft's trajectory passes behind a planet, the spacecraft-antenna line of sight penetrates to greater and greater depths of the planet's atmosphere. The spacecraft's signal will be attenuated by the neutral atmosphere's optical depth $\tau(\nu)$, which depends on the constituents, density, and temperature profile of the atmosphere. Tracking the signal amplitude, therefore, constrains the atmospheric structure. For ringed planets, the same technique determines the structure of the rings.

For a plasma, the dispersion relation leads to a frequency-dependent refractive index n , with $n^2 = 1 - \omega_p^2/\omega^2$, for a wave with a free-space frequency of $\omega = 2\pi\nu$. The plasma frequency ω_p is given by $\omega_p^2 = 4\pi n_e e^2/m_e$, where n_e is the electron density, e is the electron charge, and m_e is the electron mass. By monitoring the phase of a spacecraft's signal or using transmissions at two frequencies, scientists can determine the electron density integrated along the line of sight.

Such measurements can be used to determine the structure of a planet's ionosphere in a manner analogous to determining the structure of the neutral atmosphere. For the solar wind, a spacecraft serves as a point probe within the plasma. Tracking the signals from interplanetary spacecraft, scientists can probe the plasma physics of the solar wind, such as the spectrum of density irregularities.

Using radio-science techniques with the DSN, scientists have also tested some predictions of general relativity. For example, measurements of time delays to the two Viking Mars probes as the line of sight passed close to the disk of the Sun provided a striking confirmation of the gravitational redshift prediction.

Various astrophysical systems, such as two black holes in close orbit around each other, have been proposed to be possible sources of gravitational waves. A spacecraft and Earth represent freely falling bodies, and distortions in the local spacetime metric should produce variations in the travel time of light between them. Precise timing of the signals to spacecraft, notably those of the Pioneer, Viking, Voyager, and, most recently, Cassini missions, has led to increasingly stringent constraints on the amplitude of gravitational waves, with frequencies of order 10^{-4} Hz, washing over the solar system. Although gravitational waves have not yet been detected, the limits achieved with the DSN will not be surpassed until there is a multiple-spacecraft interferometer that uses lasers to monitor the inter-spacecraft distances.

From deep space to everyday life

In the course of producing ever more sensitive antennas and receiving systems, DSN personnel have developed technologies that have since transitioned to everyday life. In many cases, the technology was invented elsewhere, but DSN personnel developed the first applications outside of a laboratory. Here we highlight two examples of such technologies.

As the *Galileo* mission illustrated, signal encoding can enable higher data rates because errors can still be recognized at lower signal powers. The technique was first implemented on the *Mariner 6* and *Mariner 7* spacecraft and resulted in data rates astonishingly higher than initially planned: 16.7 bps, compared with the 0.27 bps planned. The cyclic error-correcting codes based on an algorithm developed by Irving Reed and Gustave Solomon became a standard DSN means of achieving higher data rates. The performance of Reed-Solomon codes was such that the Consultative Committee for Space Data Systems, an international forum serving the world's space agencies, adopted them as a standard for space communications. Later, the codes were implemented in the digital television broadcasting satellite standard, and they are now a routine feature in many data-storage media.

A more prosaic example was the construction of the 64-m DSN antennas. Unexpected cracking in the concrete pedestal supporting the Goldstone antenna was discovered in 1980. Further investigation revealed that a chemical reaction between the concrete's aggregates, such as silica, and cement caused the aggregates to expand and slowly crack the concrete over time. The so-called alkali-aggregate reaction is well known within the construction industry,

and highway agencies had already identified it by 1940. What was unexpected was the rate of failure in the Goldstone pedestal. The DSN worked with the construction industry to develop a new concrete mix to repair it. In turn, that experience of working with the DSN has led construction firms to formulate better concrete mixes for highways.

The next half-century

Undoubtedly, the next 50 years will see the DSN continue to deliver stunning images and data from spacecraft across the solar system and to peer deep into the universe. Not only will planetary missions continue to use the DSN, but astrophysical missions, such as the *James Webb Space Telescope*, will increasingly use it as they seek to move farther from Earth and the Sun to make ever more sensitive measurements.

Moreover, the international space community is likely to become increasingly integrated. The *Cassini-Huygens* mission is only one of the long-standing interactions between NASA and ESA. Another, more recent instance that involves DSN communications is the ongoing *Rosetta* mission to comet 67P/Churyumov-Gerasimenko. More generally, an agreement is in place between ESA and NASA to use the DSN for various ESA missions, and ESA is beginning to establish its own series of deep-space antennas, largely modeled on the DSN.

Similarly, the DSN has been an integral part of Japan Aerospace Exploration Agency missions and has been engaged with the Indian Space Research

Organisation as it begins to conduct deep-space explorations such as its Mars Orbiter Mission.

The DSN is also developing technologies, such as laser communications, designed to achieve even higher data-transmission rates. Rather than static images, future deep-space spacecraft will send back movies, and rather than single spectra, they will deliver complex, multidimensional data products analogous to what satellites around Earth produce.

We would not have been able to write this article without the dedicated efforts of many people at the Goldstone, Madrid, and Canberra complexes; at JPL; and at NASA headquarters.

Additional resources

- ▶ D. J. Mudgway, *Uplink-Downlink: A History of the Deep Space Network 1957-1997*, NASA SP-2001-4227, NASA (2001).
- ▶ J. H. Yuen, ed., *The Deep Space Communications and Navigation Series*, Wiley (2003-13), available at <http://descanso.jpl.nasa.gov/monograph/mono.html>.
- ▶ L. J. Deutsch, "The Galileo Spacecraft: A Communications Legacy for Future Space Flight," in *The Three Galileos: The Man, the Spacecraft, the Telescope—Proceedings of the Conference Held in Padova, Italy on January 7-10, 1997*, C. Barbieri et al., eds., Springer (1998), p. 95.
- ▶ J. I. Statman, L. J. Deutsch, "Galileo's Telecommunications Using the Low-Gain Spacecraft Antenna," in *The Three Galileos*, p. 107.
- ▶ L. J. Deutsch, "Resolving the Cassini/Huygens Relay Radio Anomaly," in *2002 IEEE Aerospace Conference Proceedings*, vol. 3, IEEE (2002), p. 3-1295.
- ▶ "Deep Space Network Now" (a real-time view of the spacecraft being tracked), <http://eyes.nasa.gov/dsn/dsn.html>. ■



DO YOU KNOW WHERE YOUR FLANGES COME FROM?



MDC VACUUM FLANGES ARE PROUDLY MADE IN THE USA!



DEL-SEAL™ CF METAL SEAL FLANGES, ISO KF KWIK-FLANGE™, ISO LF LARGE-FLANGE™, & ANSI-ASA FLANGES



MDC Vacuum Products, LLC
23842 Cabot Boulevard
Hayward, California 94545 USA

Toll Free: 800-443-8817
sales@mdcvacuum.com

WWW.MDCVACUUM.COM