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Voyager Telecommunications: The Broadcast from Jupiter

Attention to detail, complex coding, cyrogenic masers, and a global antenna network tell us of another world.

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Summary. Sweeping past Jupiter, the Voyager 1 spacecraft presages a new era in the exploration of the solar system. Not since the TV return from Apollo has a spacecraft returned information of such volume and pictures of such startling clarity. Yet this feat was accomplished from a distance 1770 times as great as that of the lunar adventure. The communication system responsible for this remarkable achievement is a compilation of elements ranging from tiny integrated circuits to enormous ground antennas. This article seeks to describe the way in which data are returned from these fascinating, faraway bodies and to convey the excitement of the engineering work that supports our scientific endeavors.

Giant Jupiter has given up some of its secrets in an unprecedented flood of multicolored images, spectrograms over huge ranges of the electromagnetic regime, particle counts, and a host of intriguing and startling data. The preliminary results of this mission are described in this issue of *Science*. In this article we describe how these data were returned to make it appear that we were receiving the evening news from Jupiter.

The star in our story is the Voyager telecommunications system. Its province extends from the tiny integrated circuits that put together the transmission in complex algebraic ways to the people and tools of the Jet Propulsion Laboratory (JPL). The signal path passes from Jupiter's environs to the 2.7-million-kilogram antenna behemoths of the Deep Space Network (DSN) (*1*) that collect the fraction of an attowatt (10^{-18} W) with which the spacecraft illuminates each square meter of Earth, and through the global NASA communications system (*2*) that brings the data home to JPL. All these elements play together to interpret and display the images and information that the spacecraft discerned 40 minutes earlier and 700 million kilometers away.

Fifteen years ago, when Mariner IV passed Mars, 20 pictures of the surface were returned. They showed a barren, lunar-like surface, substantially different from the topography we know today (*3*). This biased interpretation of the diverse martian terrain was caused by the paucity of data that could be returned with the techniques then available. In describing the Voyager system, we are discussing a spacecraft that returns data at a rate nearly 14,000 times as fast as was possible a decade and a half ago, while transmitting from more than three times as far away as Mariner IV.

This increase in capability (a factor of 150,000, when the range difference is accounted for) is largely the result of improvements in both the spacecraft and ground systems. No breakthroughs were required, but rather refinement after refinement, and the application of new technology when it was judged sufficiently mature to add its contribution.

To give a picture of how this work proceeded, we first describe some mechanisms for the long-distance, free-space transmission of information by means of radio waves. We then turn to the Voyager requirements to show how these mechanisms are put to use and present a summary of the Voyager data return accomplishments. Finally, we discuss the future of telecommunications as an enabler of the exploration of the cosmos.

Deep Space Communications: A Primer

The radio link between the ground and a spacecraft is a tool for the transmission of information and control. Its most glamorous use is for telemetry, the return of data that tell us something about the spacecraft's surroundings. Telemetry is characterized by its volume—lots of data—and by its requirements for moderate to high quality: few errors of transmission are permitted. Video data use large volumes of telemetry and, because of the redundancy present in a picture of a natural object, video data have a need for only moderate quality. That is, since there is a high correlation between adjacent pieces of a TV picture, a substantial amount of error (snow) can

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Table 1. Typical Voyager telecommunications parameters.

Parameter	Unit	Value		
		Telemetry		Command
		X-band	S-band	
Carrier frequency, f	Gigahertz	8.4	2.3	2.1
Transmitter power, P_t	Watts	21.3	6.6	1×10^4
Antenna gain, G_t	Unitless	6.5×10^4	3.2×10^3	1.2×10^6
Range at Jupiter, R	Meters	6.8×10^{11}	6.8×10^{11}	6.8×10^{11}
Receiving antenna diameter	Meters	64	64	3.7
Receiving antenna effective area, A_r	Square meters	1.1×10^3	2.2×10^3	3.9
System losses, L	Unitless	1.2	1.1	1.0
System noise temperature, T_s	Kelvins	28.5*	22.3	1.5×10^3
Power flux density at receiving antenna, $P_tG_t/4R^2$	Watts per square meters	2.4×10^{-19}	3.6×10^{-21}	2.0×10^{-15}
Signal-to-noise ratio, P_r/N_0†	Hertz^{-1}	6.5×10^5	2.3×10^4	3.7×10^5

*This number may increase by a factor of 10 in the rain. †115.2 kilobits per second requires a P_r/N_0 of 2.1×10^5 for a BER of 5×10^{-3}; 40 bits per second requires a P_r/N_0 of 3.2×10^2 for a BER of 5×10^{-3}.

be removed later from the received picture. Nonimaging science data are usually of lesser volume and have more stringent needs for accuracy. Very few errors can be tolerated in such data without producing a garbled message.

Information must also be conveyed to the spacecraft from the ground. The less we know about the target body, the more adaptable the spacecraft and mission plan must be. This adaptability is achieved by ensuring that the spacecraft can alter its planned profile in a way that enhances the overall scientific output. This alteration is performed by transmitting radio waves from the ground to the spacecraft (uplink) that tell it to take a specified action, with specified parameters, at a definite time. This uplink telemetry is known as command. It is characterized by a low data volume (when compared to telemetry) and a requirement for extremely high quality. No misinterpretation of the mission director's orders can be tolerated.

The radio link has a third, less advertised function which is as vital to mission success as the first two. In their passage through space, the signals transiting between spacecraft and ground are altered by the medium through which they travel, by gravity, and by the relative velocity of the spacecraft and ground stations. Further, the signals are delayed substantially over these very long paths. By exceedingly accurate measurements of the radio-wave characteristics, the position of the spacecraft, its velocity, and its acceleration can be determined. Simultaneously, important data are gained on the structure, composition, and temperature of the atmosphere of a planet that may occult the signal, on the plasma state along the ray path, and on planetary and solar gravitational fields. Thus, the process of transmitting radio signals to and from a cooperative target can allow us to navigate the spacecraft to its destination, measure properties of the gas and plasma in the path, and determine gravitational and relativistic effects. These "radiometric" data are characterized by their very low rate, their need for long-term stability, the extreme accuracy of measurement necessary (sometimes to parts in 10^{13}), and by the extent of data processing required to turn the signal into information (4).

The performance of these three functions, telemetry, command, and radiometrics depends on a class of parameters known generically as signal-to-noise ratios or SNR's. For each measurement that is desired, the quality with which that measurement can be made is dependent on the amount of signal that is present in relation to the noisy environment in which that signal must be detected. In general, the quality of the measurement can be improved only by increasing the signal power, quieting the environment, or increasing the efficiency with which the SNR is used.

Let us now examine these options, speaking for convenience in the language of telemetry, that is, considering the spacecraft to be the broadcaster.

Signal power can be increased by three actions. First, the transmitter power can be increased. This, of course, has system repercussions. Even though the spacecraft-transmitted power (typically between 10 and 30 watts) is less than that required to operate a refrigerator light bulb, the input power required to generate it represents a substantial fraction of the total spacecraft power (5).

A more palatable approach is to increase the usefulness of that power by focusing it more intensely on the target (the ground antenna) and by providing the largest possible ground antenna area with which to collect the incident energy. Better focusing requires a larger spacecraft antenna; thus we fly as large an antenna as size and weight constraints and the ability to aim the resulting narrow beam will permit (6).

The third action is to reduce to an absolute minimum those losses which are under the designers' control. Clearly some losses must be accepted; for example, the loss due to the constant microwave static radiated by the universe itself. Other losses, such as ohmic loss and impedance mismatch are reduced as far as a reasonable hardware configuration will permit.

The reception process introduces most of the noise or static that corrupts the incident signal energy. Every object radiates energy at radio frequencies. Indeed, even the omnipresent 3 K thermal background of the universe produces radio noise that is an important fraction of the signal power we can hope to supply to the ground receiver. One of the most remarkable achievements of the DSN has been its implementation of receiving antennas and amplifiers whose noise production is scarcely more than this background radiation. Because the ordered energy levels of the atoms and molecules themselves provide the required signal amplification, rather then the free electrons which do the job in vacuum tubes and transistors, the cryogenically cooled maser amplifiers of the DSN produce a noise power that is actually less than the 3 K background that the universe itself adds. In typical operations the total system noise power corrupting the spacecraft signal is less than 4×10^{-21} W in the control loop that detects the spacecraft central transmission frequency (the carrier). Thermal fluctuations in electron devices do not permit this kind of performance.

These considerations go into producing an SNR that is defined by the equation

$$P_r/N_0 = (P_tG_t/4\pi R^2)\, A_r(1/LkT_s) \quad (1)$$

where P_r is the received power in watts; N_0 is the noise spectral density, in watts per hertz; P_t is the transmitted power, in watts; G_t is the gain or focusing power of the transmitting antenna and is that fraction of the sky to which the signal is confined divided by the entire sky solid angle, steradians divided by steradians (unitless); R is the distance between transmitter and receiver, in meters; A_r is the effective area of the receiving antenna, in square meters; L is the total loss encountered from all attenuation mechanisms other than distance, unitless ($1 \leq L < \infty$); k is Boltzmann's constant = 1.38×10^{-23} joules per kelvin; and T_s is the system equivalent noise temperature, in kelvins.

This equation is fundamental because in all aspects of telecommunications the utility of the power received depends only on its relation to the noise that corrupts it. Thus, while signals from the spacecraft may illuminate Earth with attowatts of power, the noise in the system is kept to a small fraction of that value; hence the signal-to-noise ratio can be very large and it is set by design to provide all the signal energy that is necessary to estimate accurately what message was originally sent. To demonstrate this relationship and give the reader a feel for the magnitude of the effects involved, we provide in Table 1 some typical numbers for the Voyager system for each of the two frequencies at which the spacecraft transmits, and for the single frequency at which it receives.

Physically, Eq. 1 simply says that the signal-to-noise ratio, P_r/N_0, is equal to the power flux density, W/m^2, playing on the surface of the receiving antenna ($P_tG_t/4\pi R^2$), times the area which gathers that power, A_r, divided by the losses endured, L, and the noise power per hertz, $N_0 = kT_s$, W/Hz.

If both the spacecraft and ground antennas have a fixed aperture, Eq. 1 can be written in a different form, since the gain of an antenna is directly related to its effective area (6):

$$P_r/N_0 = P_tA_tA_rf^2/c^2R^2L\ kT_s \qquad (2)$$

where A_t is the effective area of the transmitting antenna, in square meters; f is the transmitted frequency, in hertz; and c is the speed of light on the medium, 3×10^8 m/sec in the near vacuum of space.

All of the telecommunications link requirements must be satisfied within the constraints imposed by the planned mission and by spacecraft limitations. The basic trajectory of the spacecraft defines transmission range, Doppler shifts, and angular geometry all as functions of time and also defines the required life of the hardware. The spacecraft that carries the telecommunication system equipment constrains the size, weight, and power consumption of the equipment and places limitations on antenna beamwidths and pointing accuracies. Hence the designers' ingenuity must be used to meet the mission requirements for data quantity and quality with the minimum spacecraft power and antenna size possible. It is the efficiency with which these resources are used that determines the success or failure of a particular design.

Equation 2 demonstrates that higher frequencies generally result in better performance (7). The frequency band allocated for deep space research, about 8.4 gigahertz, is used for Voyager telemetry. On this "carrier" are modulated the spacecraft data, already coded for protection from error. It is the choice of modulation and coding methods that determines the efficiency with which the SNR is used.

The methods of modulation and coding chosen are strongly affected by the data quality required. For each data type an allowable error rate must be defined by the experimenter. This is necessary in order to make the most efficient use of the power available. Since noise invariably corrupts the signal, the estimate of what bits (8) were originally sent will occasionally be incorrect. Normal variations in the noise process will sometimes reverse the polarity of the decision process, substituting a "one" when a "zero" was sent, and vice versa. Some data are particularly sensitive to such errors, while other data are more robust.

Voyager imaging data can accept a bit error rate (BER) or probability of bit error of 5×10^{-3}. Most other data are not as tolerant. The Voyager nonimaging science has a requirement for a BER of 5×10^{-5}. It would be extremely inefficient to provide this latter error rate for all data because obtaining a lowered BER requires either higher received power or additional coding complexity.

Modulation of the carrier is done by varying the phase of the transmitted wave in a precise manner. In general, this results in a signal, $S_r(t)$, whose mathematical description is as follows:

$$S_r(t) = (2P_r)^{1/2}\sin(\omega_c t + \theta(t) + \theta_0) \quad (3)$$

where P_r is total received power; ω_c is (radian) carrier frequency; and θ_0 is uniformly distributed phase noise.

Generally,

$$\theta(t) = \sum_{i=1}^{N} \theta_i S_i(t)\, D_i(t) \qquad (4)$$

where θ_i is the constant chosen for optimum performance, the "modulation angle"; $S_i(t)$ is the subcarrier waveform normalized to $S_i(t)_{max} = 1$; $D_i(t)$ represents data bits or symbols (see below), $D_i(t) = \pm 1$; and N is the number of data channels in the system. The subcarrier functions to keep the data spectrum out of the bandwidth of the control loop that detects and estimates the carrier phase, and to maintain spectral separation between data channels. A square wave, $S_i(t) = \pm 1$, is usually used because it provides the most efficient use of the available power. Then by estimating the transmitted phase on the ground, we can reconstruct the data that were originally sent.

It is not necessary for $D_i(t)$ to be the data bits themselves, and in fact for the same bit error rate substantial energy can be saved by coding the data. For an uncoded channel each symbol is one data bit; that is, each transmitted phase shift $+\theta_i$ or $-\theta_i$ [$D_i(t) = \pm 1$] corresponds to the zero or one that was output from the instrument. A coded channel is one for which the value of the data bit is determined by more than one symbol in a deterministic way. In other words, many phase shifts may be used to determine one bit. This redundancy of transmission provides a means of determining the correct data bit in the presence of symbol errors, at the cost of expanding the frequency occupancy of the signal. The result is that the bit error rate is lowered for a given value of the data SNR, or, conversely, that a given data SNR will produce a lower bit error rate.

There are many algorithms that provide good performance improvements over the uncoded case; Fig. 1 gives some examples. In general, however, the greater the performance advantage of using the code, the more complex is the process of decoding. The practical limit in gain due to coding then is the speed of the ground computers which can be applied to decoding.

One way in which we can send simultaneously two data streams of differing error requirements is by choosing $i = 2$. Using $\theta_0 = 0$ for illustrative purposes, we can expand the trigonometric function to get an equivalent expression

$$S_r(t) = (2P_r)^{1/2}\,[\underbrace{\cos\theta_1\cos\theta_2\sin\omega_c t}_{\text{Carrier component}} + \underbrace{S_1(t)\,D_1(t)\sin\theta_1\cos\theta_2\cos\omega_c t}_{\text{Data 1 component}} + \underbrace{S_2(t)D_2(t)\cos\theta_1\sin\theta_2\cos\omega_c t}_{\text{Data 2 component}} - \underbrace{S_1(t)\,D_1(t)\,S_2(t)\,D_2(t)\sin\theta_1\sin\theta_2\sin\omega_c t}_{\text{Intermodulation product}}]$$

The power in the signal is distributed as follows: carrier power, $P_r \cos^2 \theta_1 \cos^2 \theta_2$; data 1 power, $P_r \sin^2 \theta_1 \cos^2 \theta_2$; data 2 power, $P_r \cos^2 \theta_1 \sin^2 \theta_2$; and intermodulation power, $P_r \sin^2 \theta_1 \sin^2 \theta_2$. By appropriate selection of θ_1 and θ_2 the total power P_r can be allocated between the carrier, data 1, data 2, and the intermodulation products to achieve widely differing error rates, provided the required data channel SNR's can be obtained with the available P_r/N_0.

However, note that the intermodulation product represents wasted power and hence lowers the communications efficiency, and while the signals may be combined in different ways than the simplest method shown here, there is always such a loss in a multichannel system. Nevertheless, until Voyager, this was the method of choice for space communications involving transmission of two data streams with widely disparate error rate requirements because the alternative of transmitting the entire data stream with the lower bit error rate was even more costly to performance.

As computer speeds have increased, a more interesting alternative has become available and is the one used on Voyager. First, note that if $i = 1$, no power is lost from the signal; it is all usable. The use of more than one channel is inherently inefficient. Suppose then we simply encode the two data types differently and subsequently combine them into a single symbol stream, providing more protection for the more fragile data while not loading up the robust data with unnecessary overhead. Such a scheme is called concatenated coding and is illustrated in Fig. 2. With this system, the Voyager requirements for a two-orders-of-magnitude BER difference between imaging and nonimaging data can be easily supported with very little loss in channel efficiency. The cost is in increased ground-processing complexity.

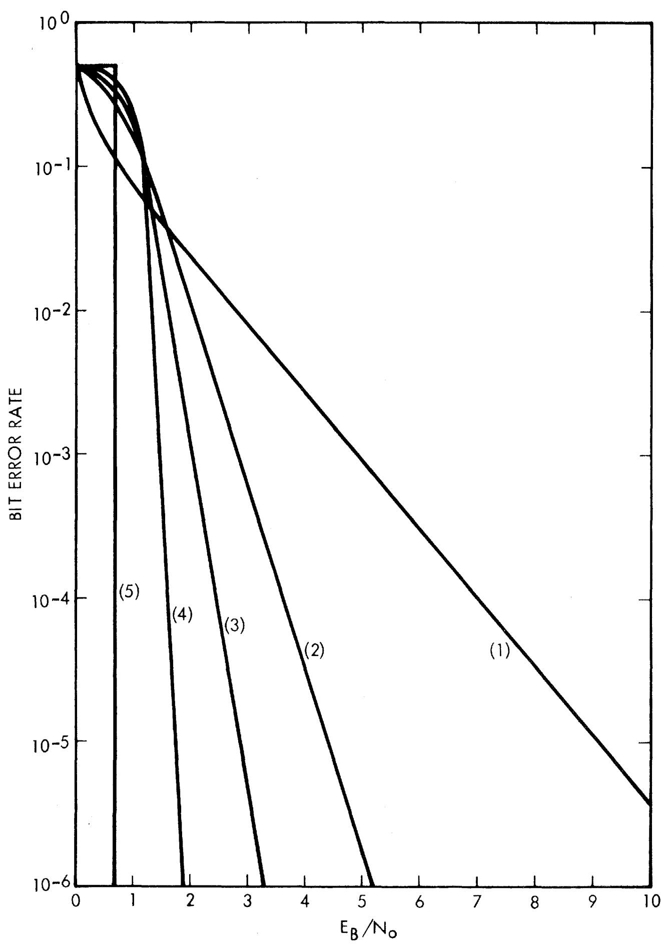
Optimizing all of the many link parameters while remaining within the system constraints is the task faced by the deep space communications system designer. In the process of design development, some of the parameters are controllable. The operating frequencies may be selected within the space research allocations, spacecraft antenna size may be chosen, the telemetry coding schemes may be specified, the power levels for the different link components may be optimized, and operating bandwidths may be selected. These choices are highly coupled and all are subject to limitations, but nonetheless, they are controllable parameters and are subject to design trade-offs. Other parameters that affect the links are less controllable. Some of these are Earth weather which degrades our signals; noise temperatures of the galactic background, sun, and planets; solar system geometry; and even the angle at which the ground station observes the spacecraft (low elevation angles put more air in the signal path).

Now that we have laid some foundation for understanding the manner in which a telecommunications system performs its function, we shall describe the Voyager implementation.

The Voyager Design: Spacecraft

The design of any telecommunications system begins with an examination of the mission requirements for telemetry, command, and radio metrics. For Voyager the telemetry data rate requirements vary over several orders of magni-

Fig. 1. Different methods of encoding, or adding redundancy to the transmitted data, result in different requirements for signal-to-noise ratio to obtain the same bit error rate. Illustrated are four curves of bit error rate plotted against signal energy per bit, $E_B = P_r T_b$ divided by noise spectral density, N_0, the appropriate SNR for this parameter. T_B is the bit duration. Curve 1 is for no added redundancy, the uncoded case. Curve 2 is the code used for the Mariner Mars missions, 1969 and 1971; the Mariner Venus Mercury mission, 1973; and the Viking mission, 1976. Curve 3 is the Voyager imaging code (inner code), and curve 4 is the Voyager nonimaging science concatenated code (see text). Curve 5 is the theoretical upper bound on performance improvement (infinite bandwidth case), Shannon's limit (*16*).



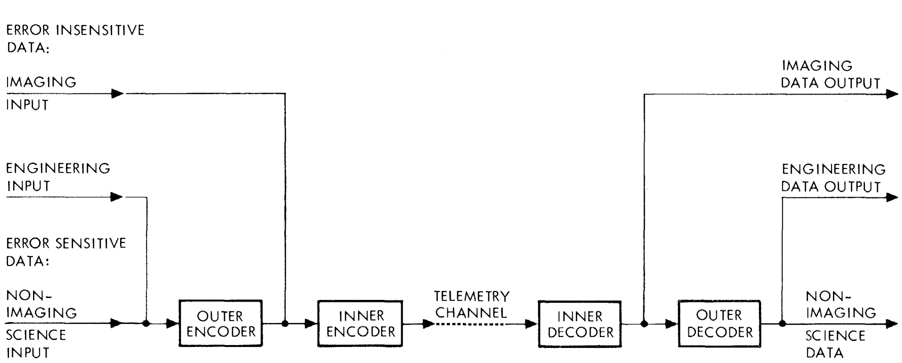


Fig. 2. Concatenated coding scheme of the type used for Voyager telemetry. To simplify ground processing, Voyager engineering data were protected by the outer code, even though this was not demanded by the performance requirements. The 40 extra symbols required per second were an insignificant tax on the hundreds of kilosymbols per second routinely transmitted.

tude as the mission experiences frenetic months of activity around its four, or more, planetary encounters (Voyager 2 may see Uranus and even Neptune) separated by the relative calm of cruise phases lasting more than a year. The encounter telemetry requirements include imaging science, nonimaging science, and spacecraft engineering data. The imaging science and special electromagnetic waveform science require the highest data rate. The desired maximum frame rate of one picture every 48 seconds translates into about 107,000 bits per second (one picture consists of 800 × 800 picture elements; each "pixel" is an eight-bit binary number indicating the intensity level of that part of the picture). Nonimaging science requires a maximum rate of 3560 bits per second, and engineering data require a modest 40 bits per second. In contrast, the cruise periods require a maximum rate of 2580 bits per second for nonimaging science along with the same 40 bits per second for the engineering data.

The command link data rate requirements are determined by the size of the onboard computers which control the spacecraft. Most onboard activities are preprogrammed into these computers by periodic command sequences. It is desirable to complete these transmissions within the view period of a single ground transmitter station (about 8 hours). In order to have the capability to completely reload the computer in this time, the command link operates at 16 bits per second. The required bit error rate is 1×10^{-5}, the most stringent BER threshold of the design.

In addition to the telemetry and command data transmission links, the telecommunication system provides vital data for navigation and radio science. The location and velocity of the spacecraft is determined by a combination of range and Doppler measurements (*9*). Range is determined by transmitting a code to the spacecraft and retransmitting it to Earth. The measured time delay gives an estimate of radial distance. The instantaneous Doppler shift of the carriers is used to determine radial velocity, and the variations of Doppler shift induced by Earth rotation are used to determine the angular position of the spacecraft (*4*). Radio science experimenters use the carriers to measure planetary atmosphere absorption, radio beam refraction, gravitational parameters, and relativistic effects, and use the differential phase and ranging signal delay to measure the charged particle content of the ray path (*10*).

The actual design of a telecommunications system for a specific mission is invariably based on the systems designed for previous missions. Budgets and development schedules simply do not allow total redesign. Design of spacecraft systems tends to be conservative and uses proved approaches and components when possible. Obviously, repair after launch is limited to correcting problems that can be anticipated in the design process. The design is generally begun with a comparison of the mission requirements and the known capabilities of previous designs. New hardware techniques result from experiments flown on previous missions. New coding and modulation schemes are extensively ground-tested.

The Voyager telecommunications systems design was heavily influenced by the Mariner-Venus-Mercury (MVM) and Viking systems. None of these, however, would provide the tenfold improvement needed for the Voyager telemetry

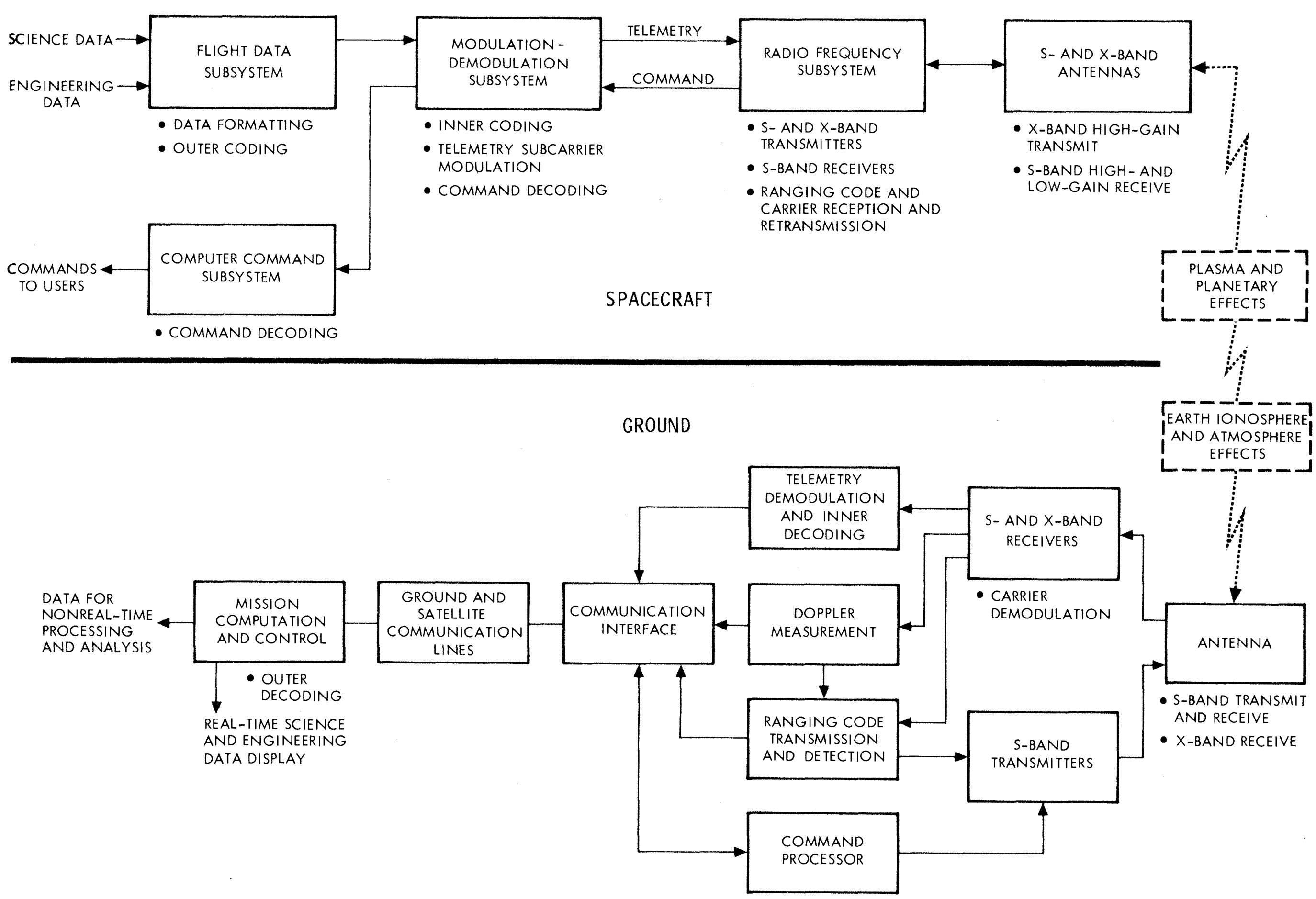


Fig. 3. Block diagram of the Voyager telecommunications system.

link. Both MVM and Viking were S-band systems (operating at 2.3 GHz), but both flew low-power X-band (8.4 GHz) transmitters as experiments. X-band was therefore considered proved technology. Voyager thus became the first spacecraft to use X-band as the primary encounter telemetry link frequency. However, since X-band reception capability was only available at the DSN's largest (64 m) ground stations, S-band was designated as the primary cruise link. This substantially relieved inter-mission scheduling conflicts (Helios, Viking, Pioneer, Voyager) so that the big antennas could view the spacecraft in more active mission phases while Voyager cruise telemetry was received by the smaller (26 and 34 m) and more available facilities.

A block diagram of the Voyager telecommunication system is shown in Fig. 3. The major design constraints were as follows. The size of the spacecraft antenna was limited by the interior dimensions of the launch vehicle shroud and by the limits of the spacecraft attitude control system capability to accurately point the extremely narrow X-band antenna beam. Both S-band and X-band transmitters were designed to operate at two power levels since both were required to have about 20-W output at some time in the mission, but the spacecraft could not stand the thermal load that would have occurred if we allowed the two to operate simultaneously in the 20-W power modes.

Table 2. Deep Space Network antenna characteristics.

Location	Deep space station identification	Antenna size (m)	Frequency
Australia			
Tidbinbilla	42	26	S-band
Tidbinbilla	43	64	S-, X-band
Honeysuckle Creek	44	26	S-band
Spain			
Robledo	61	26	S-band
Robledo	63	64	S-, X-band
Cebreros	62	26	S-band
Goldstone, California			
Pioneer	11	26	S-band
Echo	12	34	S-, X-band
Mars	14	64	S-, X-band

As the design proceeded, detailed predictions of the system performance were made for each phase of the mission. These predictions included a statistical model of the weather effects expected on the X-band links, since this frequency is subject to severe noise temperature increases when it rains. A mission profile was then designed which specified the telemetry rates to be used during every pass over each deep space station. The strategy was based on a 90 percent probability of receiving the planned data rate and included a strategy for reducing the data rate by command when rain produced severe degradation.

The design features that lead to the Voyager improvement in system capability can be summarized as follows.

1) Use of X-band rather than S-band for telemetry.

2) Development of a dual-power (12 and 22 W) X-band traveling wave tube amplifier, designed to minimize weight and maximize efficiency while operating over a design life of 50,000 hours.

3) Use of a 3.7-m antenna. This antenna, the largest solid reflector ever flown, has a very narrow beam at X-band and presents severe requirements on antenna pointing (0.14°). The spacecraft attitude control system provides the requisite capability.

4) Development of a single-channel telemetry system with concatenated coding to provide efficient transmission of data with two levels of error rate performance.

Figure 4 shows the complete spacecraft, crowned by its high-gain antenna. The Voyager system telemetry capacity is so great that were it possible to implement this capacity on a communications satellite it would permit every U.S. citizen to speak to a U.S.S.R. counterpart simultaneously—more than 500 million phone conversations!

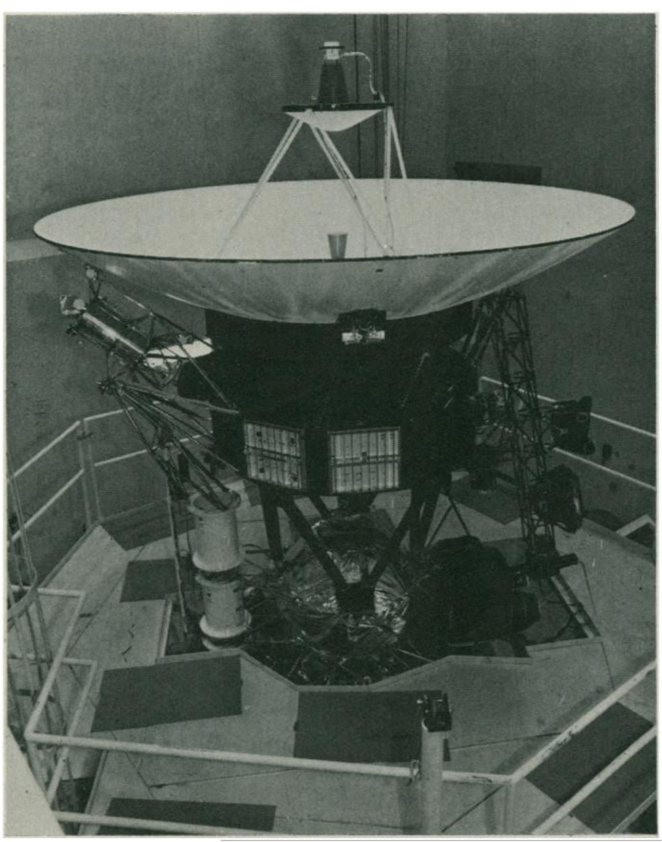
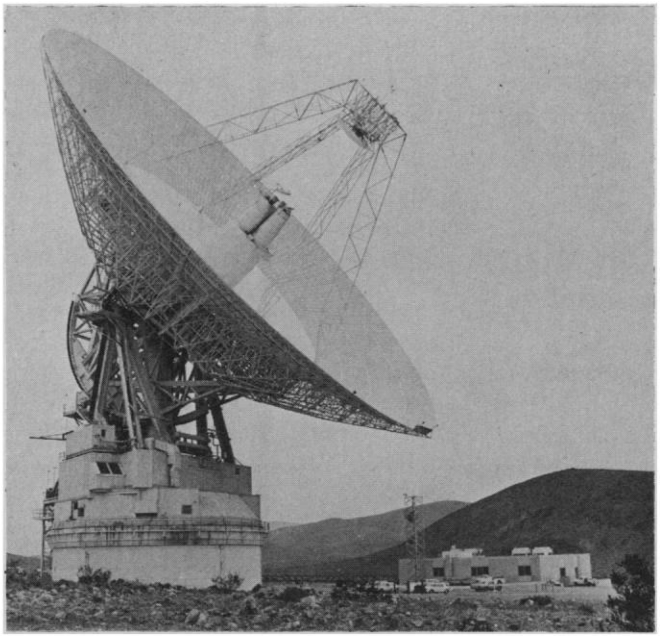


Fig. 4. The Voyager spacecraft in its launch configuration with its appendages stowed.

The Voyager Design: Ground System

Selected elements of the DSN, along with the NASA communications system's data transmission capabilities, form the tracking and data system which so ably supported Voyager's operational and scientific achievements. Here we describe the ground data system's key characteristics, giving primary attention to the DSN's deep space stations.

The DSN provides the United States with communications capability for space exploration at planetary distances. The network is an important national resource of international scope and global scale. Spanning three continents, its communications complexes are located near Canberra, Australia; Madrid, Spain; and Goldstone, California. These locations, having a longitudinal separation of about 120°, provide for continuous tracking of spacecraft traveling in or near the plane of ecliptic. Each of the three complexes is composed of three operational deep space stations. Table 2



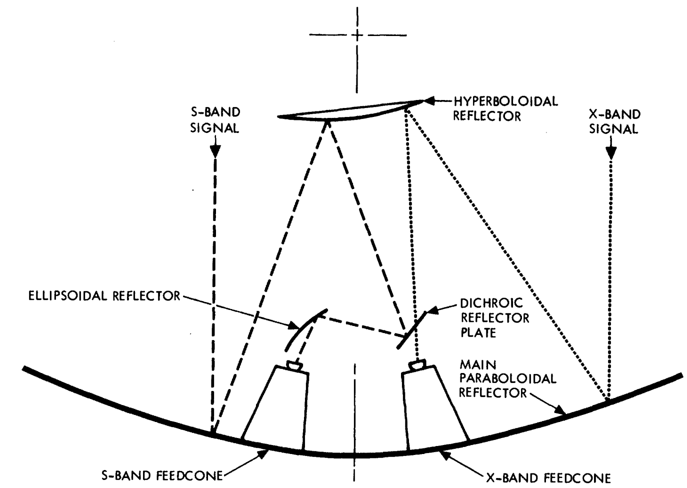


Fig. 5 (left). A 64-m Deep Space Station (DSS-14 at Goldstone, California). **Fig. 6** (above). The reflex feed used on the DSN's 64-m antennas makes possible the reception of two widely separated frequencies. Shown here are two single-ray traces to illustrate the manner in which the different frequencies are brought to a focus at different points.

provides basic antenna characteristics associated with each complex. Stations with 26-m antennas played an important role during Voyager's interplanetary cruise operations. However, the 64-m stations were the essential element for data acquisition during the Jupiter encounter. Since this encounter is of primary interest here, we will focus mainly on the typical 64-m station and its communications with JPL. The three 64-m stations that make up the encounter-support subnetwork are essentially identical except for location.

During January through April 1979, both Voyager 1 and the Pioneer Venus Orbiter were in critical, primary mission phases. Both required continuous coverage from the 64-m subnetwork. The competing spacecrafts' station viewing periods of about 10 hours each had nearly complete separation in time. Therefore, all tracking requirements could be met if the subnetwork sustained near-continuous operations, with maintenance, calibration, and countdown times reduced significantly below normal. Meeting Voyager 1's critical data quantity, quality, and timeliness requirements in the presence of this loading condition gave the DSN one of its greatest challenges. The objective was to recover all critical Voyager data and deliver at least 99 percent of it error-free in a real-time or near real-time manner. This included handling of extended periods of 115,200 bits-per-second data by way of the X-band link. The DSN's international team of people met this challenge in a near problem-free manner.

The 64-m-diameter, dish-shaped antenna shown in Fig. 5 is the DSN's most visible asset. These antennas were built in natural bowl-like areas to gain the advantage of terrain shielding from man-made radio interference.

Acquisition of the Voyager downlink signal begins when this 0.34-hectare (0.85-acre) antenna is computer-driven in azimuth and elevation to be on-point near the local horizon as the spacecraft rises. The antenna surface, a perfect paraboloid to 1 millimeter (root-mean-square of surface error), is suitable for both S-band and X-band frequencies. Figure 6 illustrates the Cassegrainian optics which collect a radio signal on the primary surface and reflect it onto the hyperbolic subreflector where it is focused on the feed cone assemblies (small antennas that direct the energy from the large reflector to the receiver masers). A reflex feed assembly in front of the feed cones provides for separation and simultaneous handling of Voyager's S- and X-band signals. The X-band signal passes directly through a dichroic plate (*11*) into the X-band feed cone, while the S-band signal is reflected from the dichroic plate into the S-band cone via an ellipsoidal reflector.

Precision pointing of these steerable 2.7-million-kilogram antennas is essential for maintaining expected communication performance when operating at the X-band frequency and beamwidth. Mispointing of only 0.02° at X-band would result in losing fully half of the incident signal power. Consequently, operations for Voyager employ an automated conical scanning technique that involves minute excursions of the ground antenna about the commanded pointing angle to find and maintain the optimum pointing. Pointing is thus maintained through the full range of azimuth and elevation despite wind loading and gravitational deformations of this huge structure. Indeed, the maximum losses due to these effects reduce the antenna's effectiveness by only 13 percent in winds up to 32 kilometers per hour.

Acquiring Voyager's weak signal in the presence of noise from various sources demands that the critical first amplification be done in a very low noise device. The key to achieving the very low X-band system noise temperature of about 25 K lies in the cryogenically cooled ruby maser. This device contributes only 2.2 K to the system temperature. The maser is coupled directly to the feed horn to minimize losses and ohmic noise.

After preamplification in the maser the carrier signal is detected and the Doppler information and ranging code are extracted. The principal technique used in detecting and tracking weak coherent signals in the presence of noise is the phase-lock loop in the station receiver. The 64-m antenna, cryogenic masers, and phase-lock loop receiver provide an acquisition system that is capable of coherently tracking carrier signals as weak as 4×10^{-21} W (0.004 attowatts), 85 million times more sensitive than a home TV.

After the carrier has been detected in the receiver, the station next must detect and synchronize its phase to the subcarrier that carries Voyager's telemetry data. Again, this is accomplished by a phase-lock loop technique designed to track the subcarrier. Detection and removal of the subcarrier and carrier leave only the data, and the next step is to detect the bit or symbol transitions in the data. Voyager's 115,200-bits-per-second coded data are seen as symbols at a rate of 230,400 symbols per second. Symbol synchronization is accomplished and is followed by decoding of the inner code (see Fig. 2).

With the telemetry signal and its data amplified, detected, and decoded, the deep space station's function of data extraction is completed. The next job is packaging the data for handling in subsequent recording and ground communications steps while preserving its quality and quantity. The telemetry processor assembly formats the high-rate science data into 4800-bit blocks which are identified by station and spacecraft. The data must be again protected for the journey from ground station to JPL, hence included in the block is an added error code. In ground transmission we have the luxury of requesting a retransmission of the data if an error appears on the first attempt. Thus, by a combination of error detection and retransmission we assure a low probability of undetected errors in the archival records.

Voyager's encounter data of up to 115,200 bits per second are transmitted from the station to JPL by wideband circuits that include land lines, terrestrial microwave, and communications satellites. Goldstone's data come via a 230-kilobit-per-second ground microwave link. Data from the Spanish station is split into three streams and communicated over three 56-kilobit-per-second circuits in a triplex mode via satellite to Goddard Space Flight Center in Maryland and then to JPL. Communications for Voyager 1's data from Australia were limited to a single 56-kilobit-per-second circuit. Therefore, deep space station 43 (Table 2) first recorded the data at 115,200 bits per second and then replayed the data at line rate.

At JPL, the DSN communications terminal simultaneously feeds the data to DSN processors for recording, monitoring, and validation and to the JPL Mission Control and Computation Center for detailed processing, including decoding the nonimaging science data. Imaging and nonimaging data are routed to separate computers for processing. Voyager experimenters receive their preliminary data in real time as they attempt to provide the public with information during the high drama of the encounter itself. Pictures, of course, are in high demand. Later, non-real-time processing produces the final data products that experimenters will closely study for months to come.

Table 3. Voyager 1 telecommunications results for Jupiter encounter.

Telemetry
Total data bits during Jupiter encounter: 2×10^{11}
Total encounter imaging frames: 18,770
Ninety-eight percent data return (90 percent required)
Command
Computer loading: 112,151 words (launch through 11 April 1979)
Real-time sequence changes: 890 during Jupiter encounter
Radiometric accuracy
Knowledge of spacecraft range: 10 m (1 σ)
Knowledge of spacecraft velocity: 0.5 mm/sec (1 σ)

Telecommunications Results

Voyager 1 has met or exceeded all of its telecommunications requirements. Table 3 details some of the extraordinary performance achievements. Of particular note is the high percentage of data returned. Many of the most exciting Voyager measurements appear in only a small portion of the total data return. For example, only three pictures detected Jupiter's ring, and only a few showed Io's erupting volcanoes. Data taken around Io's flux tube lasted for just 20 minutes. All of the data were critical and 98 percent of the data were successfully received. In general, as stated by Robert Frosch and Alan Lovelace, Administrator and Deputy Administrator, respectively, of NASA, "Superlatives fail us. The data speaks for itself" (*12*).

The Future

Nearly a billion kilometers from home, the travels of the Voyagers have just begun. Voyager 1, having gained energy by imperceptibly slowing Jupiter, now races toward Saturn. From Saturn it will depart the solar system at a steady rate of about 3 astronomical units (AU) per year (*13*). Fuel for attitude control is expected to last for a decade or more, and will thus allow Voyager to return information on interstellar space, that region beyond the sun's influence. If sufficient fuel were available, and if the hardware remained functional, the telecommunications design would be capable of returning data for a much longer period, so that Voyager would say adieu in about 100 years as its range exceeded 300 AU (about 0.005 light-year).

Voyager 2 may provide even more excitement than offered by its sister ship, for this spacecraft may tour all of the giant planets: after Jupiter, Saturn; after Saturn, Uranus, and perhaps Neptune, before racing to the stars.

Saturn is twice as far from us as Jupiter, and Uranus is twice as far again. Thus the spacecraft power that illuminates the earth will decrease by a factor of 4 from its Jupiter value at the Saturn planetary rendezvous, and by a factor of 16 at Uranus.

One advantage of flying missions of long duration is that while the spacecraft system is fixed, sufficient time exists for application of new technology to the ground portion of the link, the stations of the DSN. Right now, these stations are being altered to recover some of the signal power loss due to distance and thus achieve as high a data rate as possible for our flyby of Saturn. Although achieving four times the Jupiter performance at Saturn encounter is not possible with the funds and time available, about 40 percent of the difference will be absorbed by the application of improved maser amplifiers, improved antenna feeds, and by sophisticated combining of the energy received by both the 64-m and 34-m antennas which will be located at each DSN site (*14*). These refinements will allow us to again offer real-time imaging from a distant world. By 1986, a new larger antenna facility may permit the return of higher data rates from Uranus than we will see from Saturn, if designs now proceeding come to fruition.

Beyond Voyager

One thing we learn in planetary exploration is how little we know. Each new planet, and each new level of detail reached puts certain of our models in disarray. Each is a new experiment with which to test and improve our understanding of physical law, using planets as laboratories on a scale impossible to duplicate on Earth. We will go back to each of the planets to continue our quest and we will perform even more difficult communications tasks for future missions, sometimes with breakthroughs, but more often the detailed hard work, pressing harder and harder against theoretical limits by achieving greater accuracies on all fronts. Even now we plan for missions that will demand 100 times the capability that Voyager required: orbiters of the planets, probes and rovers for their atmospheres and surfaces, and radar imaging of obscured neighbors like Venus. With constant dedication, increasingly international efforts are opening windows into the universe with frail radio links. Indeed, fledgling plans now exist for extending our ears to the stars to learn whether other beings might broadcast microwave communications just as we do (*15*). In time, we may speak of light-years as our basic measure instead of the astronomical unit which serves for our own neighborhood.

References and Notes

1. The California Institute of Technology, Jet Propulsion Laboratory, develops and operates the Deep Space Network for NASA under the programmatic guidance of the NASA Associate Administrator for Space Tracking and Data Systems.
2. The Goddard Space Flight Center, NASA, manages the communications system services.
3. W. K. Hartmann and O. Roper, "The New Mars," *NASA Spec. Publ. 337* (1974).
4. W. G. Melbourne, *Sci. Am.* **234**, 58 (June 1976).
5. The efficiency of radio-frequency transmitters ranges between about 20 and 35 percent in the regime to about 15 GHz and falls off gradually thereafter with today's technology. This means that for a typical Voyager mode, say 8.4-GHz transmissions at 22 W and 2.3-GHz transmissions at 6.5 W, more than 110 W of raw power is required. This represents nearly one-fourth of the total spacecraft power capability.
6. The gain, or focusing capability of an antenna, G is related to its effective area A by the equation, $G = 4\pi f^2 A/c^2$, where f is the transmitting or receiving frequency and c is the propagation velocity of the wave. Gain is proportional to the number of distinct directions to which the antenna can be pointed and hence inversely proportional to the beamwidth. Thus as the antenna effective area increases, the beamwidth decreases and the antenna becomes increasingly difficult to aim.
7. Higher frequencies generally result in better performance. However, the system temperature T_S becomes significantly greater as we approach the water vapor resonance at 22.2 GHz, thus robbing the upper frequencies of this advantage. At the 8.4-GHz prime telemetry mode of Voyager, large degradations from free-space performance are experienced during rainstorms at the ground receiving site.
8. The rate of data return of a spacecraft is measured in bits per second. A bit is simply a binary digit, and has the value one or zero. Thus, for example, a pulse of positive voltage might indicate a one and a pulse of negative voltage a zero. By the use of bits we can transmit any information, provided a dictionary of the meaning of various numbers is maintained. For example, the number 17 could be sent as 10001 if binary arithmetic is the chosen manner of translation.
9. The received frequency is altered by the relative radial velocity, V, of the spacecraft and ground stations. Thus, if the carrier frequency, f_c, is transmitted, a change in frequency $f_c(V/c)$ is observed at the receiver. This is known as the Doppler shift (relativistic effects being omitted).
10. See R. L. Koehler, *J. Geophys. Res.* **73**, 15 (1968).
11. A dichroic plate reflects one frequency while being transparent to a second frequency. In this case the plate used is transparent to X-band and reflects S-band.
12. Telefax to Dr. Bruce C. Murray, Director, Jet Propulsion Laboratory, 7 March 1979, following Voyager 1's closest approach to Jupiter on 5 March.
13. An astronomical unit, or AU, is the mean distance from sun to Earth, about 150 million kilometers. Jupiter orbits the sun at about 5 AU, Saturn at 10 AU, and Uranus at 19 AU.
14. Deep Space Stations 61 in Spain and 42 in Australia are being converted from 26-m S-band to 34-m antennas with S-band and X-band capability.
15. B. Murray, S, Gulkis, R. Edelson, *Science* **199**, 485 (1978).
16. C. E. Shannon and W. Weaver, *The Mathematical Theory of Communications* (Univ. of Illinois Press, Urbana, 1959).

17. We thank W. H. Higa, E. R. Scruggs, S. A. Prather, J. A. Ramsey, M. T. Ingham, R. C. Chandlee, and Lee Scot of JPL for assistance with the manuscript and figures and A. L. Lane and R. P. Mathison of JPL and S. T. Edelson for critical review and comment. This article represents one aspect of research carried out by JPL, California Institute of Technology, under NASA contract NAS 7-100.