

Chapter 1

Deep Space Communications: An Introduction

Joseph H. Yuen

1.1 Introduction and Overview

Communications are required and critical to the success of space missions. From the moment of launch, the only connection between a spacecraft and the Earth is the communications system. This system enables return of data from spacecraft to Earth, the tracking of the spacecraft, and commanding the spacecraft to perform any actions that it cannot perform automatically.

Since the beginning, with Sputnik in 1957 and Explorer in 1958, space missions have gone farther and have become more and more demanding in data return to enable far more ambitious science goals. This is particularly so for probes in deep space—at the Moon and farther. In the 1960s and 1970s, the missions were planet flybys, which typically have short encounter periods. Then the missions progressed in the 1980s and 1990s to plant orbiters, which have long and sustained scientific observations—often years of continuous operation. In the 2000s, missions involved landing rovers that moved around on the surface of planets to engage in scientific investigations. In 2012, the latest of these, Mars Science Laboratory (MSL) rover was landed on Mars for years of continuous active scientific investigations.

To overcome the enormous communication distance and the limited spacecraft mass and power available in space, the Jet Propulsion Laboratory's (JPL's) deep space communications technologies developed for spacecraft of the

National Aeronautics and Space Administration (NASA) and NASA's Deep Space Network (DSN) ¹ have enabled every JPL deep space mission ever flown, and contributed to the development of exciting new mission concepts. Figure 1-1 summarizes the evolution of deep space communications capabilities and performance of our spacecraft since first NASA spacecraft in 1958, and it projects to the future capabilities. One can see the tremendous improvements over the years. To continue meeting the increasing demand on deep space communications systems, JPL will need to increase its capability by a factor of ten during each of the coming decades.

This book is a collection of some JPL space missions selected to represent typical designs for various types of missions; namely, Voyager for fly-bys in the 1970s, Galileo for orbiters in the 1980s, Deep Space 1 for the 1990s, Mars Reconnaissance Orbiter (MRO) for planetary orbiters, Mars Exploration Rover (MER) for planetary rovers in the 2000s, and the MSL rover in the 2010s. The cases we have selected were chosen from the JPL Design and Performance Summary series, issued by the Deep Space Communications and Navigation Systems Center of Excellence (DESCANSO) [1]. The case studies of this book illustrate the progression of system design and performance from mission to mission; as stated in the foreword of the series by DESCANSO leader Joseph H. Yuen when the series was launched. The case studies provide the reader with a broad overview of the missions systems described. Besides the systems designs, the case studies provide actual flight mission performance details of each system.

We have provided only the necessary editing to fit within the book and some updates as missions have progressed. As much as possible, we have preserved the original authors' content largely unchanged.

¹ NASA missions in low Earth orbit communicate through either the Near Earth Network (NEN) or the SN (space network), both operated by the NASA Goddard Space Flight Center (GSFC). The SN has of a number of Tracking and Data Relay Satellites (TDRS) in geosynchronous orbits. In addition, the European Space Agency (ESA) operates a number of ground stations that may be used to track NASA deep space missions during the hours after launch. Also, commercial companies operate ground stations that can communicate with NASA missions. The remainder of this book primarily describes communication performed by the Deep Space Network operated for NASA by JPL. (Because of their specific locations, stations of these other networks sometimes are planned to provide time-critical tracking assistance during launch and early mission phases of NASA's deep space missions.)

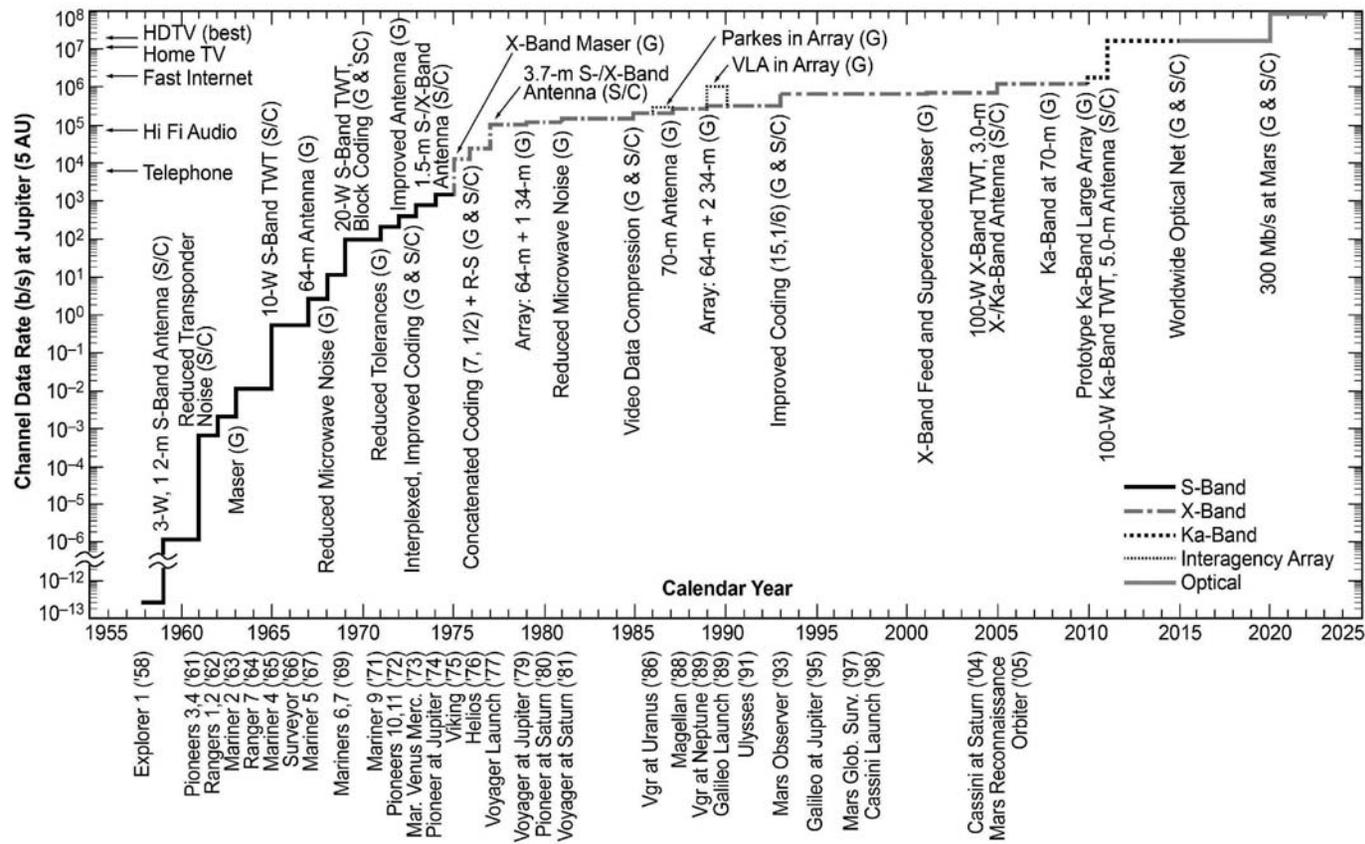


Fig. 1-1. Deep space communications downlink data rate evolution.

This chapter summarizes the theoretical background for telecommunications link analysis and telecommunications design control, respectively. The chapter has been adopted from Yuen, 1982 [2], and refers to chapters of that monograph for greater detail.

1.2 Telecommunications Link Analysis

The performance of a telecommunications system depends on numerous link parameters. Advanced modulation techniques, coding schemes, modern antennas, transmitters, and other advances all improve communications efficiency in their own ways. For designing an entire communications system, communications engineers put all the components or subsystems together and determine performance capability. Signal performance metrics, such as signal-to-noise-spectral-density ratios, are defined in this section. In addition, the component link parameters that enhance or impair the performance are defined.

1.2.1 Received Power

General questions used for performance computation are derived from the basic equations of communications in the medium between transmitting and receiving systems [3]. The first step in link analysis is to calculate the received signal power. Received power P_R is computed by the following equation:

$$P_R = P_T L_T G_T L_{TP} L_S L_A L_P L_{RP} G_R L_R \quad (1.2-1)$$

Where P_R is the received signal power at the input to the receiver or preamplifier, P_T is the total transmitted power at antenna terminals, L_T is the transmitting circuit loss between transmitting antenna terminals and radio case due to cabling, G_T is the transmitting antenna gain, L_{TP} is the pointing loss of the transmitting antenna, L_S is the space loss, L_A is the atmospheric attenuation, L_P is the polarization loss between transmitting and receiving antennas due to mismatch in polarization patterns, L_{RP} is the pointing loss of the receiving antenna, G_R is the receiving antenna gain, and L_R is the receiving circuit loss between receiving antenna and receiver due to cabling. Equation (1.2-1) consists of a large number of parameters in product form. Different types of communications links have different components but the form of Eq. (1.2-1) remains unchanged.

The space loss, or numerical ratio of received power to transmitted power between two antennas, is given by

$$L_S = \left(\frac{\lambda}{4\pi r} \right)^2 \quad (1.2-2)$$

where λ is the wavelength of the radio signal and r is the distance between spacecraft and ground antennas.

The transmitting antenna gain G_T can be related to the effective antenna aperture A_T as

$$G_T = \frac{4\pi A_T}{\lambda^2} \quad (1.2-3)$$

where λ is the wavelength of radio signal. The effective antenna aperture A_T is related to the actual antenna aperture A_i by the relation

$$A_T = \mu A_i \quad (1.2-4)$$

where μ is the antenna efficiency factor. The receiving antenna gain is similarly defined (see Chapter 8 of Ref. [2] for more detailed discussions).

Some of the parameters in Eq. (1.2-1) are not defined in exactly the same way on all projects. For example, the transmitting circuit loss L_T is sometimes accounted for by decreasing the effective transmit antenna gain and/or by decreasing the effective transmitted power, obviating L_T . Also, the atmospheric attenuation (for clear, dry weather) is ordinarily accounted for in the ground antenna gain. No matter what the precise definitions are, the parameters must account for the entire telecommunications link.

The received power is referenced to some point in the receiving circuit. Of course, the choice of reference point affects L_R . On the uplink (from ground to spacecraft), the point of reference is usually the input port of the spacecraft transponder. On the downlink (from spacecraft to ground), the point of reference is the input to the maser amplifier. Whatever the reference, the noise equivalent temperature of the receiving system must be referenced to that same point if signal-to-noise ratios (SNRs) are to be computed correctly.

1.2.2 Noise Spectral Density

The noise for an uplink is dominantly thermal, internal to the amplifier in the front end of the spacecraft receiver. For the downlink, thermal noise in the station's low noise amplifier (LNA) is minimized by using helium-based cooling of the LNA. A large portion of the total receive system noise comes from outside the LNA, in particular from the atmosphere, hot bodies in the field-of-view of the antenna, the 2.7-kelvin (K) cosmic background, and that portion of the ground seen by antenna sidelobes.

It is assumed that the receiving system noise has uniform spectral density in the frequency band containing the signal. The one-sided noise spectral density N_0 (in units of watts/hertz, W/Hz) is defined as

$$N_0 = kT \quad (1.2-5)$$

where k is Boltzmann's constant = 1.380×10^{-23} J/K, $\tilde{k} = 10 \log k = -198.6$ decibels referenced to milliwatts (dBm)/(Hz K), and T is the system equivalent noise temperature. The uniform spectral density assumption and Eq. (1.2-5) are valid for the microwave frequency signals that are currently being used for deep space telecommunications. For signals in other frequency regions, such as in optical frequencies, different expressions should be used [3].

1.2.3 Carrier Performance Margin

Carrier phase tracking performance is dependent on the signal-to-noise ratio (SNR) in the carrier tracking loop. For either an uplink or a downlink, the carrier SNR in a bandwidth $2B_{LO}$ is defined as M_c where

$$M_c = \frac{P_c}{2B_{LO}N_0} \quad (1.2-6)$$

where P_c = portion of received power in the residual carrier, and B_{LO} = one-sided threshold loop noise bandwidth. Here, P_c is calculated from P_R using the modulation indices of the link and depends on the type of modulation used (see Chapter 5 of Ref. 2).

The above definition of carrier margin was chosen because a phase-locked loop receiver loses lock when P_c drops below $2B_{LO}N_0$ watts (W) (see Chapter 3 of Ref. 2). Thus, $P_c = 2B_{LO}N_0$ defines carrier threshold. \tilde{M}_c is calculated as

$$\widetilde{M}_c = \widetilde{P}_c - \widetilde{2B}_{LO} - \widetilde{N}_0 \quad (1.2-7)$$

and represents the number of decibels the received residual carrier is above carrier threshold. Another popular name for M_c is carrier SNR in $2B_{LO}$. However, this is a misnomer since $B_{LO}N_0$, not $2B_{LO}N_0$, is the noise power in a thresholding loop. So carrier SNR in $2B_{LO}$ equals one-half the carrier SNR in a thresholding loop.

The minimum acceptable carrier margin, in general, is not 0 dB. For swept acquisition of the uplink, the minimum useful P_c is in the neighborhood of $2B_{LO}N_0$ watts (W). That is, the minimum useful carrier margin is about 10 dB. For the downlink, the DSN recommends that carrier margin be at least 10 dB. Furthermore, carrier margins for two-way Doppler may need to be larger than 10 dB, depending on required radiometric accuracies.

1.2.4 Telemetry and Command Performance Margins

For both telemetry and command,

$$ST/N_0 \text{ to receiver} = \frac{S}{RN_0} \quad (1.2-8)$$

Where S is the portion of received power in the data modulation sidebands, and R is the data bit rate. Here S is calculated from P_R using the modulation indices of the link. The parameter ST/N_0 to receiver is sometimes denoted by E_b/N_0 , which is the signal energy per bit to noise spectral density ratio. And

$$ST/N_0 \text{ output} = [ST/N_0 \text{ to receiver}] L_{\text{system}} \quad (1.2-9)$$

where L_{system} is the system losses. Threshold ST/N_0 is defined by the bit error probability required of a link. The bottom line of a telemetry or command link analysis is the performance margin. In decibels (dB)

$$\text{performance margin} = ST/N_0 \text{ output} - \text{threshold } ST/N_0 \quad (1.2-10)$$

1.2.5 Ranging Performance Margin

The ranging channel involves transmitting a ranging modulation or code from the DSN to the spacecraft, where it is modulated and then, together with receiver noise, is used to modulate the downlink from the spacecraft to the DSN (see Chapter 4 of Ref. 2). The ranging SNR at the spacecraft is

$$\text{ranging input SNR} = \frac{P_{R(u/l)}}{B_R N_{0(u/l)}} \quad (1.2-11)$$

where $P_{R(u/l)}$ is the portion of received uplink power in the ranging modulation sidebands, $N_{0(u/l)}$ is the uplink (that is, one-sided noise spectral density of the spacecraft receiver), and B_R is the one-sided noise bandwidth of the transponder ranging channel. Here $P_{R(u/l)}$ is calculated from the uplink P_R using the modulation indices of the uplink. The ranging signal-to-noise-spectral-density ratio returned to the DSN is

$$\text{received SNR} = \frac{P_{R(d/l)}}{N_{0(d/l)}} \quad (1.2-12)$$

where $P_{R(d/l)}$ is the portion of received downlink power in the ranging modulation sidebands, and $N_{0(d/l)}$ is the downlink one-sided noise spectral density. Here, $P_{R(d/l)}$ is a function not only of the downlink P_R and the downlink modulation indices but also of ranging input SNR. This is because ranging is a turnaround channel. Some of the modulation sidebands on the downlink are turnaround noise sidebands.

$$\text{output SNR} = [\text{received SNR}] L_{\text{radio}} \quad (1.2-13)$$

where L_{radio} is the radio loss of the ranging system. The value of the required SNR is specified by required radiometric accuracies and desired integration time (see Chapter 4 of Ref. 2).

The bottom line of a ranging link analysis is the performance margin, in dB,

$$\text{ranging performance margin} = \text{output SNR} - \text{required SNR} \quad (1.2-14)$$

1.3 Communications Design Control

A small number of decibels is usually all that separates an inadequate link design from a costly overdesign. For this reason, extreme attention must be paid to performance prediction for deep space telecommunications systems.

If all link parameters were constant and precisely known to the telecommunications engineer, a simple accounting of the link parameters could predict performance. The real world is not so accommodating, however. Some link parameters vary with spacecraft environment, others with ground station parameters and the communications channel conditions. Some are associated with link components that have manufacturing tolerances.

In the early days of space exploration, engineers had little data and were relatively inexperienced in designing deep space telecommunications systems. Hence, they tended to be very conservative; they used a deterministic worst-case criterion [4–6] to assure sufficient link margins in guarding against uncertainties. Experience over many lunar and planetary flight projects has demonstrated that this approach is practical from the point of view of engineering and management [6–8]. The major disadvantages of this deterministic worst-case criterion are that it provides no information about the likelihood of achieving a particular design value. Hence, cost tradeoff and risk assessment cannot be done quantitatively.

Over the years, more experience was gained in deep space telecommunications systems design. Designers evolved a technique for treating telecommunications performance statistically [8, 9], removing the major disadvantages of the deterministic approach while preserving its advantages. Since 1975 this statistical technique has been used in the design of deep space telecommunications systems. It is described in this section.

1.3.1 Design Control Tables

The communication link margin is computed using an equation of the following form:

$$y = y_1 y_2 \dots y_k \quad (1.3-1)$$

where y_i , $i = 1, 2, \dots, K$ are parameters of the communication link such as in Eqs. (1.2-1) and (1.2-6). This equation is presented in its general form, without its detail components. Different types of communications links have different components, but the form of this equation remains unchanged.

The overall telecommunications system consists of a large number of parameters in product form. Hence, expressed in the dB domain, it becomes a sum of these parameters; that is,

$$x = x_1 + x_2 \dots x_K \quad (1.3-2)$$

where

$$x = 10 \log_{10} y \quad (1.3-3)$$

and

$$x_i = 10 \log_{10} y_i, \quad i = 1, 2, \dots, K \quad (1.3-4)$$

In managing the system design, it is most convenient to put this in tabular form with these parameters and entries. This table is referred to as a design control table, or DCT. All of the factors that contribute to system performance are listed in the order that one would find in tracing a signal through the system. Sample DCTs of the telemetry, command and ranging links can be found in Chapters 2 through 7 for six case study missions.

To every parameter in a DCT a design value, along with its favorable and adverse tolerances, is assigned by designers. These tolerances are used not as a hidden safety margin of each parameter; rather, they reflect probable

uncertainties, including measurement tolerance, manufacturing tolerance, environmental tolerance, drift of elements, aging of elements, parameter modeling errors, and others. The table readily indicates the parameters with the largest tolerances—hence, the areas where more knowledge and hardware improvement might be most profitable.

The design procedure and performance criterion selection for deep space communications links are described in the following subsection.

1.3.2 Design Procedure and Performance Criterion Selection

The design procedure for deep space telecommunications systems design and the selection of a particular criterion for conservatism are both driven by weather conditions in the signal path between the ground station antenna and the spacecraft on telecommunications performance. “Weather” refers both to conditions in the Earth’s atmosphere (humidity, precipitation, wind) and to the presence of charged particles in the path through space from the top of the atmosphere to the spacecraft.

1.3.2.1 Weather Effects. Weather requires special consideration. For carrier frequencies at or above X-band, the randomness that weather introduces to the link dominates all other sources of randomness. There are two techniques for incorporating weather into telecommunications design control. The simpler one, the percentile weather technique, is described in this section. It is a reasonable estimate of the weather effects on link performance. Often a reasonable estimate suffices for preliminary system design and performance assessment purposes. The percentile weather technique is attractive for its simplicity. Conversely, for detailed design and link performance monitoring purposes, a more accurate estimate is required.

The percentile technique for incorporating weather into telecommunications design control requires the preparations of two design control tables. In the first design control table, a dry atmosphere and clear sky over the Deep Space Station (DSS) is assumed. In the second design control table, x -percentile inclement weather is assumed. What is meant by “ x -percentile” weather is that with x percent probability a pessimistic assumption is being made about weather effects; moreover, with $(100 - x)$ percent probability an optimistic assumption is being made. As an example, 95-percentile means that 95 percent of the time the degradation due to weather is less than predicted, while 5 percent of the time the weather degradation is worse.

1.3.2.2 Design Procedure. The design procedure is described here. The procedure unfolds as a sequence of six steps during which the philosophy of

telecommunications design control reveals itself. The discussion below follows Refs. [8] and [9].

Step 1. Three values are assigned to most link parameters: design, favorable tolerance, and adverse tolerance. All three values are to be in decibel representation. Those parameters that are not assigned three values should receive only a design value (in decibels). Data bit rate, space loss, and threshold (or required) SNR ratios are regarded as deterministic and only have design values. The weather-dependent parameters—atmospheric attenuation and, on the downlink, incremental noise temperature due to clouds—should be assigned only design values (noise temperature is in units of kelvin, not decibels). In fact, the design values of the weather-dependent parameters should be based on the assumption of clear, dry weather. Later, as explained in the previous paragraph, the design procedure is to be repeated with weather-dependent design values assigned on the basis of x -percentile inclement weather. The following definitions serve as a guide in the assignment of values to a link parameter:

- Design value = the a priori estimate of a parameter,
- Favorable tolerance = the best case of a parameter minus the design value,
- Adverse tolerance = the worst case of a parameter, short of failure, minus the design value.

Noise temperatures, noise spectral densities, and noise bandwidths have favorable tolerances with negative values and adverse tolerances with positive values. The opposite is true of all other link parameters that get assigned tolerances. Tolerances reflect one or more of the following: a limit cycle, a manufacturing tolerance associated with a link hardware component, a dependence on spacecraft environment, and other uncertainties.

Step 2. Arrange the link parameters in a vertical listing—a design control table—and identify independent groups among them.

Step 3. Within each of the independent groups, add the design values and the favorable and adverse tolerances so that there is only one design value with its associated favorable and adverse tolerances for each group.

Step 4. Assign a probability density function (pdf) to each independent group. Typically, on uniform, triangular, Gaussian, and Dirac-delta (for those groups without tolerance) pdf's are used. The assignment made by the Telecommunications Prediction and Analysis Program (TPAP) are tabulated in Chapter 10 of Ref. 2. In case a probability density function is nonzero over the entire real line such as the Gaussian density function, use the absolute sum of

its favorable and adverse tolerances as its 6-sigma (6 standard deviations) measure.

Step 5. Compute for each independent group (random variable) its mean and variance. Having been computed from a design value and tolerances all expressed in decibels, the mean will, of course, be in decibels (and the variance in decibels squared).

Step 6. Compute the mean and variance of the desired performance or carrier margin by algebraically summing the means and adding the variances obtained in step 5. What is meant by “algebraically summing” is that some means—those corresponding to noise spectral density, noise bandwidth, data bit rate, and threshold (or required) SNRs—are subtracted rather than added.

It is certainly true that a precise pdf of the overall link margin can be obtained by convolving the pdf’s of the K independent random variables. However, the link margin tolerance distribution is well approximated by a Gaussian distribution by invoking the central limit theorem, since the overall link consists of K independent random variables formed in step 2 above. This simplifies the computational complexity to the point that hand calculation is indeed practical. Moreover, the pdf’s of the K independent random variables were only estimated. It seems difficult to justify using tedious convolution to achieve a precise solution based on imprecise information, if an approximation is indeed satisfactory. A more worthwhile effort would be making a more accurate estimate of the pdf’s of the K independent random variables.

The above procedure is repeated with the weather-dependent parameters being assigned design values based on x -percentile inclement weather. The weather percentile not only differs from site to site but may also may be defined on a monthly or seasonal basis. The performance or carrier margin is finally considered predicted with the specification of four members:

- (1) Mean margin with clear, dry weather
- (2) Mean margin with x -percentile weather
- (3) n -sigma margin with clear, dry weather
- (4) n -sigma margin with x -percentile weather

where “ n -sigma margin” equals mean margin minus n standard deviations. The value n is typically 3 for command links and 2 for links carrying telemetry or providing radiometric data.

1.3.2.3 Performance Criterion Selection. In order to assure successful operation and guard against adverse situations, we must provide sufficient link

margins. Based on the design procedure described previously, one can choose link performance that will not deviate from its mean margin by more than 3-sigma (three standard deviations) with probability 0.99. This 3-sigma value is used as an uncertainty measure for the link. Depending on how much risk is acceptable, we can choose any number of sigma values. Hence, a useful design criterion is: *the mean value of the link SNR must exceed the required SNR by an amount equal to or larger than the n-sigma*. Alternatively, one can choose a level of probability of success, then use the corresponding required SNR.

References

- [1] *DESCANSO: Deep Space Communications and Navigation Systems* website, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, includes *Design and Performance Summary Series*. <http://descanso.jpl.nasa.gov/> (accessed October 30, 2014)
- [2] J. H. Yuen, editor, *Deep Space Telecommunications System Engineering*, National Aeronautics and Space Administration, Washington, District of Columbia, July 1982. (Also reprinted by Plenum Press, New York, 1983.)
- [3] J. R. Pierce and E. C. Posner, *Introduction to Communication Science and Systems*, Plenum Press, New York, 1980.
- [4] R. E. Edelson, B. D. Madsen, E. K. Davis, and G. W. Garrison, "Voyager Telecommunications: The Broadcast from Jupiter," *Science*, vol. 204, no. 4396, pp. 913–921, June 1, 1979.
- [5] R. E. Edelson, editor, *Telecommunications Systems Design Techniques Handbook*, Technical Memorandum 33-571, Jet Propulsion Laboratory, Pasadena, California, July 15, 1972.
- [6] M. F. Easterling, "From 8-1/3 Bits per Second to 100,000 Bits per Second in Ten Years," *Conference Proceedings, ITC'74*, Los Angeles, California, 1974.
- [7] V. L. Evanchuk, "117.6 kbps Telemetry from Mercury In-Flight System Analysis," *Conference Proceedings, ITC'74*, Los Angeles, California, 1974.
- [8] J. H. Yuen, *A Practical Statistical Model for Telecommunications Performance Uncertainty*, Technical Memorandum 33-732, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, June 15, 1975.
- [9] J. H. Yuen, "A Statistical Model for Telecommunication Link Design," *Proceedings, National Telecommunications Conference*, New Orleans, Louisiana, A77-15115 04-32, Institute of Electrical and Electronics Engineers, New York, pp. 25–17 to 25–21, December 1976.