PRENTICE HALL
SPACE TECHNOLOGY SERIES

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AEROSPACE TELEMETRY
VOLUME II

PRENTICE-HALL INTERNATIONAL SERIES
IN SPACE TECHNOLOGY

Aerospace Telemetry

Volume II

HARRY L. STILTZ, editor

President, Stiltz Sales and Engineering Co.

Prentice-Hall, Inc., Englewood Cliffs, N.J.

PRENTICE-HALL INTERNATIONAL, INC., *London*
PRENTICE-HALL OF AUSTRALIA, PTY. LTD., *Sydney*
PRENTICE-HALL OF CANADA, LTD., *Toronto*
PRENTICE-HALL OF INDIA (PRIVATE) LTD., *New Delhi*
PRENTICE-HALL OF JAPAN, INC., *Tokyo*

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Current printing (last digit):
11 10 9 8 7 6 5 4 3 2

Library of Congress Catalog Card Number 61-15664

Printed in the United States of America
01829C

PRENTICE-HALL INTERNATIONAL SERIES
IN SPACE TECHNOLOGY

C. W. Besserer and Floyd E. Nixon, Editors
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Preface

Aerospace Telemetry, Vol. II is designed as a supplement to *Aerospace Telemetry,* Prentice-Hall, Inc., 1961. It does not outdate or revise any material covered in the latter book, but merely extends that material to include additional telemetry techniques and a closer look at telemetry systems accuracies.

The editor has been privileged to serve as Program Director for the Aerospace Telemetry School in Atlanta, Georgia for several years and has thus kept abreast of the educational requirements of our aerospace engineers. Through personal contact with hundreds of engineers from all segments of the aerospace industry, it was found that most students, having mastered the fundamentals of Aerospace Telemetry, desired to progress into the more advanced areas such as deep space probes and adaptive telemetry techniques. They wanted to analyze the FM/FM system to determine if this technique could continue to hold its place in the telemetry field year after year. They weren't convinced that the most widely used telemetry techniques were necessarily the best; they wanted to take a look at such newly developed techniques as PACM and Single Sideband FM. These are our space age engineers to whom this book is dedicated.

The editor and authors of *Aerospace Telemetry, Vol. II* sincerely hope that the material presented herein will fulfill the desires of our telemetry and associated engineers.

HARRY L. STILTZ
Editor

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Satellite and Space Probe Telemetry

by Robert W. Rochelle

Part A. Characteristics of Space Telemetry

1.0 Introduction to Space Telemetry

Since Galileo first turned his telescope skyward, man has been intensely interested in the detailed characteristics of the heavenly bodies. It may never have occurred to Galileo that the regions between our earth and the planets might contain phenomena which have an everyday effect on our lives, regions which scientists later found to be teeming with electrons, protons, ions, magnetic fields, hydromagnetic waves, micrometeorites, and radiation with frequencies from direct current to cosmic rays. The development of man-made satellites has made it possible to measure directly these characteristics and phenomena.

On February 1, 1958, the United States launched its first satellite designed to detect the presence of radiation or energetic particles above our atmosphere. From this experiment came the telemetered results which culminated in the discovery of the Van Allen radiation belts. Since that

*National Aeronautics and Space Administration, Goddard Space Flight Center.

time, many satellites and space probes have been launched to seek out and clarify some of these mysteries of nature.

These spacecraft all contained some type of communication system which was instrumental in handling the collected data and relaying it back to earth. Even from a completely passive satellite such as Echo I, which was simply a 100 feet-in-diameter aluminum-coated plastic sphere, or from the very complex Orbiting Geophysical Observatory (OGO), which carried two independent data systems, much could be learned about the communications channel problems with which telemetry engineers are faced.

Although the basic principles of satellite and space-probe telemetry are the same as for rocket and aircraft telemetry, there are some differences which impose severe restraints on the design. The prime differences become a function of the communication efficiency, weight, power requirement, and reliability of the system design. Because of the wide differences in spacecraft missions, one finds a considerable variety among the various spacecraft telemetry systems.

The designer of spacecraft telemetry systems has a large number of techniques at his command to cope with the many-faceted problems of space communications. The selection of the proper modulation system can be made only after one has considered such items as the type of data, rate of data flow, spacecraft weight and power availability, antenna gain, available bandwidth, transmission path, receiver antenna gain, receiver noise figure, detection efficiency, tape recorder effects, and volume of data. In this part, a few of the pertinent characteristics of space modulation systems will be given.

2.0 Space Channel

The channel through which we are to communicate must, first of all, be defined. As a first approximation the space channel may be considered as an ideal channel. At 136 mc, one of the frequency bands assigned for space telemetry, the noise masking the signal is primarily cosmic in origin and is essentially flat over the narrow assigned bandwidth. Propagation from an orbiting spacecraft to earth is always through the ionosphere. Since these transmitting frequencies are much higher than the ion or electron gyrofrequencies in the ionosphere, the channel has no memory. A channel with memory is particularly unsuited for time-multiplexed telemetry systems, since intersymbol interference is likely to occur.

Unfortunately, this idealized channel does not always exist. During important measurements on space phenomena such as solar flares, the communication path can be disturbed and signal-to-noise ratio deteriorates. This occurs at precisely the time when the most valuable readings are being received. The aurora also has an effect on the signals propagated to the high latitude receiving stations. Man-made interference can occasionally be a source for errors. Even poor speed control on tape recorders can cause

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nonlinear modulation of the signals, and sometimes a noisy tape recorder can far overpower the radio noise received from our galaxy.

3.0 Galactic Noise

Radio noise sources both within and external to our galaxy are responsible for a background radio-frequency noise power which limits communication range. Part of this noise comes from the thermal emission of interstellar gases; the remainder comes from nonthermal radio stars such as our own sun. Most of the radio stars are within our galaxy, and their radiation is many times more intense than that from the thermal sources. Above 1000 mc the noise radiated by these stars is essentially thermal and is inversely proportional to the square of the frequency. Below 1000 mc the noise is nonthermal and is inversely proportional to the frequency raised to the 2.8 power.* This accounts for the more rapid rise of radio noise power at the lower frequencies.

If an antenna, pointing skyward, is terminated in a matched load, the power in that load is the sum of two noise power contributions. One is the thermal noise power of the matched load kT_oB, where k is Boltzmann's constant, T_o is the noise temperature of the matched load in degrees Kelvin, and B is the bandwidth; and the other is the received sky noise kT_AB, where T_A is the noise temperature of the antenna. By using a sufficiently narrow-beam antenna, the noise temperature of the sky can be mapped by plotting the antenna noise temperature as a function of the celestial coordinates, right ascension and declination. Figure 1.1 is an extrapolation of the radio sky-noise background for 136 mc. When relatively wide-beam antennas are used, their noise temperatures can be computed by averaging the temperatures which fall inside a projection of the beam pattern onto this chart. The dotted line is the location of the galactic equator on the celestial sphere. This indicates those directions looking through the thickest parts of the galaxy and is characterized by the high noise temperature. The dashed line of Figure 1.1 shows the path that the moon traces on the celestial sphere during a typical lunar month. The radio noise temperature along this path would be the intensity levels of noise power that one could expect from the reception of signals transmitted from a satellite placed in orbit around the moon.

4.0 Communications Efficiency

Because of the restrictions that satellite and space-probe telemeters must operate with minimum power and weight and communicate over extremely

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*I. S. Shklorsky, *Cosmic Radio Waves*, trans. (Cambridge, Massachusetts: Harvard University Press, 1960).

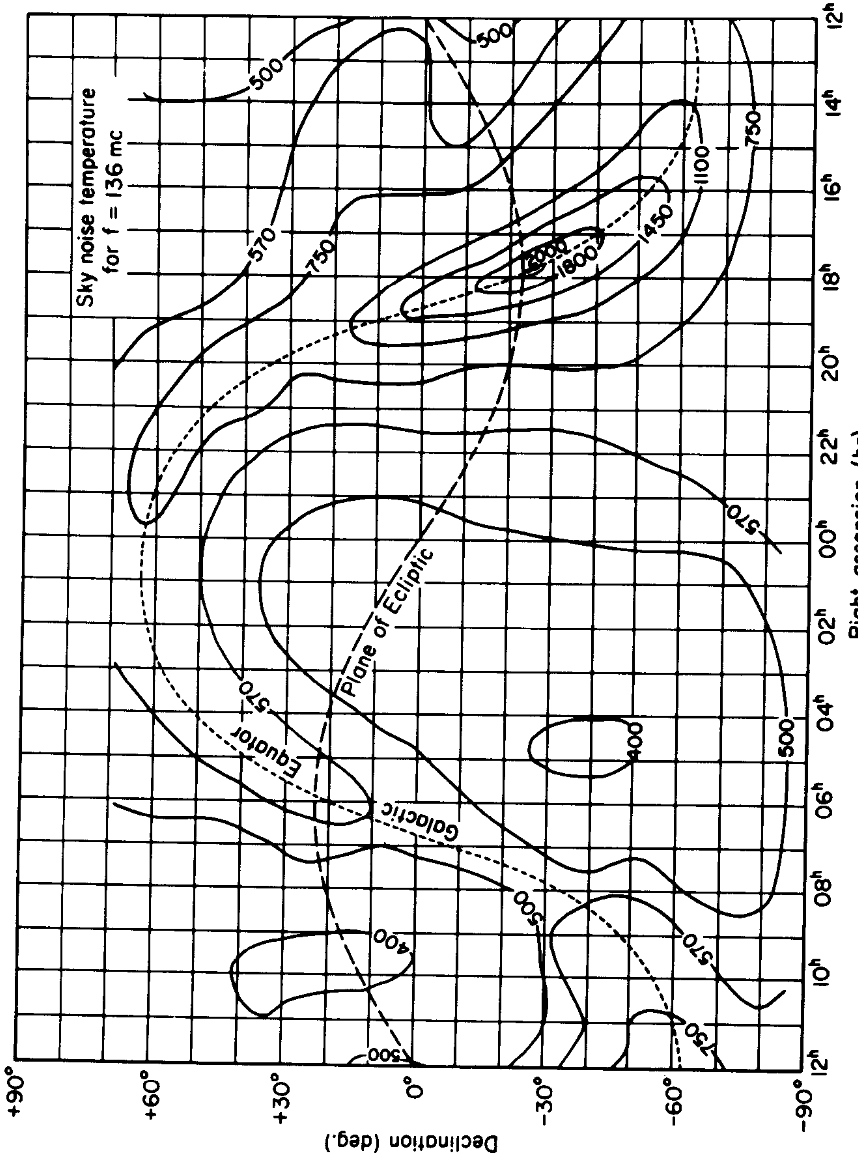

Fig. 1.1. Celestial-sphere map of radio noise intensity at 136 mc.

long ranges, the communication system should be extremely efficient. Shannon* pointed out in 1947 that the transmission range could be extended with no increase in energy by properly encoding the signal at the transmitter. There are a number of ways that a signal can be encoded to take advantage of Shannon's theorem; all of these require, however, that the bandwidth be increased over the original information bandwidth. By increasing the bandwidth or spreading the signal over more of the frequency spectrum, the transmission range can be increased, contrary to what one feels on an intuitive basis. The increase in transmission range may be exchanged instead for an improvement in the output signal-to-noise ratio, resulting in a lower probability of making an error in the data. Most telemeters employed in spacecraft to date take advantage of Shannon's theorem in one way or another. Since bandwidth has not been a limiting factor for this type of mission, it may be expanded to improve the output signal-to-noise ratio and lower the probability of error. Three types of modulation have found widespread use in space telemetry applications. These are pulse-code modulation (PCM), pulse-amplitude modulation (PAM), and frequency modulation (FM). Pulse-frequency modulation (PFM), which is a special form of PAM/FM, has enjoyed usage on a number of the small scientific-type satellites. It combines some of the better features of PCM with those of FM. All of these modulation methods in general expand the bandwidth to obtain lower probabilities of making errors in the data.

4.1 *Pulse-Code Modulation*

Pulse-code modulation is one of the modulation forms which trade bandwidth for signal-to-noise ratio. For space use it is generally classified into two types: uncoded and coded. Uncoded PCM is the common type represented by the encoding of a datum point into an n-bit binary word; the number of values which the datum point may have is 2^n. If the number of values which the datum point may have is 2^k, where k is less than n, then the PCM is said to be coded. The extra number of bits, $n - k$, are the check digits in the PCM word.

4.1.1 *Uncoded PCM.* If the voltage output from an experiment or sensor is confined to a bandwidth B, it can be shown from the sampling theorem that a minimum of $2B$ samples per second is needed to describe the voltage adequately, the samples being less than $1/2B$ seconds apart. To transmit the amplitude of a sample, it is encoded as an n-bit binary word. It will then take a bit rate of $2nB$ bits per second to encode the analog voltage from the sensor as an uncoded PCM bit stream. On a theoretical basis, an uncoded PCM signal can be passed through a bandwidth of one-half the bit rate. The mini-

*C. E. Shannon, "A Mathematical Theory of Communications," *Bell Sys. Tech. Jour.*, Vol. **27**, No. 3 (July, 1948), 379–423; and No. 4 (October, 1948), 623–56.

mum bandwidth through which the encoded signal can be transmitted is then nB cycles per second. By using uncoded PCM the bandwidth over the original signal has been increased by a factor of n. The signal is now less susceptible to noise perturbations, since it takes considerably more noise power to cause an error in the reception of one of the n bits than it does to receive correctly the sample amplitude to an accuracy of one part in 2^n parts. Uncoded PCM shows great utility in space applications, since it is already in a form readily handled by general-purpose digital computers. To decrease further the susceptibility of the encoded PCM signal-to-noise effects, it may be further coded.

4.1.2 *Coded PCM.* Since there are various degrees of coded PCM, one must have measuring units which are adequate to describe their efficiency. There are two parameters which are useful in describing the performance of a telemetry system. These are the error probability and the energy-per-bit to noise-power-density ratio. The error probability is defined as the ratio of the total number of errors in a block of data to the total number of samples, words, or bits in that block. It becomes a statistical measure of the system performance, since it tells what fraction of errors is present in the data. For example, in an uncoded PCM system using ten-bit words, if one found 328 word errors in a block of 65,536 words, the probability of word error would be 5×10^{-3}. The bit-error probability would be approximately

$$P_e = \frac{328}{65{,}536 \times 10} = 5 \times 10^{-4}$$

or one-tenth as great, assuming that no more than one bit error occurred in any word.

It is desirable to obtain the error probability as a function of the energy-per-bit to noise-power-density ratio. A spacecraft can usually furnish only a certain amount of energy for each information bit to be transmitted. This energy is competing with the receiver background noise composed mainly of the radio noise from stellar sources and the thermal noise generated in the front end of the receiver as well as from several minor sources. The noise is assumed to be white additive gaussian noise and is described by measuring the noise power in a one cps band; this gives the noise power density. Beta, then, is defined as

$$\beta = \frac{ST/n}{N/B} \tag{1.1}$$

where S = signal power at receiver terminals.
T = time length of coded data word.
n = number of information bits in coded data word.
N = noise power at receiver terminal.
B = noise bandwidth.

One way to code an uncoded PCM signal is to add an extra bit for parity. Take the three-bit binary code of Table 1.1(a), which can code a voltage into eight levels. If an "even" parity bit is added to each word, the code set in Table 1.1(b) results. Let us now encode an analog voltage to a three-bit accuracy. Instead of transmitting the three-bit value of Table 1.1(a), its four-bit equivalent in Table 1.1(b) is transmitted in the same length of time.

Table 1.1

(a)	(b)	
000	0000	A
001	0011	B
010	0101	C
011	0110	D
100	1001	E
101	1010	F
110	1100	G
111	1111	H

(a) Three-bit binary code. (b) Three-bit binary code with even parity.

On the ground a set of four matched filters and a maximum-likelihood detector are used to estimate which of the eight four-bit words was transmitted. The words are detected in a group and not singly as in uncoded PCM. Each of the filters is matched to one of the binary waveforms of the first four words in Table 1.1(b); that is, for the filter matched to word A, the output will be zero when words B, C, or D are fed to it, but maximum output will result from word A. The filter performs the function of multiplying a stored version of waveform A with the incoming signal and integrating over a word length, calling a "one" as plus one and a "zero" as minus one. These four waveforms form an orthogonal set in that the cross correlation between any two words is zero. When waveform H, the complement of A, is fed into the filter matched to waveform A, a maximum negative output will result. This is the biorthogonal characteristic of the code set.* The maximum-likelihood detector selects one of the four matched filters which has the largest absolute magnitude voltage. A positive output indicates that the best estimate of what was transmitted is the stored waveform of that matched filter. If the maximum output is negative, the best estimate is the complement of the stored waveform of that filter. The improvement in output signal-to-noise ratio occurs because the signal voltage is adding linearity in the integrator while the noise voltage during each bit period is adding as the square root of the sums of the squares.

Curves have been derived which compare the probability of making an error when three bits are encoded as in Table 1.1(a) against the error proba-

*A. J. Viterbi, "On Coded Phase-Coherent Communications," *IRE Trans. on Space Electronics and Telemetry,* Vol. **SET-7** (March, 1961), 3–14.

bility for the code of Table 1.1(b). The independent variable is taken to be β, the signal energy per bit to noise-power-density ratio. In Figure 1.2 the $n = 1$ curve corresponds to the code set of Table 1.1(a) in which three information bits are encoded as three data bits. This is the uncoded case.

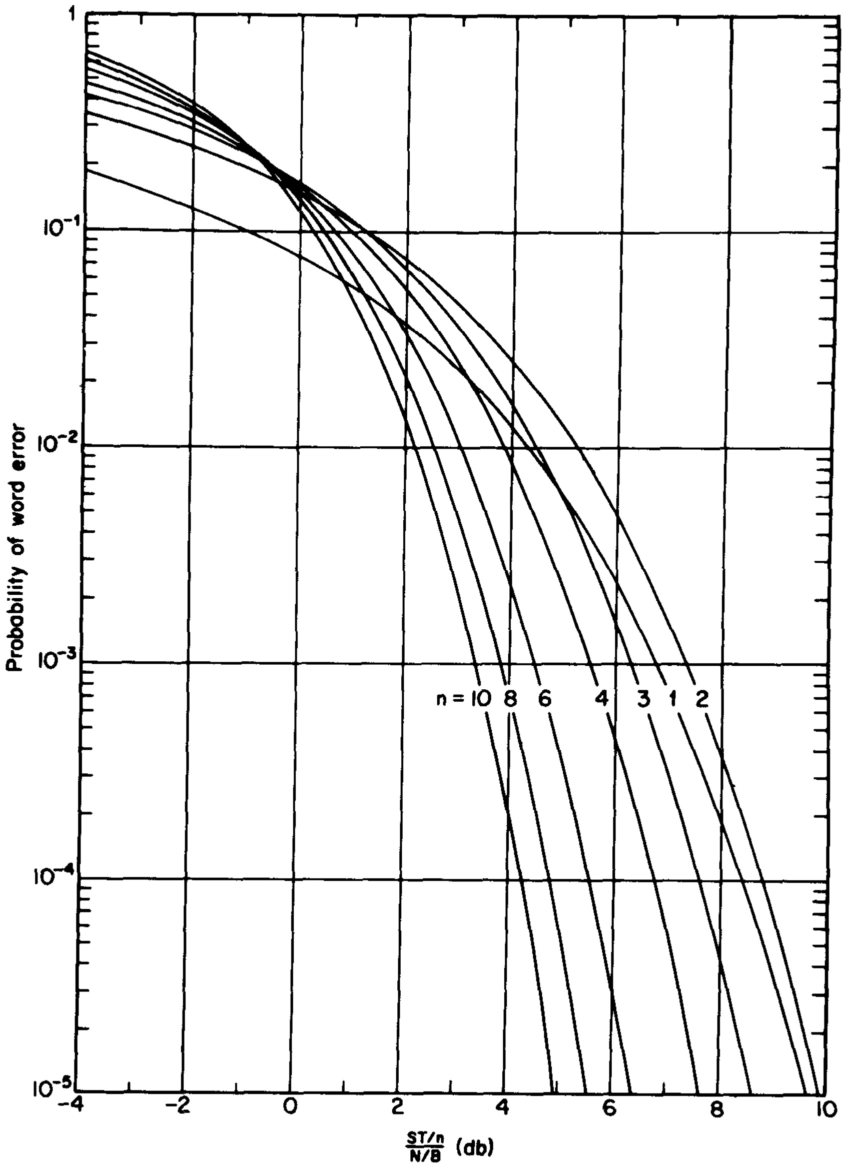

Fig. 1.2. Bi-orthogonal word-error probability curves for coherent detection.

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