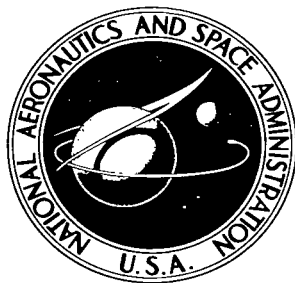


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# AN EFFICIENT CODING SYSTEM FOR DEEP SPACE PROBES WITH SPECIFIC APPLICATION TO PIONEER MISSIONS

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**NATIONAL AERONAUTICS AND SPACE ADMINISTRATION**

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SUMMARY

Rate  $1/2$  convolutional encoding with sequential decoding has been investigated for application to deep space probe telemetry links which are characterized by a gaussian channel with coherent matched filter detection of phase shift keyed signals. A (50, 25) code was optimized and its performance evaluated by means of computer simulations. Data for these studies were organized into blocks of 224 information bits where 14 bits were known at the end of each block for purposes of synchronization and to aid in decoding. Results show that the basic coding technique yields a gain of at least 6.5 dB over no coding.

For error detection, a technique of reverse decoding was investigated. This technique, used in conjunction with extending the known sequence at the end of each block to 21 bits, permits an additional 0.9-dB gain.

A large portion of the report is concerned with the implementation of this coding scheme on Pioneer missions. Since Pioneer is an operational program, the mission-dependent equipment is analyzed to determine the modifications required for introducing error correction coding to a no-coded telemetry link.

INTRODUCTION

Coding is introduced into the space communications telemetry link to permit more information to be transmitted at a given power within a maximum allowable error rate. Coding increases the number of data bits transmitted by the insertion of parity bits into the information bit stream. For the coding process, the encoder takes the information data and computes, according to a fixed rule, the parity bits to be transmitted. The data rate increase caused by the addition of parity bits is distinguished from an actual information rate increase afforded by a coding gain.

Quite obviously, if a fixed amount of power is to transmit a given information rate in an otherwise fixed communications system, the introduction of additional data (parity bits) reduces the available power per transmitted data bit. Hence, for fixed power, the bit-error rate from the data demodulator will be greater with coding than with no coding. Thus, the task of the decoder, which is inserted following the data demodulator, is to correct errors made by the data demodulator. The insertion of the encoding and

decoding functions into a communications system is illustrated in figure 1. To achieve a coding gain, the error rate after decoding must be less than it is for no coding.

Several approaches for introducing coding into the space communications telemetry link have been investigated at Ames Research Center and elsewhere. From an implementation standpoint, the coding state of the art for the deep space channel is typified by the 8-bit biorthogonal telemetry system built and evaluated at Goddard Space Flight Center (ref. 1). The gain of this biorthogonal system is 4 to 5 dB over no coding. The coding system reported here gives at least 6.5 dB over no coding. Although the work was done for application to the Pioneer program,<sup>1</sup> most of the results are general and are summarized in this report. This report describes:

- (1) The gains both in information rate and data accuracy afforded by the coding system; and
- (2) The modifications of the present Pioneer system necessary for realizing these gains.

Any alteration to an operational system must be examined from the viewpoint of its effect on all parts of the system. To that end, the rather minor addition to the Pioneer spacecraft, the changes to the ground equipment, and the Ames Research Center data processing system, as well as operational constraints, are analyzed and reported herein. Rather stringent constraints were imposed in order to minimize the modifications to an operational system. The further improvements in coding performance that could be made by removing certain restrictions are also discussed.

#### NOTATION

$E/N_0$	signal energy per transmitted bit per noise spectral density
$E_b/N_0$	signal energy per information bit per noise spectral density
$P_e, P_{eM}$	bit-error probability for NRZ-L and NRZ-M transmission, respectively
bps	bits per second
DSS	Deep Space Station
DTU	Digital Telemetry Unit
D/S	Demodulator/Synchronizer
GOE	Ground Operational Equipment

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<sup>1</sup>A brief discussion of the basic Pioneer communication system is given in appendix A.

I & D    Integrate and Dump  
NRZ-L    Non-Return-to-Zero Level  
NRZ-M    Non-Return-to-Zero Mark  
PCM      Pulse Code Modulation  
PSK      Phase Shift Keying  
TPS      Tape Processing Station  
TWT      Traveling Wave Tube

### CODING SYSTEM CONSTRAINTS FOR PIONEER MISSIONS

The Pioneer deep space probe series is an approved NASA program for five spacecraft, with two spacecraft (Pioneer VI and VII) now in orbit about the sun. In order to introduce coding into future Pioneer missions, several constraints are necessarily imposed or appear appropriate. One constraint is that coding would be commandable to permit no-coding operation whenever desired. That is, all spacecraft data formats and ground data processing, both real-time and off-line, will be the same as now employed on Pioneer VI and VII, for the no-coding option. This commandable mode may be appropriate for any space mission that might consider using coding (other than a simple parity check code). During the launch phase and for the first few station passes of any deep space mission the signal strength will probably be quite high and coding of the data will be unnecessary. Also, due to the necessity of early assessment of spacecraft soundness, orientation maneuvers, and other operational considerations, it may be desirable to minimize the number of components in the telemetry link. Thus, a spacecraft could be launched in a no-coding mode just as the scientific experiments are not turned on until sometime after launch.

A second constraint is that there will be no internal modifications to the spacecraft Digital Telemetry Unit (DTU) for the coding function. Any required pre-encoding data conditioning, other modulation frequencies, etc., will be provided by the spacecraft encoder. This is primarily imposed to minimize spacecraft modifications.

It is also highly desirable to have the Scientific Data System (SDS) 920 computers at the Deep Space Stations (DSS) do most of the decoding in order to provide near real-time data to the Mission Control Center. However, an alternate approach for decoding using additional ground equipment is being investigated.

Pioneer VI and VII data are organized into 7-bit words consisting of 6 data bits and a seventh parity check bit. This is a simple encoding scheme that is used for error detection only. Figure 2 shows the theoretical performance of this parity error detection scheme with the demodulator bit-error rates shown as a parameter. Under present Pioneer criteria, bit-rate change

is made when the bit-error rate of the ground Demodulator/Synchronizer<sup>2</sup> (D/S) exceeds  $10^{-3}$ . At this point, the undetected word error rate is about  $7.0 \times 10^{-6}$  and the deletion rate (parity error rate) is  $4.0 \times 10^{-3}$ . (See fig. 2).

During the code study and code selection phases of work (ref. 2) a minimum target gain of 3 dB was set as a criterion for performance improvement. The gain comparison was referenced against the nominal performance of Pioneer VI and VII for the bit-rate change criterion given above. It should be noted here that the criteria for comparison are rather important. For example, if no coding of any kind were used as reference, the design minimum coding gain would be increased over the above specified target of 3 dB by about 2.6 dB. This is illustrated by the comparison between word error probability for no coding versus the word error probability for the simple parity detection scheme as shown in figure 3. In this figure the 6-bit word error rate is plotted versus  $E_b/N_0$ , the signal energy per information bit. Deletion rate is shown as a parameter which, of course, is zero for the no-coding case.

The coding scheme discussed in this report exceeds the 3-dB target gain and in fact provides an additional gain of at least 0.9 dB which will be regarded as an engineering safety factor. The detailed coding performance is discussed in the section on code determination and performance.

It is suggested that on the first launch in which coding is used, the communication system modifications be kept to a minimum; this dictates that the full potential of the coding scheme not be immediately utilized. Specifically, it is proposed that the system be capable of reverting to a "no-coding"<sup>3</sup> option with exactly the capabilities that now exist. This implies that for no coding, the modulation index will be set for a match of carrier and data power at the 8 bps maximum range. With this criterion, only one modulation index will be available, which is set before launch. In this case then, maximum range cannot be increased much due to the degradation produced by the ground receiver phase lock loop when it is operated beyond the designed maximum range. It follows that a 3-dB coding gain can be used to (1) improve data quality (reception accuracy), and (2) extend each bit-rate range during the mission except the maximum one. Except during the "no-coding" mode, the 8 bps information rate will not be used since this entire range can be handled by coding with an information rate of 16 bps. A normalized mission profile showing bit-rate changes for the Pioneer parity check case and the coding scheme (assuming a 3-dB gain) is given in figure 4.

For the latter missions utilizing coding, it would be desirable to extend the maximum mission range, either with two modulation indices (changed upon command) or with one index which would put less power in the data channel. The latter alternative has the disadvantage of reducing the bit-rate ranges for other than the lowest bit rate, whereas a variable modulation index would not require this trade-off between maximum and intermediate bit-rate ranges.

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<sup>2</sup>The D/S is the Pioneer unit which provides the optimum data demodulation and bit synchronization of the biphase modulated telemetry data subcarrier.

<sup>3</sup>In relation to Pioneer, "no coding" refers to the simple parity check scheme without any further data conditioning.

It is proposed in general that "listen only" stations<sup>4</sup> receive data in the uncoded form. That is, the spacecraft should be commanded from the previous GOE station to a "no-coding" mode as well as a lower bit rate, if required, if the next station to view the spacecraft is a "listen only" station. There are several reasons for suggesting this procedure. First, results of computer analysis of test tapes from the Goldstone DSS show that there is considerable degradation while demodulating taped data in subcarrier form at the Pioneer Tape Processing Station (TPS). Second, the nature of the errors is changed; specifically, the phase reversal error, which seldom occurs in GOE demodulated data, becomes a predominant error source. A high frequency of this type of error causes considerable difficulty in decoding non-return-to-zero-level (NRZ-L) data. (This is the data form to be transmitted when operating in the coded mode.)

A final reason for commanding the spacecraft to a "no-coding" mode over "listen only" stations is that, should a "listen only" station receive coded data, the decoding will have to be done in the TPS at Ames Research Center. This will lengthen the processing time in the IBM 7094 system, which is explained as follows. The DSS-generated magnetic tapes containing the noisy subcarrier telemetry data are normally demodulated at the TPS with playback at 16 times real time. These data are formatted by an SDS 910 computer onto a digital tape for subsequent decommutating, data quality tagging, etc., on the IBM 7094 computer. Because of the high-speed playback, the decoding will have to be done by the 7094 instead of the 910. If the longer processing time required for decoding is not considered significant, then another commandable mode could be provided that would convert the output of the encoder to a non-return-to-zero-mark (NRZ-M) bit stream before modulation. This would alleviate the phase reversal problem, but the stated gains produced by coding would be reduced. The reduction in gain is due to the higher error rate in demodulating NRZ-M data since all single D/S errors become two adjacent errors when the NRZ-M is converted to the original NRZ-L form. However, the exact amount of degradation under this condition has not been determined.

## SELECTED CODING SYSTEM

### Code Determination and Performance

Based on the studies reported elsewhere (ref. 2), the technique chosen for coding is convolutional encoding with sequential decoding. (For a generalized discussion see ref. 3.) The selection of the appropriate convolutional code was determined by several factors. Because of the D/S limitations (discussed later), low rate codes could not be used; because of rather extensive hardware modifications to accommodate clocking, rate 1/3 codes were also discarded, leaving the class of rate 1/2 convolutional codes. In general, the longer the constraint length (the number of encoding shift register stages), the better a code will perform. However, certain practical constraints

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<sup>4</sup>"Listen only" stations are those not configured with Pioneer Ground Operational Equipment (GOE); the noisy data subcarrier is recorded on magnetic tape for later processing.



imposed by the encoder, decoder, and the format of the data fixed the maximum constraint length at 25, requiring a shift register of 25 positions in the spacecraft encoder. The resulting encoder can be built within expected size, weight, and power restrictions. Also, one SDS 920 computer word can be used to represent the entire shift register required by the decoder to duplicate the encoder.

A technique described by W. H. Lyne (ref. 4) was used to optimize the encoder connections for parity computations. Given the first  $N-1$  taps of the encoder shift register, this method decides whether to tap register position  $N$  or to leave it untapped, according to which tap condition yields the most different set of  $2^{N-1}$  messages that contain an error in position  $N$ . The difference of each of the messages is measured by the Hamming distance, which is a count of all the bits in an error message which differ from the correct message.

The code selection algorithm was computer programmed to evaluate all the Hamming distances for each tap choice at a given node and then to select the best choice on the basis of the rules given in reference 4.

This technique was used to find two codes whose connections yielded identical Hamming distances up through 21 positions. Because the number of computations grows as a power of  $N$ , this technique consumes a prohibitive amount of computer time for  $N$  greater than 21. At this point, one of the two codes, also found by Lyne, was selected because its tapped shift register connections appeared most symmetrical; thus the code would perform better in a reverse decoding technique to be described later.

The 21-position code was then expanded to 25 positions by trying all the combinations of code connections in the last four positions in a sequential decoder and selecting that set which gave the best performance. For this code, the parity bits are formed from the encoder register positions 1, 2, 4, 6, 8, 9, 12, 14, 15, 16, 20, 21, 22, 24, and 25.

The decoding algorithm, attributed to R. M. Fano of MIT (ref. 3), was modified to cause the decoder to force the bit decisions on certain known words and on the seventh bit for words which have a parity check bit provided by the Digital Telemetry Unit (DTU) in the spacecraft. This technique effectively provides an additional error-correcting capability to the code. A brief description of the decoding algorithm is given in appendix B.

Two of the decoder parameters, bias and threshold spacing, have been tentatively set for simulation purposes, but are not necessarily fixed at their final optimum values. Also, the decoder parameters have been set for a gaussian channel in which the quantization points are set 0.7 standard deviation apart. This arrangement provides a basis on which to conduct simulation tests. A program for use as a flexible research tool was written in FORTRAN IV language for the IBM 7094 on which all the preliminary tests have been made. In this program the quantization scheme and other decoding parameters can be varied by the investigator. The output of the program yields a

history of the channel errors and decoder performance on a frame-by-frame basis and also a detailed printout of the decoded information stream when "undetected" errors are committed by the decoder.

In evaluating decoder performance, one of the most important quantities to be monitored (in addition to the undetected error rate) is the amount of time required to decode a given amount of data. This is indicated by the number of times the decoder makes a tentative bit decision. Each decision, called a node trial, requires a number of logical operations by the computer decoder. As the errors in the data increase, the decoder must make more trials in order to decode the information successfully.

The set of curves in figure 5 shows the number of frames decoded (in terms of percent of the total number of frames) versus the number of node trials made by the decoder for channel bit-error rates of 0.03, 0.05, 0.07, 0.09, and 0.10. As an example of the use of this set of curves, note that if there is time for only 1000 trials before the decoder must abandon one frame and proceed to another (a realistic value of 512 bps), only 80 percent of the frames could be decoded at an error rate of 0.10; but 99 percent of the frames could be decoded at a bit-error rate of 0.07.

In the proposed deletion scheme, all frames requiring more than a specified number of trials would be suspected of having undetected errors and, consequently, would be discarded. Table I shows the undetected error rate and deletion rate based on deleting all frames requiring more than 12,000 trials for those runs shown in figure 5. It also shows the equivalent dB gain (in addition to overcoming the 3-dB rate loss) for each channel bit-error rate over the present bit-rate change point ( $P_{eM} = 10^{-3}$ ) using the present Pioneer scheme of parity tagging.

The performance of the coding scheme is shown in table I and figure 6. For comparison, the performance of the present Pioneer system, with one parity bit per word, is shown on line 1. Present Pioneer operations require a change of bit rate when the bit-error probability of the D/S output for NRZ-M data,  $P_{eM}$ , reaches  $1.0 \times 10^{-3}$ . (The corresponding NRZ-L bit-error probability,  $P_e$ , is about  $0.5 \times 10^{-3}$ .) Corresponding to this bit-error rate, the word deletion rate and undetected word error rate (previously discussed in reference to fig. 2) are also shown on line 1. For the rate 1/2 code proposed, the transmitted bit rate is twice the information bit rate; to overcome this rate loss, the D/S must operate at the point equivalent to a  $P_e$  of  $1.0 \times 10^{-2}$  as shown in figure 6. Note in table I, line 2, that the deletion rate (undecodable data rate) and the undetected word error rate are both zero. Although there is no gain over no coding in terms of dB, there is a definite gain in data quality. For the same performance in data quality, line 3 of table I represents the coding gain that can be achieved at a  $P_e$  of 7 percent; this gain can be utilized in extending any given bit-rate range. Lines 4 and 5 show the code performance as the bit-error probability is allowed to increase further. Two of the corresponding operating points for the D/S are shown in figure 6.

To evaluate the operation of the DSS and TPS computers for decoding, two machine language-decoding programs were written,<sup>5</sup> one for the SDS 920 computer and the other for the IBM 7094. These are prototypes for the final decoder subroutines and also will be used to determine approximate core requirements and computer time required.

The physical realization of the coding system components is discussed in the following sections.

### Spacecraft Encoder Characteristics

If the spacecraft DTU is assumed to be unmodified, then the encoder has the configuration shown in figure 7. The encoder is assumed to have access to all signals from the DTU such as bit-clock pulses and frame-rate pulses which are available to the scientific instruments. The information data input to the encoder is provided as biphase modulated NRZ-M data from the DTU. The data output of the encoder is then fed to the RF modulator. A commandable bypass switch permits the encoder to be switched out and the data output returned to the normal mode of operation. Because of the error carryover effects produced by NRZ-M data and because alternate bits to be transmitted are parity bits, there is one pre-encoding function to be performed, namely, converting the biphase modulated NRZ-M data to NRZ-L data. This can be done, for example, by sampling and holding at  $T$ -second intervals (where  $T$  is the inverse of the bit rate) to remove the subcarrier. A modulo-2 adder and one-unit delay will take out the differential modulation (fig. 7(b)).

The convolutional encoder unit itself consists of a 25-stage shift register with 15 stages tapped to compute parity; the parity bit is a logic "1" if there is an odd number of "1's" in the tapped registers and a logic "0" otherwise. Every information bit is transmitted unchanged with alternate transmitted bits being parity data. As far as the encoder is concerned, all data received from the DTU are information; that is, the encoder makes no distinction between actual sensor data bits and the DTU parity check bits or fixed words. The encoder shift register is reset to zeros once during every 32-word frame (reset occurs between the fourteenth and fifteenth bits of the original frame) so that the decoding can be accomplished on a frame-by-frame basis.

The final step in the encoding process is to remodulate the encoded data onto the square-wave subcarrier. At information rates of 512 and 256 bps the frequency of this subcarrier is 2048 Hz as before; at the lower information rates (64, 16, and 8 bps), it will be 512 Hz. The reason for this change is that the D/S cannot meet its specifications for the required low signal-to-noise ratios at high subcarrier-to-bit-rate ratios (see appendix C and fig. 8).

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<sup>5</sup>These were written under Contract NAS2-3637 by Codex Corporation.

## Decoder Characteristics

Since the encoder shift register is set to zeros every frame, the initial code synchronization can be done on a frame-by-frame basis in a way analogous to the conventional frame synchronization. The code synchronization routine must perform a three-way search in order to determine:

- (1) The proper grouping of the information and parity bits in the pair, which is a 1-bit ambiguity;
- (2) Whether or not the data demodulator locks up to the "in-phase" signal as transmitted or the "out-of-phase" signal, and;
- (3) The beginning of the encoded frame.

After the decoder is synchronized, data are decoded a frame at a time. The decoding algorithm is given in appendix B. If a frame is encountered that the decoder cannot completely decode in the time available, a set of zeros is stored in place of the decoded data and the decoder proceeds to the data of the next frame. This set of zeros constitutes a signaling guide for an off-line processing mode at the TPS; this is discussed in the section on tape processing station operation.

## GROUND OPERATIONAL EQUIPMENT

### Demodulator/Synchronizer

The D/S constitutes a matched filter which integrates the signal energy during each bit time. The voltage levels at the integrator output (integrate-and-dump (I & D) levels) are a measure of the quality of the received bits. The decoder utilizes a digitized representation of those levels in the decoding process; the digital values are also recorded on the DSN station magnetic tape recorders (Ampex FR-1400) for backup decoding at the TPS, if required.

For DTU information bit rates of 512, 256, 64, 16, and 8, the required encoded data rates for transmission are 1024, 512, 128, 32, and 16 bps. Thus, the D/S must operate at three additional bit rates. In addition, it has been shown that (see appendix C) a subcarrier-to-bit-rate ratio of 32 is the maximum that can be permitted in order to achieve the necessary performance from the D/S. This implies that an additional subcarrier frequency is needed to meet these requirements - namely, a 512-Hz subcarrier for coded bit rates of 128, 32, and 16 is proposed. The operation of the D/S at this subcarrier frequency has been tested (see appendix C) and the results indicate that the unit can meet its required performance specifications.

## Computer Buffer

With coding, the data are transmitted at a rate equal to twice that of the information rate. In addition to this rate change, each demodulated PCM bit is further qualified by adding two additional bits which represent one of four levels from the D/S I & D output. Thus, each demodulated bit is expanded into 3 bits that are used during decoding; that is, if the information rate is 512 bps, then the bit rate to the decoder is six times this rate, or 3072 bps (3 bits to represent the information data bit received and 3 bits to represent the coding parity bit received). Since the decoder, in either the software or hardware approach, uses data in the form of an information-parity pair as a composite unit of information, it is desirable to transfer data to the decoder in 6-bit quantities. The required modifications to the computer buffer have been analyzed for the case where the decoding is accomplished by the SDS 920 computer. Similarly, the modifications to the ground test equipment, namely the data format generators and error-rate tester, have been detailed, but will not be reported here.

## TAPE PROCESSING STATION OPERATION

As has been previously discussed, decoding of data will be done at the DSS either by a software routine in the SDS 920 or in special purpose hardware. However, as a backup for computer failure or "difficult to decode" frames of data, it is desirable to have the capability at the TPS of transferring the quantized I & D bits onto the digital tape for decoding during the first phase of digital tape processing. The magnetic tape recordings from GOE stations will contain the data in two forms. When the data are decodable at the station, the TPS will operate as with Pioneer VI and VII tapes since the PCM track will consist of decoded data. Since the recorded undecodable frames of data will generally occur randomly, an automatic mode switching capability must exist at the TPS. The first indication at the TPS that a flow of data was not decoded at the DSS is that the parity of the third word of the telemetry frame does not check. (The undecodable frames will be recorded on the PCM track as all zeros.) The encoding frame begins at the third word of each telemetry frame and ends in the second word of the next telemetry frame<sup>6</sup> and each parity-checked word is forced to check in the decoding procedure. While the A register, which converts the serial PCM bit sequence to parallel in the logic of the TPS, is loading the third and fourth decoded PCM words, there is adequate time to switch to a separate mode that will permit the logic to transfer the quantized I & D data into the SDS 920 and onto digital tape. This mode increases the data flow to six times the normal decoded PCM rate.

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<sup>6</sup>For format C (the 64-word format) the encoding frame will begin at the third and thirty-fifth words of each frame.

## EXPERIMENTAL DATA

All simulation results discussed thus far have assumed the channel to consist of PSK modulation signals with sampled and quantized output of an ideal coherent biphase demodulator. The channel noise characteristics were assumed to be independent, additive, and gaussian. However, perfect coherent demodulation of biphase modulated data is not achievable in practice. The question is how far does the D/S output depart from the gaussian channel, and how does the departure affect the sequential decoding performance.

Some representative data from the D/S have been recorded and digitized with the TPS D/S for use as input to the computer sequential decoder routine. For these tests, the noise was added directly to the biphase modulated sub-carrier. The results of decoding these data are shown in table II. Although there is some degradation at  $P_e = 8.7$  percent compared to computer simulated data with the ideal gaussian channel, the 7.4 and 6.2 percent data do meet the undetected error requirements. The 7.4 percent data should represent the worst case for the D/S since these data were obtained with a subcarrier-to-bit-rate ratio of 32.

Recently, overall system performance of sequential decoding has been determined with the Goldstone DSS RF receiver as the predominant noise source. Results show that a coding gain of 3 to 4 dB can be achieved for Pioneer bit rates of 256, 64, 16, and 8 bps. The details of the channel and the performance of sequential decoding will be reported elsewhere.

## SUGGESTED SYSTEM IMPROVEMENTS

In order to improve the error correction and detection performance of the optimized (50, 25) code without increasing the code constraint length, several approaches have been investigated. First, the parity bit attached to the Pioneer 6-bit data words is computed from bits 1, 3, and 5. Since the decoder can use this redundant information effectively, it follows that this parity bit could be replaced by a parity check bit on all 6 bits in the word. Computer simulations have been made to determine the improvement realized by this modification. A comparison of lines 1 and 5 of table III shows a factor of 2.1 decrease in undetected word error rate for  $P_e = 9$  percent.

Two known words, frame sync and mode identification, for the Pioneer case, are forced to be correct in the decoding process. (These bits are referred to as the "tail.") This technique of forcing known bits aids in decoding words near the tail. However, a significant proportion of words in error occurs in the two words (telemetry words 31 and 32) preceding the known words. This shows that the 14 known bits in the tail are insufficient to make the probability of error in words 31 and 32 as low as other words in the frame. To eliminate this problem, simulation results indicate that if the number of known bits in the tail is 21, all decoded words have about equal probability of being in error. Lines 1 and 2 of table III indicate the

corresponding decrease in word error probability with a 21-bit tail. For Pioneer this could be accomplished, for example, by moving the frame synch complement word from word position 16 to position 32 in the frame, thus giving the required 21 bits which then consist of frame synch complement, frame synch, and mode ID.

Another technique, reverse decoding, has been developed and investigated. In this process, decoding proceeds from the last bit to the first bit in a decoding frame. Because the last 24 bits in the frame must be known in order to "prime" the reverse decoder shift register, it is necessary that the frame be completely decoded in the forward direction. The information/parity pairs used for reverse decoding are extracted from the original channel symbols and are separated by 48 bits. (If the transmitted sequence is  $i_1, p_1, i_2, p_2, \dots, i_n, p_n, i_{n+1}, p_{n+1}, \dots$ , then  $i_n$  is associated with  $p_{n+24}$  for reverse decoding;  $i_n$  is associated with  $p_n$  for forward decoding.) This effectively provides the reverse decoder with different data (on a decision-by-decision basis) from which it should arrive at the correct data sequence. The known words are forced in the same manner as for forward decoding; but for the parity checked words, the bit  $i_1$  of the word is forced to make parity check rather than bit  $i_7$  which normally is the parity check bit.

The technique of reverse decoding may be used in the following way. If there are any discrepancies between the results of forward and reverse decoding, the corresponding words that differ will be deleted. Any frames which failed to decode backward will also be deleted. The results show one weakness of data frames with only a known 14-bit tail. Namely, if there are any errors committed in words 31 and 32, decoding in reverse will not decode these words differently from the forward decoding, so that these errors are not detected. These results are shown in lines 3 and 4 of table III. Simulation runs indicate that the technique of reverse decoding with a 21-bit tail yields an undetected error rate of 0.0 for data with  $P_e = 0.09$ . This performance is comparable to that of the basic (50, 25) code at  $P_e = 0.07$ , and thus results in an additional coding gain of 0.9 dB. It should be noted that decoding has fewer restrictions in a "local" sense when the decoding of 1-3-5 parity data is compared with that of 1 through 6 parity data where the parity bits are forced to check. That is, the decoding path is less constrained during a frame for the 1-3-5 parity than for the 1 through 6 parity case. Thus, the combination of reverse and forward decoding for error detection is slightly better for the 1-3-5 parity (see lines 4 and 8 of table III for  $P_e = 10$  percent). The reverse technique can be included in the same decoding software subroutines which now provide only forward decoding. Of course, the average time to decode a frame will be approximately doubled.

## CONCLUSIONS

A coding system utilizing the approach of convolutional encoding and sequential decoding has been described for application to deep space missions. It is shown by computer simulations for the gaussian channel that a coding

gain is realized (3.9 dB compared to the present Pioneer parity check code or 6.5 dB compared to no coding for satisfying Pioneer error-rate requirements). Preliminary laboratory tests indicate that with minimum modifications the Pioneer mechanized PSK modulation and detection system can be utilized for this coding scheme.

Improvements can be made on the rate 1/2 code by several approaches. First, the Pioneer parity check code on bits 1, 3, and 5 of each word can be replaced by a parity on bits 1 through 6. The undetected word-error rate out of the sequential decoding process is thereby reduced by a factor of about 2. Second, the technique of reverse decoding every frame that was decodable forward has been shown to be useful in error detection. Furthermore, a 21-bit known word sequence at the end of each block (frame) reduces the undetected error rate in decoding the last few words (preceding the known sequence). For the 1-3-5 parity scheme, the addition of a 21-bit tail and reverse decoding increases the basic coding scheme gain from 3.9 dB to about 4.8 dB.

Ames Research Center

National Aeronautics and Space Administration

Moffett Field, Calif., 94035, April 17, 1967

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## APPENDIX A

### PIONEER PROGRAM

The objective of the Pioneer program is to measure interplanetary phenomena at distances at least to 50 million miles from the earth and at distances of approximately 0.8 to 1.2 AU from the sun. Phenomena of particular interest relate to the characteristics of the magnetic fields, plasma, cosmic dust, electron density, and cosmic rays of both solar and galactic origin.

The Pioneer spacecraft is spin-stabilized, cylindrical, and weighs approximately 140 pounds (including scientific instruments). On-board power is supplied from solar cells covering the curved surface of the cylindrical structure. The spacecraft telemetry system is capable of transmitting scientific and engineering data at distances up to approximately 50 million miles from the earth. Greater communication distance is achievable by the use of the DSS 210-foot antenna facility at Goldstone, California.

The Pioneer program has mission-dependent equipment at four Deep Space Stations (DSS) to transmit commands to and receive and demodulate telemetry data from the Pioneer spacecraft. The DSS are at Goldstone, California (DSS-12); Johannesburg, South Africa (DSS-51); Tidbinbilla, Australia (DSS-42); and Robledo, Madrid, Spain (DSS-62).

Selected near real-time data are transmitted from the DSS via teletype to the SFOF<sup>1</sup> for further distribution to Ames Research Center, Stanford University, and Thompson-Ramo Wooldridge (TRW) Systems. All telemetry data received at the DSS are recorded on magnetic tape and shipped to Ames for processing of the data thereon. At Ames the telemetry data are sorted for further transmittal to the appropriate user of the data.

#### Pioneer Communication System

Spacecraft communication subsystem.- The communication system for the Pioneer spacecraft consists of an S-band radio link which

- (a) Transmits scientific and spacecraft engineering measurement data,
- (b) Receives command signals from the ground,
- (c) Provides one- and two-way Doppler measurement capability

Antenna.- The spacecraft antenna system consists of three antennas. The two low-gain antennas are a broad-beam type having multislots and are linearly polarized. Their plane of polarization is perpendicular to the spin

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<sup>1</sup>SFOF is the Space Flight Operations Facility located at Jet Propulsion Laboratory near Pasadena, California.

axis. The third, a high-gain antenna, is a colinear broadside array and is also linearly polarized. The plane of polarization is parallel to the spin axis. The beam of the antenna is axially symmetric with respect to the spin axis and has a width of above  $5^{\circ}$ , as measured at the -3 dB points in a plane containing the spin axis. The maximum gain of this antenna is 11 dB.

Transmitter.- The spacecraft transmitter is made up of a solid state exciter and a TWT power amplifier. Power output of the driver is approximately 40 mW and may be switched by ground command to only one of the two low-gain antennas or to one of two TWT power amplifiers. Each TWT has a power output of approximately 7.7 W. Either TWT may be turned on or off, or switched either to one of the two low-gain antennas or the high-gain antenna by ground command.

Receiver.- The spacecraft has two frequency addressable phase-lock loop receivers which demodulate the received signal from the ground and send the resulting command tones to both decoders. The command message contains a decoder address that selects one of the decoders to implement the command. The noise figure of the system is 8 to 10 dB and the noise bandwidth is 20 Hz.

Digital telemetry unit.- The digital telemetry unit in the spacecraft provides several modes of operation and accepts as inputs: (1) digital signals from the experiments, (2) a limited number of analog signals from the experiments, (3) the readout of the data storage unit, and (4) analog signals from the engineering measurement sensors. The digital telemetry unit generates the frame synchronization words, the mode identification word, and the parity check bit attached to each 6 bits of data. The output of the digital telemetry unit is a 2048-Hz square wave which is biphase modulated with the time multiplexed PCM bit train using a non-return-to-zero-mark (NRZ-M) format. This square wave phase modulates the transmitter/carrier in all modes of operation. The digital telemetry unit also supplies the scientific instruments with the timing and spacecraft status signals required by the experiments for proper operation with the digital telemetry unit. The 5-bit rates selectable by ground command are 512, 256, 64, 16, and 8 bps.

Also, by ground command it is possible to select one of four data formats<sup>2</sup> for transmitting the data. Changes in format occur immediately after the digital telemetry unit receives the command and, therefore, can occur at any time with respect to the data being telemetered. Format A contains 32 words and is one of the main frames for scientific information. Under normal conditions, this format is used at the two highest bit rates. Format B contains 32 words and is the second main frame for scientific information. Under normal conditions, this format is used at the three lowest bit rates. Format C is a 64-word format containing predominantly engineering data. Format D contains 32 words and is a third main frame for scientific data. Data from only a single scientific instrument are contained in this format so that it is used only on a limited number of occasions. When not selected via ground command for operation as a main frame format, the engineering format C data (64 words) are subcommutated by one word of the scientific main frame format. This is normal spacecraft operation. One additional main frame word is used

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<sup>2</sup>For two of the formats of Pioneer VI and VII see figures 9(a) and 9(b).

to subcommutate 16 words (format E) of scientific data which are gathered at a rate lower than that used to record main frame scientific data.

### Ground Operational Equipment

To provide the capability for partially processing the telemetry data received from the spacecraft, for sending commands to the spacecraft and for testing the ground equipment to verify that it is performing satisfactorily, Pioneer has at DSS-12, -42, -51, and -62 the mission-dependent equipment described hereinafter.

A brief functional description of the equipment is given below.

Demodulator/synchronizer.- The primary function of the demodulator/synchronizer is the demodulation of the 2048-Hz square wave subcarrier which is biphase modulated by the data bit stream and the generation of bit-clock pulses which are synchronous with the data bits. The demodulator/synchronizer accomplishes this function at any of the 5-bit rates. It accepts as an input the subcarrier from the DSS receiver and outputs three signals:

- (a) Serial NRZ-L data
- (b) Bit-clock pulse train
- (c) Sync status signal

Command encoder.- The function of the command encoder is to produce a command message, corresponding to a manually inserted command, which is 23 binary bits long and consists of 150 Hz (0) and 240 Hz (1) tones which phase modulate the DSS transmitter/carrier. The equipment is designed to permit visual inspection of the inserted command and computer verification that the inserted command and the transmitted command are correct.

Computer buffer.- The computer buffer provides the necessary circuits for connecting special purpose equipment to the SDS 920 computer. Except for the computer's own peripheral equipment, the buffer provides the only input from the rest of the system. The buffer supplies the interface between the computer and the following equipment:

- (a) Demodulator/synchronizer (telemetry data)
- (b) FR-1400 tape recorder (recorded telemetry data)
- (c) Data format generator (test telemetry data)
- (d) Command encoder (command verification)
- (e) Monitor receiver (command verification)

The telemetry data input system is provided with a collection register to assemble from 1 to 14 bits for computer processing. The command input of the buffer accepts 13 signals from the command encoder and 2 from the monitor receiver. The 13 signals from the encoder consist of 10 bits of address and command, 1 bit to indicate whether the unit is in normal or emergency operation, 1 bit to indicate whether the interrupt is for gross verification or bit verification, and the interrupt to act as timing. The signal from the monitor receiver is a tone (150 or 240 Hz) used in the bit-by-bit check of the command. The buffer converts the tones from the monitor receiver to voltage levels.

Error-rate tester.- The error-rate tester provides periodic semi-automatic checks on the performance of the demodulator/synchronizer while subjecting it to an input which simulates a noisy, real-time, biphase modulated subcarrier. The tester supplies the demodulator with a noisy modulated subcarrier of known signal-to-noise ratio and bit sequence. The unit compares the reconstructed data returned by the demodulator with the original NRZ-L data generated with the tester. The tester is capable of modulating a 2048-Hz subcarrier with NRZ-M data at bit rates of 8, 16, 64, 256, and 512 bps. The error counting period is variable in decades from  $10^3$  to  $10^6$  bit times. Any of three signal-to-noise ratios may be selected: 7.3 dB; 9.8 dB; and 11.4 dB. The tester generates internally the binary sequence 111100010011010 which biphase modulates the subcarrier. However, it is possible to substitute the PCM data stream available from the data format generator for the internally generated binary sequence.

Data format generator.- The data format generator simulates the normal telemetry information and provides test input signals to portions of Pioneer mission-dependent equipment. It is not used during normal operation. The data format generator output is a 2048-Hz square wave subcarrier biphase modulated by an internally generated bit stream. The generator is capable of supplying the required output signals in any format, mode, and bit rate of the Pioneer spacecraft system. Regardless of the mode, format, and bit rate selected, the contents of the telemetry words are selected manually as follows:

- (a) Any specific main frame word is chosen and the contents of the word are fixed to any arrangement of bits.
- (b) Either a fixed pattern is chosen for all words, or a distinctive word number is chosen for each word except for the word chosen in (a), the frame sync words, the subcom ID word, the extended frame count word, and the mode ID words.
- (c) Any subcom word is chosen and the contents of the selected word are fixed with any desired arrangement of bits when format A, B, or D is selected.

Transponder.- The transponder provides an RF simulation of the Pioneer spacecraft so that the DSS may be tested for compatibility with the spacecraft and telemetry communication requirements and provides the capability of closed-loop operation with the Pioneer mission-dependent ground operational equipment.

The transponder is composed of two spacecraft receivers (one on each assigned Pioneer spacecraft frequency), diplexer, low-power transmitter driver, command decoder, a display and control panel, and a power supply assembly housed in a separate container.

## APPENDIX B

### DECODING ALGORITHM

For each information bit fed into the shift register of the spacecraft encoder from the DTU, 2 bits are generated and sent to the data modulator. The first of these is the information bit itself, and the second is a modulo-2 sum of the information bits in register positions 1, 2, 4, 6, 8, 9, 12, 14, 15, 16, 20, 21, 22, 24, and 25. At the DSS the signal is received and demodulated. The I & D output of the D/S is quantized into one of eight levels for each transmitted bit and sent to the computer buffer as 3 bits - 2 bits augmented by a sign. Thus, a transmitted binary digit is transformed by the channel into one of eight symbols. These symbols are retrieved from the computer buffer by the DSS computer as a 6-bit information/parity pair as discussed in the section on GOE.

The eight possible channel symbols for one transmitted bit are assigned a set of transition probabilities; each member of the set is the probability that a particular symbol will be received, provided a 0 or a 1 was transmitted. A set of transition probabilities is given in table IV for a normal distribution quantized to eight levels. The error probability is 0.06, and the quantum level separation is 0.7 standard deviation. A graphical representation is given in figure 10 along with the assignment of symbols to quantum levels.

A metric value is defined for each channel symbol, provided a 0 or a 1 was transmitted, by the formula

$$\text{bit metric} = \log_2 \left[ \frac{P(\text{received symbol/transmitted bit hypothesis})}{1/2 P(\text{received symbol}/0) + 1/2 P(\text{received symbol}/1)} \right] - \text{bias}$$

where P is the specified transition probability. The branch metric is the sum of the bit metrics for the information and parity bits for one branch.

As each information/parity pair is selected for decoding, two branch metric values for that pair are found from a table, one assuming a 0 was input into the spacecraft encoder and the other assuming that a 1 was input into the encoder. The decoder computes the correct information/parity combination by using an encoder configuration identical to that of the spacecraft and the previous 24-bit decisions. There are four metric tables for this purpose, one for each possible information/parity combination (00, 10, 01, and 11). One table for an information/parity pair of 0,0 is given in table V. The channel alphabet and transition probabilities from which this table was derived are those of figure 10 and table IV; the bit metric bias is 0.5. The other three tables contain the same entries, but are ordered differently to correspond to the different transmitted bits. The most likely branch (the one with the highest metric value) is selected as a trial choice and the corresponding bit

is inserted into the decoder's shift register. Its metric value is then added to the total of the metrics of the previous decisions for the frame being decoded.

Because of noise on the channel, it is possible that an incorrect decision will be made by the decoder and a bit which is in error will be inserted into the shift register. However, since the bits in the decoder shift register do not match those that were in the encoder, the succeeding sequence of parity bits generated by the decoder will not correspond to those sent by the encoder. This discrepancy shows up quickly since few of the channel symbols received will closely match those generated by the decoder as possible choices. These bit choices will have small or negative metric values, and the total metric will fall below a predetermined threshold. When this happens, the decoder recognizes a possible error condition and enters a search mode. (It is also possible that the decoder is proceeding correctly, but that noise has caused the metric value to drop below the threshold.)

In the search mode, the decoder executes a systematic search through the tree of possible information/parity sequences in order to find a better fit to the received sequence, if one exists, before the decoding process is allowed to continue. The threshold value is lowered in fixed increments and the tree is searched according to a set of rules in order to find a valid path whose total metric never falls below that threshold. In doing so, the decoder may decide to select the second best choice for information/parity pairs that might have been received in error. As soon as the decoder decides on a new path (or arrives back at the old path with a lower threshold) the search mode is left and the decoding process continues as before. As the decoding proceeds successfully, the threshold value is raised in fixed increments (always remaining below the total value of the metric) so that possible error conditions may be detected most quickly. A flow diagram of this basic procedure is shown in figure 11. A more detailed discussion may be found in reference 3.

The structure of the Pioneer formats is such that much is known about the data as they are received from the spacecraft. Information bits are arranged into groups of 7 bits to form data words. With certain exceptions, the seventh bit of each word is a parity check on bits 1, 3, and 5. Data words are organized into frames of 32 words where words 1 and 17 are always a fixed frame sync word (Barker word) and its complement and word two is a mode identification. This information is used by the sequential decoder subroutine module of the station program to:

- (1) Synchronize the frame for the entire program,
- (2) Locate the starting point of the decoding process, and
- (3) Force the decoding process on words that are known and on the seventh bit of words that are parity checked in order to speed the computation and reduce the probability of undetected errors.

To force the decoder on parity means that the seventh bit of each parity checked telemetry word is determined by the decoded parity checked bits in

that word, and the corresponding branch is chosen regardless of whether it had the best metric. On the other hand, forcing the decoder on only fixed bits (or words) implies that these data bits are known independently of previous data bits, and the decoded branch is chosen from the known information. The metric value for both cases is determined from the received I & D levels.

Because sequential decoding has an inherently variable decoding rate, several restrictions have been imposed to determine the point at which decoding should be suspended and further attempts made at some subsequent time, off-line.

Since the encoder is reset at one-frame intervals, the computer decodes one frame at a time. Data are continually input and buffered by the computer for processing via an interrupt system as each information/parity pair appears in the computer buffer. If one complete frame is input before the previous frame is decoded, the decoder proceeds immediately to the most recent frame. Decoded data output for recording is delayed by exactly two frames from real-time. The decoded data are available in the computer to the other program functions, such as real-time printouts, limit checking, etc. The decoder will also estimate an error rate for the main program on the basis of corrections made in the received sequence. This estimation will replace the present parity error-rate printout in the coded mode, since parity and known words will exactly check in the decoded data.



## APPENDIX C

### DEMODULATOR/SYNCHRONIZER PERFORMANCE TESTS

Performance tests completed to date on the Pioneer GOE D/S provide a limited verification of the design philosophy. Extensive tests on the unmodified D/S have determined its threshold of operation. The laboratory equipment used to perform these tests is similar to the GOE "Error-Rate Tester."

Two conclusions were drawn from these tests. First, the D/S can maintain lock and perform within 1 dB of the theoretical performance for coherent PSK at low normalized signal-to-noise ratios ( $E/N_0$ ), for high bit rates. At low values of  $E/N_0$ , its performance is principally limited by the dynamic range of the input AGC preamplifier and chopper multipliers. Stable performance can be obtained at  $E/N_0 \geq 0$  dB for bit rates of 64 bps or higher (see fig. 8).

Second, phase inversion has little effect on error rates over the stable performance range of the D/S. In other words, once the D/S locks onto the signal, it seldom accumulates enough phase error to invert the channel PCM. This indicates that a NRZ-L format can be used instead of NRZ-M; thus the additional degradation due to the mark format can be eliminated.

To reduce performance thresholds for low bit rates, a 512-Hz subcarrier frequency is proposed. Since no time constants change in the D/S phase-lock loops for different subcarrier frequencies, a simple logic change permits the D/S to demodulate the 512-Hz subcarrier.

The D/S was tested with a 512-Hz subcarrier modulated by a 15-bit pseudo-noise sequence at 16 bps and 64 bps. Performance was found to be approximately 1 dB off theoretical for values of  $E/N_0 \geq -1$  dB, and phase inversion rate was as low as with the higher subcarrier frequency. Performance of the D/S was not tested at all the proposed new bit rates because of the numerous wiring changes and additional components required; but there is no reason to expect problems at these bit rates since the most critical bit rate, namely, 16 bps with the 512-Hz subcarrier, was proven in the laboratory tests.

The final performance check, of course, required making a complete RF link test at the Goldstone DSS to assure that the DSN receiver does not degrade the D/S performance at the lower signal-to-noise ratios. These results will be reported separately.

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TABLE I.- CODE PERFORMANCE

	Comments	$P_e$ , channel bit error probability	Word deletion rate (parity error rate or undecodable data rate)	Undetected word error rate	Gain over Pioneer parity error detection scheme with $10^{-3}$ bit error criterion, dB	
1	Pioneer with parity detection only	Target bit-rate change	$1.0 \times 10^{-3}$	$4.0 \times 10^{-3}$ (parity error rate)	$7.0 \times 10^{-6}$	Not applicable
2	Proposed (50, 25) code	Coding "break-even" point (overcome 3 dB rate loss)	$1.0 \times 10^{-2}$	0 (undecodable data rate)	0	0
3	↓		$7.0 \times 10^{-2}$	0	0	3.9
4			$9.0 \times 10^{-2}$	$1.0 \times 10^{-3}$	$1.1 \times 10^{-4}$	$4.8^a$
5			$10.0 \times 10^{-2}$	$5.3 \times 10^{-3}$	$4.1 \times 10^{-4}$	$5.2^a$

<sup>a</sup>Coding gains achievable if undetected word error rates were met.

TABLE II.- CODING PERFORMANCE WITH EXPERIMENTAL DATA

Run	Number of frames in test run	Subcarrier frequency, Hz	Information bit rate, bps	$P_e$ , percent	Undetected word error rate	Deletion rate
1	998	2048	512	8.7	$1.9 \times 10^{-4}$	$1.8 \times 10^{-2}$
2	920	2048	512	6.2	0	$1.1 \times 10^{-3}$
3	530	2048	64	7.4	0	$2.1 \times 10^{-2}$

TABLE III.- CODE PERFORMANCE WITH VARIOUS DECODER OPTIONS

	$P_e$ , channel bit-error probability, percent	Word deletion rate (undecodable data)	Undetected word-error rate
1 Basic (50, 25) code with 14-bit forced tail for 1-3-5 parity	9	$1.0 \times 10^{-3}$	$1.1 \times 10^{-4}$
	10	$5.3 \times 10^{-3}$	$4.1 \times 10^{-4}$
2 Same as (1) except 21-bit tail	9	$1.0 \times 10^{-3}$	$7.8 \times 10^{-5}$
	10	$5.3 \times 10^{-3}$	$3.0 \times 10^{-4}$
3 Same as (1) except use of reverse decoding	9	$1.5 \times 10^{-3}$	$3.5 \times 10^{-5}$
	10	$8.3 \times 10^{-3}$	$1.4 \times 10^{-4}$
4 Same as (2) except use of reverse decoding	9	$1.5 \times 10^{-3}$	0 <sup>a</sup>
	10	$8.3 \times 10^{-3}$	$2.6 \times 10^{-5}$
5 Same as (1) except 1 through 6 parity	9	$5.0 \times 10^{-4}$	$5.3 \times 10^{-5}$
	10	$2.8 \times 10^{-3}$	$2.7 \times 10^{-4}$
6 Same as (2) except 1 through 6 parity	9	$5.0 \times 10^{-4}$	$5.3 \times 10^{-5}$
	10	$2.8 \times 10^{-3}$	$1.7 \times 10^{-4}$
7 Same as (3) except 1 through 6 parity	9	$7.5 \times 10^{-3}$	0 <sup>a</sup>
	10	$5.9 \times 10^{-3}$	$1.2 \times 10^{-4}$
8 Same as (4) except 1 through 6 parity	9	$7.5 \times 10^{-4}$	0 <sup>a</sup>
	10	$5.9 \times 10^{-3}$	$3.5 \times 10^{-5}$

<sup>a</sup>On the basis of simulation runs no errors have been committed, but because of sample size this entry is statistically only less than  $10^{-6}$ .

TABLE IV.- TRANSITION PROBABILITIES FOR NORMAL DISTRIBUTION WITH  $P_e = 0.06$  AND QUANTUM SEPARATION = 0.7 STANDARD DEVIATIONS

Channel symbol	Probability that 1 was transmitted	Probability that 0 was transmitted
7	0.00014	0.29288
6	.00143	.26871
5	.01050	.24213
4	.04791	.13630
0	.13630	.04791
1	.24213	.01050
2	.26871	.00143
3	.29288	.00014

TABLE V.- BRANCH METRIC TABLE FOR TRANSMITTED 0,0

		Information symbol							
		0	1	2	3	4	5	6	7
Parity symbol	0	-2.90	-5.55	-8.52	-12.10	-1.39	-1.02	-0.96	-0.95
	1	-5.55	-8.20	-11.17	-14.75	-4.04	-3.67	-3.61	-3.59
	2	-8.52	-11.17	-14.14	-17.72	-7.01	-6.64	-6.58	-6.57
	3	-12.10	-14.75	-17.72	-21.30	-10.59	-10.22	-10.16	-10.15
	4	-1.39	-4.04	-7.01	-10.59	.12	.49	.55	.56
	5	-1.02	-3.67	-6.64	-10.22	.49	.86	.92	.93
	6	-.96	-3.61	-6.58	-10.16	.55	.92	.98	.99
	7	-.95	-3.59	-6.57	-10.15	.56	.93	.99	1.00

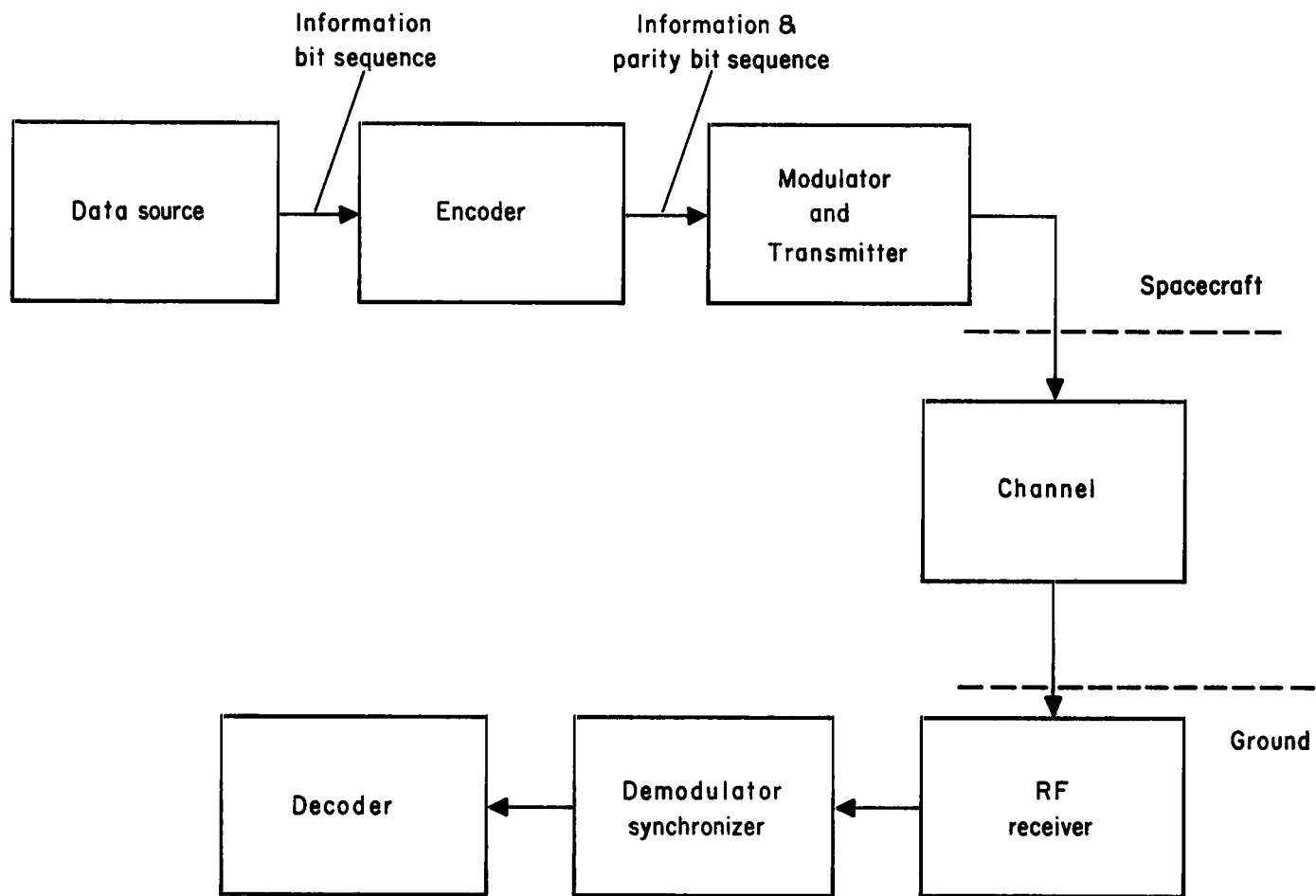


Figure 1.- Coding system configuration.

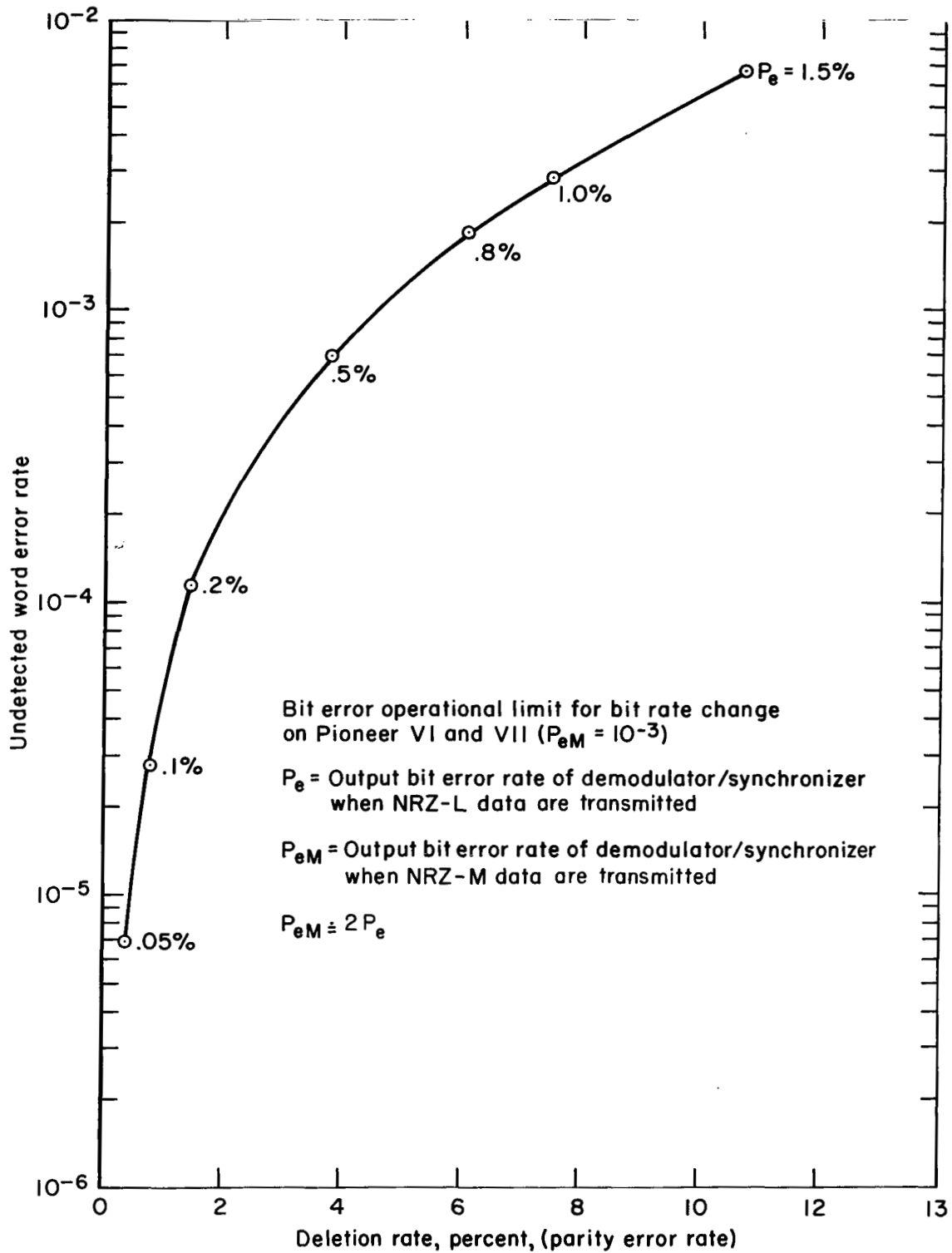


Figure 2.- Theoretical performance of parity error detection.

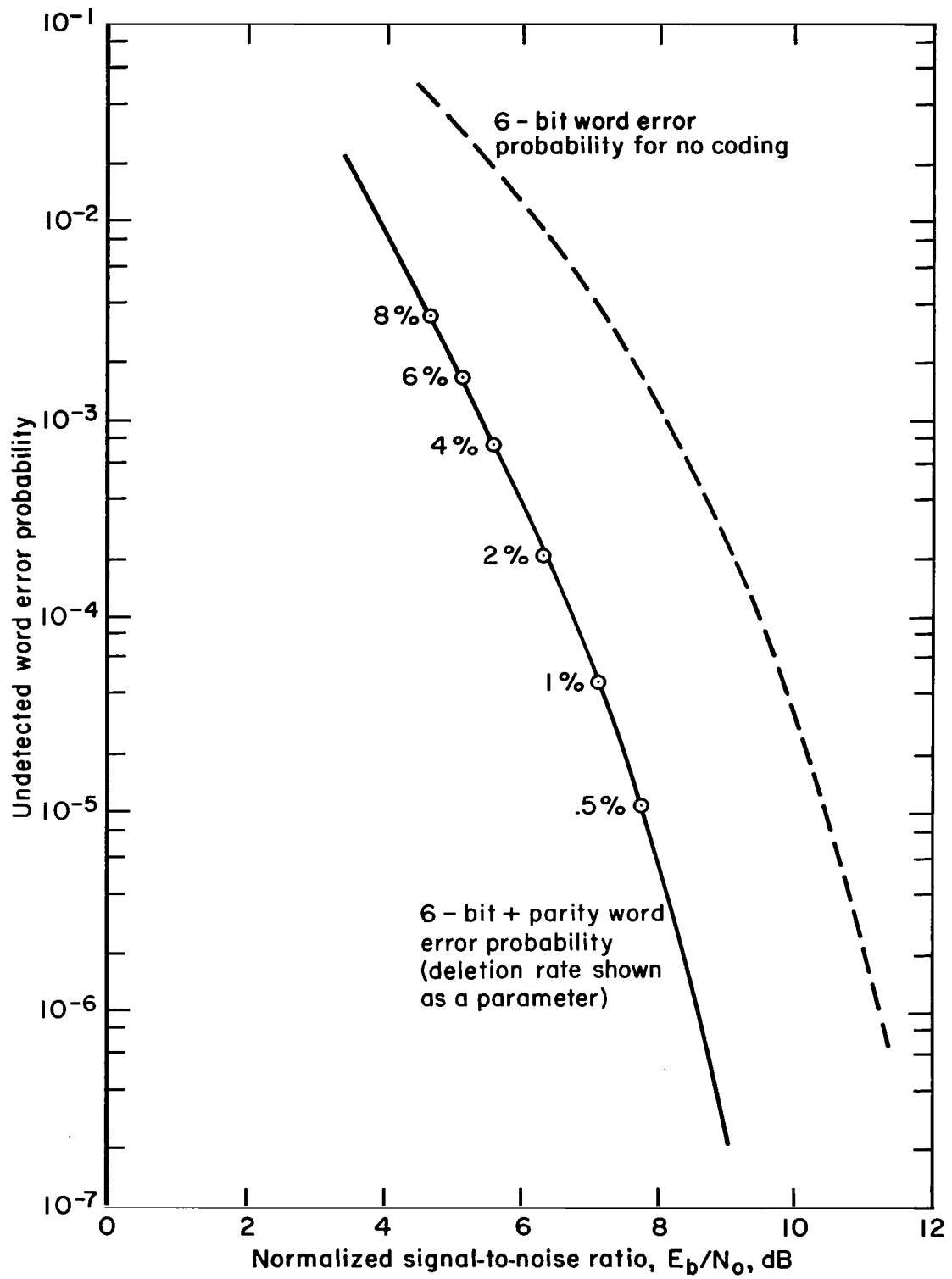


Figure 3.- Performance of parity error detection compared to no coding.



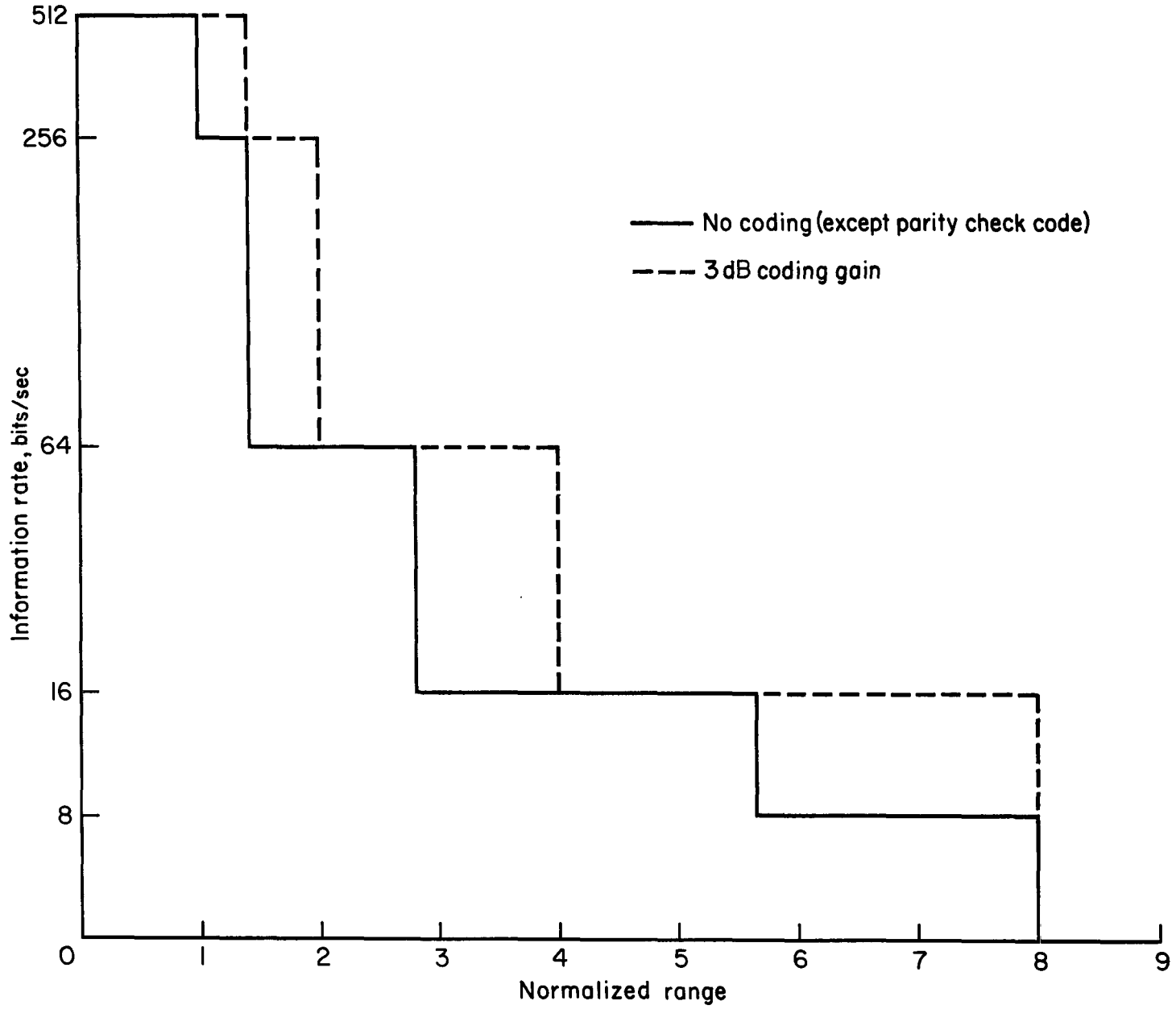


Figure 4.- Information rate vs. normalized range.

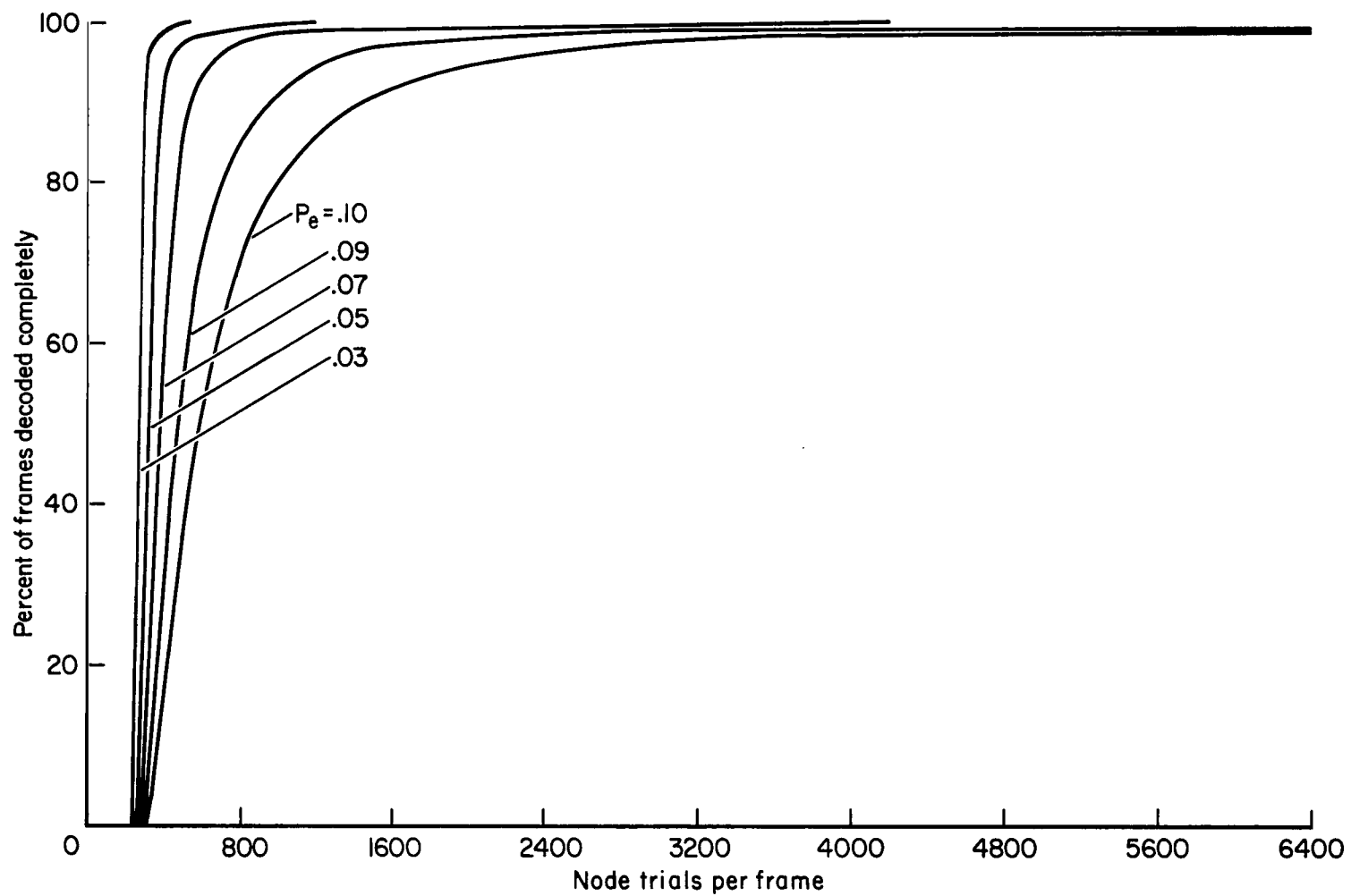


Figure 5.- Decoder computation rate performance.

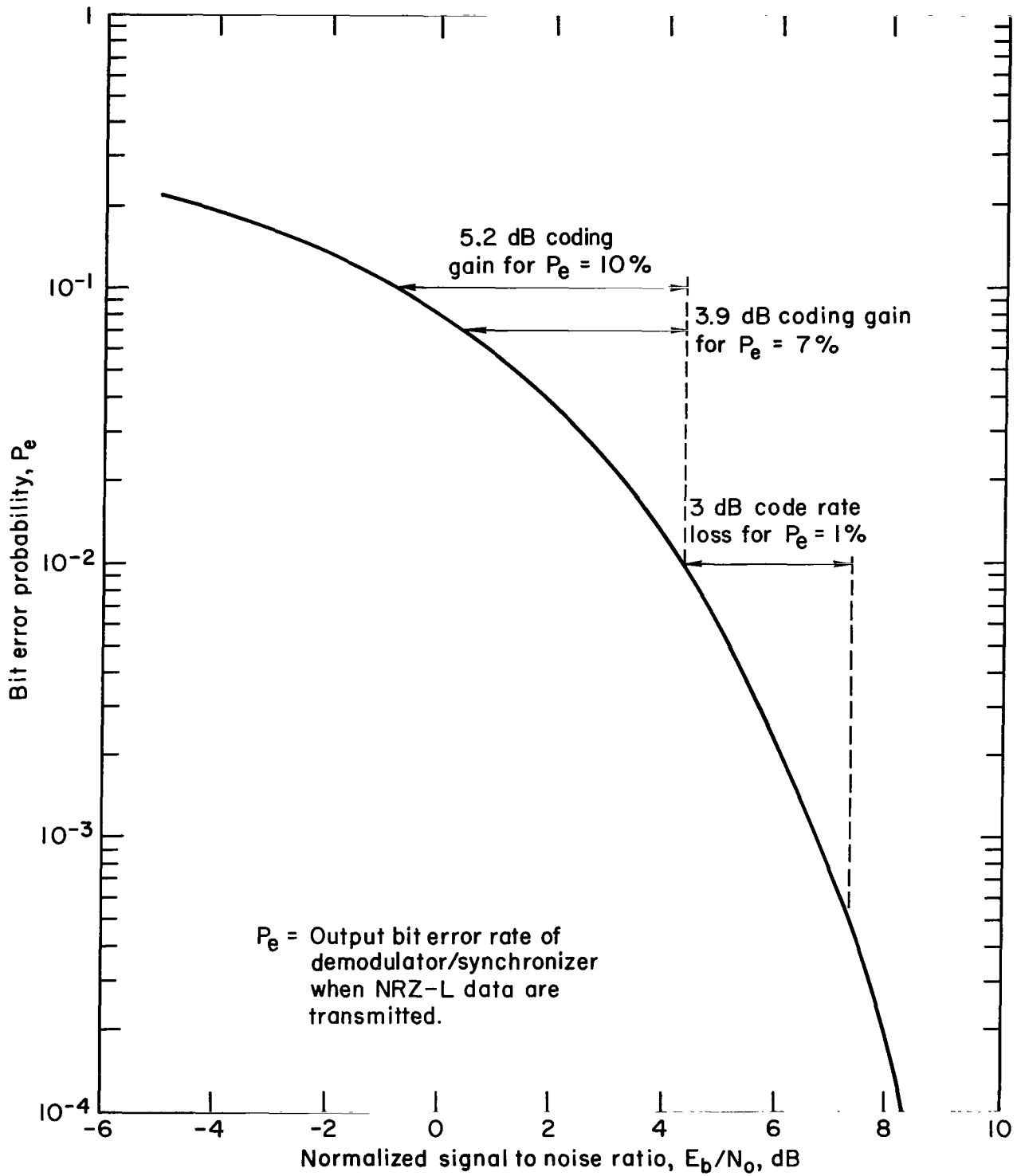
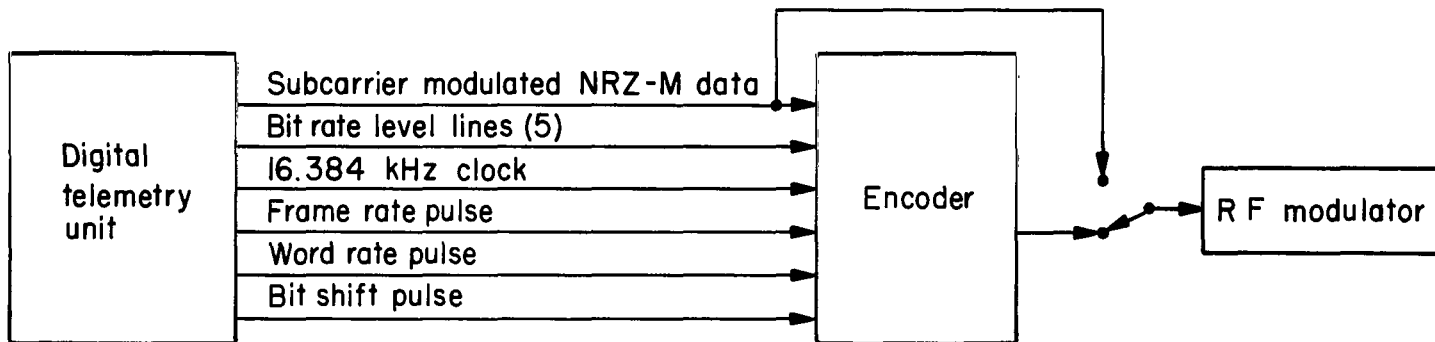
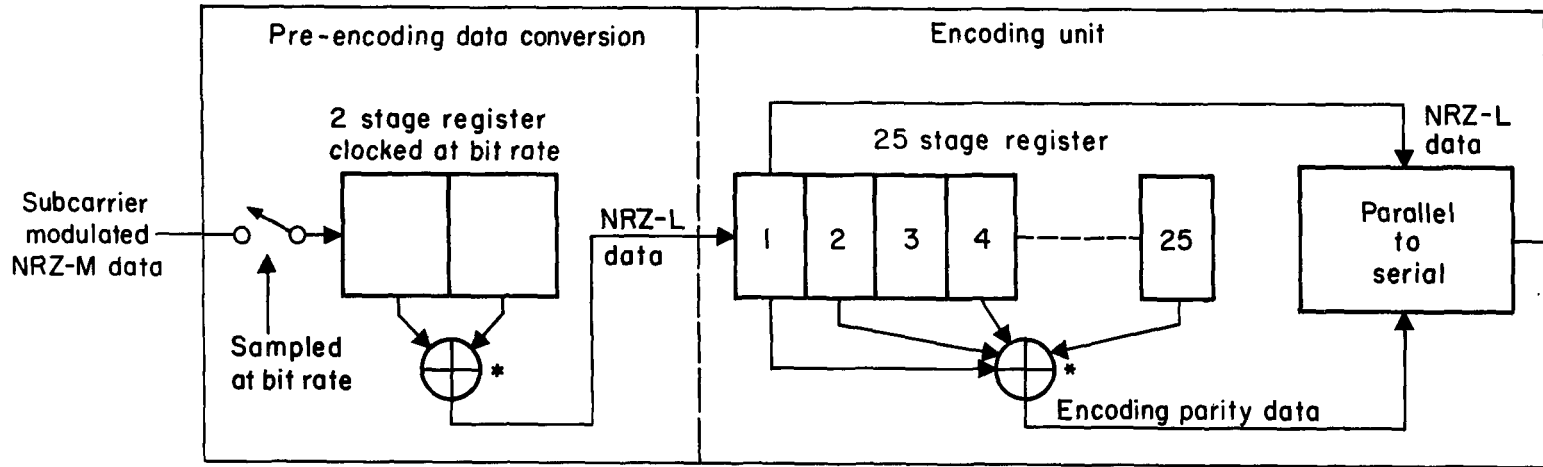


Figure 6.- Performance of coherent PSK detection.

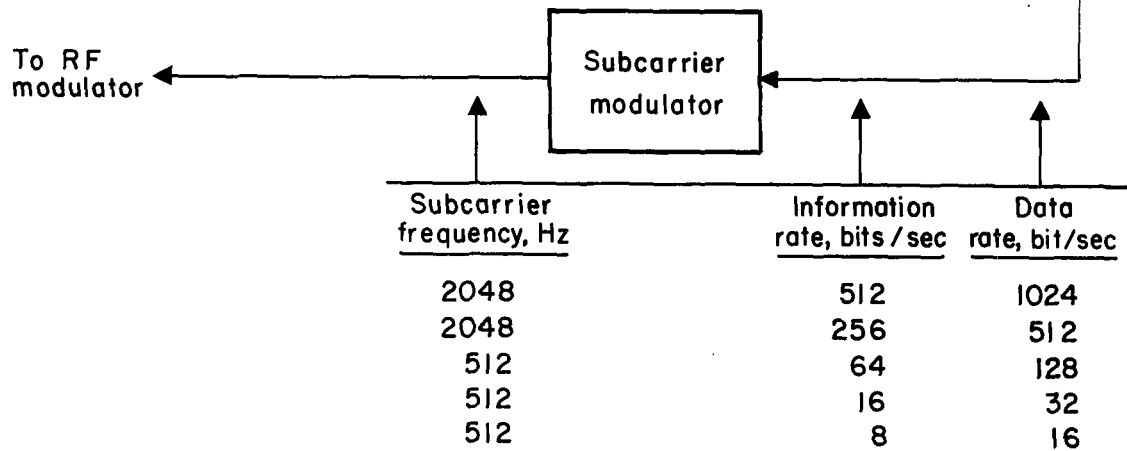


(a) Encoder interfaces.

Figure 7.- Spacecraft encoder.



\*Modulo 2 adder: Output = 1 if odd numbers of ones in tapped registers and 0 otherwise



(b) Encoder functional diagram.

Figure 7.- Concluded.

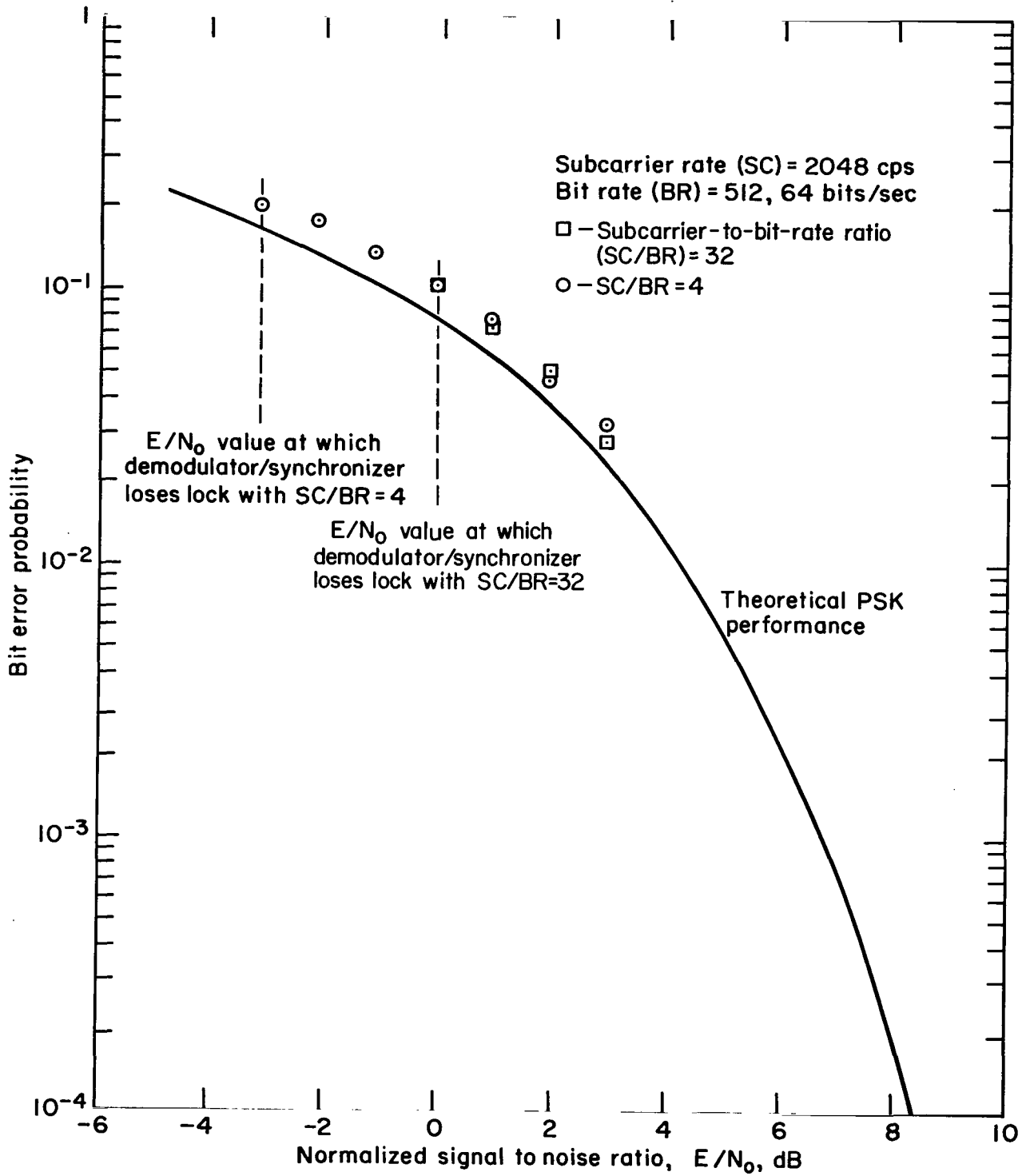


Figure 8.- Results for Pioneer Demodulator/Synchronizer tests.

1	2	3	4
Frame sync	Mode ident	Scientific subcomm	Aa
5	6	7	8
		Ba	
9	10	11	12
	Ab		Da
13	14	15	16
Ea		Ca	
17	18	19	20
Frame sync compliment	Subcomm ident	Engineering subcomm	Ae
21	22	23	24
25			
		Ga	
29			

- A - Cosmic ray (Chicago)
- B - Magnetometer (GSFC)
- C - Plasma (MIT)
- D - Cosmic ray (GRCSW)
- E - Radio propagation (Stanford)
- G - Plasma (NASA/ARC)

Lower case letters denote separate data lines

(a) Word assignments for format A (scientific).

Figure 9.- Word assignments for Pioneer VI and VII formats.

1	2	3	4	5	6	7	8
Frame sync	Mode ident.		Bi-level	Bi-level	Bi-level	Bi-level	Bi-level
9	10	11	12	13	14	15	16
Bi-level	Bi-level	Bi-level	Bi-level	Bi-level	Bi-level		
17	18	19	20	21	22	23	24
Frame sync complement							
25	26	27	28	29	30	31	32
33	34	35	36	37	38	39	40
Frame sync	Mode ident.	Af	Ag				
		Analog	Analog				
41	42	43	44	45	46	47	48
49	50	51	52	53	54	55	56
Frame sync complement							
57	58	59	60	61	62	63	64
							Be
							Analog

(b) Word assignments for format C (engineering).

Figure 9.- Concluded.



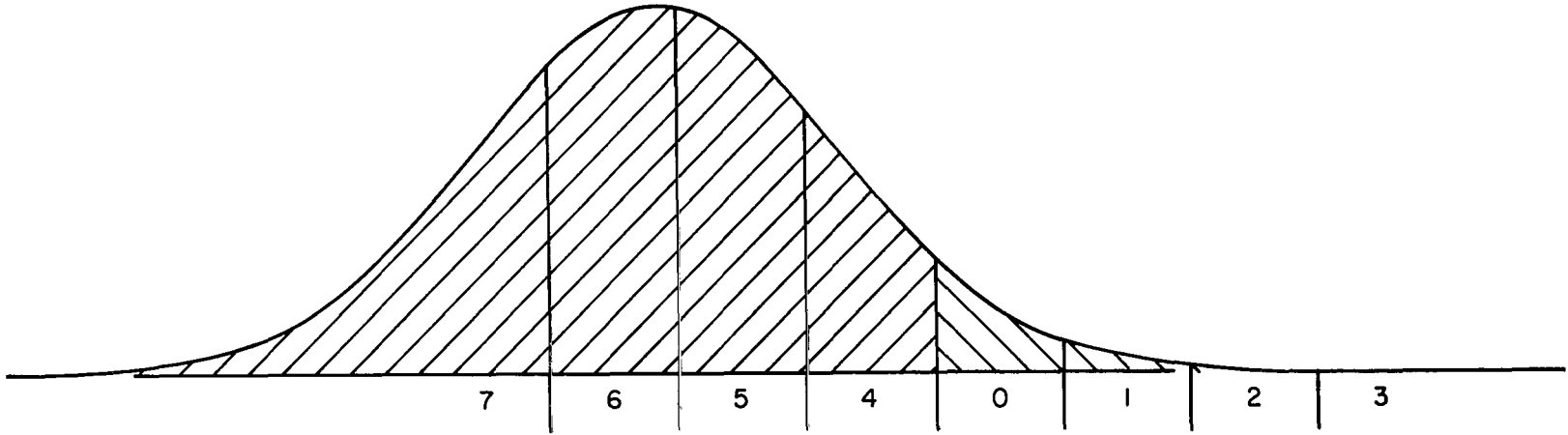


Figure 10.- Normal distribution for transmitted "0" with  $P_e = 0.06$ . Curve shows the quantum level assignments for 0.7 standard deviation separation.

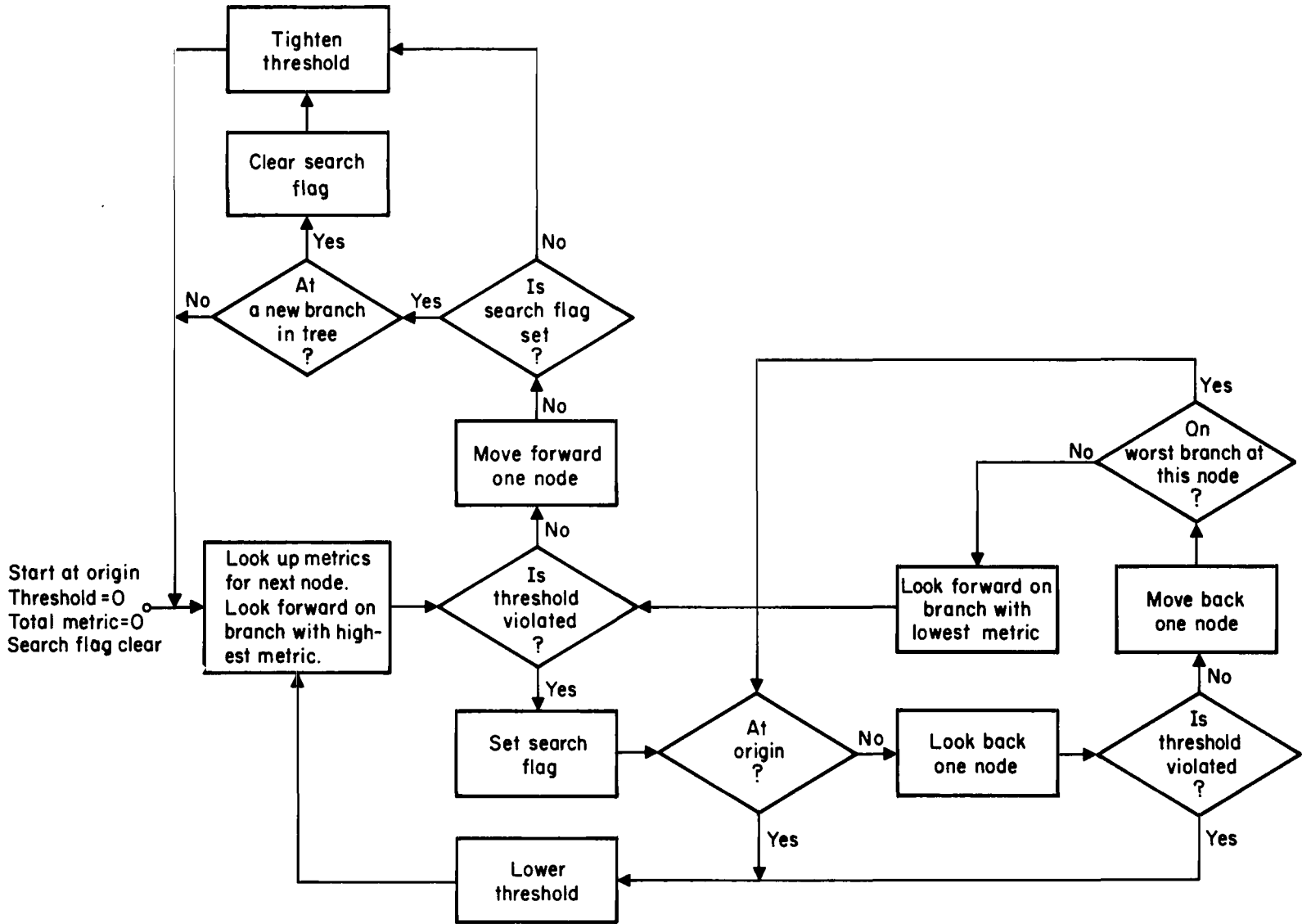


Figure 11.- Basic decoder algorithm.

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