CHANNEL NOISE—A LIMITING FACTOR ON THE PERFORMANCE OF A CLASS OF ADAPTIVE TECHNIQUES

G. L. RAGA

Summary The effects of channel noise on a class of adaptive sampling techniques based on the concept of removal of redundant data samples were investigated. Assuming a system of fixed bandwidth and fixed transmitter power, the channel noise forces the adaptive system to operate at a lower bit error probability than the equivalent PGM system since in the adaptive system each transmitted bit represents more information. This limitation was partially overcome by adding error criterion of unequal weighting to the data which enabled the system to operate at essentially the same bit error probability as the PCM system with a net coding efficiency greater than the coding efficiency of the error-correction code. Experimental results from subjective tests, and the RMS error demonstrate that a new error criterion must be developed for the class of adaptive techniques.

Introduction The purpose of this paper is to report on the results of an experimental program to determine the effects of channel noise on a class of adaptive techniques. Solutions to certain problem areas are postulated and the net efficiency of the coding techniques is determined.

The field of adaptive-compression telemetry techniques is relatively new compared with such areas as television and speech-bandwidth compression. One of the earlier papers on the subject, whose central theme was the design of an efficient telemetry system, appeared in 1959.[(1)] Since that time, effort has been concentrated in four major areas of adaptive sampling, preprocessing, selective monitoring, and efficient encoding.

From the available literature it appears that the majority of the users and investigators of telemetry compression are considering the zero-order interpolator. An unfortunate discrepancy exists in the terminology since the zero-order interpolator is frequently described as a zero-order predictor,[(2)] self-adaptive compression,[(3)] an adaptive sampling technique,[(4)] selective monitoring,[(5)] run-length encoding.[(6)] floating aperture,[(7)] redundancy removal,[(8)] and the step method.[(9)]

Each of these techniques, although sounding basically different, operates indentically. Although these techniques have been applied to a telemetry source, they can also be applied to a television source. For the purposes of illustration, the source will be considered a television source. Assume that we start with word one, line one, of a television frame. Word one is compared with word two; if the absolute value of the difference is less than K, word two is disregarded and the process continues until the difference is greater than K, say at word j. At this point, word one is transmitted to a buffer store along with the distance from word one to word j. Word j then replaces word one and is used as a basis, and the process continues. It is this class of adaptive techniques that will be investigated.

Problem Definition The use of adaptive techniques for data transmission can be applied to various sources, including video, speech, and telemetry data. There are three possible ways to take advantage of the adaptive technique: If the bandwidth is fixed, adaptive-compression techniques can save transmitter power; if the transmitter power is fixed, bandwidth can be conserved; if both the transmitter power and bandwidth are fixed, more information can be transmitted per unit time.

Assume, for example, that photographs are transmitted from an earthorbiting vehicle with rf parameters as given in Figure 1. With the channel capacity fixed at $A = 10^6$ bits/second and by employing data compression, more information can be received per unit time. If the PCM television frame is composed of x samples/line and y lines/frame, each sample is quantized to n bits/sample, and F frames/second can be transmitted, the data rate is

$$R = Fnxy \text{ bits/second} \tag{1}$$

The number of frames of data that can be transmitted is

$$F = \frac{A}{nxy} \text{ frames .} \tag{2}$$

The amount of information that can be transmitted in t seconds is I = Ft.

If F can be increased, I increases, and a savings results. One way of increasing F is to decrease nxy by some form of data compression.

Adaptive Sampling Techniques The adaptive sampling technique that will be discussed is the zero-order predictor. Assume that the frame of dat is composed of xy samples. If the coding algorithm is applied, the result is a sample reduction of

$$C_s = \frac{xy}{S} , \tag{3}$$

where S is the number of nonredundant samples/frame. To reconstruct the data at the ground stations, it is necessary to address each nonredundant sample. Assuming that the absolute magnitude and address of each sample in a line is transmitted, the gross average data compression is

$$C_g = \frac{nxy}{\left[\log_2 (x) + n\right] S} \quad . \tag{4}$$

For example, consider n = 6 bits, x = y = 256. Then

$$C_g = 0.429\ C_s \ . \tag{5}$$

Hence, to address the nonredundant samples, approximately a 60% reduction in compression results.

For the purposes of this analysis, it will be assumed that instead of the absolute address of the nonredundant samples, the incremental distance, Δx, between nonredundant samples will be transmitted; that is,

$$C_g = \left[\frac{n}{\log_2 (\Delta x) + n}\right] C_s \ . \tag{6}$$

For n = 6 and $\Delta x = 16$, we have $C_g = 0.6\ G_s$.

With this form of addressing, the sample reduction compression is only 40% rather than the 60% achieved with absolute addressing.

Channel Noise Channel noise is another limiting factor on efficiency of an adaptive sampling technique.

Under the constraints of fixed transmitter power and bandwidth, the effects of channel noise on the zero-order predictor will be more pronounced than on PCM data transmission. Each transmitted segment now represents, on the average, C_s elements. Therefore, a single bit error will affect many elements. It will be shown later that, depending upon the system implementation, a single error can destroy an entire frame of data, single line of data, or just a few samples.

For the zero-order predictor analyzed, it will be assumed that perfect line synchronization is available and the first element transmitted of each line is correct. With these constraints, the maximum degradation that can be caused by a single bit error is the loss of an entire line of data; however, the error can not propagate into the next line. The most logical solution to the problem is to increase signal power; (10) however, this is not permissible under the constraints of the stated problem. Therefore, once the channel characteristics are specified, it is necessary to add error protection to minimize error propagation by means of error detection and correction or error detection and retransmission. For the purposes of this paper it will be assumed that the former case will be employed, that the channel is binary symmetric, and that the type of error protection will be a single-error-correcting coding of the Hamming class. In this case, the net data compression is reduced further by the amount of redundancy the error-correcting code adds. In general, if P bits is the amount of redundancy added to each transmitted word, the net data compression is given by

$$C_n = \frac{nxy}{\left[\log_2 (\Delta x) + n + P\right] S} \tag{7}$$

or

$$C_n = \left[\frac{\log_2 (\Delta x) + n}{\log_2 (\Delta x) + n + P}\right] C_g , \tag{8}$$

which is merely a restatement of the fact that the net compression is equal to the gross average data compression times the efficiency of the error-correcting code. Carrying through the previous example, but adding a (14, 10) Hamming code,

$$C_n = 0.429\ C_s ; \tag{9}$$

that is, when error protection and addressing are employed on the system, the net data compression is approximately 43% of the sample reduction. With the basic terms defined, it is now possible to compare the performance of the adaptive sampling system.

The basis of comparison of the system's performance with that of other systems will be a subjective evaluation; however, so that the data can possibly be extrapolated to other sources, the rms error will also be used as a basis. In general, for the zero-order predictor the peak error is normally specified as being an error criterion; however, because of the expansion of errors due to channel noise, this can not be used as a basis of comparison. Since this error-expansion factor is quite pronounced for the lower error rates, there is a need for another error criterion. As a consequence, the experimental program was initiated to investigate the effects of channel noise.

Experimental Program The objectives of the experimental program were to evaluate subjectively the effects of channel noise on PCM and compressed data, to,determine experimentally the rms error as a function of compression, and to determine experimentally the rms error between the compressed data and PCM data at varying channel bit error probabilities.

Figure 2 is a block diagram of the conceptual experiment. A photograph was scanned by EDITS (EMR's Experimental Digital Television System). The digital data then were transferred to EMR's ASI-210 Digital Computer, processed by the computer with various coding algorithms, channel noise was injected into the compressed data, and the data then were decoded and transmitted back to EDITS to be displayed and photographed. A third path existed in the computer: the addition of error correction in the form of a (7, 4) or (14, 10) Hamming code. The (7, 4) code, which was the easiest to implement and the fastest operational, was used to protect only the Δx positional bits since an error in position is weighted far heavier than an error in intensity. A (14, 10) Hamming code which protected both the intensity and the positional information was also implemented on the computer. This code has the same net coding efficiency as the (7, 4) code; however, its figure of merit (the ratio of the word error probability after coding to the word error probability before coding) is not as large as that of the (7, 4) code and is an order of magnitude greater in complexity in both implementation and encoding time. However, as anticipated, the code performed more efficiently than the (7, 4) code.

Error Performance In the past, most investigators have ignored the effects of channel noise on PCM data or have argued that with compression the bandwidth is reduced and therefore the noise also is reduced. It is obvious that an error in the most significant bit has more of an effect than an error in the least significant bit and, of course, all errors are equally weighted. A derivation of the rms error as a function of the channel bit error probability is a straight forward matter. The rms error as a function of the channel bit error probability (P_e^b) and the number of quantizing bits, N, is given by

$$rms_{PCM} = \sqrt{\frac{P_e^b}{3}\left(1 - \frac{1}{4^N}\right)} \ . \qquad (10)$$

Errors in a video PCM scene occur as a salt-and-pepper effect and are constrainted to individual samples; however, for the zero-order predictor this is not the case.

For the zero-order predictor a single-bit error can propagate the average sample reduction, it can propagate the entire length of a line and destroy all the samples, or it can merely cause a finite percentage of the samples in the line to be in error. Assume that Δx is encoded to M bits and the intensity to N bits; therefore, for each nonredundant sample and (N + M)-bit word is transmitted.

Figure 3 represents the error analysis model. State A occurs when the decoder is in perfect synchronization with the encoder; that is, when transmission is error free. State B is when a single-bit error occurs in intensity bits; this will cause an error to propagate the average sample reduction and then return to State A. State C represents the system being completely out of sync; however, the error propagation is finite since this can be described as a sliding synchronization state--that is, an error in the least significant bit of Δx will cause a displacement of ±1 sample for each segment, but the remaining elements will still maintain the correct intensity since there exists an average number of successive samples of the same intensity equal to the sample reduction. Once the system enters State

C, it can not reenter State A without additional constraints on the decoder. For the purposes of this analysis the decoder returns to State A at the start of each line. State D occurs when an error occurs in the most significant bits. Such an error will cause complete loss of synchronization with zero probability of returning to State A, and in general, a complete loss of each line occurs. As with State C, State D will return to State A at the beginning of each line by external control.

Assuming that the channel bit error probability is given by P_e^b, the probability of being in State A is $(1 - P_e^b)$ and the rms = 0. The probability, to a first-order approximation, of being in State B is given by

$$\text{Prob (State B)} = \frac{N}{N + M} \cdot \tag{11}$$

The probability of being in State C or D is the same and is given by

$$\text{Prob (State C)} = \text{Prob (State D)} = \frac{1}{2}\left(\frac{N}{N + M}\right) \cdot \tag{12}$$

The rms error can be considered as an rms error-expansion factor. Assuming that the encoded frame is used as a basis of comparison, the rms error is given by

$$\text{rms}_{ZOPE} = \sqrt{\frac{1}{4x}\left(MS_A + MS_B + MS_C + MS_D\right)} \cdot \tag{13}$$

Hence, an error in intensity will have an rms value of

$$\text{rms} = \sqrt{\frac{P_e^b}{3}\left(1 - \frac{1}{4^N}\right)} , \tag{14}$$

and it will occur (N/N+M)% of the time and will propagate C_s samples. Thus,

$$R_{MS_B} = C_g \sqrt{\frac{P_e^b}{3}\left(1 - \frac{1}{4^N}\right)} . \tag{15}$$

An error in Δx that will cause the system to enter State C will occur M/2(N+M)% of the time and will cause an rms error,

$$\sqrt{\frac{P_e^b}{3}\left(1 - \frac{1}{4^N}\right)} , \tag{16}$$

to be weighted by $E\{S_L\}$ samples/line times the E {D} , the expected value of the displacement. It can be shown that

$$E\{S_L\} = \sqrt{\frac{1}{3}\left[\frac{Nx}{(N+M)\ C_g}\right]^2 + \frac{Nx}{2(N+M)\ C_g} + \frac{1}{6}} \tag{17}$$

and

$$E\{D\} = \sqrt{\frac{1}{2^M}\left(\frac{16^{M/2} - 1}{3}\right)} \tag{18}$$

for M, an even integer.

A single bit error in Δx that will place the system in State C will have an rms value of

$$rms_C = \frac{M}{2(M+N)}\left[\frac{P_e b}{3}\left(1 - \frac{1}{4^N}\right)\left[\frac{1}{2^M}\ \frac{(16^{M/2} - 1)}{3}\right]\left[\frac{1}{3}\left[\frac{Nx}{(N+M)C_g}\right]^2 + \frac{Nx}{2(N+M)C_g} + \frac{1}{6}\right]\right]^{1/2} \tag{19}$$

An error of Δx that will place the system in State D will have an rms value of

$$\sqrt{\frac{P_e b}{3}\left(1 - \frac{1}{4^N}\right)} \tag{20}$$

occurring M/2(M+N)% of the time weighted by a factor $E\{\zeta\}$.

It can be shown that this is given by

$$E\{\zeta\} = \sqrt{\left[\frac{(N+M)C_g}{N\sqrt{6}}\right]^2 - \frac{(N+M)C_g\, x}{2N} + \frac{x^2}{3}}\ . \tag{21}$$

Therefore, the rms error introduced when the system is in State D is given by

$$rms_D = \frac{M}{2(M+N)}\sqrt{\frac{P_e b}{3}\left(1 - \frac{1}{4^N}\right)\left[\left(\frac{(N+M)C_g}{N\sqrt{6}}\right)^2 - \frac{(N+M)C_g\, x}{2N} + \frac{x^2}{3}\right]}\ . \tag{22}$$

The total rms error expansion for the zero-order predictor is given by

$$rms_{ZOPE} = \sqrt{\frac{MS_A + MS_B + MS_D + MS_C}{4x}} \quad . \tag{23}$$

This is only part of the total error which is caused by channel noise, and it is relative to the encoded frame. The total error is given by this error plus the rms error due to the encoding process.

RMS Error Due to Encoding The concept of the coding algorithm introduces an rms error that, due to the coding technique itself, is irreducible. For the zero-order predictor with an error band of ±K elements, in a single frame of data there are on the average

$$S = \frac{Nxy}{(N+M)\ C_g} \tag{24}$$

samples which by definition are correct. Hence, the number of possible elements that could be in error is given by

$$xy \left(1 - \frac{N}{(N+M)C_g}\right) , \tag{25}$$

or [1 - N/ (N+M)C_g] % of the elements may be in error. The expected value of the error is given by

$$E\{\epsilon\} = \sqrt{\frac{2K^2 + 3K + 1}{6}} \quad . \tag{26}$$

However, of these elements that may be in error, the expected number that could be in error is determined by the amount of redundancy in the frame of data. Let PE be defined as the amount of redundancy where, as the error band increases, the amount of redundancy increases also; therefore, the percentage of elements that may be in error is given by

$$\left[1 - \frac{N}{(N+M)\ C_g}\right] \left[1 - PE(N)\right] \quad . \tag{27}$$

Consequently, the rms error due to the encoding algorithm is given by

$$rms_{ZOP} = \frac{1}{2^N} \sqrt{\left[1 - \frac{N}{(N+M)C_g}\right] \left[\frac{2K^2 + 3K + 1}{6}\right] \left[1 - PE(N)\right]} \quad . \tag{28}$$

The total rms error as a function of the channel bit error probability is given by

$$rms = rms_{ZOP} + rms_{ZOPE}. \qquad (29)$$

These theoretical predictions will now be compared with actual experimental results.

Experimental Results Due to the nature of the source data, both subjective and rms experimental results will be given.

Subjective Results--Figure 4 compares the subjective results of a zero-order predictor, the 6-bit PCM original, and the linear-approximation coding technique. For rather large apertures (error bands), contouring results for the zero-order predictor; the contouring can be minimized somewhat by the linear-approximation technique. The zero-order predictor can be thought of as a run-length (zero-slope) encoder with an error band. The linear approximation allows a finite number of slopes with an error band; therefore, it should eliminate the contouring effect as the aperture is gradually increased. Figure 5 illustrates the subjective effect of varying the compression for the zero-order predictor.

The effects of channel noise on a zero-order predictor are given in Figure 6. Here the error band is fixed and the channel bit error probability is varied from 10^{-4} to 10^{-1}. We can see that channel noise raises the lower limit on permissible channel noise compared with PCM. Therefore, with the channel capacity and transmitter power fixed, it is necessary to add error protection to the compressed transmitted data.

Figures 7, 8, and 9 illustrate the effectiveness of the (14, 10) and (7, 4) code at a channel bit error probability of 10-3 with the compression variable. Here, the effects of channel noise become more pronounced as compression increases. However, the error protection is quite effective in reducing the error expansion.

RMS Error Results--As stated earlier, the rms error for the zero-order predictor can be considered as consisting of two parts: the irreducible coding error and the error caused by the effects of channel noise giving an rms error expansion. Figure 19 plots the rms error as a function of the gross average compression. At an error band of ±5 out of 64 possible levels, the rms error is 3.54%; however, the peak error is 7.85%. Since the peak error is normally specified and the actual rms error is less than one-half peak, it appears that peak error is not an especially good criterion in describing the zero-order predictor. Furthermore, recalling the subjective photos of Figure 4, which contain an rms error of 3.54% (a high value relative to the quantizing noise), it can be seen that subjectively the picture is acceptable. Therefore, it appears that neither the rms or peak error appears to be acceptable error criterion for television data. Also given in Figure 10 is Equation (28) which is the analytical prediction of the rms error. It might be pointed out that although the rms error is not a good error criterion for TV in certain telemetry channels, it will be acceptable, and the analytical expression should be valid for telemetry data.

Figure 11 illustrates how effective the error-correction code is along with the equivalent PCM error. The error-correction code, which is a monotonically increasing function with decreasing bit error probability, can never reduce the error below the basic rms error of the coding technique. As the error rate increases, the rms error and the rms error with protection converge to approximately 25%. Below $P_e^b = 10^{-2}$, the effectiveness of the error-correcting code decreases; so its usefulness also decreases.

The analytical prediction based on Equation (29) agrees quite well with the experimental results. It appears that there exists an optimum error reduction as evidence by the PCM and zero-order predictor with the (14, 10) code having nearly the same rms error at $P_e^b = 10^{-2}$. In this case, at the same rms error, the zero-order predictor without error protection operates at $P_e^b = 9 \times 10^{-4}$. Hence, Figure 12 plots what can be called a bit error improvement factor--that is, the ratio of the bit error probability after coding to the bit error probability before coding the same rms error. For example, at Pe b = 10-2 with the (14, 10) code, for the same rms error without protection, the zero-order predictor operates at Pe b = 9 x 10-4, or a bit error improvement of 11.1.

The improvement with coding can also be seen from Figure 13 which plots the difference between the rms error without and with error protection as a function of the channel bit error probability. Here we are multiplying the figure of merit of the error-correcting code by the rms error where both curves are a function of P_e^b. The figure of merit of the code is a monotonically increasing function of decreasing P_e^b whereas the rms error for the zero-order predictor is a monotonically decreasing function to a constant value with decreasing P_e^b. This seems to indicate that there exists an optimum operating channel bit error probability for maximum error reduction; however, this error probability is not necessarily optimurn for minimum rms error. Hence, by plotting the difference of Equation (23) and the equation modified by the figure of merit of the error-correcting code, one can obtain Figure 13, which experimentally gives the Optimum P_e^b for maximum rms error reduction.

In view of Figure 13, the data were replotted in Figure 14 to give a figure of merit for the error-correcting code. Given a minimum acceptable rms error before error correction, it is possible to determine the rms error after error correction. This can be considered as a figure of merit for the error-correcting code with the zero-order predictor.

Figure 15 and 16 show how another error criterion could possibly be employed. Both rms error and percent similarity for the zero-order predictor and linear approximator relative to the encoded form are plotted. Note that for the zero-order predictor without channel noise, the rms error is 3.54% whereas the percent similarity relative to the original data is 35.2%. It appears that the percent similarity has more meaning than the rms error at this particular point.

Conclusions It can be concluded that under the constraints of fixed bandwidth, compression can be used to obtain more information per unit time. Furthermore, under these constraints, some form of error protection must be employed. The type and form of the error protection will be a compromise between implementation, desired efficiency and channel characteristics. When error protection is employed on the class of techniques, the effectiveness of the code is decreased considerably. Sample reduction is not a valid way to compare system performance of this call of techniques. The effects of channel noise are more pronounced on compressed systems; therefore, error protection is required. When addressing of the nonredundant samples and the redundancy of an errorprotection code are considered, the net coding compression is reduced more than 50%.

This particular experimental program requires additional effort to verify the analytical expressions as applied to the broad category of telemetry data. Various addressing techniques, including optimum encoding of the addresses, might be investigated as a means of increasing the net compression and the effects of channel noise on the self-synchronizing codes to be investigated. Although the television source was employed in the analysis, it must be emphasized that, in general, these results will apply to the broad class of adaptive sampling telemetry techniques since the television source can be considered to be an extremely active telemetry channel.

Bibliography

1. Zukerman, L. G. , and Ross, I. , "Some Coding Concepts to Conserve Bandwidth," Proc. National Telemetering Conference; 1959.

2. Hulme, J. R. and Schomburg, R. A., "A Data Bandwidth Compression for Space Vehicle Telemetry," Proc. National Telemetering Conference; 1962.

3. Weber, D. R. and Wynhoff, F. J. , "The Concept of Self-Adaptive Data Compression," Proc. National Symposium on Space Electronics and Telemetry; 1962.

4. Berkowitz, M., "Adaptive Data Sampling System," PGTSET Record; 1963.

5. Morton, G. W. and McLeannan, M. A., "A Prototype Selective Monitoring System. for Physiological Data," PGTSET Record; 1963.

6. Blasbalg, H., "Message Compression," IRETSET, Vol. SET-8, No. 3; September 1962.

7. Eisenberger, I. and Posner, E. , "Data Compression by Quantized Floating Aperture System," JPL Space Progrrams Summary No. 37-17; October 1962.

8. Gardenhire, L. W. , "The Use of Digital Data Systems," Proc. National Telemetering Conference; 1963.

9. Palermo. C. J., Palermo, R. V. , and Horwitz, H., "The Use of Data Omission for Redundancy Removal, " International Space Electronics Symposium Record; 1965.

10. Raga, G. L. , "A Unified Viewpoint on Digital Television Compression," Proc. National Telemetering Conference; 1965.

COMMUNICATION-LINK PERFORMANCE

Parameter	Nomenclature	Value	Value (db)
Transmitter Power	P_t	2 watts	3 db
Transmitting Antenna Gain	G_t	Omni	0 db
Receiving Antenna Gain	G_r	60' Parabolic	49.9 db
Receiving System Temperature	T_r	200° K	
Transmitting Frequency	f	2300 MHz	
Receiving Noise Spectral Density	Φ_k		−205.6 dbw/cps
Range	R	5000 n.mi.	
Free Space Loss	L_s		179.0 db
Miscel. Spacecraft Loss	L_m		3 db
Design Margin	L_t		6 db
Bit Rate	R_b	10^6 bps	60 db
Energy/bit to Noise Spectral Density	E/(N/B)		10.5 db
FM Bandwidth	B_{if}	700 kHz	58.5 db
Carrier to Noise Ratio	C/N		12 db

FIGURE 1

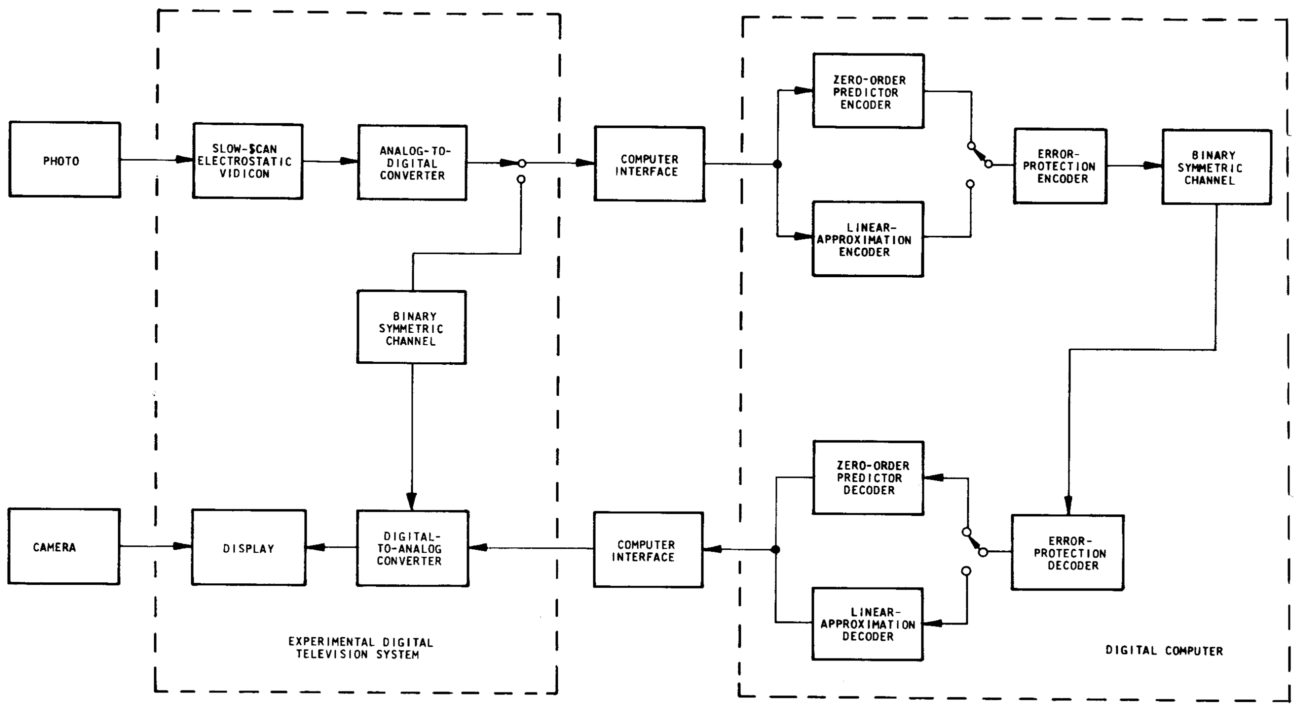


FIGURE 2
EXPERIMENTAL SETUP

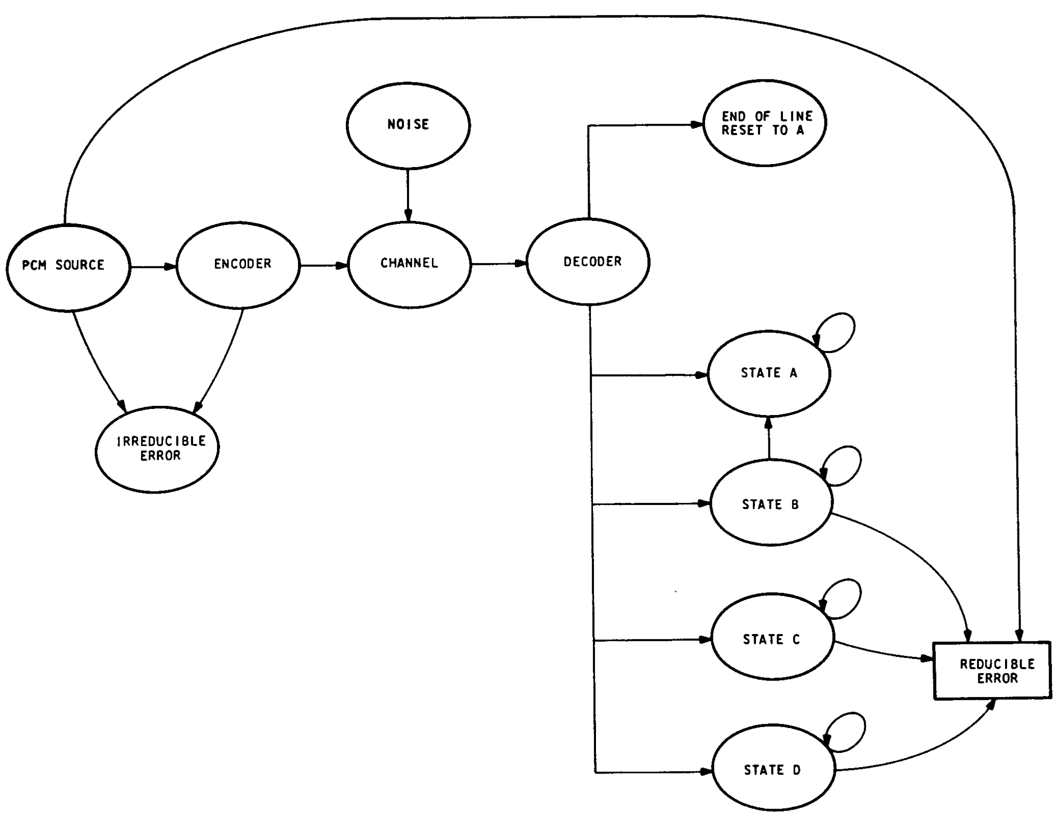


FIGURE 3
ANALYSIS MODEL

Linear Approximator
$C_s = 7.53$
RMS = 3.53%

6 Bit PCM

Zero-Order Predictor
$C_s = 6.05$
RMS = 3.54%

Figure 4

Comparison of Zero-Order Predictor and Linear Approximation Coding Techniques

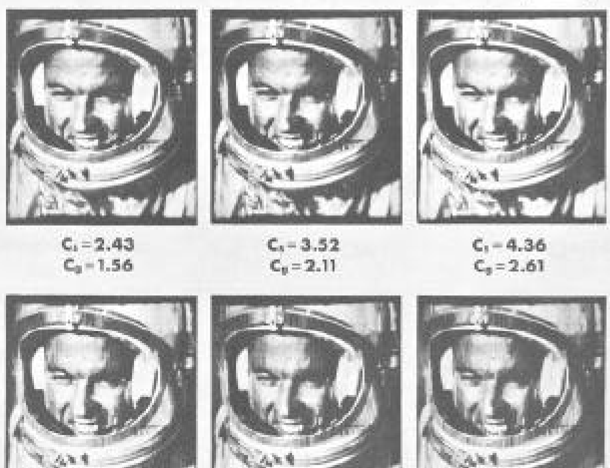


Figure 5

Subjective Comparison of the Effects of Zero-Order Prediction Data Compression

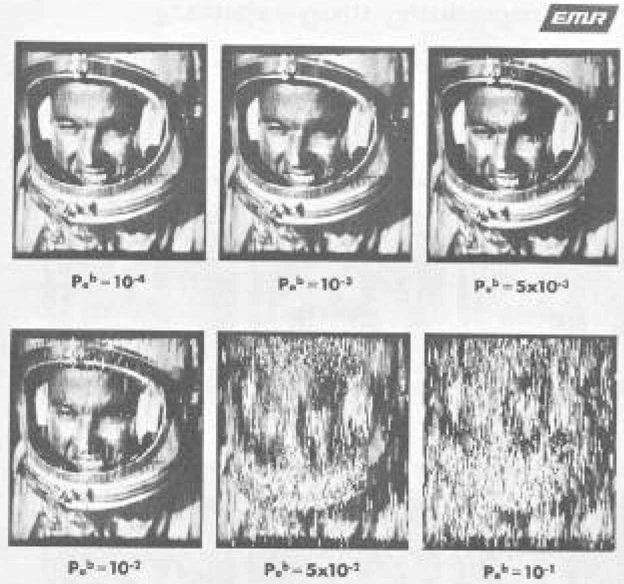


Figure 6

The Effects of Channel Noise on a Zero-Order Predictor with a Sample Reduction of 6:05 and a (14,10) Hamming Code

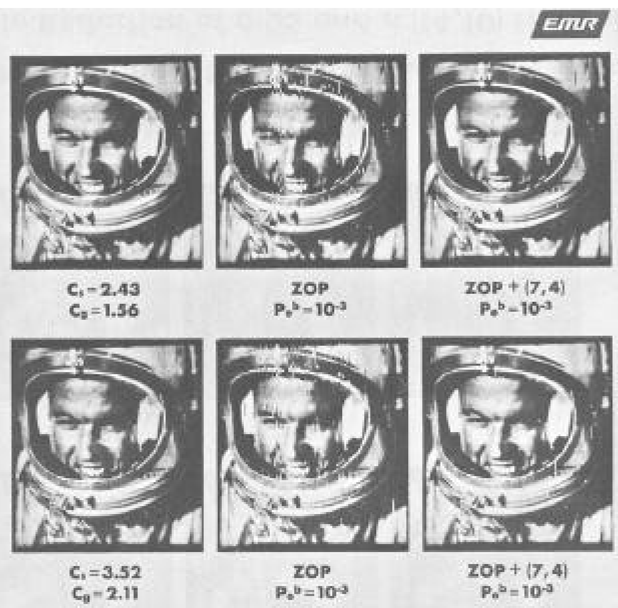
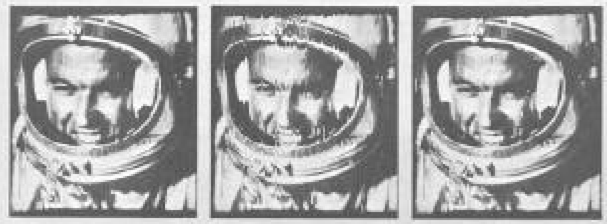
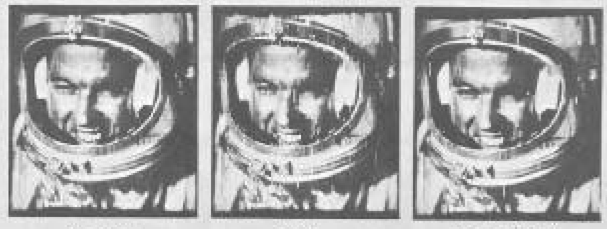


Figure 7

The Effects of Channel Noise on a Zero-Order Predictor Data Compactor



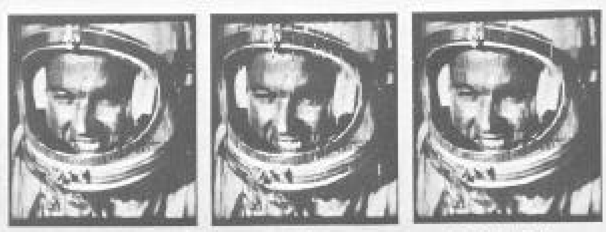
$C_s = 4.36$, $C_g = 2.61$ | ZOP, $P_e^b = 10^{-3}$ | ZOP + (7,4), $P_e^b = 10^{-3}$



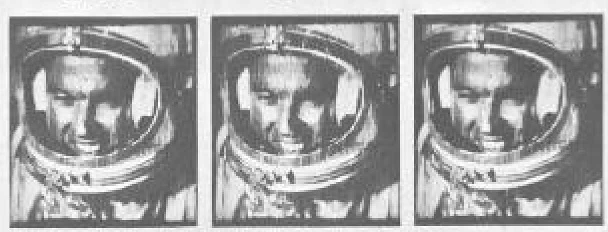
$C_s = 5.21$, $C_g = 3.12$ | ZOP, $P_e^b = 10^{-3}$ | ZOP + (7,4), $P_e^b = 10^{-3}$

Figure 8

The Effects of Channel Noise on a Zero-Order Predictor Data Compactor



$C_s = 6.05$, $C_g = 3.63$ | ZOP, $P_e^b = 10^{-3}$ | ZOP + (7,4), $P_e^b = 10^{-3}$



$C_s = 6.82$, $C_g = 4.09$ | ZOP, $P_e^b = 10^{-3}$ | ZOP + (7,4), $P_e^b = 10^{-3}$

Figure 9

The Effects of Channel Noise on a Zero-Order Predictor Data Compactor

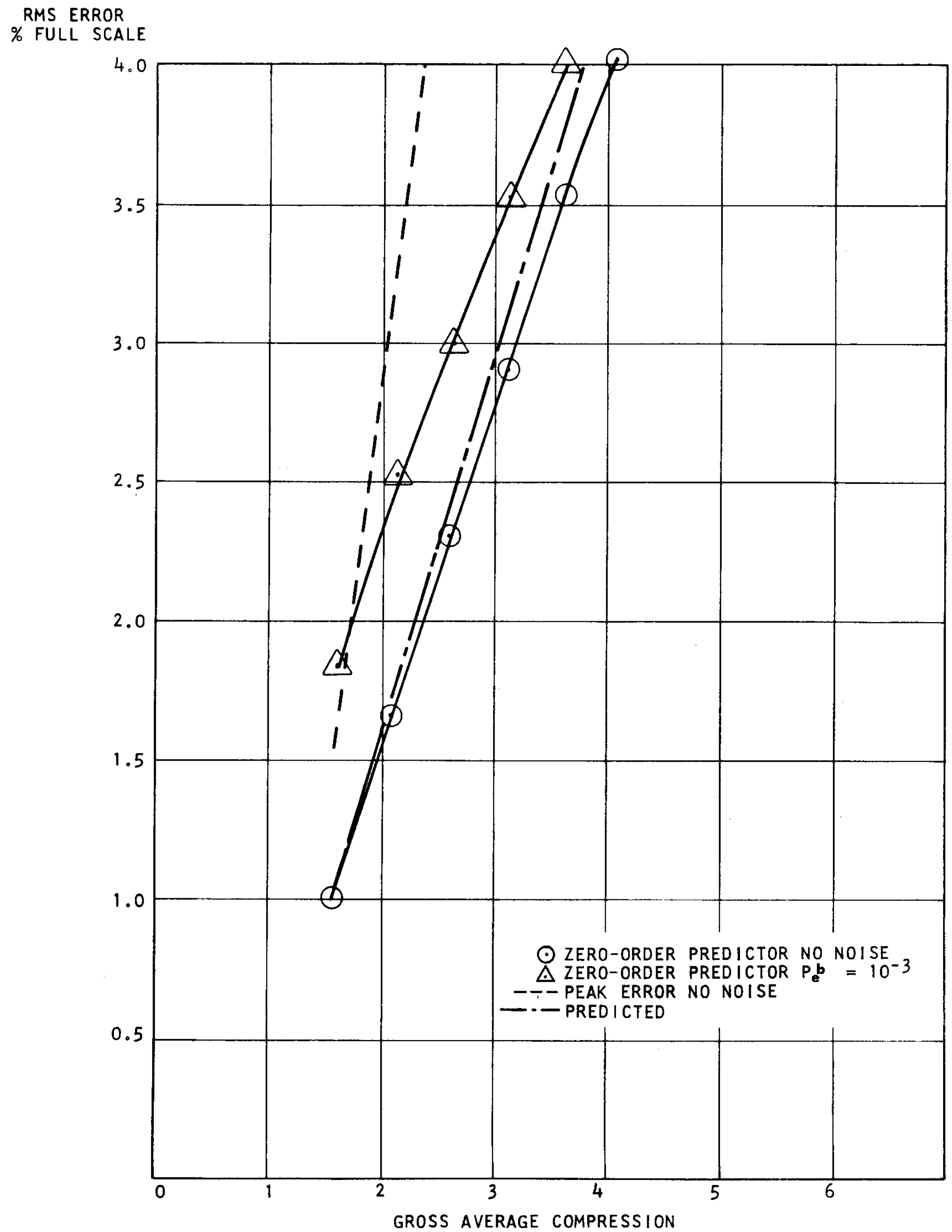


FIGURE 10
RMS ERROR VERSUS GROSS AVERAGE COMPRESSION
FOR ZERO-ORDER PREDICTOR

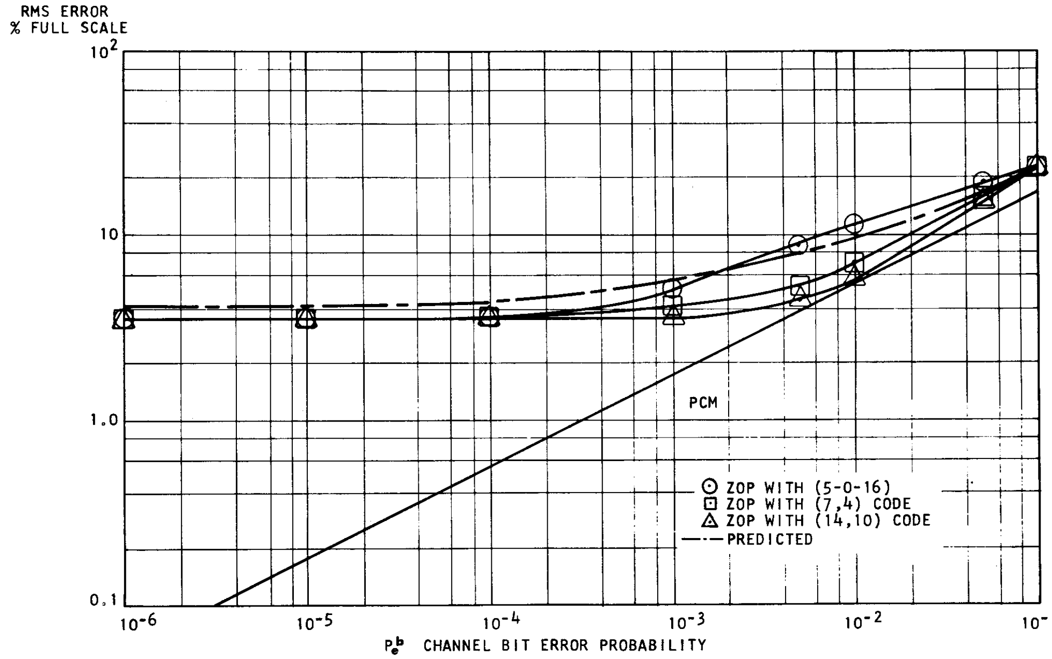


FIGURE 11
RMS ERROR VERSUS CHANNEL BIT ERROR PROBABILITY FOR ZERO-ORDER PREDICTOR WITH AND WITHOUT ERROR PROTECTION

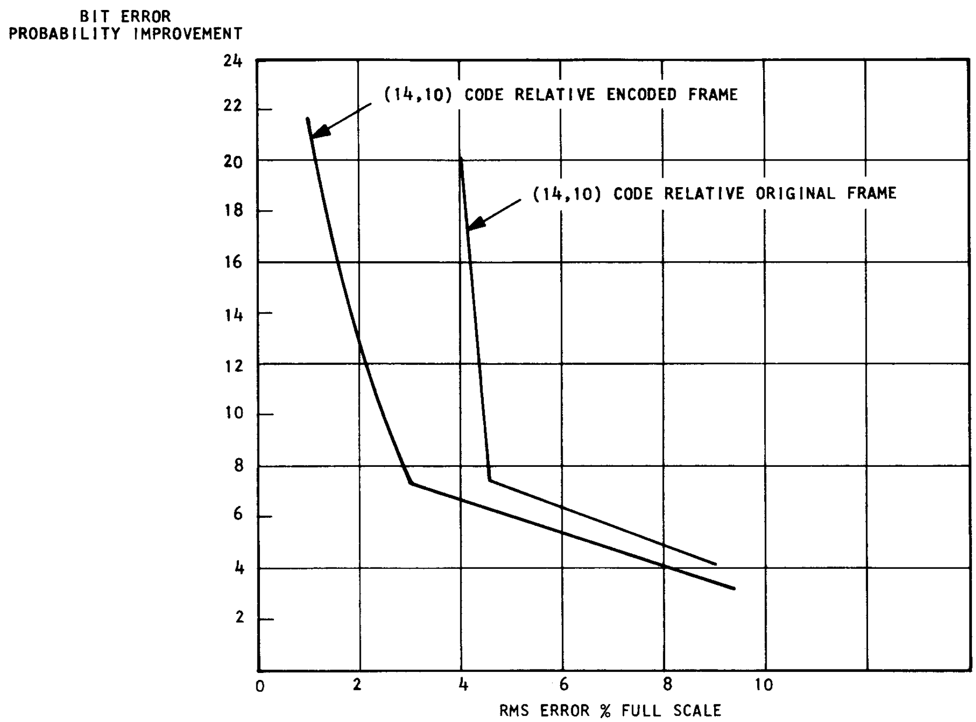


FIGURE 12
BIT ERROR PROBABILITY IMPROVEMENT FOR (14, 10) CODE RELATIVE TO ORIGINAL AND ENCODED FRAMES FOR ZERO-ORDER PREDICTOR (5-0-16)

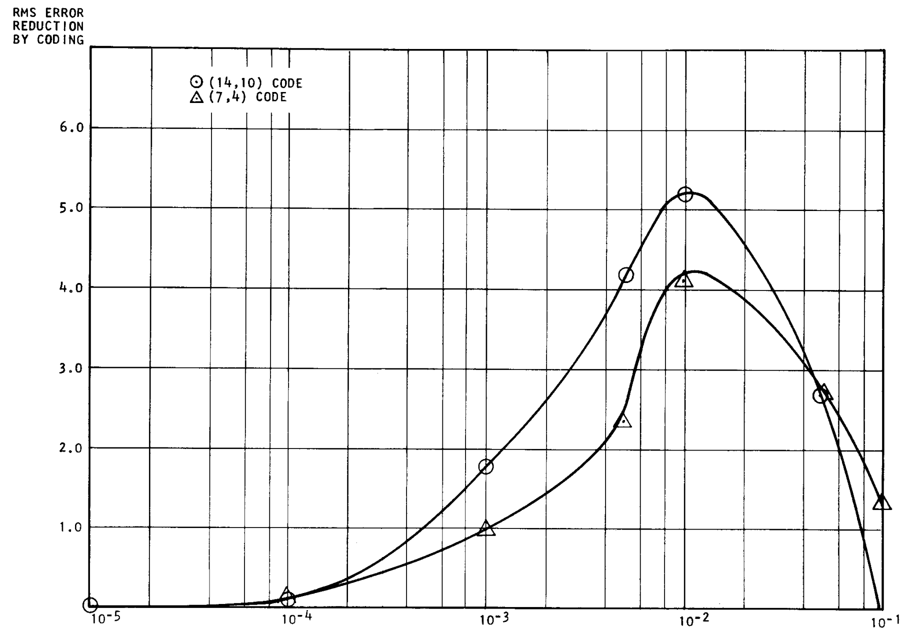


FIGURE 13
REDUCTION IN RMS ERROR BY CODING VERSUS CHANNEL BIT ERROR PROBABILITY FOR THE ZERO-ORDER PREDICTOR (5-0-16)

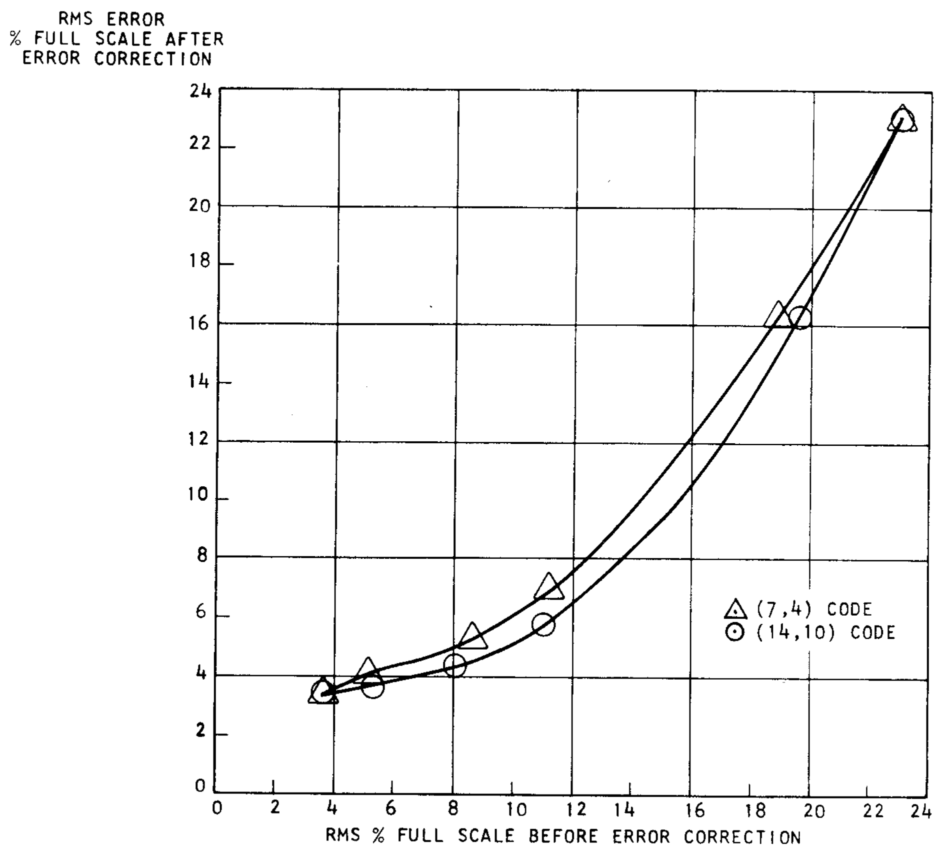


FIGURE 14
RMS ERROR AFTER ERROR CORRECTION VERSUS RMS ERROR BEFORE ERROR CORRECTION FOR ZERO-ORDER PREDICTION (5-0-16)

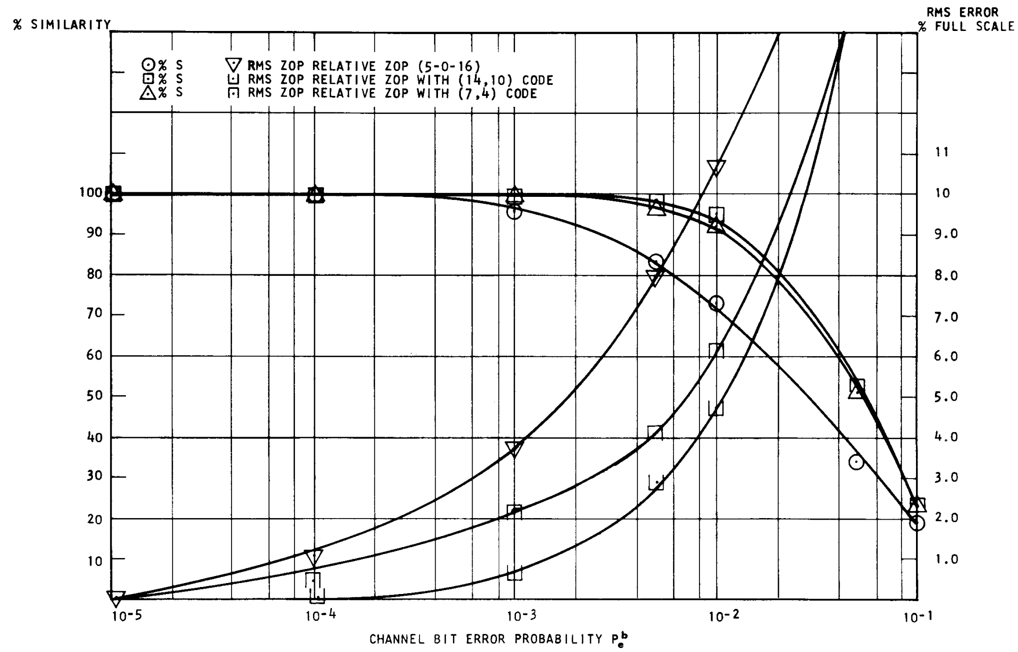


FIGURE 15
RMS ERROR AND PERCENT SIMILARITY VERSUS CHANNEL BIT ERROR PROBABILITY FOR ZERO-ORDER PREDICTOR WITH AND WITHOUT ERROR PROTECTION

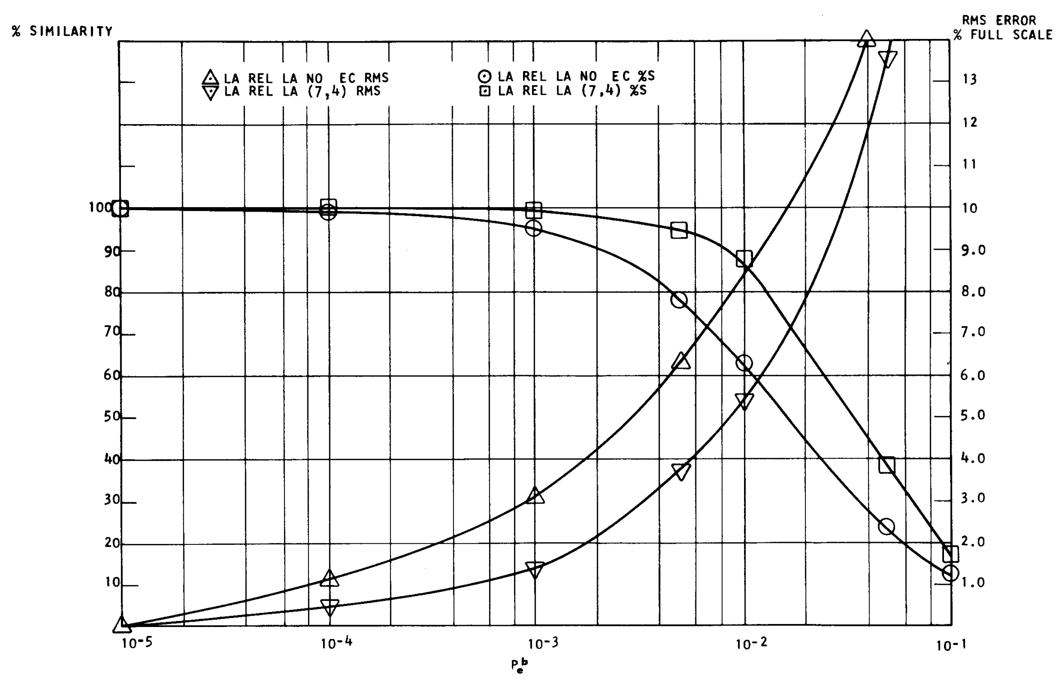


FIG. 16
RMS ERROR AND PERCENT SIMILARITY VERSUS CHANNEL BIT ERROR PROBABILITY FOR LINEAR APPROXIMATION WITH AND WITHOUT ERROR PROTECTION