Experimental Comparison Of Pulse Code Modulation Codes For Magnetic Recording

E. L. Law
Instrumentation Department
Pacific Missile Test Center
Point Mugu, California.

Summary. The bit error probability (BEP) versus signal-to-noise ratio (SNR) was experimentally determined for Non-Return-to-Zero-Level (NRZ-L), Bi-Phase-Level (BIØ-L), Delay Modulation (DM) and Miller Squared (M^2) codes for a bandpass channel. This was done by passing the data through a 400 Hz to 500 kHz Bessel bandpass filter and linearly adding noise. The power spectral density of the noise was shaped to match the noise out of an analog magnetic tape recorder running at 30 inches per second (in./s). This provided a simulation of an optimum wideband 2.0 MHz tape recorder running at 30 in./s (no flutter, tape dropouts, etc.). The bit rate, pattern, and code to be tested were then selected. The SNR was varied until the bit error probability was approximately 10^{-6} With a commercial Pulse Code Modulation (PCM) bit synchronizer with a "good" dc restorer and a pseudo-random pattern at 1.0 megabits per second (Mb/s) (33.3 kilobits per inch (kb/in.) equivalent packing density), NRZ-L had a 4 dB SNR advantage over DM and a 14 dB advantage over BIØ-L for a BEP of 10^{-6} through the bandpass channel. At 1.5 Mb/s, NRZ-L had a 6 dB advantage over DM and a 10^{-6} BEP was not achievable with BIØ-L coding. For a synchronizer with no dc restoration NRZ-L had only a 1 dB advantage over DM at 1.0 Mb/s and also only a 1 dB advantage at 1.5 Mb/s. M^2 gave the same results as DM for pseudo-random data. However, M^2 was relatively insensitive to patterns while DM and NRZ-L required a higher SNR with a "good" dc restorer and lost synchronization completely with no dc restorer for worst case 16-bit repeating patterns.

Introduction. Time division multiplex telemetry data has usually been recorded by pre-detection techniques. However, the maximum PCM bit rate that can be recovered from a 900 kHz pre-detection carrier (highest standard frequency) is only slightly over 1 Mb/s for NRZ-L. Therefore, a different technique is needed to handle PCM bit rates higher than 1 Mb/s for NRZ-L and 500 kb/s for BIØ-L. The technique usually used is to record the baseband PCM signal directly on the tape. King[1] reported on the results of tests to

This work was sponsored by the Naval Air Systems Command under a task assignment in support of the Telemetry Group of the Range Commanders Council.

determine the maximum achievable packing density for various codes for a 10^{-6} BEP. This effort is a continuation of King's work.

Test Set-up. The test set-up is shown in figure 1. An idealized tape recorder was simulated by passing the PCM data through a 400 Hz to 500 kHz Bessel bandpass filter and summing the filtered PCM data with gaussian noise which was spectrally conditioned (see figure 1) to match the noise out of a tape recorder running at 30 in./s. The terminal slopes of the bandpass filter were 24 dB/octave. The passive filter network at the input to the summing amplifier performs the proper spectral conditioning. The noise spectral density is shown in figure 2. The attenuator allowed the noise to be varied in one dB steps. The SNR was calibrated as follows:

1) A 2047 bit pseudo-random pattern at 100 kb/s was generated. The noise was removed from the summing amplifier and the PCM signal was measured using a true root mean square (rms) digital voltmeter.

2) The PCM signal was removed from the summing amplifier, the noise attenuator was set to 0 dB, the noise was filtered by a filter with an equivalent noise power bandwidth of 500 kHz and unity gain. The rms of the noise was then set at 15 dB below the rms of the PCM signal.

Therefore, the SNR as used in this report is equal to the rms signal out of the bandpass filter divided by the noise in a 500 kHz bandwidth. This is equivalent to the definition of SNR for analog magnetic tape recorders in Range Commanders Council document 118-75.

The randomizer consists of a 17 stage shift register with stages 15 and 17 exclusive-or'ed with the input. The data can be recovered by inserting the randomized data into a similar device after detection by the PCM bit synchronizer. A disadvantage of the randomizer is that it multiplies the errors. This error multiplication results in a 0.5 dB SNR penalty at a 10^{-6} BEP. However, randomization tends to remove pattern sensitivity and this more than compensates for the 0.5 dB penalty. A diagram of the randomizer/derandomizer is given in figure 3.

Test Results. Tests were performed using NRZ-L, DM and BIØ-L codes with a 2047 bit pseudo-random pattern for bit rates of 0.6 to 2.0 Mb/s using a good commercial PCM bit synchronizer. The SNR was varied until the BEP was 10^{-6}. The tests were repeated for randomized NRZ, odd-parity NRZ, and DM codes for the 16-bit repeating patterns that gave the highest BEP for each code. A 6-bit staircase[2] pattern with a variable number of repetitions of each 6-bit word before incrementing the value of the word by one was also used. The results of tests with 4, 64, and 256 repetitions are presented in this paper. The test results are shown in figures 4, 5, and 6 respectively. The data shows that for a pseudo-random pattern NRZ-L has a 4 dB advantage over DM at bit rates between 0.8 Mb/s and 1.5 Mb/s and a larger advantage at higher bit rates. The BIØ-L code performs much worse than NRZ-L and DM because it requires twice the bandwidth of NRZ-L.

The tests with the pseudo-random pattern were also performed with the Bessel bandpass filter replaced by a 400 Hz to 500 kHz Butterworth bandpass filter. This caused the channel to have a non-constant group delay which introduced additional distortion. At 1 Mb/s the SNR had to be increased by 2 dB for NRZ-L and 6 dB for DM. At 1.2 Mb/s the SNR had to be increased by 4 dB for NRZ-L and 10 dB for DM. These increases are with respect to the SNR required to achieve a 10^{-6} BEP when using the Bessel filter. Therefore, DM appears to be more susceptible to poor phase equalization than NRZ-L.

For the worst case patterns (“1000000010000000" for odd-parity NRZ-L (3/4 of energy at dc) and “1011011011011010" for DM (¼ dc)) odd-parity NRZ-L performed 3 dB better than DM at 0.7 Mb/s. The performance of the two codes was equal at 1.2 Mb/s and DM was nearly 3 dB better at 1.3 Mb/s. Randomized NRZ-L did not appear to be sensitive to repeating 16-bit patterns. It performed at least 3 dB better than DM and odd-parity NRZ-L at all bit rates between 0.8 and 1.5 Mb/s. At 1.2 Mb/s, DM performed 2 dB worse for the worst case 16-bit repeating pattern than for a pseudo-random pattern, odd-parity NRZ-L performed 6.5 dB worse than NRZ-L. All bit rates are actual user data rates. Therefore, the plotted bit rate for odd-parity NRZ-L is 0.875 times the bit rate into the bandpass filter.

For the repeating digitized staircase, randomized NRZ-L was again always at least 3 dB better than DM. DM performed the same for 4, 64 and 256 repetitions of each 6-bit word. The DM performance with the repeated staircase was nearly the same as for the pseudo-random pattern. Randomized NRZ-L performed the same for 4, 64 and 256 repetitions for bit rates up to 1.6 Mb/s. At 1.7 Mb/s the performance for 64 and 256 repetitions was degraded by 3.5 dB from the performance with 4 repetitions. A 10^{-6} BEP could not be achieved at 1.8 Mb/s for 64 and 256 repetitions with randomization. Bursts of errors (with occasional bit slips) occurred for both the 1.7 Mb/s and 1.8 Mb/s cases. This implies some pattern sensitivity for randomized NRZ-L at high bit rates. It appeared that most of the single bits of one polarity were being lost. The bit error performance between bursts was the same as for 4 repetitions. It is not known if this problem is peculiar to this particular implementation of a randomizer. The performance of NRZ-L (without randomization) for 4 repetitions was degraded by 2 dB from the performance with pseudo-random data. The PCM bit synchronizer would not synchronize with NRZ-L and 64 or 256 repetitions of each 6-bit word. Sixty-four repetitions gives 389 bits without a transition. The maximum specified number of bits without a transition for which the PCM bit synchronizer will maintain synchronization is 64 (at a 10 dB SNR).

Tests were also conducted with NRZ-L, DM and M^2 codes using a PCM bit synchronizer from the Ampex Corporation. The Ampex Corporation also provied an M^2 encoder. The Ampex synchronizer was mainly designed for the M^2 code and did not have a dc restorer because the M^2 code does not have a dc component. The results of tests of the Ampex synchronizer with a pseudo-random pattern as the input are shown in figure 7. The DM and M^2 codes performed the same for all bit rates with a pseudo-random pattern. The performance with NRZ-L was about 1 dB better than the performance with DM and M^2 for bit rates up to 1.6 mb/s. At 1.7 Mb/s and 1.8 Mb/s, NRZ-L performed 3 dB better than DM and M^2. The Ampex synchronizer and the other synchronizer performed within 1 dB of each other for bit rates up to 1.6 Mb/s for DM with a pseudo-random pattern. At higher bit rates, the Ampex synchronizer performed better than the other synchronizer. The other synchronizer performed 4 dB better than the Ampex synchronizer for pseudo-random NRZ-L at bit rates below 1.2 Mb/s. At higher bit rates the performance of the two synchronizers was nearly the same for pseudo-random NRZ-L. The Ampex synchronizer would not achieve a 10^{-6} BEP for the worst case odd-parity NRZ-L and DM 16-bit patterns at 1.0 Mb/s because of the lack of a dc restorer. The BEP for M^2 was not a function of pattern as long as the pattern included a “101". A 10^{-6} BEP at 1.0 Mb/s could not be achieved using the Ampex synchronizer with DM and 64 or 256 repetitions of the 6-bit staircase. The performance of the Ampex synchronizer with the M^2 code and the repeating staircase was the same as its performance with a pseudo-random pattern. It should be emphasized that the Ampex synchronizer was designed for use with the M^2 code. The tests with the other codes were performed to determine the effects of a lack of dc restoration.

Tape Recorder Results. The maximum PCM packing densities (BEP of 10^{-6}) for pseudo-random PCM data reported by King[1] for a wideband 2.0 MHz tape recorder with a 34 dB SNR running at 30 in./s were: 41 kb/in. (1.23 Mb/s) for NRZ-L, 38.3 kb/in. (1.15 Mb/s) for DM and 23.3 kb/in. (0.70 Mb/s) for BIØ-L. These rates were not achievable for all tracks of the tape recorder. The minimum data rates under the above conditions were: 93 kb/s for NRZ-L, 9 kb/s for DM and 2 kb/s for BIØ-L. These results were reconfirmed as part of this study. These results are for analog recorders with bias recording (2 dB overbias) and setup for 1% third harmonic distortion. This is the way existing analog recorders are usually setup. These conditions were found to be as good as any other conditions for digital recording with bias.

A study will be conducted to determine the performance of various codes under real-life recording and playback conditions (including crossplay between machines). A selection of recorders similar to that existing at the various telemetry receiving and processing facilities will be used. This study will not include parallel track recording. The results of this study should be available in late 1977.

General Comments. All of the codes discussed in this paper have advantages and disadvantages. BIØ-L is probably the best code for low packing densities (under 10 kb/in.). However, it is not satisfactory for high packing densities (above 20 kb/in.). Randomized NRZ suffers from error multiplication (small penalty) and it also does not have a maximum run of bits without a transition. However, the probability of 40 bits in a row without a transition at the output of the randomizer with the input uncorrelated to the randomizing technique is $2^{-40} \simeq 10^{-12}$. Therefore, this would happen every 10^{12} bits on the average. At a packing density of 33.3 kb/in. and with 9000 foot reels of tape, there would be one sequence of 40 bits without a transition (per track) every 278 reels of tape on the average. Since most commercial PCM bit synchronizers are specified to handle 64 bits without a transition, this does not appear to be a problem. The DM and M^2 codes require “101” patterns for proper synchronization. Most telemetry data probably has enough of these occuring so that there would be no problem. The biggest hazard is that the synchronizer would not output the proper data after a dropout which caused lack of synchronization until a “101” sequence appeared in the data. The odd-parity code has the disadvantage of having one-eighth of the bits set aside for parity. This reduces the data bits that can be recorded per inch. However, the parity bit lends itself nicely to error detection. Both the DM and odd-parity codes are also subject to worst case pattern problems. These problems can be reduced by using a PCM bit synchronizer with a “good” dc restorer.

Conclusions. It has been shown that randomized NRZ-L performs better than the other codes tested when the PCM data is bandpass filtered and then summed with spectrally conditioned noise. These results apply to PCM bit synchronizers with “good” dc restorers. However, tests need to be run using several recorders to determine the effects under real-life conditions.

References.

1) D. A. King, “Comparison of PCM Codes for Direct Recording”, International Telemetering Conference, 1976, Los Angeles, California.

2) T. A. Jensen, “Factors in the Choice of Test Patterns Used to Measure Bit Error Rate in High Bit Rate Recording”, International Telemetering Conference, 1976, Los Angeles, California.

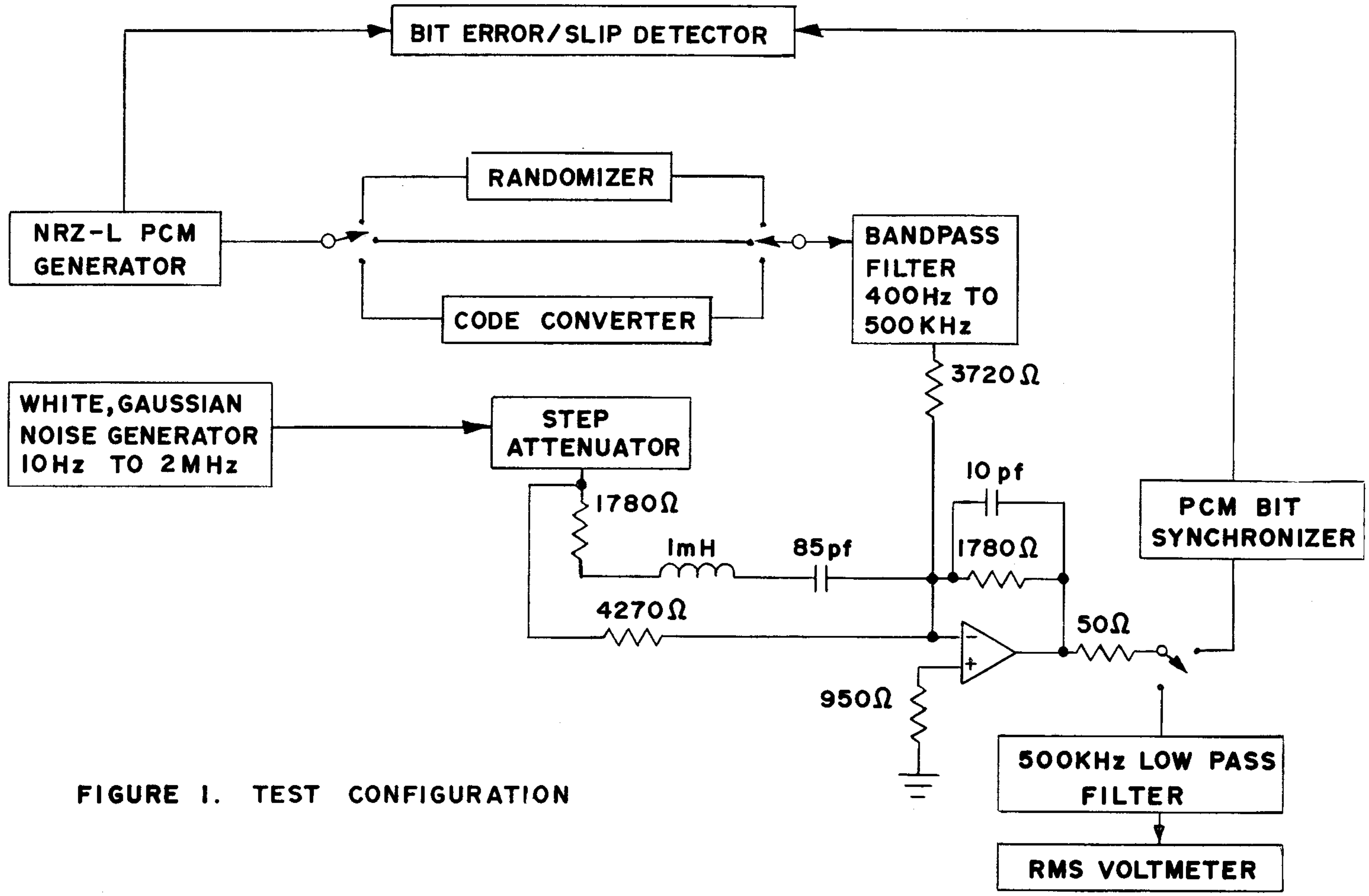


FIGURE 1. TEST CONFIGURATION

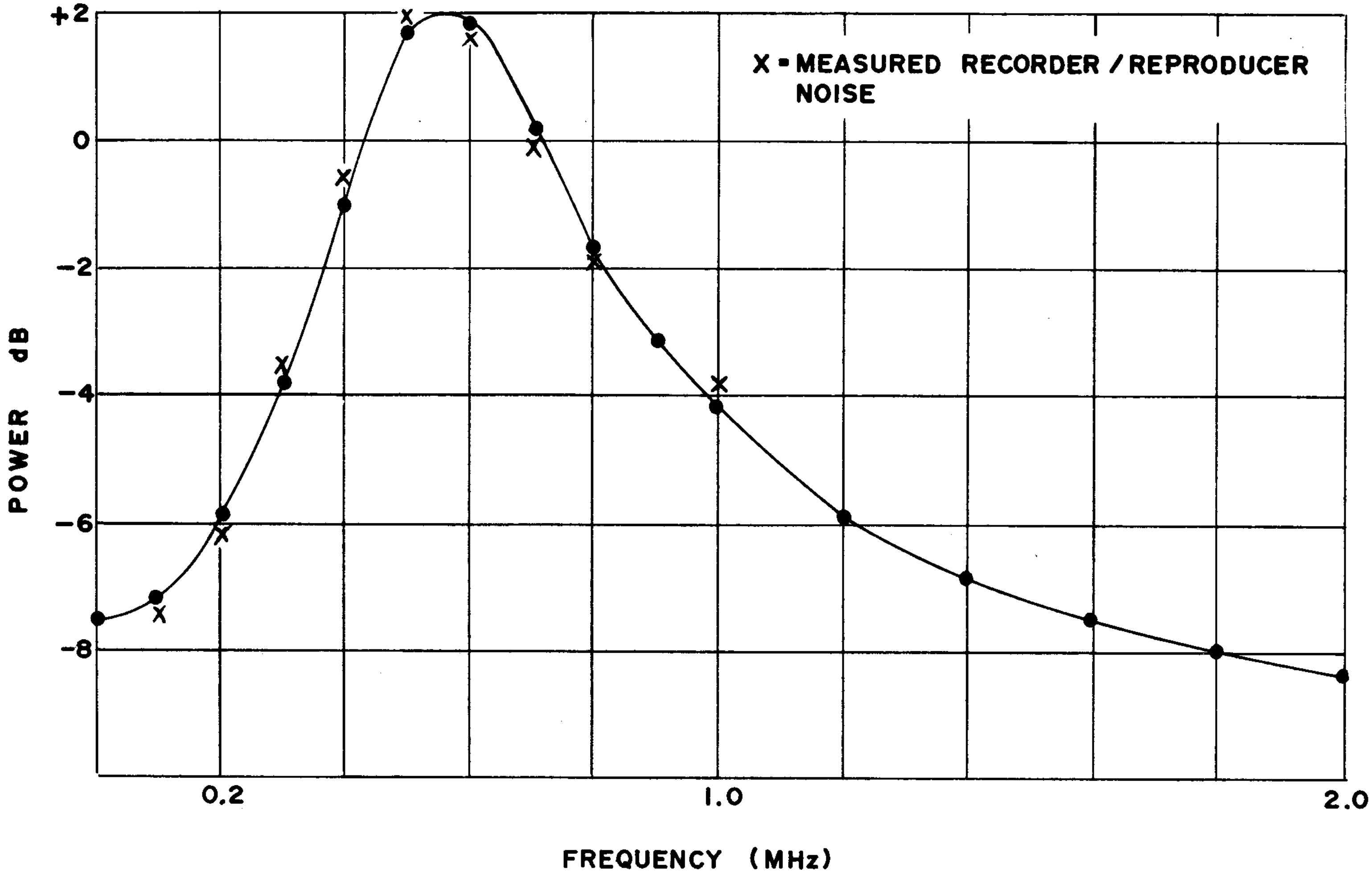
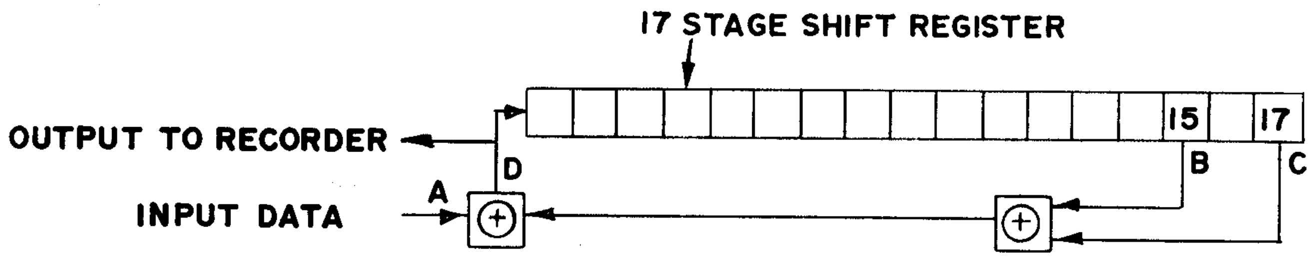
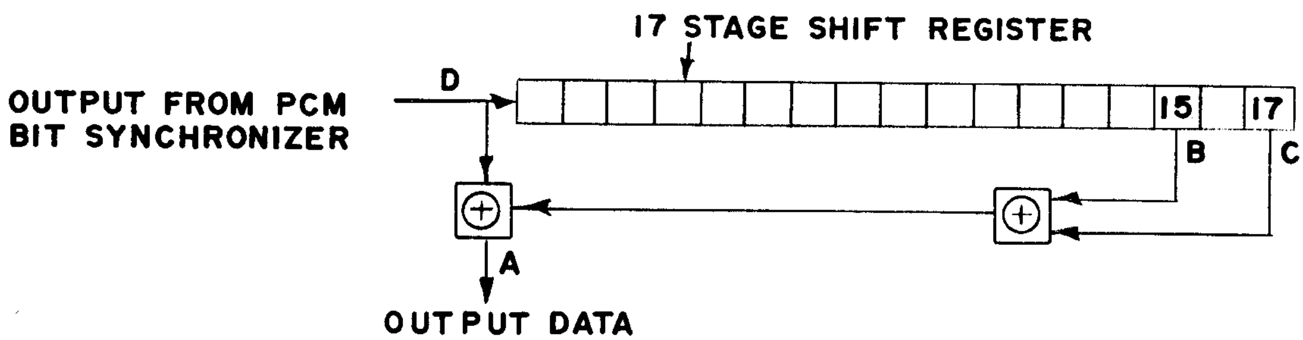


FIGURE 2. NOISE POWER SPECTRAL DENSITY AT INPUT TO PCM BIT SYNCHRONIZER



RANDOMIZER



DERANDOMIZER

$$D = B \oplus C \oplus A$$

$$B \oplus C \oplus D = B \oplus C \oplus B \oplus C \oplus A$$

$$= B \oplus B \oplus C \oplus C \oplus A \quad \text{COMMUTIVITY}$$

AND $B \oplus B = C \oplus C = 0$

$$= 0 \oplus A$$

$$= A$$

FIGURE 3 RANDOMIZER/DERANDOMIZER

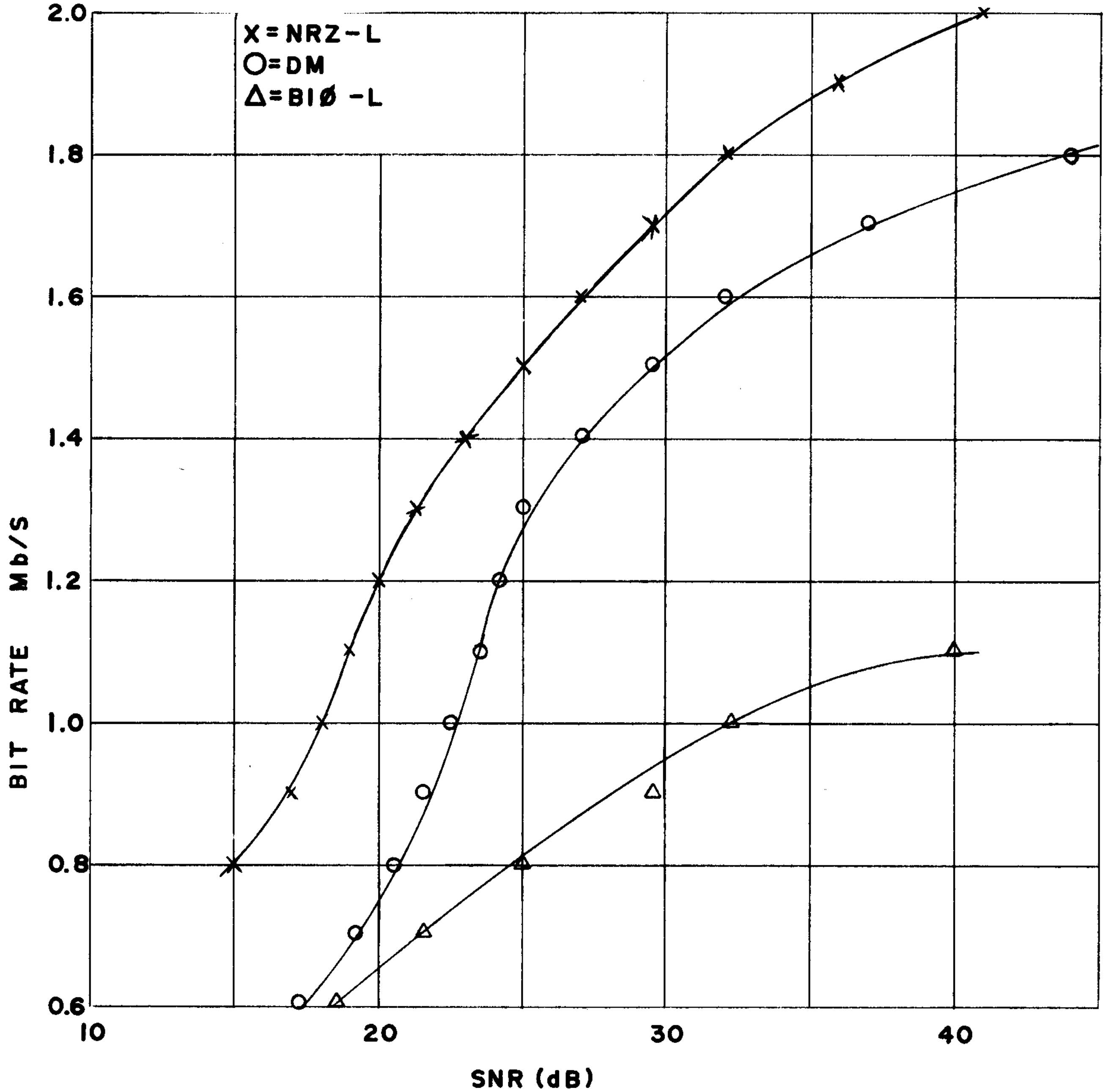


FIGURE 4. BIT RATE VERSUS SNR FOR 10^{-6} BEP, PSEUDO-RANDOM PATTERN, COMMERCIAL PCM BIT SYNCHRONIZER

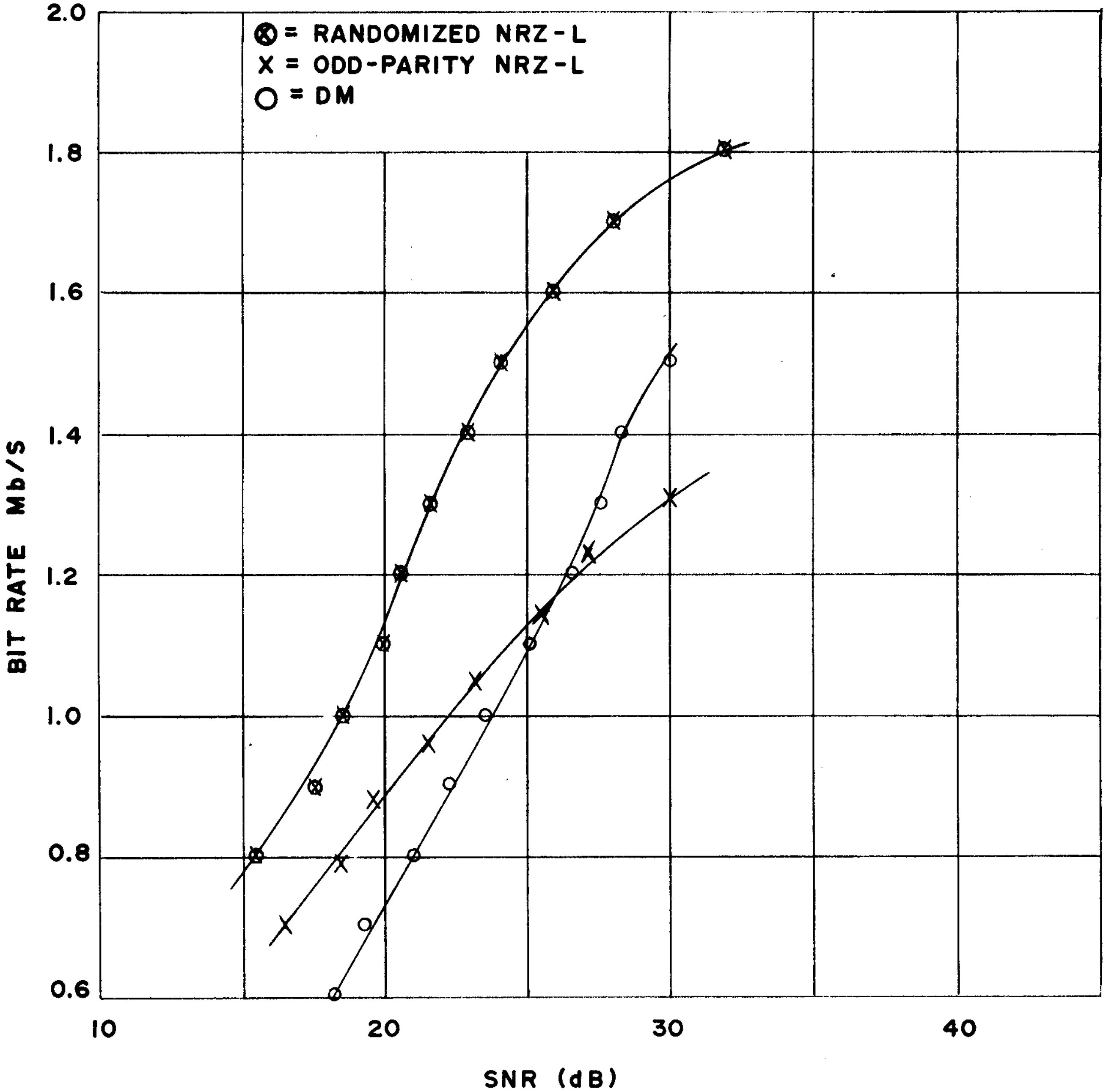


FIGURE 5. BIT RATE VERSUS SNR FOR 10^{-6} BEP, REPEATED 16-BIT WORST CASE PATTERNS, COMMERCIAL PCM BIT SYNCHRONIZER

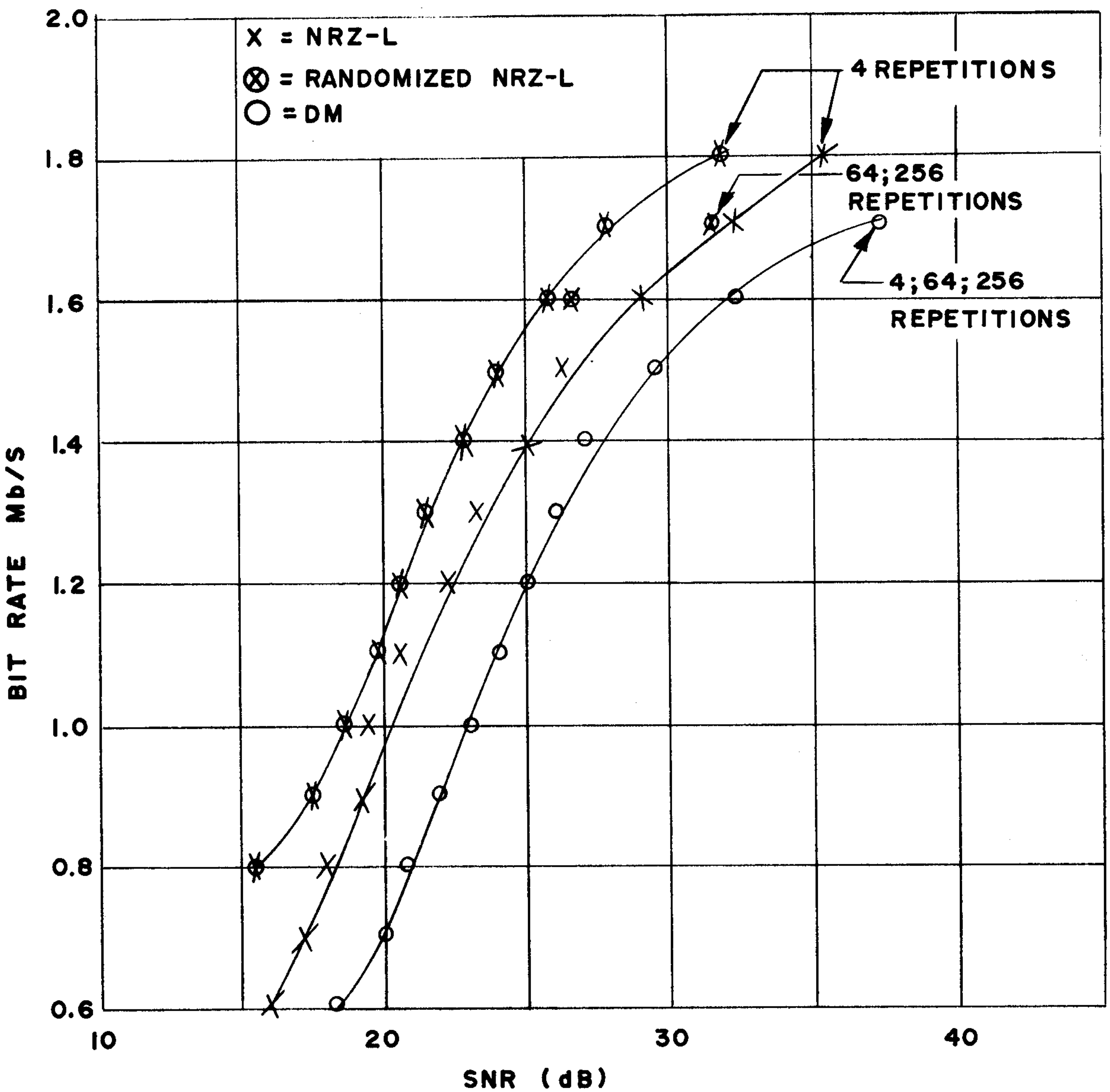


FIGURE 6. BIT RATE VERSUS SNR FOR 10^{-6} BEP, REPEATED 6-BIT STAIRCASE, COMMERCIAL PCM BIT SYNCHRONIZER

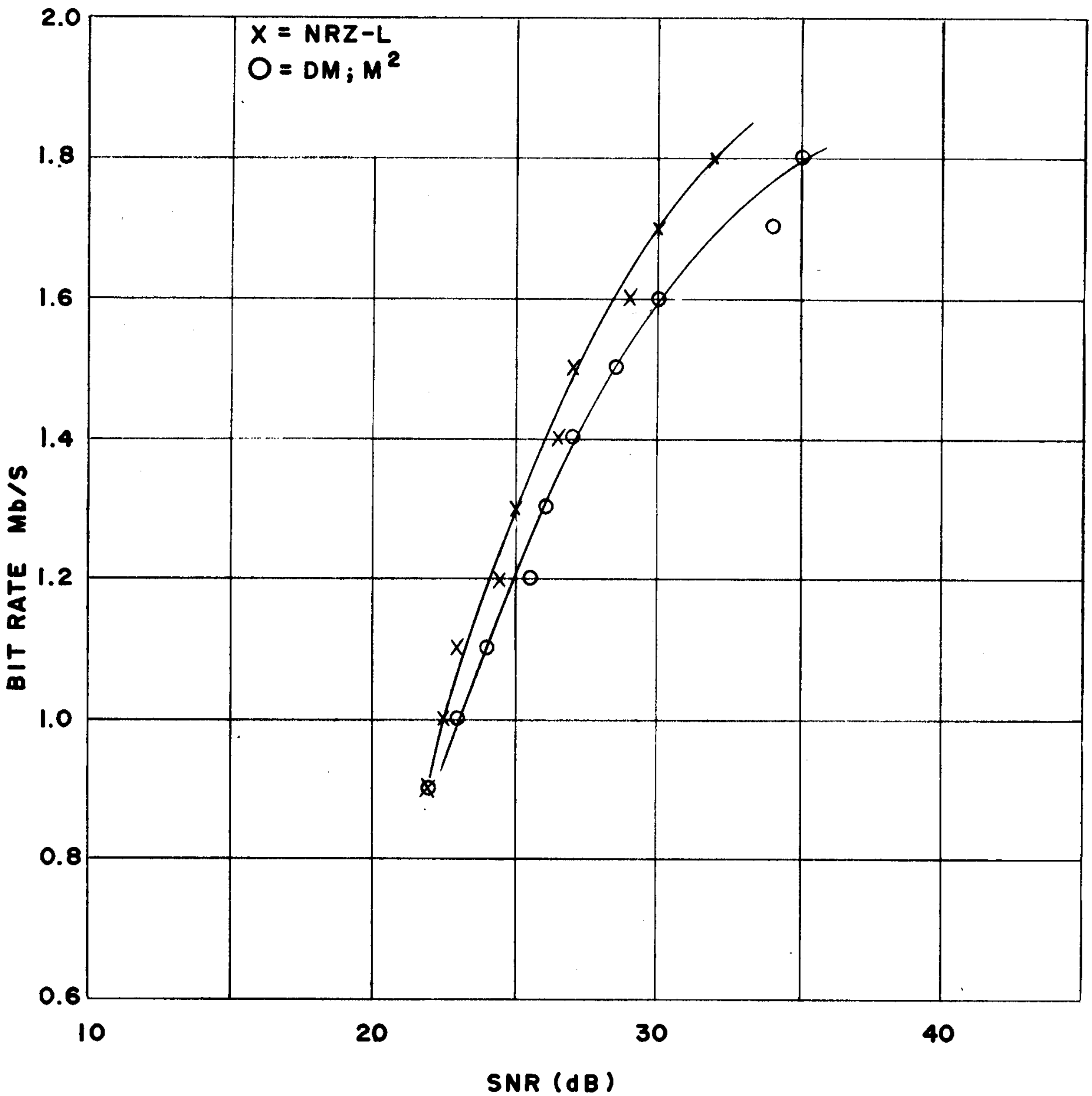


FIGURE 7. BIT RATE VERSUS SNR FOR 10^{-6} BEP, PSEUDO-RANDOM PATTERN, AMPEX PCM SIT SYNCHRONIZER