PULSE CODE MODULATION TELEMETRY
Properties of Various Binary Modulation Types

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ABSTRACT

This paper discusses the performance of pulse code modulation/frequency modulation (PCM/FM), pulse code modulation/phase modulation (PCM/PM) and phase shift keying (PSK) in the "real-world" of range telemetry. The topics addressed include:

1. Radio frequency (RF) spectra
2. Bit error rate (BER) versus pre-detection signal-to-noise ratio (SNR)
3. Peak carrier deviation
4. Premodulation and receiver predetection filtering
5. PCM codes
6. Magnetic recording

The purpose of this paper is to provide the reader with information needed to choose the best modulation method, PCM code, premodulation filter bandwidth and type, receiver settings, and recording method for a particular application.

INTRODUCTION

Many methods exist for the transmission of telemetry data. This paper will only discuss methods for the transmission of digital data. The Telemetry Group of the Range Commanders Council has sponsored this study to compare the performance of these methods under simulated range conditions.

Tests were performed to characterize the performance of the various PCM modulation methods under a variety of conditions. The test set-up is shown in figure 1. The tests were

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conducted in both a laboratory environment and also at the Pacific Missile Test Center's main telemetry receiving and recording facility.

RADIO FREQUENCY SPECTRA

Sample RF spectra produced by the various modulation techniques under discussion are shown in figures 2A through 2J. The premodulation filter bandwidth was equal to the bit rate for the non-return-to-zero (NRZ) signals and equal to twice the bit rate for the bi-phase (BIØ) signals. The premodulation filter was a 5-pole linear phase low pass filter. The top line of all photos is the unmodulated carrier power. The bit stream was a 2047-bit pseudo random sequence. The approximate radiated bandwidths for the various modulation techniques are listed in table 1. Radiated bandwidth is defined as the bandwidth which contains all signals which are less than 60 dB below the unmodulated carrier power when measured in a 3 KHz bandwidth.[1] The bandwidth values will be different if a different definition is used. All of the modulation techniques except narrow band NRZ/FM and wideband PSK produce spectral "spikes" which widen the radiated bandwidth.

BIT ERROR RATE PERFORMANCE

The measured BER versus predetection SNR in a bandwidth equal to the bit rate is presented in figure 3. The test conditions for the data shown in figure 3 were:

Intermediate frequency bandwidth (-3 dB):

all PM data - 3.3 MHz
NRZ-L FM - 500 KHz
BIØ-L FM - 1.0 MHz

Premodulation filter bandwidth (-3 dB):

all NRZ-L data - 500 KHz
all BIØ-L data - 1.0 MHz

Premodulation filter type: 5-pole linear phase

Bit pattern - 2047 bit pseudo random sequence
Video filter bandwidth - 2.0 MHz

PCM bit synchronizer detector:
all PM data - integrate and dump

NRZ-L FM - filter and sample
BIØ-L FM - integrate and dump

PM and PSK demodulator loop bandwidth:

1 KHz.

The SNR in a bandwidth equal to the bit rate required to yield a 10^{-5} BER is shown in table 2 for several PCM signal types. These results agree reasonably well with other published results (see references 2, 3, 4, and 5).

PEAK CARRIER DEVIATION

The optimum peak deviation for NRZ PCM/FM has been shown to the ≈ 0.357 times the bit rate[2,3] (178.5 KHz for 500 Kb/s) when the intermediate frequency (IF bandwidth is equal to the bit rate. The actual optimum value is a function of the phase and amplitude characteristics of the receiver IF and video filters and also the bit detector characteristics. The measured optimum value is always close to 0.357 with modern telemetry receivers and bit synchronizers. Increasing the peak deviation to 0.41 times the bit rate requires an increase of ≈ 0.3 dB in SNR with an IF bandwidth equal to the bit rate. This is equivalent to an increase in transmitter power of 0.3 dB or 7.15 percent. Decreasing the peak deviation to 0.25 times the bit rate or increasing it to 0.5 times the bit rate required an increase of ≈ 1.2 dB in SNR. These values will vary slightly with different IF bandpass filters, FM eemodulators and PCM bit synchronizers.

The optimum peak deviation for unfiltered PCM/PM is 90°. This peak deviation also produces a carrier null. When premodulation filtering is introduced, a peak deviation of greater than 90° is required to produce the carrier null. For nonrandom data the actual peak deviation for carrier null is a function of the probability of single bits and the transition density (for NRZ-M this translates to the probability of consecutive “ones” and the ratio of “ones” to the total of “ones” plus “zeros”). The carrier null occurred for a peak deviation of 99° for a 500 KHz constant delay (CD) premodulation filter and a peak deviation of 107° for a 250 KHz CD premodulation filter. The SNR for a 10^{-5} BER with carrier null was the same as for 90° peak deviation (see table 2). The only difference in SNR for 10^{-5} BER was observed with a 250 KHz CD premodulation filter and the integrate and dump bit detector. The carrier null data was ≈ 0.3 dB better than the 90° peak deviation data under these conditions. However, the bast bit detector with this premodulation filter was the filter and sample detector. Both deviations performed the same with this detector.

The optimum peak deviation for BIØ PCM/FM was determined to be ≈ 0.625 times the bit rate for the equipment used in this test. This value is somewhat higher than the value of 0.5 calculated by Cartier.[3]

The optimum peak deviation for BIØ PCM/PM with no premodulation filter is 90°. BIØ-L PCM/PM (±60°) required approximately 1.2 dB more RF power to achieve a 10^{-5} BER than BIØ-M PCM/PM (±90°). The theoretical value is 1.5 dB. The lower deviation system has the advantage that a carrier tracking phase demodulator can be used instead of a carrier reconstruction and track demodulator.

REMODULATION FILTERING

The premodulation filter which resulted in a 10^{-5} BER at the lowest SNR was NO premodulation filter for all of the modulation techniques tested. The disadvantage of not using a premodulation filter is that the RF spectrum is very wide for most of the modulation techniques if no premodulation filter is used.[4,5] Linear phase filters generally caused slightly less degradation in data quality than constant amplitude (CA) filters with the same -3 dB band-width. The phase modulation systems suffered more degradation due to premodulation filtering than the frequency modulation systems. There are two major reasons for this:

1. The IF bandwidth was narrower for the FM systems and therefore more filtering occurred in the IF which tended to mask the premodulation filtering effects.

2. The noise at the output of PM/PSK demodulators is additive, white and gaussian so a decrease in bit energy relates directly to the probability of the noise exceeding the bit energy and causing a bit error. Most bit errors in PCM/FM are caused by what is termed “click” or “pop” noise which is produced when the demodulator is captured by the noise. These “pops” have enough energy to cause a bit error in either a reduced amplitude bit or a full amplitude bit.

RECEIVER IF BANDPASS FILTERING

The optimum IF bandwidth for PCM/PM signals when using a Costas loop or carrier tracking demodulator is the widest available bandwidth that does not allow interfering signals into the demodulator. No tests were performed with a squaring loop demodulator therefore this statement may not be true for a squaring loop demodulator. The widest available IF band-width is also not optimum if predetection recording is being used because the conversion to the tape carrier frequency will cause the noise to be folded around zero frequency. For example, if a PCM signal were to be predetection recorded using a 900 KHz tape carrier and a 3.3 MHz IF bandwidth, the noise power at a frequency

1 MHz above the IF center frequency would be translated to the same frequency as the noise power 800 KHz above the IF center frequency. This would decrease the SNR at the demodulator input and therefore increase the BER at the output. This applies to FM, PM and PSK signals. The optimum IF bandwidth for NRZ PCM/FM is equal to the bit rate. The disadvantage of using this bandwidth is that receiver tuning is very critical. Small tuning errors can degrade the data quality by several dB. Increasing the IF bandwidth to 1.5 times the bit rate results in a data quality loss of only 0.7 dB and allows some margin for tuning errors, IF bandpass nonsymmetry, transmitter frequency drift, etc. The "best" receiver IF bandwidth for predetection recording of NRZ PCM/FM is approximately twice the bit rate. The playback bandpass filter can then be adjusted for best data qualit

The optimum IF bandwidth for BIØ-L PCM/FM is approximately twice the bit rate. Increasing the bandwidth to 3 times the bit rate causes approximately a 0.5 dB loss in data quality for premodulation filter bandwidth equal to twice the bit rate but improves the data quality by 0.2 dB for a premodulation filter bandwidth equal to the bit rate.

RECEIVER/DEMODULATOR VIDEO BANDWIDTH

The "best" video bandwidth is usually the widest one available. Most PCM bit synchronizers contain filters which attempt to minimize the BER. Adding excessive video filtering may make an oscilloscope display look less noisy but usually increases the BER! However, some PCM bit synchronizers do not contain the necessary filtering ror optimum bit detection. If one is unsure of the characteristics of a certain PCM bit synchronizer one should either perform tests to determine the best video filter or talk to the bit synchronizer manufacturer.

PCM CODES

The relevant properties of the various NRZ and BIØ codes are:

1. NRZ-L and BIØ-L are both antipodal codes which means that their bit error performance is optimum. The mark and space versions of these codes have a BER that is twice the BER of the level versions for isolated bit errors. This is equivalent to an SNR penalty of ≈ 0.3 dB at a BER of 10^{-5}.

2. NRZ codes do not have guaranteed transitions. Long sequences without transitions can cause problems for the phase lock loop in the PCM bit synchronizer. BIØ codes have at least one transition each bit period. The disadvantage of this is that BIØ codes require approximately twice the bandwidth of NRZ codes.

3. NRZ codes can have large DC and low frequency content. This can cause severe problems if one AC couples an NRZ signal. BIØ codes have zero DC content. This is mandatory for use with PM demodulators. Standard PM demodulators will not work with NRZ signals because of the large DC and low frequency content.

4. The mark and space versions of both NRZ and BIØ are polarity insensitive. This is a definite advantage when using a PSK demodulator where the output polarity has an equal chance of being the same as or opposite to the transmitted polarity.

PHASE SHIFT KEYING

One method of generating RF signals which have a 180° phase difference between the two output states is to drive the IF port of a doubly balanced mixer with the baseband PCM signal[6]. This is equivalent to multiplying the RF carrier by ±1 if the PCM signal is rectangular. This method is called PSK in this paper. The BER performance of PSK is essentially the same as the performance of PCM/PM (±90°) if the insertion loss of the doubly balanced mixer is ignored[5]. However, doubly balanced mixers typically have an insertion loss of 3-4 dB[6]. Therefore, the transmitter gain after the modulation section must be increased. The transmitter output amplifier must also be linear because nonlinearities will cause the RF output spectra with premodulation filtering to become wider. One advantage of a PSK transmitter (versus FM or PM transmitters) is the relative simplicity of the modulation section. The RF spectrum of PSK is also narrower than the RF spectrum of PCM/PM (±90°). The PSK modulator is simply a frequency translator which translates the baseband signal to the RF center frequency. PSK does not have the spectral "spikes" which occur with PCM/PM if the mixer is properly designed and driven by the proper amplitude baseband signal with no spectral "spikes".

MAGNETIC RECORDING

There are four major methods for recording PCM signals[1]:

1. Predetection recording
2. Direct recording of the video output
3. FM recording of the video output
4. High density digital recording of the detected video output

The IRIG Telemetry Standards (reference 1) contain recommendations for the minimum and maximum bit rates for these recording methods. The magnetic record/reproduce portion of the tests have not been completed at this time. These test results will be included in a technical publication which should be published in early 1983. This technical publication will also include additional data on the other topics addressed in this paper. Copies can be obtained by contacting the author.

CONCLUSIONS

1. PCM/PM (±90°) signals can achieve better data quality than PCM/FM signals with the same radiated power if wide bandwidths are available.

2. Optimum NRZ-L PCM/FM requires only 1 dB more RF power to achieve a 10^{-5} BER than wideband NRZ-M PCM/PM (±90°). Optimum NRZ-L PCM/FM requires less RF power than NRZ-M PCM/PM (±90°) to achieve a 10^{-5} BER if the radiated RF spectral occupancy must be narrow.

3. BIØ-L PCM/FM requires ≈ 2 dB more RF power than NRZ-L PCM/FM for a 10^{-5} BER. BIØ-L also requires more RF bandwidth.

4. BIØ-M PCM/PM (±90°) requires ≈ 2.3 dB less RF power than BIØ-L PCM/FM for a 10^{-5} BER if the premodulation filter bandwidth is equal to twice the bit rate.

5. The optimum peak deviations for the various modulation types are:

NRZ PCM/FM - 0.357 times bit rate
BIØ PCM/FM - 0.625 times bit rate
NRZ PCM/PM - 90° or carrier null
BIØ PCM/PM - 90° or carrier null.

6. The optimum premodulation filter bandwidth is the widest bandwidth that allows the radiated RF spectrum to fit within the required RF bandwidth.

7. The optimum receiver IF bandwidth for NRZ PCM/FM is equal to the bit rate, however a bandwidth between 1.5 and 2 times the bit rate will minimize operational problems without significantly reducing data quality.

8. The optimum receiver IF bandwidth for BIØ PCM/FM is equal to twice the bit rate. A bandwidth equal to three times the bit rate will minimize operational problems without significantly reducing data quality.

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Table 1. Radiated Bandwidth for various PCM modulation types

Modulation Type	Code	Peak Deviation	Premodulation - Bandwidth (-3 dB)	Radiated Bandwidth (-60 dB)
FM	NRZ	125 KHz	500 KHz	1.54 MHz
FM	NRZ	178 KHz	500 KHz	1.54 MHz
FM	NRZ	178 KHz	250 KHz	1.2 MHz
FM	NRZ	178 KHz	---	2.5 MHz
FM	NRZ	250 Khz	500 KHz	2.5 MHz
PM	NRZ	90°	500 KHz	4.0 MHz
PM	NRZ	90°	250 KHz	2.0 MHz
PM	NRZ	99°	500 KHz	4.0 MHz
PSK	NRZ	90°	500 KHz	1.9 MHz
PSK	NRZ	90°	250 KHz	1.2 MHz
PSK	NRZ	90°	---	8.0 MHz
FM	BIØ	250 Khz	1000 KHz	3.0 MHz
FM	BIØ	312 Khz	1000 KHz	3.0 MHz
PM	BIØ	60°	1000 KHz	6.0 MHz
PM	BIØ	90°	1000 KHz	8.0 MHz

Table 2. SNR in bandwidth equal to bit rate (500 Kb/s) for 10^{-5} BER for Various PCM signal types and filter bandwidths

PCM Code	Modulation Type, Peak Deviation	Premod Filter Bandwidth (KHz)	IF Bandwidth KHz	SNR (dB) for 10^{-5} BER
NRZ-L	PM (±90°)	None	3300	10.6
NRZ-M	PM (±90°)	None	3300	10.9
NRZ-M	PM (±90°)	None	1500	11.1
NRZ-M	PM (±90°)	None	1000	11.6
NRZ-M	PM (±90°)	1 MHz CD	3300	11.1
NRZ-M	PM (±90°)	1 MHz CA	3300	11.3
NRZ-M	PM (±90°)	500 KHz CD	3300	11.4
NRZ-M	PM (±90°)	500 KHz CD	3300	11.7
NRZ-M	PM (±90°)	250 KHz CD	3300	12.5
NRZ-M	PM (±90°)	250 KHz CD	3300	12.8
NRZ-M	PM (±90°)	500 KHz CD	3300	11.4
NRZ-M	PM (±107°)	250 KHz CD	3300	12.5
NRZ-M	PM (±99°)	None CD	3300	11.2
NRZ-L	FM (±178 KHz)	None	500	11.9
NRZ-L	FM (±178 KHz)	500 KHz CD	500	11.9
NRZ-L	FM (±178 KHz)	500 KHz CA	500	11.9
NRZ-L	FM (±178 KHz)	250 KHz CD	500	12.7
NRZ-L	FM (±178 KHz)	250 KHz CA	500	12.9
NRZ-L	FM (±178 KHz)	None	750	12.6
NRZ-L	FM (±178 KHz)	None	500 CA	12.6
NRZ-L	FM (±178 KHz)	None	1000	13.7
NRZ-L	FM (±178 KHz)	500 KHz CD	1000	13.7
NRZ-L	FM (±178 KHz)	500 KHz CA	1000	13.7
NRZ-L	FM (±178 KHz)	250 KHz CD	1000	13.9
NRZ-L	FM (±178 KHz)	250 KHz CD	1000	14.3
NRZ-L	FM (±125 KHz)	None	500	13.1
NRZ-L	FM (±205 KHz)	None	500	12.2
NRZ-L	FM (±250 KHz)	None	500	13.1
BIØ-L	PM (±60°)	None	3300	12.9
BIØ-L	PM (±60°)	1 MHz CD	3300	13.3
BIØ-L	PM (±60°)	1 MHz CA	3300	13.1
BIØ-L	PM (±60°)	500 KHz CD	3300	14.9
BIØ-L	PM (±60°)	500 KHz CA	3300	14.8

PCM Code	Modulation Type, Peak Deviation	Premod Filter Bandwidth (KHz)	IF Bandwidth KHz	SNR (dB) for 10^{-5} BER
BIØ-M	PM (±90°)	1MHz CD	3300	11.7
BIØ-L	FM (±312 KHz)	None	1000	13.9
BIØ-L	FM (±312 KHz)	1 MHz CD	1000	14.0
BIØ-L	FM (±312 KHz)	1 MHz CA	1000	14.0
BIØ-L	FM (±312 KHz)	500 KHz CD	1000	15.4
BIØ-L	FM (±312 KHz)	500 KHz CA	1000	15.4
BIØ-L	FM (±312 KHz)	None	1500	14.5
BIØ-L	FM (±312 KHz)	1 MHz CD	1500	14.5
BIØ-L	FM (±312 KHz)	1 MHz CA	1500	14.6
BIØ-L	FM (±312 KHz)	500 KHz CD	1500	15.2
BIØ-L	FM (±312 KHz)	500 KHz CA	1500	15.2
BIØ-L	FM (±250 KHz)	None	1000	15.3

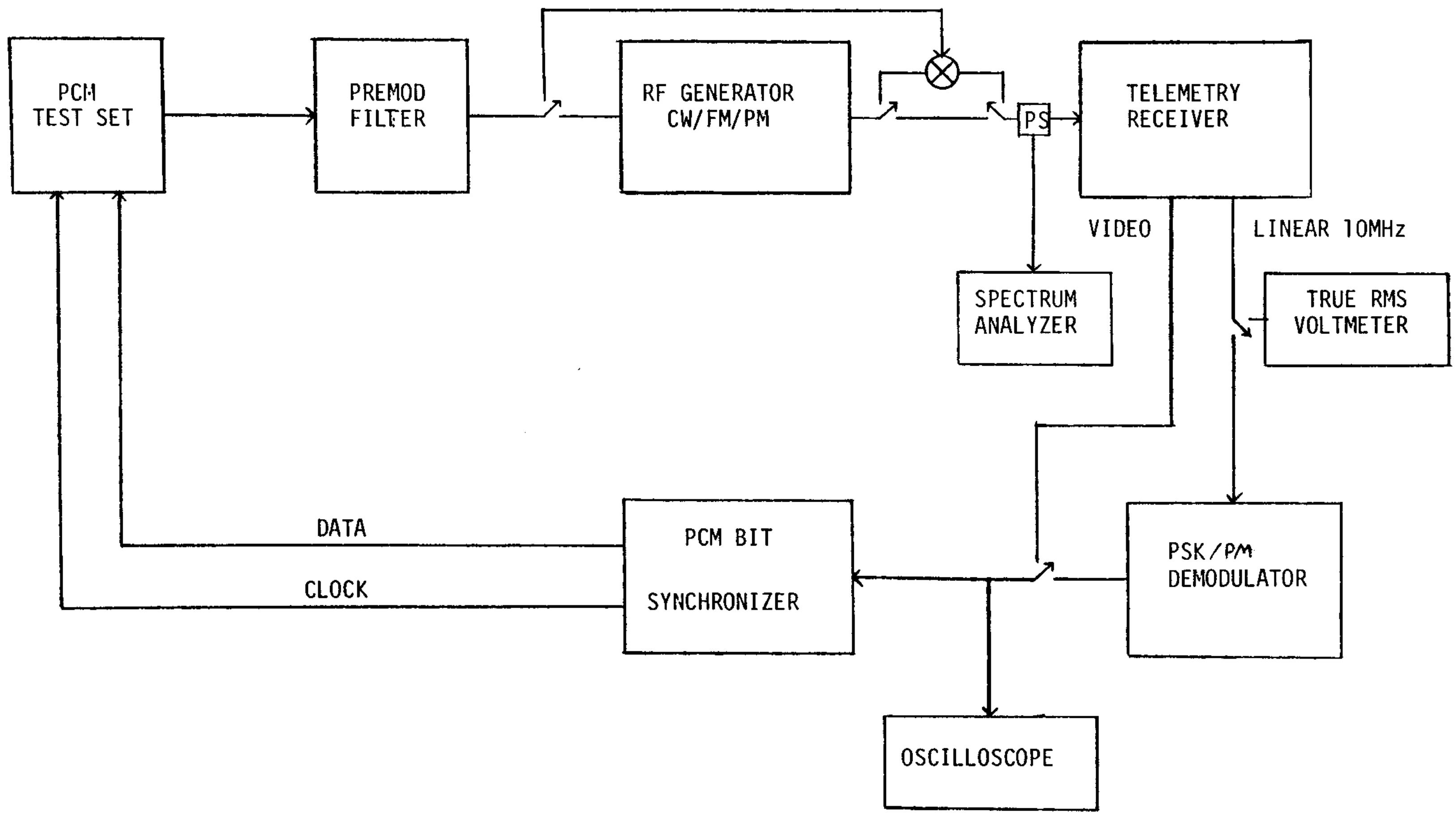

Figure 1. Test Setup.

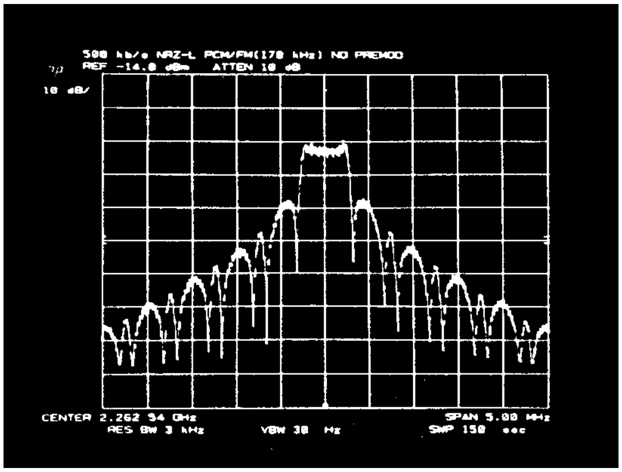

Figure 2A. NRZ-L PCM/FM(±178 kHz)
No Premodulation Filter

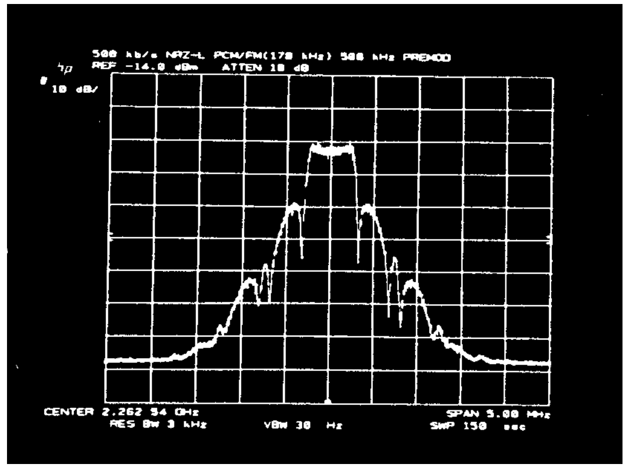

Figure 2B. NRZ-L PCM/FM (±178 kHz)
500 kHz Premodulation Filter.

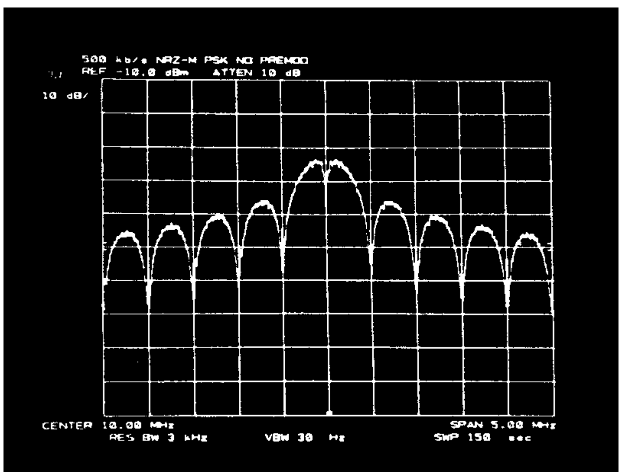

Figure 2C. NRZ-M PSK No Premodulation Filter.

Vertical: 10 dB/division
Horizontal: 500 kHz/division

Figure 2. RF Spectra of Various Binary PCM Modulation Types (500 kB/s).

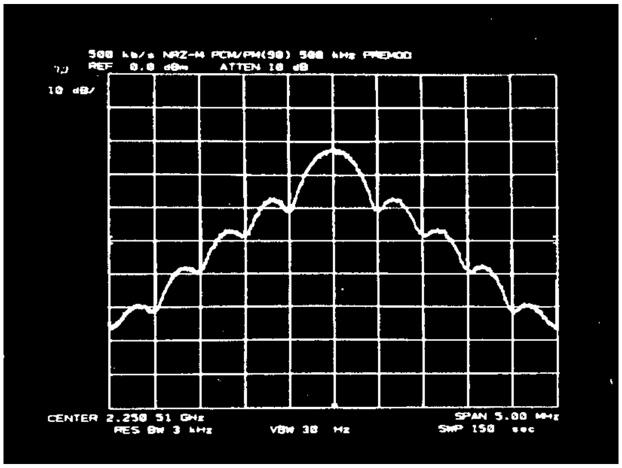

Figure 2D. NRZ-M PCM/PM(±90°) 500 kHz Premodulation Filter.

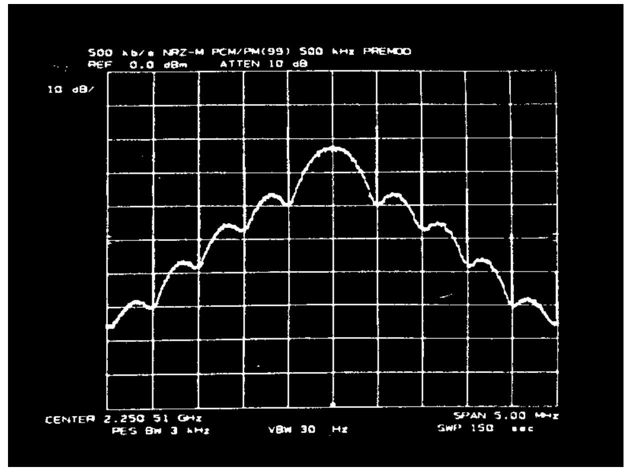

Figure 2E. NRZ-M PCM/PM(±99°) 500 kHz Premodulation Filter.

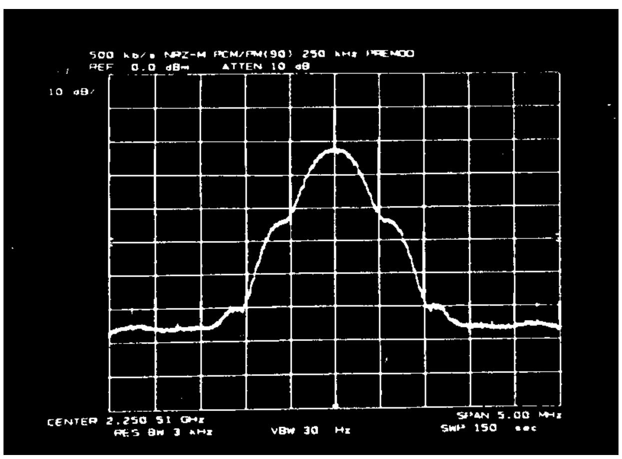

Figure 2F. NRZ-M PCM/PM(±90°) 250 kHz Premodulation Filter.

Figure 2. RF Spectra of Various Binary PCM Modulation Types (500 kB/s).

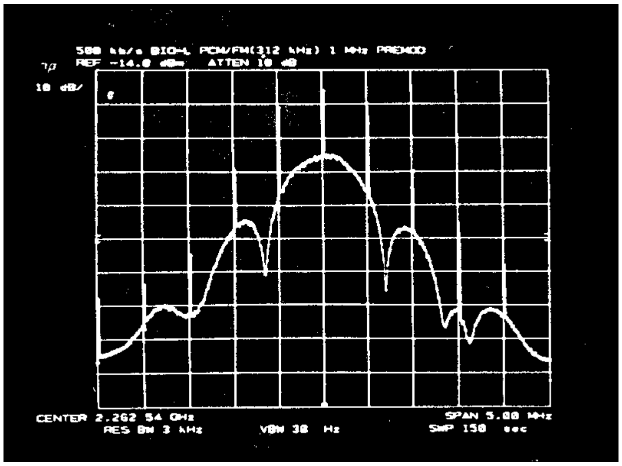

Figure 2G. BI∅-L PCM/FM(±312 kHz)
1 MHz Premodulation Filter.

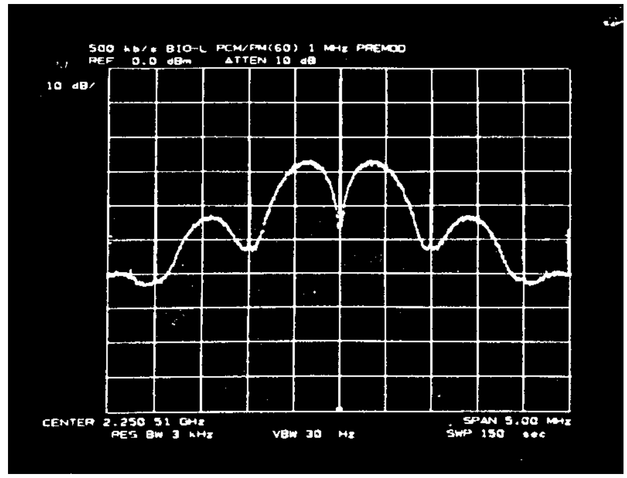

Figure 2H. BI∅-L PCM/PM(±60°)
1 MHz Premodulation Filter.

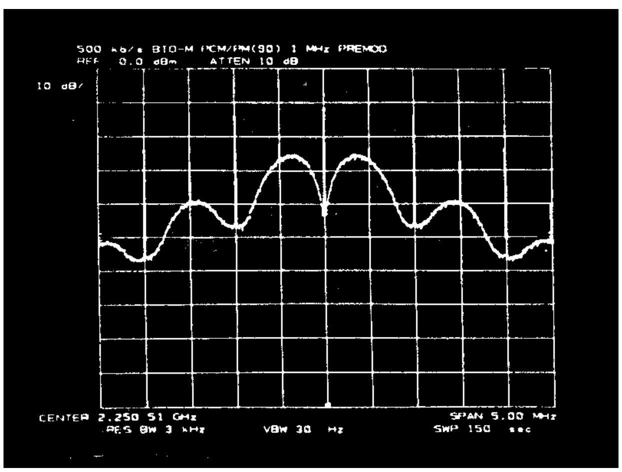

Figure 2I. BI∅-M PCM/PM(±90°)
1 MHz Premodulation Filter.

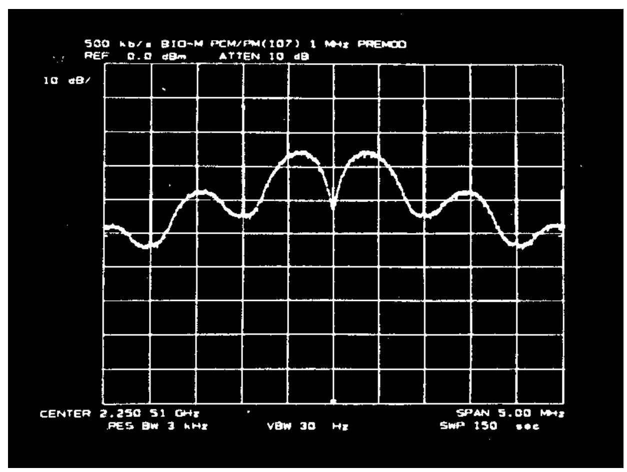

Figure 2J. BI∅-M PCM/PM(±107°)
1 MHz Premodulation Filter.

Figure 2. RF Spectra of Various Binary PCM Modulation Types (500 kB/s).

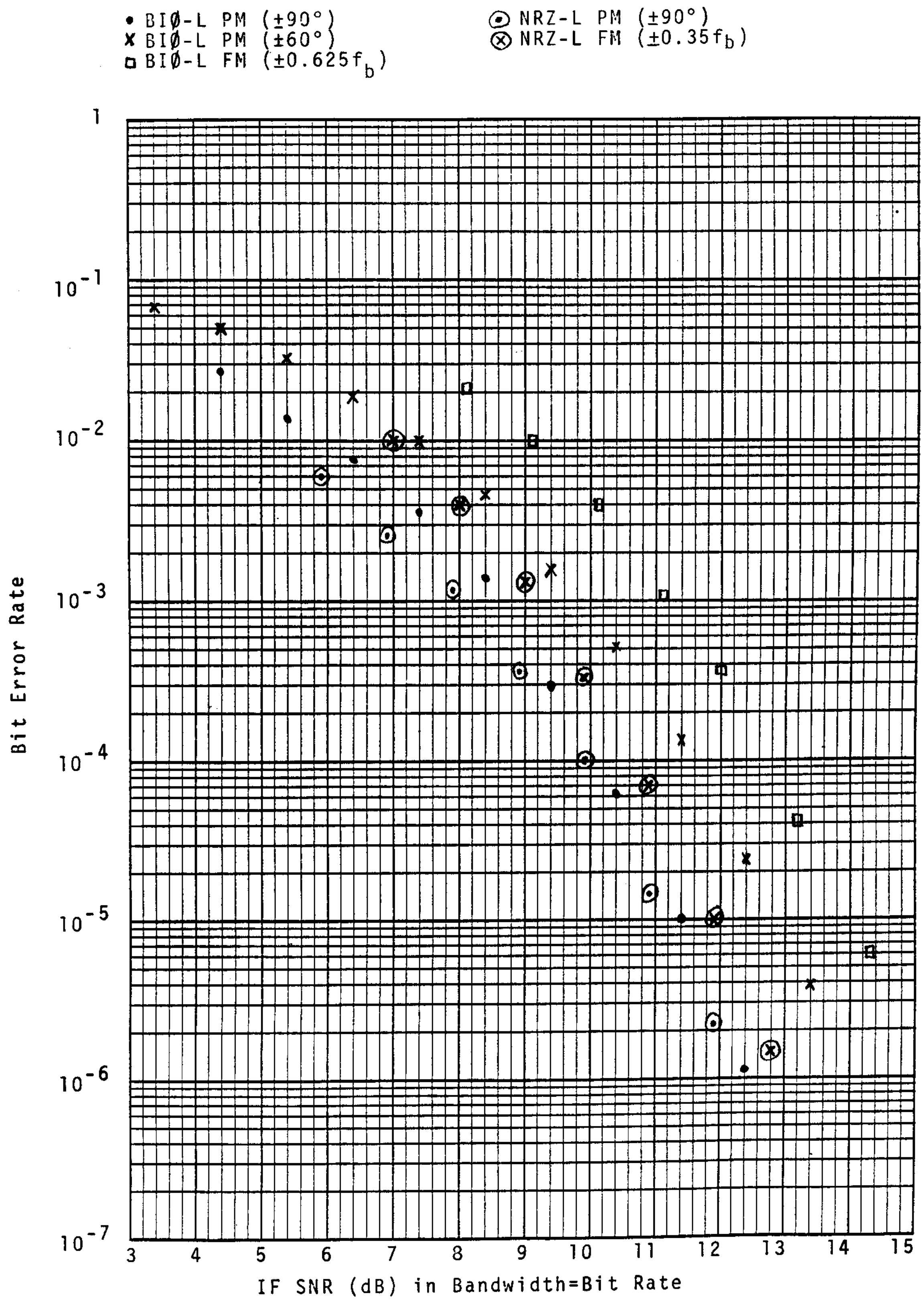

Figure 3. BER versus IF SNR for several PCM formats.