APPENDIX C

Pulse Code Modulation Standards
(Additional Information and Recommendations)

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Acronyms

BEP	bit error probability
Biϕ	bi-phase
dB	decibel
FM	frequency modulation
IF	intermediate-frequency
NRZ-L	non-return-to-zero level
PCM	pulse code modulation
SFID	subframe identifier
SNR	signal-to-noise ratio

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APPENDIX C

Pulse Code Modulation Standards (Additional Information and Recommendations)

1.0 Bit Rate Versus Receiver Intermediate-Frequency Bandwidth

The following subparagraphs contain information about selection of receiver intermediate-frequency (IF) bandwidths. Additional information is contained in RCC document 119, Telemetry Applications Handbook.[1]

The standard receiver IF bandwidth values are listed in Chapter 2, Table 2-1. Not all bandwidths are available on all receivers or at all test ranges. Additional bandwidths may be available at some test ranges. The IF bandwidth, for data receivers, should typically be selected so that 90 to 99 percent of the transmitted power spectrum is within the receiver 3-decibel (dB) bandwidth.

For reference purposes, in a well-designed pulse code modulation (PCM)/frequency modulation (FM) system (non-return-to-zero level [NRZ-L] data code) with peak deviation equal to 0.35 times the bit rate and an IF bandwidth (3 dB) equal to the bit rate, a receiver IF signal-to-noise ratio (SNR) of approximately 13 dB will result in a bit error probability (BEP) of 10^{-6}. A 1-dB change in this SNR will result in approximately an order of magnitude change in the BEP. The relationship between BEP and IF SNR in a bandwidth equal to the bit rate is illustrated in Figure C-1 for IF bandwidths equal to the bit rate and 1.5 times the bit rate. An approximate expression for the BEP is:

$$BEP = 0.5\, e^{(k \bullet SNR)} \qquad \text{(C-1)}$$

where: $k \approx -0.7$ for IF bandwidth equal to bit rate
$k \approx -0.65$ for IF bandwidth equal to 1.2 times bit rate
$k \approx -0.55$ for IF bandwidth equal to 1.5 times bit rate
SNR = IF SNR•IF bandwidth/bit rate.

[1] Range Commanders Council. Telemetry Applications Handbook. RCC 119-06. May 2006. May be superseded by update. Available at http://www.wsmr.army.mil/RCCsite/Documents/119-06_Telemetry%20Applications%20Handbook/119-06.pdf.

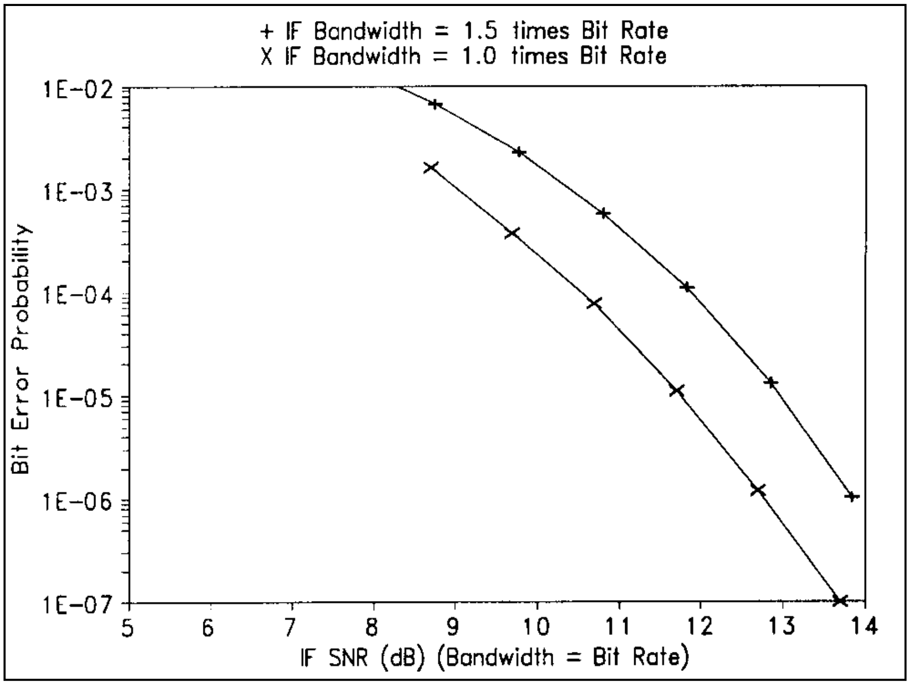

Figure C-1. BEP vs. IF SNR in Bandwidth = Bit Rage for NRZ-L PCM/FM

Other data codes and modulation techniques have different BEP versus SNR performance characteristics.

It is recommended that the maximum period between bit transitions be 64-bit intervals to ensure adequate bit synchronization.

2.0 Recommended PCM Synchronization Patterns

Table C-1 contains recommended frame synchronization patterns for general use in PCM telemetry. Patterns are shown in the preferred order of transmission with "111" being the first bit sequence transmitted. This order is independent of data being least-significant-bit or most-significant-bit aligned. The technique used in the determination of the patterns for lengths 16 through 30 was essentially that of the patterns of 2^n binary patterns off a given length, n, for that pattern with the smallest total probability of false synchronization over the entire pattern overlap portion of the ground station frame synchronization.[2] The patterns for lengths 31 through 33 were obtained from a second source.[3]

Table C-1. Optimum Frame Synchronization Patterns for PCM Telemetry

Pattern Length	Patterns									
16	111	010	111	001	000	0				

[2] A more detailed account of this investigation can be found in a paper by J. L. Maury, Jr. and J. Styles, "Development of Optimum Frame Synchronization Codes for Goddard Space Flight Center PCM Telemetry Standards." In *Proceedings of the National Telemetering Conference*, June 1964.

[3] The recommended synchronization patterns for lengths 31 through 33 are discussed more fully in a paper by E. R. Hill, "Techniques for Synchronizing Pulse-Code Modulated Telemetry." In *Proceedings of the National Telemetering Conference*, May 1963.

17	111	100	110	101	000	00				
18	111	100	110	101	000	000				
19	111	110	011	001	010	000	0			
20	111	011	011	110	001	000	00			
21	111	011	101	001	011	000	000			
22	111	100	110	110	101	000	000	0		
23	111	101	011	100	110	100	000	00		
24	111	110	101	111	001	100	100	000		
25	111	110	010	110	111	000	100	000	0	
26	111	110	100	110	101	100	110	000	00	
27	111	110	101	101	001	100	110	000	000	
28	111	101	011	110	010	110	011	000	000	0	
29	111	101	011	110	011	001	101	000	000	00	
30	111	110	101	111	001	100	110	100	000	000	
31	111	111	100	110	111	110	101	000	010	000	0
32	111	111	100	110	101	100	101	000	010	000	00
33	111	110	111	010	011	101	001	010	010	011	000

3.0 Spectral and BEP Comparisons for NRZ and Bi-phase[4]

Figure C-2 shows the power spectral densities of baseband NRZ and bi-phase (Biϕ) codes with random data. These curves were calculated using the equations presented below. Figure C-3 presents the theoretical bit error probabilities versus signal-to-noise ratio for the level, mark, and space versions of baseband NRZ and Biϕ codes and also for randomized NRZ-L. The noise is assumed to be additive white Gaussian noise.

$$NRZ\ SPECTRAL\ DENSITY \quad \alpha \quad \frac{\sin^2(\pi fT)}{(\pi fT)^2} \qquad \text{Eqn. C-2}$$

$$Bi\phi\ SPECTRAL\ DENSITY \quad \alpha \quad \frac{\sin^4(\pi fT/2)}{(\pi fT/2)^2} \qquad \text{Eqn. C-3}$$

where T is the bit period.

[4] Material presented in paragraph 3.0 is taken from a study by W. C. Lindsey (University of Southern California), *Bit Synchronization System Performance Characterization, Modeling and Tradeoff Study*, Naval Missile Center Technical Publication.

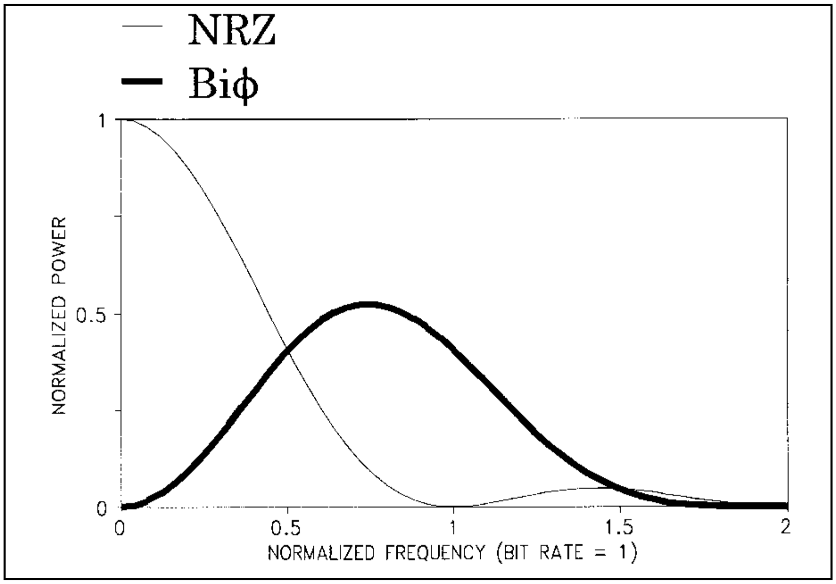

Figure C-2. Spectral Densities of Random NRZ and Biϕ Codes

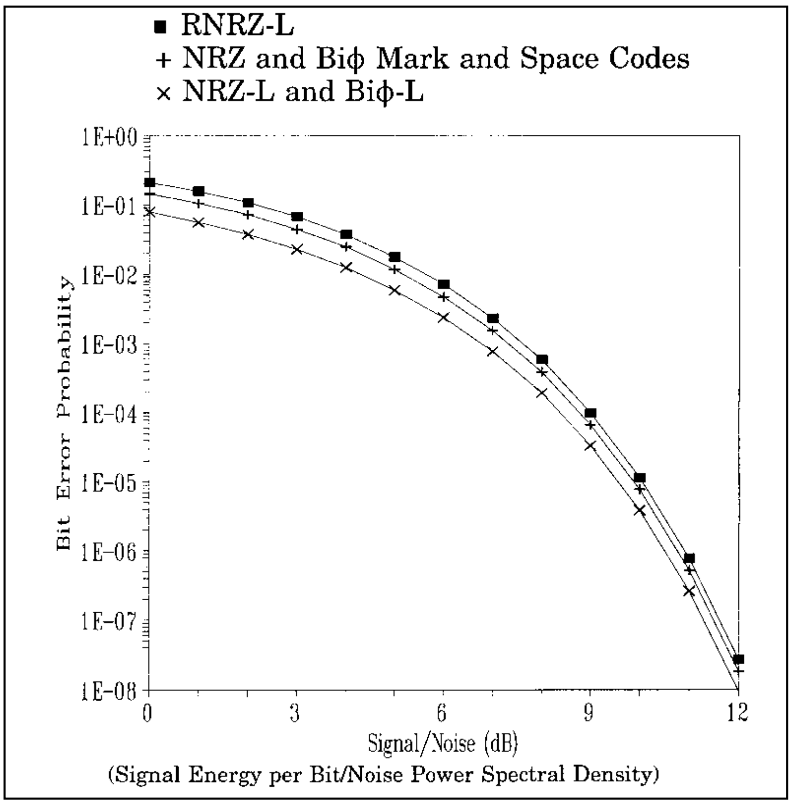

Figure C-3. Theoretical BEP Performance for Various Baseband PCM Signaling Techniques (Perfect Bit Synchronization Assumed)

4.0 PCM Frame Structure Examples

Table C-2, Table C-3, and Table C-4 show examples of allowable PCM frame structures. In each example, the minor frame sync pattern is counted as one word in the minor frame. The first word after the minor frame sync pattern is word 1. Table C-3 and Table C-4 show the preferred method of placing the subframe identifier (SFID) counter in the minor frame. The counter is placed before the parameters that are referenced to it.

Major frame length is as follows:

- Table C-2: Major frame length = minor frame maximum length.
- Table C-3: Major frame length = minor frame maximum length multiplied by Z.
- Table C-4: Major frame length = minor frame maximum length multiplied by Z.

Table C-2. Minor Frame Maximum Length, N Words or B Bits

Class I: Shall not exceed 8192 bits nor exceed 1024 words
Class II: 16 384 Bits

	Word 1	Word 2	Word 3	Word 4	Word 5	Word 6	Word 7	Word 8	Word 9	Word 10	...	...	...	Word N-2	Word N-1
Minor Frame Sync Pattern	Param A0	Param A1	Param A2	Param A3	Param A4	Param A2	Param A5	Param A6	Param A2	Param A7	...	...	...	Param A2	Param A(X)

Parameters A0, A1, A3, A4, A5, A6, ... A(X) are sampled once each minor frame.
Parameter A2 is supercommutated on the minor frame.
The rate of A2 is equal to the number of samples multiplied by the minor frame rate.

Table C-3. Major Frame Length = Minor Frame Maximum Length Multiplied by Z

Minor Frame Maximum Length, N Words or B Bits
← Class I shall not exceed 8192 bits nor exceed 1024 words. Class II: 16 384 bits. →

	Word 1	Word 2	Word 3	Word 4	Word 5	Word 6	Word 7	Word 8	Word 9	Word 10	• • •	Word N-2	Word N-1
Minor frame sync pattern	SFID= 1	FFI	Param A2	Param B1	Param A4	Param A2	Param A5	Param A6	Param A2	Param C1	• • •	Param A2	Param A(X)
	SFID= 2			Param B2						Param C2			
	SFID= 3			Param B3						Param C3			
	SFID= 4			Param B4						Param C4			
	SFID= 5			Param B2						Param C5			
	SFID= 6			Param B5						Param C6			
	SFID= 7			Param B6						Param C7			
	. .			. .	. .					. .			
	. .			Param B2						Param C(Z-1)			
Minor frame sync pattern	SFID =Z	FFI	Param A2	Param BZ	Param A4	Param A2	Param A5	Param A6	Param A2	Param CZ	• • •	Param A2	Param A(X)

The frame format identifier (word 2) is shown in the preferred position as the first word following the ID counter. Parameters B1, B3, B4, B5, . . . BZ, and C1, C2, C3, . . . CZ are sampled once each subframe, at 1/Z multiplied by the minor frame rate. Parameter B2 is supercommutated on the subframe and is sampled at less than the minor frame rate, but greater than the subframe rate.

Table C-4. Major Frame Length = Minor Frame Maximum Length Multiplied by Z

Minor Frame Maximum Length, N Words or B Bits

← Class I shall not exceed 8192 bits or exceed 1024 words. Class II: 16 384 bits. →

	Word 1	Word 2	Word 3	Word 4	Word 5	Word 6	Word 7	Word 8	Word 9	Word 10	• • •	Word N-2	Word N-1
Minor frame sync pattern	SFID1 =1	FFI	Param A2	SFID2 =1	Param B1	Param A2	Param A5	Param E1	Param A2	Param C1	• • •	Param A2	Param A(X)
	SFID1 =2			SFID2 =2	Param B2			Param E2		Param C2			
	SFID1 =3			SFID2 =3	Param B3			Param E3		Param C3			
	SFID1 =4			SFID2 =4	Param B4			Param E4		Param C4			
	SFID1 =5			SFID2 =5	Param B2			Param E5		Param C5			
	SFID1 =6			. .	Param B5			. .		Param C6			
	SFID1 =7			SFID2 =D	Param B6			Param ED		Param C7			
	. .			. .	. .	. .		. .		. .			
	. .			. .	Param B2			. .		Param C(Z-1)			
Minor frame sync pattern	SFID1 =Z	FFI	Param A2	SFID2 =N	Param BZ	Param A2	Param A5	Param EN	Param A2	Param CZ	• • •	Param A2	Param A(X)

SFID1 and SFID2 and subframe counters.
SFID1 has a depth Z≤ 256; SFID2 has a depth D <Z. Z divided by D is not an integer.
Location of the B and C parameters are given by the minor frame word number and the SFID1 counter.
Location of the E parameters are given by the minor frame word number and the SFID2 counter.

References

E. R. Hill. "Techniques for Synchronizing Pulse-Code Modulated Telemetry" in Proceedings of the National Telemetering Conference, May 1963.

J. L. Maury, Jr. and J. Styles. "Development of Optimum Frame Synchronization Codes for Goddard Space Flight Center PCM Telemetry Standards." In Proceedings of the National Telemetering Conference, June 1964.

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W. C. Lindsey. *Bit Synchronization System Performance Characterization, Modeling and Tradeoff Study*. AD-766 974. Naval Missile Center Technical Publication. 4 September 1973. Available at http://www.dtic.mil/cgi-bin/GetTRDoc?AD=AD0766794.

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