The Advanced Receiver II: Telemetry Test Results in CTA 21

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This article describes telemetry tests with the Advanced Receiver II (ARX II) in Compatibility Test Area 21. The ARX II was operated in parallel with a Block-III Receiver/baseband processor assembly combination (BLK-III/BPA) and a Block-III Receiver/subcarrier demodulation assembly/symbol synchronization assembly combination (BLK-III/SDA/SSA). The telemetry simulator assembly provided the test signal for all three configurations, and the symbol signal-to-noise ratio as well as the symbol error rates were measured and compared. Furthermore, bit-error rates were also measured by the system performance test computer for all three systems. Results indicate that the ARX-II telemetry performance is comparable and sometimes superior to the BLK-III/BPA and BLK-III/SDA/SSA combinations.

I. Introduction

The Advanced Receiver (ARX II) [1] is a digital system that performs carrier, subcarrier, and symbol detection, as well as Doppler extraction. The latter function was demonstrated successfully at Goldstone [2] in June 1989. The telemetry functions have been added since then and tested in Compatibility Test Area 21 (CTA21). Specifically, residual carrier, subcarrier, and symbol synchronization have been added, including a symbol signal-to-noise ratio (SSNR) estimator. Sideband aiding, which requires a carrier Costas loop, and quadrature phase-shift keying capabilities have not been added yet.

This article describes the ARX-II telemetry tests which were conducted in CTA21. The ARX II was operated in parallel with a Block-III Receiver/baseband processor assembly combination (BLK-III/BPA) and a Block-III Receiver/subcarrier demodulation assembly/symbol synchronization assembly combination (BLK-III/SDA/SSA). The BPA is a baseband assembly (BBA) without the real-time combining capability and, hence, is equivalent to the BBA for the purpose of these tests.

II. Test Objectives

The objectives of the ARX-II telemetry tests at CTA21 were to:

(1) Demonstrate the added telemetry capability of the ARX II to perform subcarrier demodulation and symbol synchronization at different data rates and at varying signal-to-noise ratios.

(2) Test the interface between the ARX II and the telemetry processor assembly (TPA).

(3) Compare the ARX-II SSNR estimator's results with another SSNR estimate determined from measuring the symbol error rate (SER), referred to as the symbol error rate SNR (SERSNR), as a measure of the accuracy of the ARX-II SSNR estimator.

(4) Compare the telemetry performance of the ARX II to that of the BLK-III/BPA and BLK-III/SDA/SSA combinations.

(5) Measure telemetry performance with bit and symbol error rates for all three systems.

III. Test Description

The ARX-II telemetry test configuration in CTA21 is depicted in Fig. 1. The telemetry simulator assembly (TSA) provided a test signal consisting of a semirandom symbol stream modulated on a square wave subcarrier. Internal to the TSA, a pseudorandom sequence is generated to simulate the transmitted bits. These are later coded using a (7,1/2) convolutional code to produce the symbols which modulate the subcarrier. This telemetry baseband signal, consisting of subcarrier and data ($Sc \times D$), forms the input to an exciter which produces an uplink S-band modulated signal at 2113 MHz. A digitally controlled oscillator (DCO) produces a 44-MHz IF and the frequency of this intermediate frequency (IF) signal is multiplied by the integer 48 to obtain the S-band (2112-MHz) uplink. The exciter phase modulator has a specification bandwidth of 2 MHz (which would become a crucial parameter at high data rates) and outputs a constant power level.

The output of the exciter ($C \times Sc \times D$) is then converted to a downlink S-band signal (2295 MHz) by the translator which multiplies the frequency by the ratio 240/221. This signal is then fed into an S-band field-effect-transistor (FET) amplifier with a 4.5-dB noise figure, a 50-dB gain, and a bandwidth from 2 to 3 GHz. The operating system noise temperature was approximately 500 kelvin. The output of the S-band amplifier ($C \times Sc \times D + N$) was then sent simultaneously to the Block-III Receiver and to the multimission receiver (MMR). The MMR downconverted the S-band signal to a 300-MHz IF signal that was sent to the ARX II.

The ARX II was operated in parallel with a BLK-III/BPA and a BLK-III/SDA/SSA combination. SSNR measurements were performed by the ARX II, the BPA, and the SSA using the split-symbol moment estimator [3]. Moreover, both the transmitted symbols and the symbol clock from the TSA were passed to the ARX II, the BPA, and the SSA where SER measurements were performed. The latter measurements were mapped into an equivalent SSNR, referred to as SERSNR, assuming an additive white Gaussian noise channel. Bit-error rates (BERs) were also measured and compared for all three systems for different data rates. Symbols at the output of the SSA were fed to TPA 1, while the symbols from the output of the ARX II and the BPA shared the same input of the TPA 3 through a telemetry switch. The decoded bits from TPA 1 and TPA 3 were sent to the system performance test (SPT) computer where BER measurements took place.

Telemetry signal path verification tests were run with different test signals to verify the flow of data from the TSA to the TPA. Telemetry tests for different data rates at varying signal-to-noise ratios at the input of the receiver were done according to prepared configuration test tables. These tables represent current flight missions for different spacecraft and cover signals from the Pioneer 10 low data rate (16 bits per sec—bps) through the Magellan high data rate (268.8 kbps) signal.

The test signal was calibrated for different telemetry tests. A carrier suppression procedure was used to set up the modulation index and a Y-factor procedure was used to set up the bit SNR (E_b/N_0) at the input of the receiver. The modulation index adjustment procedure is described in Appendix A, while the Y_F setup is discussed in Appendix B. Accuracy of both procedures provides a worst-case uncertainty of ± 0.5 dB in the calibrated test signal SSNR.

IV. Test Results

The tests performed can be divided into two main classes: general telemetry tests comparing the three configurations and specific tests for the Pioneer 10 spacecraft. The objective of the first set of tests was to compare the three systems on a relative basis, while the results of the latter tests were compared to theoretically predicted results.

It is worth noting at this point the difference between SSNR degradation and SSNR loss. SSNR degradation is defined as the average reduction in SNR at the symbol matched filter output due to imperfect synchronization caused by carrier, subcarrier, or symbol tracking. For example, the SNR degradation due to imperfect carrier reference is given by

$$D_c = \mathcal{E}\{\cos^2 \phi_c\} \tag{1}$$

where $\mathcal{E}$ denotes expectation over the carrier phase error ϕ_c. SSNR loss, on the other hand, is defined as the additional SSNR needed in the presence of imperfect synchronization in order to achieve the same symbol error probability for the case of perfect synchronization. SSNR loss is shown in Fig. 2(a) and is specified at a particular SSNR or the equivalent symbol error rate. SSNR loss is typically larger than the SNR degradation and both were utilized in analyzing the measured data. Bit SNR (BSNR) loss is similarly defined as the additional BSNR required to achieve a certain BER. The performance of the (7,1/2) convolutional code (assuming Viterbi decoding with symbols quantized to three bits), in an additive white Gaussian noise channel, is depicted in Fig. 2(b) and was used to assess the bit-error rate SNR (BERSNR) loss.

A. Measurement Accuracy

Since the results are based solely on measurements, it is worthwhile at this point to discuss their confidence level. Note that the outcome of each symbol (or bit) detection is either "no symbol error" or "symbol error," i.e., a binary decision. Let $\mathcal{X}$ be a random variable denoting the number of "symbol errors" in a test of n symbols. Then, $\mathcal{X}$ can be modeled by a binomial distribution with mean np and variance $np(1-p)$, where p denotes the expected probability of symbol error (i.e., SER). Hence, the error level (the ratio of the standard deviation to the mean) becomes $\sqrt{(1-p)/np}$, with an accuracy level of $1-\sqrt{(1-p)/np}$. As an example, when testing a system with an expected probability of symbol error of 2.288 percent (SSNR = 3.0 dB) using 10,000 symbols, the results will be correct with a 93.4 percent accuracy level. On the other hand, for a 0.595 percent SER (SSNR = 5 dB), the accuracy level decreases to 87 percent. To translate the SER accuracy to its counterpart in SSNR, the performance of binary phase-shift key (BPSK) in an additive white Gaussian noise channel is used, Fig. 2(a). For example, the 93.4 percent accuracy at an SSNR of 3 dB translates into an SER of 0.02288 $\pm$ 6.6 percent (or a maximum SER of 0.02439). From Fig. 2(a), the latter SER corresponds to 2.85 dB in SSNR and, hence, a deviation or accuracy of $\pm$0.15 dB (3 − 2.85 dB) in SSNR. Similar accuracies can be obtained in terms of BSNR using Fig. 2(b).

B. Relative Performances of ARX II, BLK-III/BPA, and BLK-III/SDA/SSA

Throughout the tests to follow, the data format was non-return-to-zero (NRZ) modulated on a square-wave subcarrier with a $\pm$0.5-dB worst-case SSNR error. In the first set of tests, the SSNR was set to 1 dB and the telemetry configuration tests are shown in Table 1. It includes eight tests ranging in symbol rate from 32 symbols per sec (sps) typical of Pioneer 10 to 537.6 ksps, which corresponds to the high data channel of Magellan. In each test, the SERSNR was deduced from the measured SER and the loss was computed based on the assumption that the input SSNR is exactly 1 dB. The corresponding SERSNR loss is computed in each case and depicted in Fig. 3(a). Simultaneous measurements of the BER were made by the SPT and the corresponding BERSNR was computed using the performance of the (7,1/2) convolutional code, as given in Fig. 2(b). The resulting BERSNR loss is shown in Fig. 3(b) for all tests. Note that the SERSNR loss for all three systems agrees to within 0.2 dB for all symbol rates between 2.4 ksps and 268.8 ksps. For 32 sps and 80 sps (or the equivalent 16 bps and 40 bps), the ARX II outperformed the BLK-III/BPA and BLK-III/SDA/SSA combinations by as much as 1.2 dB in SSNR. The reason for this improvement is the capability of the ARX II to use narrower carrier loop bandwidths than the Block-III Receiver, resulting in a higher loop SNR and smaller phase jitter.

At the highest rate of 537.6 ksps, the ARX-II performance was degraded by about 0.4 dB with respect to the BLK-III/BPA combination (the SSA is specified to operate at a maximum of 200 ksps and was not operational in this case). Other tests were performed at a lower SSNR (−1 dB), and the results are shown in Fig. 4 with the test configuration in Table 2. The subcarrier and symbol synchronization loops were operating with the same bandwidths as those given in Table 1. Here again, the ARX-II SERSNR loss, Fig. 4(a), and the BERSNR loss, Fig. 4(b), at 537.6 ksps are at least 0.4 dB worse than those of the BLK-III/BPA. Furthermore, the two figures are reflecting the coding gain of 3 dB to within 0.2 dB.

The telemetry degradation of the ARX II at 537.6 ksps was of primary concern and has been thoroughly investigated. It turned out that the additional loss was really due to the filtering operation on the signal in the exciter itself, and not in the ARX II. This is the reason why the loss of the BLK-III/BPA combination also increases at that symbol rate. Figure 5 illustrates the filtering phenomenon clearly. In Fig. 5(a), the spectrum of a 1-MHz square-wave subcarrier is shown indicating only the presence of the odd harmonics. The bandwidths of the various signals and systems are indicated in Fig. 5(b); the exciter has a 2-MHz bandwidth which passes only the first harmonic of the 960-kHz subcarrier. The Block-III Receiver and the ARX II have roughly 4-MHz and 8-MHz telemetry bandwidths, respectively. Expanding a square-wave subcarrier in a Fourier series, one obtains

$$\mathcal{S}in(2\pi f_{sc}t) = \frac{4}{\pi}\sum_{n=0}^{\infty}\frac{(-1)^n}{2n+1}\sin[2\pi(2n+1)f_{sc}t] \qquad (2)$$

where f_{sc} is the subcarrier frequency. The power of any odd harmonic is proportional to $1/n^2$, as expected. The exciter limits both the BLK-III/BPA and the ARX II to the first harmonic of the signal. In the Block-III Receiver, the noise bandwidth allows the first and third harmonics of the reference subcarrier to heterodyne the noise to baseband, resulting in a noise degradation of

$$\text{BLK-III noise degradation} = \frac{1}{1 + 1/3^2} = 0.9 = -0.46 \text{ dB} \quad (3)$$

On the other hand, the ARX-II noise bandwidth allows the first through the ninth harmonics of the reference subcarrier to heterodyne the noise to baseband, resulting in a noise degradation of

$$\text{ARX-II noise degrad.} = \frac{1}{1 + 1/3^2 + 1/5^2 + 1/7^2 + 1/9^2} = 0.845 = -0.73 \text{ dB} \quad (4)$$

Removing those degradations from the measured SERSNR loss for both the BLK-III/BPA and ARX II, one obtains the dashed lines in Fig. 3(a) at 537.6 ksps, which are in total agreement with the SERSNR loss at lower data rates. If the exciter bandwidth limitations had been known before the tests, the received subcarrier in the ARX II would have been mixed with a pure sine wave, resulting in 0.73-dB improvement over the measured performance of the ARX II with a square wave and a 0.46-dB improvement over the BLK-III/BPA combination. The ARX II can heterodyne the received subcarrier with a square wave, a sine wave, or a filtered square wave such that only the first K harmonics are passed. As an example, the received subcarrier can be mixed with the combination of first and third harmonics only. All this processing can be controlled by a software command and can be changed on the fly. In case the filtering on the subcarrier is unknown to the receiver, several combinations can be experimented with in the receiver in real time and the one providing the best performance utilized. This additional flexibility is easily obtained in digital implementations and guarantees that the local subcarrier is "matched" to the received one.

C. Performance of the SNR Estimators

Recall that one of the objectives of these tests was to assess the performance of the ARX-II SSNR estimator. During these tests, the SNR estimator of the ARX II suffered from a slight hardware problem that produced a bias in the SNR estimates. The problem resulted from two missing samples in the signal power estimate, thus, degrading more at the higher symbol rates. The problem was not fixed in time for these tests, but will be fixed in the next board version. Figure 6 depicts the SSNR loss as estimated by the SSNR estimator and the SERSNR estimator for both the ARX II and the BLK-III/BPA combination. Both estimators seem to agree to within 0.2 dB in the BLK-III/BPA combination, except at the lowest rate where the difference was about 0.6 dB. In the ARX-II case, the agreement was within roughly 0.4 dB, except at the highest rate where the estimates diverged by as much as 1 dB. More tests will be conducted in the next implementation of the estimator to obtain better results.

D. Performance of the ARX II With Pioneer 10's Signal

The last set of tests were specific to the Pioneer 10 spacecraft, which transmits the lowest symbol rate of 32 sps with the weakest received signal of roughly $P_T/N_0 =$ 20 dB-Hz using the 70-m antennas. The telemetry configuration tests for Pioneer 10 are shown in Table 3, where three different values of P_C/N_0 were used, namely, 13 dB-Hz, 11 dB-Hz, and 9 dB-Hz. The ability of narrowing the carrier loop bandwidth of the ARX II is clearly shown in Fig. 7(a), where as much as an additional 1.4-dB improvement in SSNR has been obtained over the BLK-III/BPA combination. In CTA21, the optimum loop bandwidth obtained was about 0.5 Hz due to the possible presence of significant phase noise. Some of these measurements were repeated in the laboratory and the optimum loop bandwidth was further narrowed to about 0.25 Hz, adding credence to the theory of significant phase noise present in CTA21. Figure 7(b) depicts the measured SERSNR loss and the theoretical losses assuming thermal noise only. The carrier loss was computed from Fig. 8[1] for the different loop SNRs. For the subcarrier and symbol synchronization, SSNR degradation was computed,[2] respectively,

$$D_{sc} = 1 - 1.0159\sigma_{sc}, \quad \sigma_{sc}^2 = 1/\rho_{sc},$$
$$\rho_{sc} = \frac{P_D}{N_0 B_{sc}} \left(\frac{2}{\pi}\right)^2 \frac{1}{1 + N_0/2E_s} \quad (5)$$

[1] *Deep Space Network/Flight Project Interface Design Handbook, Vol. I: Existing DSN Capabilities,* JPL 810-5, Rev. D (internal document), Jet Propulsion Laboratory, Pasadena, California.

[2] J. Statman, *DSN Receiver Losses in Galileo Experiment,* JPL Interoffice Memorandum 331-88.5-050 (internal document), Jet Propulsion Laboratory, Pasadena, California, November 14, 1988.

$$D_{sy} = 1 - 0.2534\sigma_{sy}, \quad \sigma_{sy}^2 = 1/\rho_{sy},$$

$$\rho_{sy} = \frac{P_D}{N_0 B_{sy}} \frac{\mathrm{erf}^2(\sqrt{E_s/N_0})}{2\pi^2} \tag{6}$$

These formulas assume that no windowing is used in the loops and that the windowing needs to be accounted for by multiplying the loop variance by its corresponding relative window size W. The symbol synchronization loop was operated with $W_{sy} = 1/2$ and the window is accounted for in Table 4, which compares the various synchronization effects for various operating points in the test table. The subcarrier and symbol degradations are significant and surpass the carrier loss in some instances. These degradations can be reduced either by narrowing the loop bandwidths or by employing windows [4].

During the course of these tests, the ARX-II subcarrier and symbol lock detectors were not tested extensively and, as a result, require further testing. The scaling of soft symbols from the ARX II to the TPA was performed manually and needs to be automated in the next upgrade. To test the performance of future systems with a 0.1-dB accuracy, CTA21 test equipment needs to be upgraded in order to provide an accuracy better than 0.1 dB (currently, it is 0.5 dB). Furthermore, the CTA21 test capability does not support SER testing in excess of 1 Msps (537.6 ksps required recording and playback of data). All of these issues are areas of concern that need to be addressed in the future.

V. Goldstone Tests

Telemetry tests with the ARX II were performed at Goldstone in early November 1990 by tracking and demodulating signals from the International Comet Explorer (ICE), Voyager 1, Magellan low and high data rate channels, and Pioneers 10 and 11. Table 5 depicts the signal characteristics of each spacecraft tracked. Early results seem to agree with those run in CTA21, but more extensive analysis of the data is planned.

VI. Conclusion

The CTA21 tests have demonstrated the telemetry capability of the ARX II to demodulate signals with symbol rates up to 537.6 ksps. Test results specific to Pioneer 10 show a 1.2- to 1.4-dB SERSNR improvement in the telemetry performance of the ARX II versus the BLK-III/BPA combination due to the capability of the ARX II to use narrower loop bandwidths.

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[4] W. Hurd and S. Aguirre, "A Method to Dramatically Improve Subcarrier Tracking," *TDA Progress Report 42–86,* vol. April–June 1986, Jet Propulsion Laboratory, Pasadena, California, pp. 103–110, April 1986.

Table 1. Telemetry configuration test table (SSNR = 1 dB and BSNR = 4 dB)

Test number	Bit rate, bps	Symbol rate, sps	Δ Mod. index, deg	Subcarrier frequency, kHz	Input SSNR, dB	P_D/N_0, dB-Hz	P_C/N_0, dB-Hz	Carrier loop bandwidth (2 B_C)		Subcarrier bandwidth, B_{SC}, Hz			Symbol loop bandwidth, B_{SY}, Hz		
								ARX II	BLK III	ARX II	BPA	SDA	ARX II	BPA	SDA
1	16	32	65.9	32.768	1	16.0	9.0	1	3.4	0.1	0.04	0.06	0.1	0.04	0.3
2	40	80	45.0	22.5	1	20.0	20.0	2	9	0.2	0.07	0.08	0.1	0.07	0.4
3	1,200	2,400	70.0	360.0	1	34.8	26.0	6	20	0.2	0.15	0.12	0.2	0.15	0.1
4	21,600	43,200	80.0	360.0	1	47.4	32.3	6	21	0.2	0.2	0.2	0.2	0.2	0.5
5	43,200	86,400	80.0	360.0	1	50.4	35.3	6	23	0.2	0.2	0.2	0.2	0.2	1.0
6	67,200	134,400	80.0	360.0	1	52.2	37.2	6	24	0.2	0.2	0.2	0.2	0.2	1.5
7	134,400	268,800	80.0	360.0	1	55.2	40.2	6	24	0.2	0.2	0.2	0.2	0.2	N/A
8	268,800	537,600	80.0	960.0	1	58.2	43.2	6	24	0.2	0.2	0.2	0.2	0.2	N/A

Table 2. Telemetry configuration test table (SSNR = −1 dB and BSNR = 2 dB)

Test number	Bit rate, bps	Symbol rate, sps	Mod. index, deg	Subcarrier frequency, kHz	Input SSNR, dB	P_D/N_0, dB-Hz	P_C/N_0, dB-Hz	Carrier loop bandwidth (2 BL)	
								ARX II	BLK III
1	1,200	2,400	70	360	−1	32.8	24.0	6	13
2	21,600	43,200	80	360	−1	45.4	30.3	6	20
3	43,200	86,400	80	360	−1	48.4	33.3	6	22
4	67,200	134,400	80	360	−1	50.2	35.2	6	24
5	134,400	268,800	80	360	−1	53.2	38.2	6	24
6	268,800	537,600	80	960	−1	56.2	41.2	6	24

Table 3. Telemetry configuration test table for Pioneer 10

Test number	Symbol rate, sps	Δ Mod. index, deg	Subcarrier frequency, kHz	Input SSNR, dB	P_D/N_0, dB-Hz	P_C/N_0, dB-Hz	BLK-III carrier margin, dB	Carrier loop bandwidth ($2\ BL$)		ARX-II carrier loop SNR, dB	Subcarrier loop bandwidth, Hz	Symbol loop bandwidth, Hz
								BLK III	ARX II			
1	32	65.9	32.768	5	20	13	9	4.4	4.4	9.6	0.1	0.1
2									3.0	11.2		
3									1.0	16.0		
4									0.5	19.0		
5	32	65.9	32.768	3	18	11	7	4.0	4.0	8.0	0.1	0.1
6									3.6	8.5		
7									3.0	9.2		
8									1.0	14.0		
9									0.5	17.0		
10	32	65.9	32.768	1	16	9	5	3.3	3.0	7.2	0.1	0.1
11									1.0	12.0		
12									0.5	15.0		

Table 4. Various synchronization losses for Pioneer 10

Configuration parameters, dB	Symbol degradation, dB	Subcarrier degradation, dB	Carrier loop SNR, dB	Carrier loss, dB	Telemetry loss, dB
$E_s/N_0 = 5$	0.12	0.26	9.6	1.00	1.38
			11.2	0.45	0.83
$P_C/N_0 = 13$	0.12	0.26	16.0	0.07	0.45
			19.0	0.05	0.43
$E_s/N_0 = 3$ $P_C/N_0 = 11$	0.15	0.33	14	0.3	0.78
$E_s/N_0 = 1$ $P_C/N_0 = 9$	0.21	0.44	0.44	1	1.65

Table 5. Goldstone tests

Spacecraft	DSS	RF frequency	P_C/N_0, dB-Hz	Subcarrier frequency, kHz	Bit rate, bps	Symbol rate, sps	SSNR, dB
Ice	14	S-band	21	1.024	128	256	1
Voyager 1	15	X-band	25	360	600	1200	2
Magellan	15	X-band	48	960	268,800	537,600	3
				22.5	40	80	14

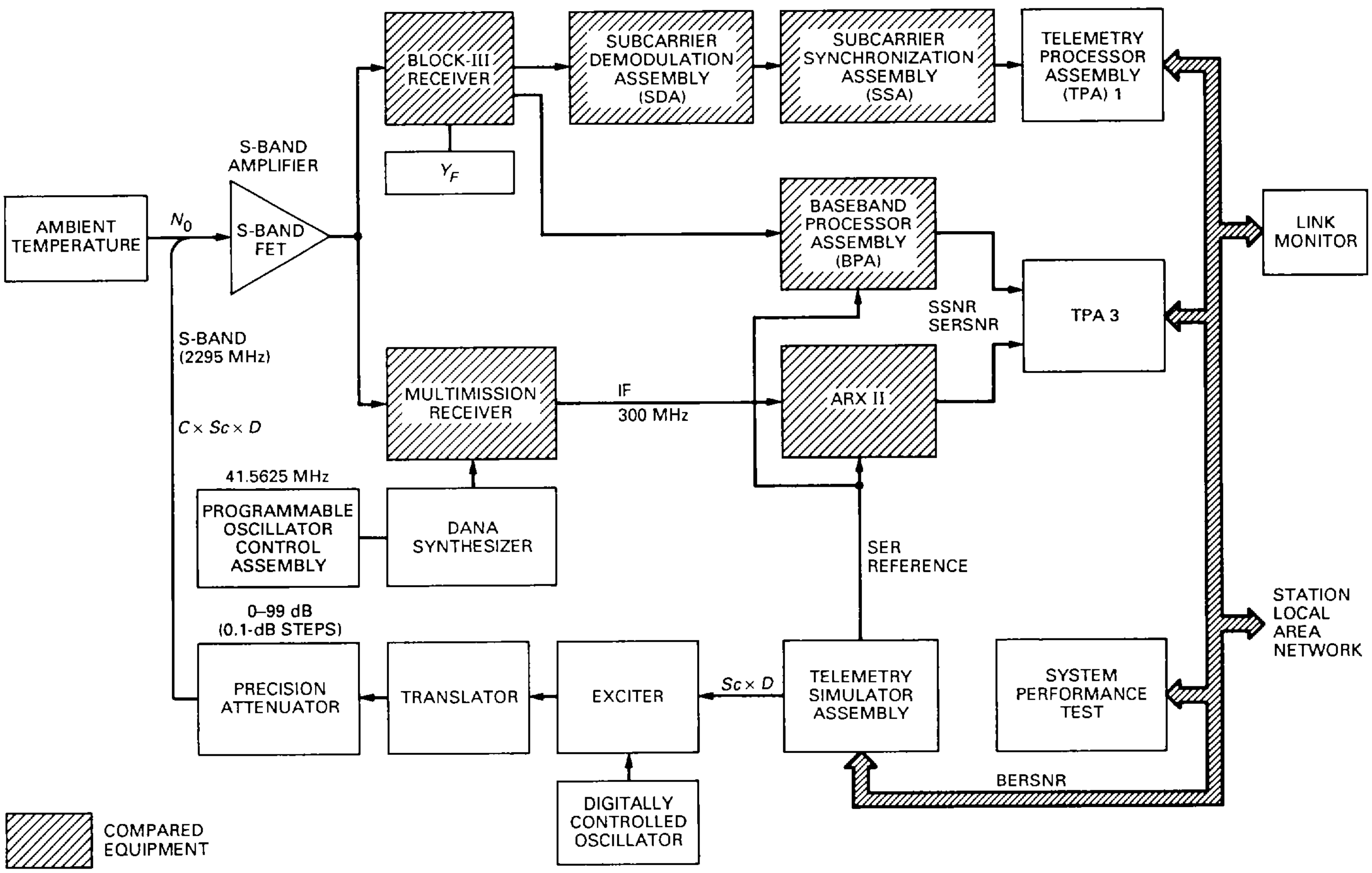

Fig. 1. ARX-II telemetry configuration test at CTA21.

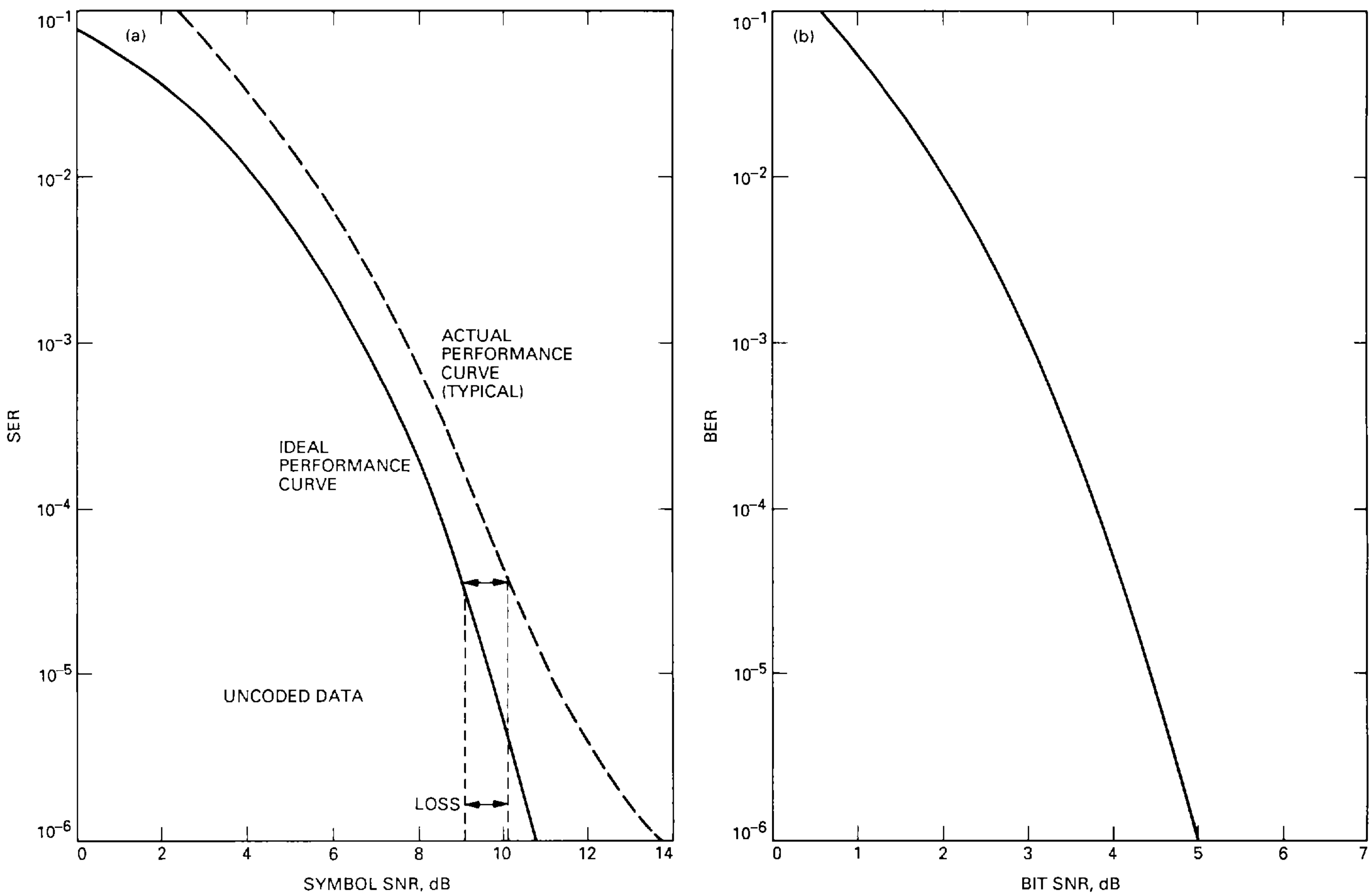

Fig. 2. Signal-to-noise ratio performance for: (a) telemetry loss definition, and (b) the (7,1/2) convolutional code using Viterbi decoding ($Q = 3$ bits).

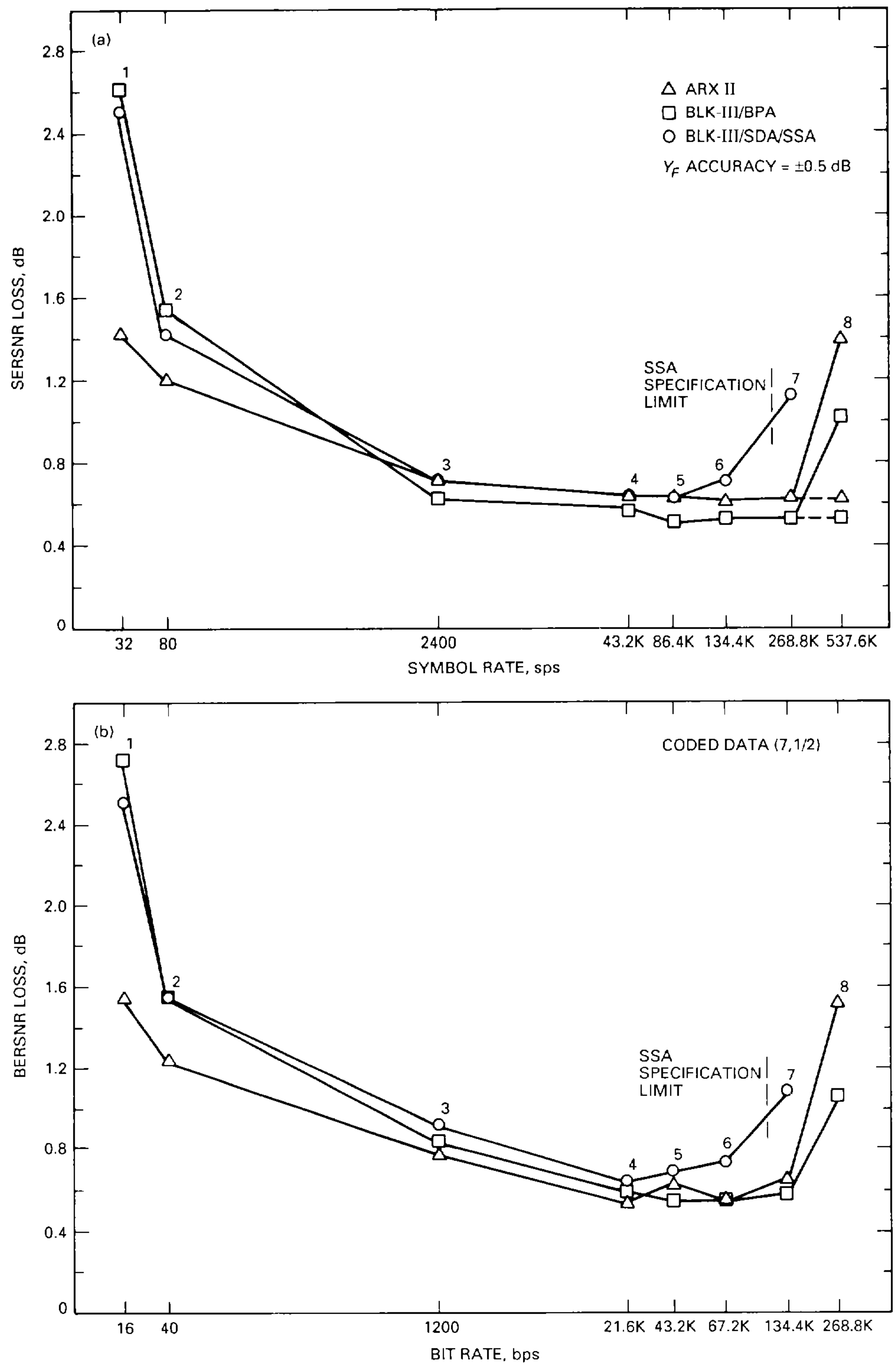

Fig. 3. Signal-to-noise ratio loss for: (a) SER versus symbol rate (SSNR = 1 dB), and (b) BER versus bit rate (BSNR = 4 dB).

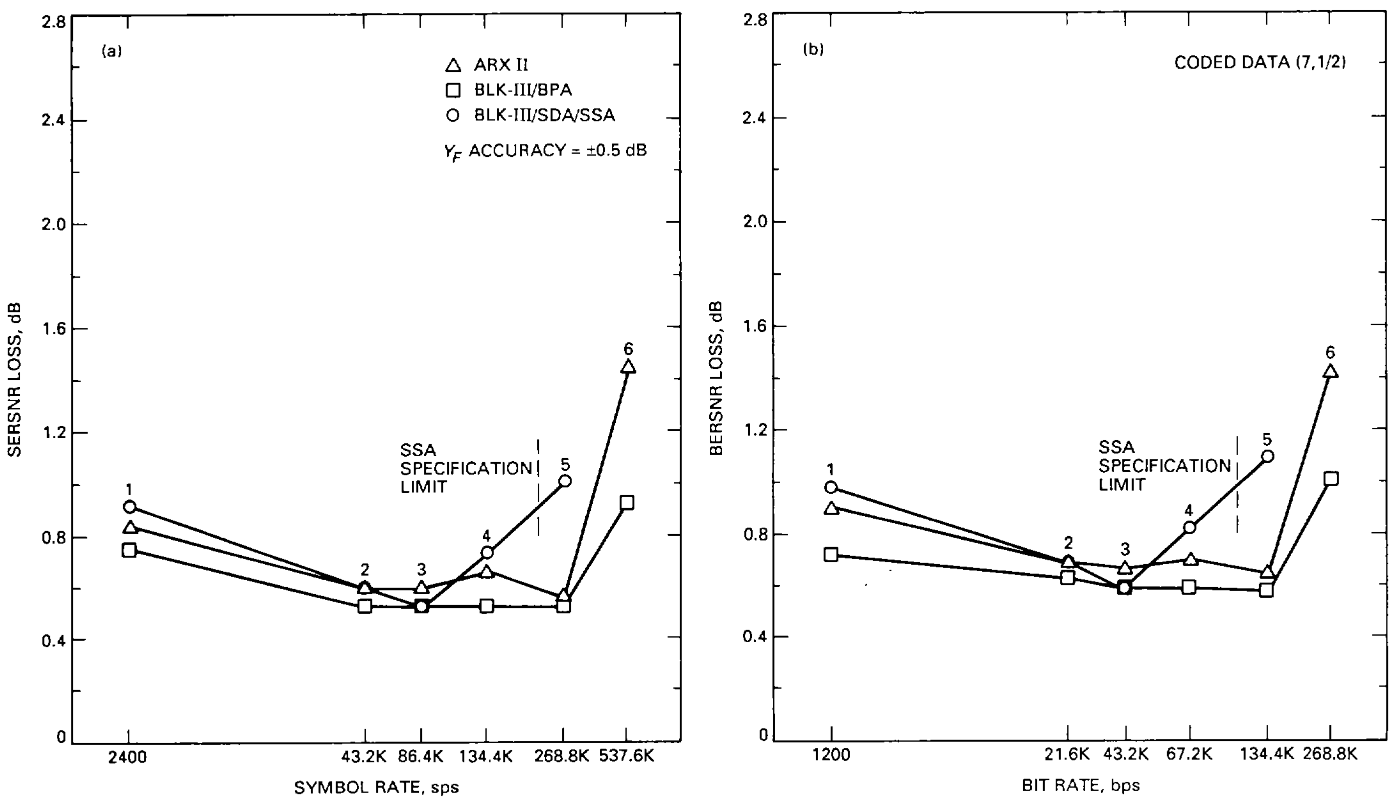

Fig. 4. Signal-to-noise ratio loss for: (a) SER versus symbol rate (SSNR = −1 dB), and (b) BER versus bit rate (BSNR = 2 dB).

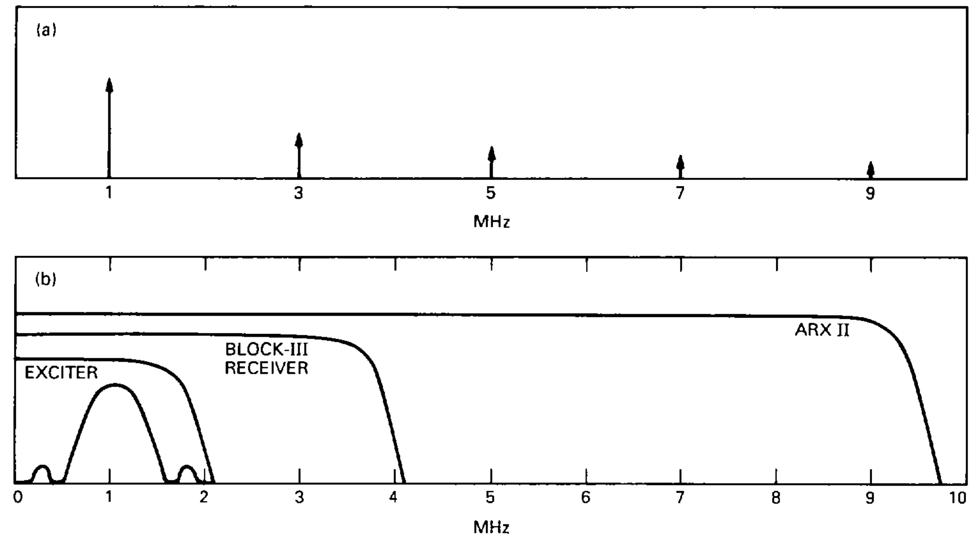

Fig. 5. Comparison of the spectrums of: (a) a 1-MHz square-wave subcarrier, and (b) the exciter, the Block-III Receiver, and the ARX II.

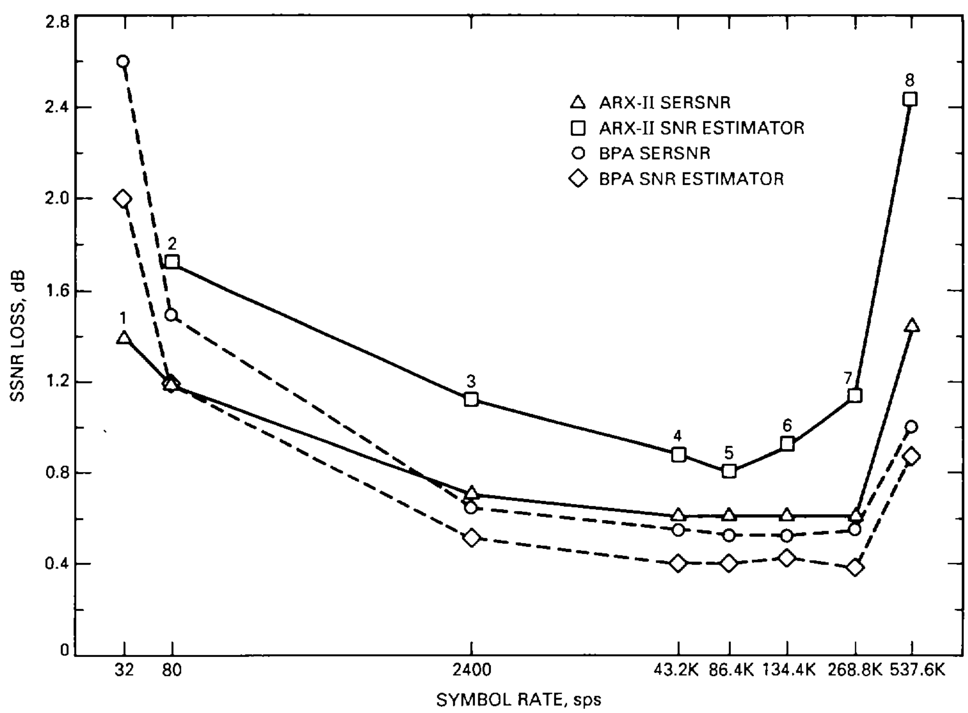

Fig. 6. SSNR and SERSNR losses versus symbol rate (SSNR = 1 dB).

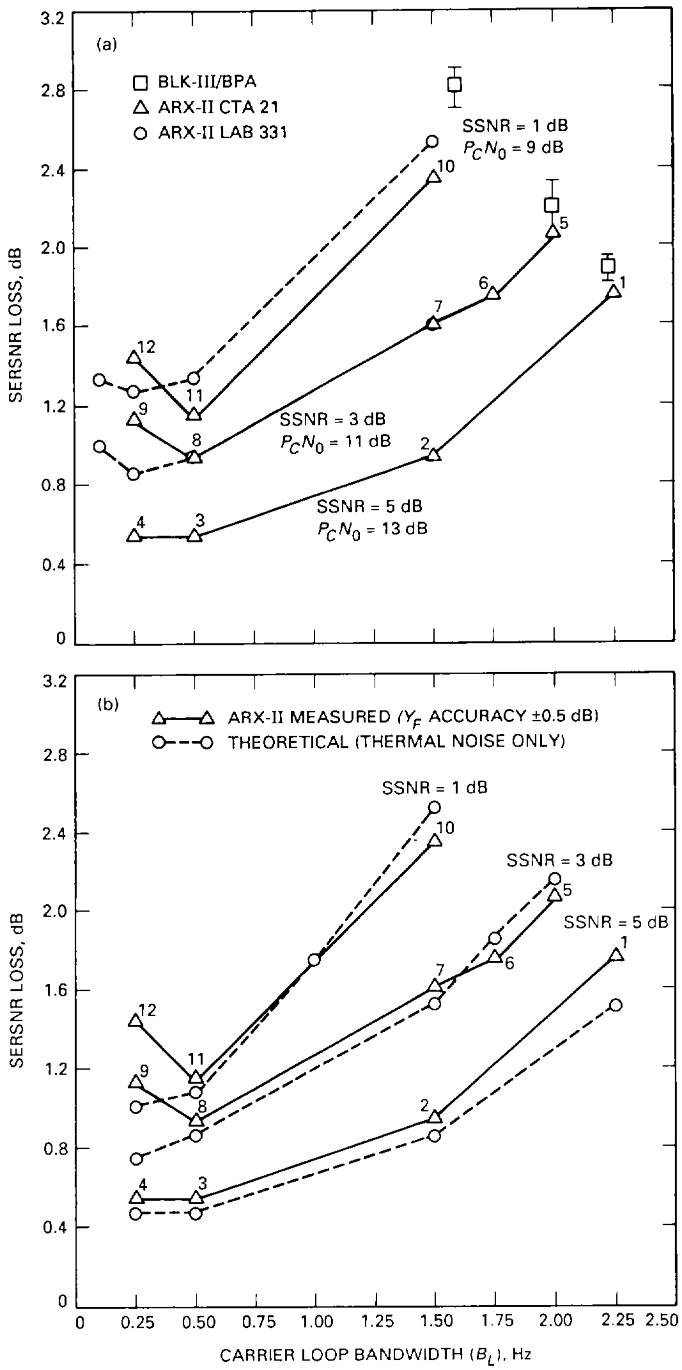

Fig. 7. Comparison of SERSNR losses: (a) versus carrier loop bandwidth, and (b) measured versured theoretical losses for Pioneer 10.

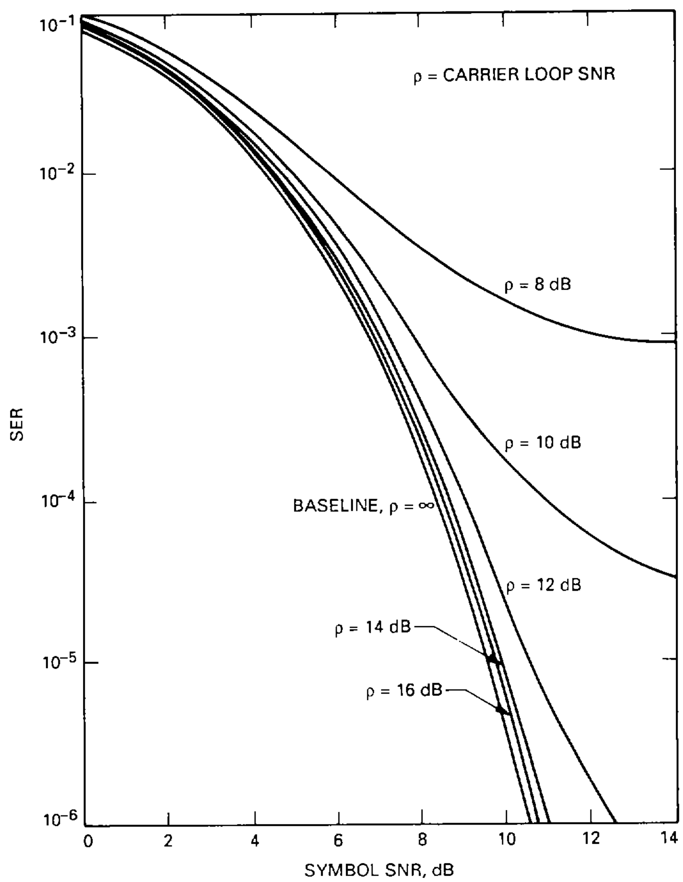

Fig. 8. SER versus symbol SNR in the presence of carrier tracking phase error.

Appendix A
Modulation Index Setup Procedure

This procedure is used to adjust the modulation index in the telemetry tests. Let P_T denote total received signal power. Then the carrier and data powers are given respectively by

$$P_C = P_T \cos^2 \Delta \tag{A-1}$$

$$P_D = P_T \sin^2 \Delta \tag{A-2}$$

where Δ denotes the modulation index in radians. The Block-III Receiver contains an automatic gain control (AGC) loop which maintains a nearly constant carrier power at the receiver's output. The carrier power is measured in a narrow bandwidth, typically a few hertz. The voltage which controls the receiver gain is measured by a digital voltmeter. The modulation index is set up as follows:

(1) The transmitter is turned on with a "very strong" carrier (all modulation off).

(2) The receiver AGC voltage is read (AGC1).

(3) A precision attenuator is added equal to the value of the carrier suppression, which is 20 $\log_{10}(\cos \Delta)$.

(4) The receiver AGC voltage is read (AGC2).

(5) The precision attenuator is adjusted until the AGC voltage is that of step (2), i.e., AGC1.

(6) The modulation is turned on.

(7) The modulation amplitude is adjusted at the TSA until the AGC voltage reads the value of step (4), i.e., AGC2.

Appendix B

Y-Factor Setup Procedure

The *Y*-factor setup procedure is used to adjust the SSNR of the received signal. It is used at both the Telecommunications Development Laboratory (TDL) and in CTA21. The procedure is very straightforward and relies on measuring the total power (signal plus noise) of a pure tone in a known bandwidth and comparing it to the noise power alone in the same bandwidth. The *Y*-factor (in decibels) is defined as

$$Y_F = 10 \log_{10}(1 + 10^{\frac{SNR}{10}}) \qquad \text{(B-1)}$$

where (also in decibels)

$$SNR = (SSNR + 10 \log_{10} R) - (20 \log_{10} \sin \Delta + 10 \log_{10} B) \qquad \text{(B-2)}$$

where R is the symbol rate and B the bandwidth of the *Y*-factor detector and A is an attenuation pad. Small values of SSNR can be precisely calibrated by *Y*-factoring an artificial SSNR which is much higher than the desired SSNR. An "add-pad" is then introduced between the transmitter and the receiver after the procedure is completed. Since the "add-pad" is a discrete-step attenuator, its finite selectable attenuation settings can be accurately calibrated beforehand and it introduces insignificant error to the *Y*-factor technique.

Intuitively, the *Y*-factor is the ratio of signal power plus noise power to the noise power in some bandwidth. It can be expressed as $(N_0B + P_T)/N_0B$ where P_T is the total signal power (typically the carrier power as the *Y*-factor procedure is performed with tones and no modulation). The equipment configuration used for *Y*-factoring is shown in Fig. 1. One of the outputs of the Block-III Receiver is a 50-MHz IF signal with no AGC, which is used in the *Y*-factor procedure. The steps in the calibration are:

(1) Calculate the *Y*-factor for the desired SSNR from Eq. (B-1).

(2) Turn the transmitter off.

(3) With the *Y*-factor attenuator at some reference, measure the power level with a power meter, i.e., measure the noise power in a known bandwidth B.

(4) Increase the *Y*-factor attenuator by the value of the *Y*-factor computed in step (1).

(5) Turn the transmitter on with all modulation off.

(6) Adjust the the RF precision attenuator until the power meter of the *Y*-factor reads the reference level of step (3).

(7) Add an attenuation pad in the precision attenuator, if applicable.

(8) Turn the modulation on.

Basically, the *Y*-factor procedure measures first noise power (N_0B), in the absence of signal, with a power meter. An attenuation exactly equal to the *Y*-factor is added to decrease the power measurement accordingly. When a tone is injected, the power meter (which is measuring signal plus noise) should read exactly N_0B if the signal power is at the right level, i.e., the power meter is reading $N_0B + P_T$ or $N_0B(1 + P_T/N_0B)$ or $N_0B\ Y_F$, but because of the attenuation by Y_F, the reading becomes N_0B. If the signal is not at the right level, the signal level is adjusted with the RF precision attenuator until the power meter reads N_0B. Actually, the *Y*-factor procedure produces the correct P_C/N_0 and, hence, the correct SSNR, since the modulation index was set as in Appendix A.