Telemetry SNR Improvement Using the DSN Advanced Receiver With Results for Pioneer 10

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A series of tracking tests was conducted in the spring of 1987 to demonstrate the reduced tracking threshold and the improved telemetry signal-to-noise-ratio performance of the DSN Advanced Receiver compared to current operational DSN systems. The Pioneer 10 spacecraft, which is now out of the solar system, was tracked on four days. The Advanced Receiver achieved an improvement in telemetry SNR of 1 to 1.5 dB over the operational system. It was demonstrated that the spacecraft carrier signal is stable enough for tracking with a receiver carrier loop bandwidth of 0.5 Hz in the one-way mode and 0.1 Hz in the three-way mode, and that the Advanced Receiver is stable at 0.1 Hz. This reduces tracking threshold by 10 to 15 dB compared to current receivers, which have minimum loop bandwidths of 1 to 3 Hz. Thus, the Advanced Receiver will enable tracking of the Pioneer 10 spacecraft until its power source fails, circa 2000, which would not be possible with current DSN systems.

I. Introduction

The digital Advanced Receiver (ARX) under development for the DSN can track signals that are 10 to 15 dB weaker than the threshold signal levels for current operational DSN receivers, as shown in Section V. It can also improve the telemetry symbol signal-to-noise ratio (SSNR) by 1 to 1.5 dB compared to that achieved with current operational receivers used near their threshold signal levels. This capability can enable the DSN to track the Pioneer 10 spacecraft until its power source fails, circa 2000, which would not be possible with current systems.

To demonstrate this improved performance, a series of tests was conducted in the spring of 1987 using an existing breadboard of the ARX [1]. The ARX tracked the Pioneer 10 spacecraft from the 64-m antenna at DSS 14, Goldstone, California. This spacecraft was used because its carrier signal level is near the threshold for current DSN systems.

The Advanced Receiver achieves its ability to track weak signals by using narrow bandwidth carrier-phase-locked loops obtained by optimizing the loop bandwidth for the specific conditions of carrier phase stability and carrier power to receiver noise spectral density. This optimization was done in near-real time during the tests using a spectral estimation method previously described [2]. The tracking threshold using the ARX is not limited by the stability of the receiver, as is the case for current operational receivers. Instead, the threshold is limited by the stability of the carrier signal received from the spacecraft. Threshold improvements of 10 to 15 dB are thereby achieved.

Besides using optimum carrier loop bandwidths, the Advanced Receiver reduces telemetry losses by realizing narrow bandwidth subcarrier and symbol tracking loops and by using sideband-aided carrier tracking to enhance carrier loop SNR without reducing loop bandwidth [1]. In addition to the theoretical improvements the Advanced Receiver offers over operational systems, realization of all loops and of the symbol-detection-matched filters in one digital system virtually eliminates losses due to biases (dc offsets) and miscalibration.

This article documents the improvements in telemetry symbol signal-to-noise ratio that were achieved during the Pioneer 10 tests. The tests were conducted when the spacecraft was in both the one-way mode and the three-way mode. In the one-way mode, there is no uplink signal from a ground station to the spacecraft; hence the spacecraft oscillator limits carrier phase stability. In the three-way mode, the downlink carrier is phase locked to an uplink carrier transmitted from a ground station other than the receiving station. Three-way tests were conducted with two different Sun–Earth probe (SEP) angles, both of which were small enough so that stability was limited by solar scintillation. Carrier power levels were so weak that the Block IV DSN receiver operated from just above to just below the minimum acceptable margin of 8.5 dB, using the 3-Hz loop bandwidth.

At all SNRs encountered, the Advanced Receiver achieved SSNRs 0.8 to 1.5 dB better than those of the operational DSN system, except when far-from-optimum loop bandwidths were used for experimental purposes, and except on one day. This improvement is in agreement with theory. At the weakest signal levels encountered, at low antenna elevation angles, the ARX had the ability to detect useful telemetry data, whereas the data detected by the standard equipment could not be decoded reliably.

II. Test Description

The Pioneer 10 tracking tests were conducted on days 119, 121, 128, and 140 of 1987 using the 64-m antenna at DSS 14, Goldstone, California. The station configuration is shown in Fig. 1.

The tests were conducted on a noninterference basis with standard Pioneer 10 tracking passes. Data from the standard tracks were used to compare results. The standard configuration for Pioneer 10 uses a Block IV receiver with a loop bandwidth of $2B_{LO}$ = 3 Hz. The 1-Hz loop bandwidth available at 2.3 GHz (S-band) on the Block IV receiver was not used at any time during the tests. The receiver output goes to a type A telemetry string consisting of a Subcarrier Demodulator Assembly (SDA), a Symbol Synchronizer Assembly (SSA), and a Telemetry Processor Assembly (TPA) computer. Type B telemetry strings with Baseband Assembly (BBA) Demodulator Synchronizer Assemblies (DSAs) are not used for Pioneer 10 because of the low symbol rate, 64 symb/s. The SSA and TPA calculate estimates of symbol signal-to-noise ratio (SSNR) using the moment method with unbiasing [3],[4]. These estimates are displayed on the Central Monitor and Control terminal and can be logged and a hard copy obtained. This hard copy was obtained on all days except the first day of tests. The ARX used the unbiased split-symbol SSNR estimator [1],[5], which is statistically more accurate than the moment method. The results of the two methods are directly comparable, since both are unbiased.

The Advanced Receiver, as used in the Pioneer 10 tests, requires the spacecraft signal to be open-loop down-converted to an intermediate frequency (IF), with the carrier at 53 MHz ± 0.5 MHz. This was done using the second Block IV receiver at the station, operated in the open loop mode. An IF output of the Block IV receiver was used as the input to the ARX. The ARX recorded its unbiased estimates of SSNR onto floppy disks, which were used in post-test processing to compare performance with that of the standard configuration. The sequences of outputs of the ARX residual carrier phase detector were also logged on the disks. Each day's pass was divided into several tests or cases. The phase data from each test were processed in near-real time on a separate microprocessor to obtain power spectral densities of the phase processes and estimates of the optimum loop bandwidths. The optimum loop bandwidth estimates were used to select parameters for the succeeding tests.

III. Theoretical Performance

This section compares the theoretical performance of the ARX with that of the standard station configuration. Performance is compared in terms of the theoretical loss in average telemetry symbol SNR due to phase error in the carrier, subcarrier, and symbol tracking loops. Curves are presented for various carrier loop configurations for the ARX, taking into account the effects of phase noise from the Pioneer 10 oscillator. This is the dominant instability in all of the tests when the spacecraft is in the one-way mode. Similar results can be obtained for the three-way mode [2]. For the three-way data in these tests, stability was limited by solar scintillation, but the stability was better than that of the Pioneer 10 oscillator.

Figure 2 shows the theoretical loss in SSNR for the standard DSN system and for the ARX, for the one-way data, as functions of input SSNR. To establish a relationship between SSNR and the ratio of carrier power to noise density, note that the modulation index is 65.9 degrees, so the data power, P_d, is 7 dB more than the carrier power, P_c. This, together with the symbol rate of 64 symb/s, results in a carrier-power-to-noise spectral density, P_c/N_0 (dB-Hz), which is 11 dB more than the SSNR. The oscillator phase noise spectral density was modeled [2] using the measured phase data as $S(f) = S_1/f^3$ rad^2/Hz with $S(1)$ = 0.0012 rad^2/Hz (on each side of the carrier). The curves shown are the sum of the losses in the carrier, subcarrier, and symbol tracking loops.

A. DSN System Losses

For the DSN system, oscillator noise was neglected, because the effect is negligible with the 3-Hz loop. Carrier tracking loss was estimated as $-10 \log_{10} (1 - 1/\rho_L)$ (dB).[1] Theoretical radio loss ranged from 0.75 dB at an input SSNR of 3 to 1.2 dB at an SSNR of 0 dB. At 3 dB, P_c/N_0 = 14 dB-Hz and the carrier margin in the 3-Hz loop is 8.2 dB, slightly below the recommended minimum margin of 8.5 dB. In Fig. 2, the loss curve for the DSN system is shown as a broken line for SNRs below this level, because cycle slipping occurs and the radio loss formula is not accurate.

The SDA was operated in the narrow bandwidth mode. Losses were obtained by interpolation to the symbol rate of 64 symb/s.[2] Subcarrier losses ranged from 0.30 dB at an input SSNR of 3 dB to 0.36 dB at 0 dB.

The SSA was operated in the medium range, narrow bandwidth mode. The losses[3] range from 0.06 to 0.09 dB at SSNRs of 3 to 0 dB.

B. Advanced Receiver Losses

Losses in the ARX arise from the carrier phase noise due to the Pioneer 10 oscillator as well as from the receiver noise. Different carrier loop bandwidths were used, and sideband aiding was used in some cases. In Fig. 2, the residual-carrier-only cases and the sideband-aided cases are identified by RC and SA, respectively, followed by the carrier loop bandwidth in Hertz. The subcarrier and symbol loop bandwidths were always 0.01 Hz.

The receiver noise contribution to carrier (radio) loss is calculated as $-10 \log_{10} (1 - 1/\rho_L)$, where ρ_L is the loop SNR. For residual carrier tracking, the loop SNR is $(P_c/N_0)/B_L$, where P_c/N_0 is the carrier-to-noise-density ratio and B_L is the loop bandwidth in Hertz. Sideband aiding with optimum weighting increases the loop SNR by a factor of $1 + (P_d/P_c)S_L$, where S_L is the squaring loss factor, $1/(1 + 1/(2\,\text{SSNR}))$. At an SSNR of 3 dB, for example, the radio loss due to receiver noise is 0.17 dB with residual carrier tracking, and 0.03 dB with sideband aiding.

The subcarrier loss is determined from the subcarrier loop SNR. This is $\rho_{sc} = (P_d/N_0B_{sc})(2/\pi)^2 S_L$, where B_{sc} = 0.01 Hz is the subcarrier loop bandwidth. The resulting loss is then approximately $4.4(\rho_{sc})^{-1/2}$ dB. Subcarrier loss is often significant because it decreases only as the square root of loop SNR, not as loop SNR. This is why the loss is significant in the SDA. In the ARX, the 0.01-Hz loop bandwidth is narrow enough to achieve loop SNRs of 35 to 32 dB. Consequently, the loss was only 0.07 to 0.11 dB at SSNRs of 3 to 0 dB, respectively. The ARX subcarrier loop thus improves SSNR by slightly over 0.2 dB compared to the SDA.

The symbol synchronization loss is calculated similarly. The loop is a transition tracking loop with a bandwidth of 0.01 Hz and a window width of $W = 1/8$ [6]. For the Pioneer tests, the loop SNR varied from 36 to 34 dB, and the loss varied from under 0.02 to just over 0.02 dB.

Figure 2 shows the losses for residual carrier loops with bandwidths of 0.25, 0.5, 0.7, and 1.0 Hz. The 0.7-Hz loop is best at the lowest SSNRs, and the 1.0-Hz loop is best at the higher SSNRs. This illustrates the optimization of carrier loop bandwidth. The losses are much less than for the DSN system except for the 0.25-Hz bandwidth, which is much too narrow for the oscillator noise. This bandwidth was used only so that its effect could be measured. For the highest SSNR encountered, 3 dB, the ARX with a residual carrier 1.0-Hz loop has 0.76 dB less theoretical loss than the DSN system.

When using sideband aiding, the best loop bandwidth is wider than that for a residual carrier loop. This is because sideband aiding reduces the receiver noise component of phase error for a given bandwidth, and optimization results in a wider bandwidth to reduce the oscillator phase noise contribution. The best bandwidth for the conditions encountered is approximately 1.3 Hz. At an SSNR of 3 dB, sideband aiding reduces the loss by 0.15 dB relative to the 1.0-Hz residual carrier loop. Total theoretical losses are only 0.19 dB

[1] ρ_L, the carrier loop SNR, was taken from Fig. 1, Section TLM-20, of the *Deep Space Network/Flight Project Interface Design Handbook, Volume I: Existing DSN Capabilities*, JPL Internal Document 810-5, Rev. D, Jet Propulsion Laboratory, Pasadena, California.

[2] As given in Fig. 6 of Section TLM-30 (PC) (Rev. A) of JPL Internal Document 810-5, Rev. D, vol. II, Jet Propulsion Laboratory, Pasadena, California.

[3] Losses were obtained from Fig. 18 of Section TLM-30 (PC) (Rev. A) of JPL Internal Document 810-5, Rev. D, vol. II, Jet Propulsion Laboratory, Pasadena, California.

for the best ARX configuration compared to 1.11 dB for the standard DSN system, an improvement of 0.92 dB.

Although the theoretical improvement in SSNR due to sideband aiding was only 0.1 to 0.15 dB in the Pioneer 10 tests, it can be much more significant in some cases. In the Pioneer tests, there was not much room for improvement over the residual carrier tracking loop. This is because the carrier phase was stable enough that optimum bandwidth residual carrier loops yielded small losses. This would not be the case at lower SNRs and the same phase stability. For example, suppose the optimum residual carrier loop had a radio loss of 0.8 dB. Sideband aiding could then reduce the loss typically by 0.6 dB, depending on modulation index and SSNR.

IV. Results

The data collected on the four days of tracking indicate that the ARX provides an improvement in received symbol SNR of 0.8 to 1.5 dB under all signal conditions encountered. In certain cases, the ARX was able to track and produce decodable telemetry when the Block IV was unable to do so.

For each day, the recovered symbol SNR is plotted against time for the ARX and the standard station configuration in Figs. 3 through 6. The ARX carrier tracking parameters were changed several times each day in order to provide a range of data for analysis. Each set of parameters defined one test. During each test, the sequence of outputs of the residual carrier phase detector was recorded onto a floppy disk. After each test, while the next test was in progress, the phase data were processed on an auxiliary computer, obtaining power spectral density plots and estimates of the contributions to phase error variance of receiver noise and of phase process noise [2]. The phase variance estimates were then used to estimate the optimum loop bandwidths for planning parameters of future tests.

A case-by-case summary of ARX carrier loop parameters, the symbol SNRs obtained by the ARX and by the standard station, and the gain in SSNR achieved by the ARX is given in Table 1. The subcarrier and symbol loop bandwidths were fixed at 0.01 Hz, except for the first four cases on DOY 140, when they were 0.2 Hz. The subcarrier frequency was 32.765 kHz. The telemetry was received at 32 b/s, for a symbol rate of 64 symb/s.

On each day, there is a general trend of decreasing SNR as a function of time due to the decrease in antenna elevation angle. On DOYs 119 and 121, the spacecraft was transmitting in the one-way mode. On DOYs 128 and 140, both the one-way and three-way modes were used, as indicated in Table 1 and in Figs. 5 and 6.

The following paragraphs discuss the operations, ARX configurations, and results on a day-by-day basis.

A. DOY 119

The first day of Pioneer 10 tracking was DOY 119. Tracking was one way, and there was no a priori information available as to the stability of the spacecraft oscillator or the minimum carrier loop bandwidth which could be used. The objectives of this day's tests were to determine the approximate optimum and minimum residual carrier loop bandwidths by tracking with loops of varying bandwidths, and to test sideband aiding.

As on all days, the ARX logged its measurements of SSNR on floppy disks. However, on this day only, the operations crew was not asked to log the SSA measurements of SSNR. Instead, a partial log of SDA SSNR measurements was made manually from observing the Complex Monitor and Control (CMC) display. Thus the comparison of SSNR results for DOY 119, Fig. 3, is not as accurate as those for the succeeding days.

Tests were run with a variety of configurations. The first case was residual carrier tracking with a 1.0-Hz loop bandwidth, and the second case was the same bandwidth with sideband aiding. Both achieved SSNRs approximately 0.9 dB better than the standard station. While performing the spectral analysis, we ran the third case with a 0.25-Hz residual carrier loop. Although able to track, the 0.25-Hz loop resulted in a 0.2-dB decrease in recovered SSNR compared with the standard station configuration. The near-real-time analysis indicated a bandwidth of 0.7 to 0.9 Hz to be optimum, corroborating the poor performance of the 0.25-Hz loop. This poor performance is attributable to the fact that the loop bandwidth is too narrow to track the phase process noise of the Pioneer 10 oscillator.

Cases 4, 5, 8, and 9 used residual carrier loops of bandwidths of 0.7, 0.5, 1.0, and 1.0 Hz, respectively. Cases 6 and 7 used 2.0- and 1.0-Hz sideband-aided loops. All achieved SSNRs 0.7 to 1.3 dB better than the standard station.

B. DOY 121

On this day, Fig. 4, we repeated the activities of DOY 119 with emphasis on improving the recording of data. The station personnel produced a hard copy of the station log of recovered SSNRs. On this day, the improvement in SSNR with the Advanced Receiver was typically 0.3 dB. The curves in Fig. 4 are not completely distinguishable; thus, Table 1 should be used to compare results. It is not known why the improvement was less on this day than on the other days. For case 3, there was no improvement relative to the standard station, because the loop bandwidth of 0.5 Hz was below optimum.

Near-real-time analysis indicated that the best performance at low SNRs could be achieved with a 1.3-Hz sideband-aided loop, with a resulting loss of approximately 0.25 dB. It was the intention to use this minimum loss configuration for the final, low-elevation-angle case to emphasize the improvement possible with the ARX. Unfortunately, an error in operator control of the ARX resulted in the use of a 1.3-Hz residual carrier loop, which achieved an improvement relative to the standard station of approximately 0.3 dB.

A series of acquisition tests was run between cases 4 and 5. Track was repeatedly interrupted, and all three loops were reacquired. The fast carrier acquisition method was used, with a sampling rate of 64 samples per second, using 64-point FFTs and accumulating four successive FFT outputs noncoherently, i.e., for four seconds. The required carrier frequency prediction accuracy was ±32 Hz, as limited by the sampling rate. The limitation of 64 samples per second was due to the particular software implementation, wherein the rate cannot exceed the symbol rate. This limitation will be removed in the future. Approximately ten reacquisitions were made, with various frequency errors up to ±25 Hz. Symbol SNR was monitored every 20 seconds, the averaging and display update time, to determine lock. All acquisitions were successful, with acquisition of all loops and good SSNR measurements occurring within one minute.

C. DOY 127/128

This day afforded the first opportunity to track the spacecraft in the three-way mode. It was anticipated that narrower loop bandwidths could be used than for the one-way mode, since the transmitted carrier reference would be a hydrogen maser rather than the spacecraft oscillator. The results are shown in Fig. 5.

For the first half of the pass, cases 1 through 6, the spacecraft transmitted in the one-way mode. Data collected here are consistent with earlier results. The optimum bandwidth was 0.9 Hz, yielding total theoretical system losses under 0.5 dB. Improvement over the standard station was 0.8 to 1.1 dB, except for case 3, for which the loop bandwidth was too wide and the improvement was only 0.6 dB.

Transmission changed to the three-way mode at 0145, during case 7, and the receiver lost lock. The SSNR estimates for this case should not be used for performance comparisons. After acquiring the three-way transmissions, as expected, the resulting decrease in carrier phase noise allowed for tracking with narrower loop bandwidths. Bandwidths of 0.5, 0.25, and 0.125 Hz were used, with a bandwidth of 0.3 Hz determined as optimum. Performance improvements relative to the standard station were 1.0 to 1.3 dB.

D. DOY 140

DOY 140 provided another chance to study the differences between one-way and three-way performance. The first three cases were one-way transmissions, and the results again agreed with the previous data. The analysis indicated an optimum bandwidth of 1.0 Hz for this day.

Transmission changed to the three-way mode at 2320. The loop bandwidth was again varied, and the optimum bandwidth was determined to be 0.75 Hz. At the time, this value was thought to be surprisingly large. The analysis was repeated several times and yielded consistent results. Further analysis conducted after the experiment resulted in the realization that on this day, the spacecraft was fairly close to the Sun. Specifically, the Sun–Earth probe (SEP) angle was 12 degrees on DOY 140 and 24 degrees on DOY 128. When the SEP angle is small, the solar corona and solar winds affect the phase stability of the received carrier. Even though a much more stable carrier phase was expected, the ARX was able to track and measure the noisy phase process so that the carrier loop bandwidth could be optimized in near-real time. Performance improvements relative to the standard station were as much as 1.5 dB at low elevation angles.

V. Threshold Improvement

Figure 7 illustrates the carrier threshold improvement which is achievable by loop bandwidth optimization. The optimum carrier loop bandwidth (left-hand ordinate) for threshold tracking is shown as a function of phase process noise spectral density for oscillator phase noise and for solar scintillation-limited phase noise. Optimum loop bandwidth is defined as the loop bandwidth which results in a phase error variance of 0.2 rad^2 at the lowest P_c/N_0. Optimization at this phase error variance was chosen because this is the variance for a phase-locked loop with no process noise and a loop SNR of 7 dB using linear theory. Under these conditions, phase-locked loops slip cycles infrequently.

The right-hand ordinate shows the minimum or threshold carrier power to receiver noise spectral density required for adequate telemetry performance. The minimum P_c/N_0 for adequate margin was taken as the level which would achieve a 10-dB loop SNR. This is slightly more conservative than the approximate loop SNR of 9 dB required to achieve the 0.2-rad^2 phase error variance at the point of optimization. This conservative approach is taken because of the lack of experimental data under threshold conditions.

The 1-Hz, 3-Hz, 10-Hz, and 30-Hz loop bandwidths of the DSN receivers are indicated along the left-hand axis of Fig. 7. Note that the 1-Hz bandwidth is available only on the Block IV receivers and only at S-band, and that it is not routinely used because of phase instabilities, static phase errors due to Earth-rate Doppler rate, and operational difficulties in compensating for Doppler rate. Note also that the DSN loops are specified in terms of $2B_{LO}$ at a "threshold" SNR, but that the actual one-sided loop bandwidth is approximately equal to the specified bandwidth for the range of loop SNRs of interest here. Along the right-hand axis is indicated the range of P_c/N_0 that occurred in the Pioneer 10 tests. The performance of the DSN 3-Hz loops degrades rapidly as P_c/N_0 decreases below 13 dB-Hz.

Two phase-process-noise spectral shapes are considered in Fig. 7: the $1/f^3$ shape characteristic of oscillator noise at low frequencies, and a $1/f^{8/3}$ shape assumed for phase noise induced by solar scintillation. In the one-way mode, we observed a phase spectral density due to the Pioneer 10 oscillator of approximately −30 dBc/Hz, 1 Hz from the carrier. As indicated, the loop bandwidth which optimizes tracking threshold is 0.5 Hz, and the minimum carrier SNR for adequate telemetry is 7 dB-Hz. This is 6.2 dB lower than the 13.2 dB-Hz level required to have the minimum recommended carrier margin with a 3-Hz bandwidth DSN receiver loop. (Although we tracked well with a 0.5-Hz loop during the tests, performance was better with a 1-Hz loop, because the carrier SNR was higher than the threshold SNR for the actual phase noise density.)

In the three-way mode, we observed spectral levels due to solar scintillation of approximately −30 dB/Hz at an SEP of 12 degrees, and −40 dB/Hz at 24 degrees. The corresponding threshold bandwidths are approximately 0.4 Hz and 0.08 Hz, and the threshold carrier SNRs are approximately 6 dB-Hz and −1 dB-Hz. These thresholds are 7 dB and 14 dB lower than for the 3-Hz loops of the current DSN receivers. This illustrates that threshold improvements of 10 to 15 dB over the current receivers are useful, and that they are achieved using the Advanced Receiver.

Finally, it was noted that both the ARX residual carrier loops and the operational receivers resulted in radio losses of approximately 0.8 dB under the conditions defined here as threshold. The ARX can usually reduce this loss to approximately 0.2 dB by using sideband aiding.

VI. Conclusions

These Pioneer 10 tracking tests show that the Advanced Receiver achieves significant performance improvements over current operational DSN systems. The threshold for acceptable carrier tracking is reduced by 10 to 15 dB, and the telemetry symbol SNR is improved by 1 to 1.5 dB when operating near threshold.

During the tests, the input SSNRs varied from 3 dB when the DSS antenna was at high elevation angles to 0 dB at low elevation angles, and the corresponding carrier power to noise spectral densities varied from 14 to 11 dB-Hz. The theoretical improvement in SSNR achieved by the ARX is 0.92 dB at an SSNR of 3 dB, when the ARX uses sideband aiding and a 1.3 Hz carrier loop bandwidth. The theoretical improvement increases to approximately 1.3 dB at an SSNR of 0 dB.

The experimental results confirmed the theory. At high elevation angles and input SSNRs of 2 to 3 dB, the ARX performed from 0.7 to 1.1 dB better than the standard DSN system except when far-from-optimum loop bandwidths were deliberately used. The improvement was 1.0 to 1.5 dB at SSNRs of approximately 1 dB.

The improvement at low SSNRs is most important because decoding is unreliable below approximately 0 dB, at the symbol detector output. For the last hour or so of each pass, the ARX achieved SSNRs above 0 dB, i.e., decodable data, whereas the standard station obtained SSNRs below 0 dB.

Finally, use of the Advanced Receiver can extend the tracking range for Pioneer 10 by 1 to 1.5 dB at the current telemetry rate of 32 b/s, compared to use of the Block IV receiver with a 3-Hz loop. It can extend the tracking range by an additional 3 dB by reducing threshold, thereby enabling good carrier tracking when the total signal is so weak that the data rate is reduced to 16 b/s. This can enable tracking until the spacecraft power source fails, near the turn of the century.

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Table 1. Case-by-case results

DOY	Case	Name	Carrier loop		Way	Symbol SNR, dB		
			BL	RC/SA		ARX	STN	Gain
118	1	RC1HZ	1.0	RC	1	2.64	1.71	0.93
118	2	SA1HZ	1.0	SA	1	2.70	1.78	0.92
118	3	RCQHZ	0.25	RC	1	1.17	1.34	−0.17
118	4	RC700	0.7	RC	1	2.27	0.98	1.29
118	5	RC500	0.5	RC	1	1.83	1.09	0.74
118	6	SA2HZ	2.0	SA	1	1.79	0.51	1.28
118	7	SADEWT	1.0	SA	1	1.09	−0.22	1.31
118	8	RC1HZ2	1.0	RC	1	0.61	−0.61	1.22
118	9	RC1HZ3	1.0	RC	1	−0.02	−0.87	0.85
121	1	TRKTST1	1.0	RC	1	2.70	2.41	0.29
121	2	TRKTST2	1.0	SA	1	2.78	2.35	0.43
121	3	TRKTST3	0.5	RC	1	2.30	2.35	−0.05
121	4	TRKTST4	0.5	SA	1	2.30	1.97	0.33
121	5	PNSET(A)	1.3	RC	1	1.10	0.69	0.41
						0.64	0.28	0.36
						0.22	0.04	0.18
127	1	RC091271	0.9	RC	1	2.85	1.93	0.92
127	2	RC05128	0.5	RC	1	2.80	2.02	0.78
127	3	RC2127	2.0	RC	1	2.59	2.01	0.58
127	4	RC091272	0.9	RC	1	2.72	1.85	0.87
127	5	SA15127	1.5	SA	1	2.71	1.62	1.09
127	6	RC091283	0.9	RC	1	2.53	1.63	0.90
128	7	1WAY3WAY*	2.0	RC	1/3*	1.03*	1.38*	–
128	8	RC051282	0.5	RC	3	1.40	0.35	1.05
128	9	RC25128	0.25	RC	3	1.41	0.33	1.08
128	10	RC125128	0.125	RC	3	1.16	−0.11	1.27
128	11	RC251282	0.25	RC	3	0.30	−0.73	1.03
140	1	RC051401	0.5	RC	1	2.01	1.30	0.71
140	2	RC2140	2.0	RC	1	2.09	1.37	0.72
140	3	RC08140	0.8	RC	1	2.49	1.49	1.00
140	4	R01140	1.0	RC	3	1.97	0.78	1.19
140	5	RC75140	0.75	RC	3	1.87	0.78	1.09
140	6	RC051412	0.5	RC	3	1.56	0.62	0.94
141	7	RC25141	0.25	RC	3	1.16	−0.23	1.39
141	8	RC38141	0.37	RC	3	1.04	0.01	1.03
141	9	SA09141	0.9	SA	3	0.82	−0.70	1.52

*Lost lock when signal changed to three-way.

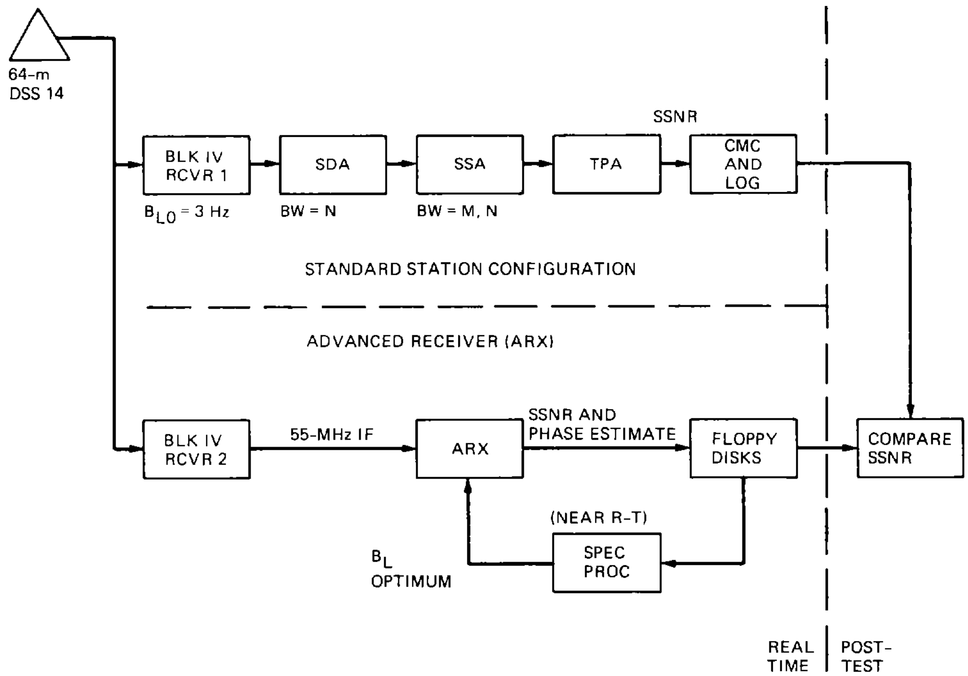

Fig. 1. Test configuration

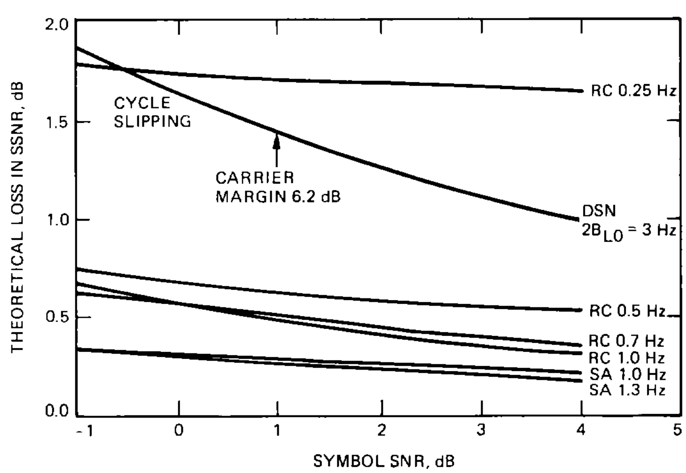

Fig. 2. Theoretical losses for the DSN system and the advanced receiver for the Pioneer 10 oscillator one-way mode (RC = residual carrier; SA = sideband aided)

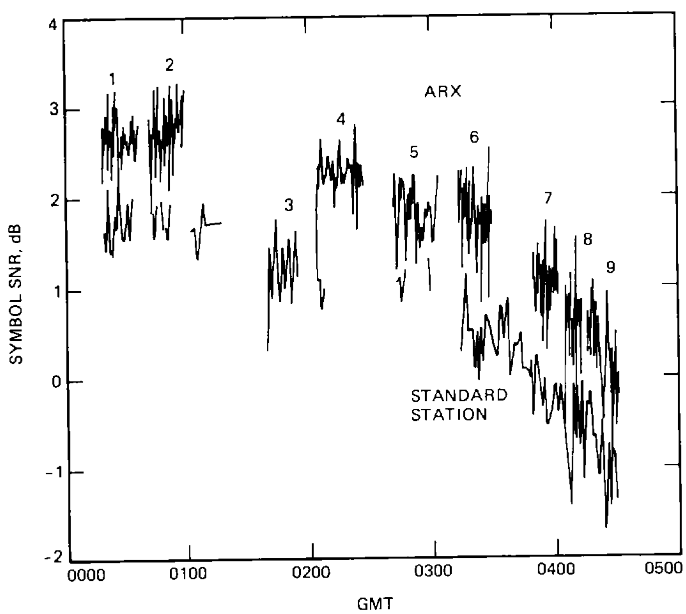

Fig. 3. Symbol SNR versus time, DOY 119

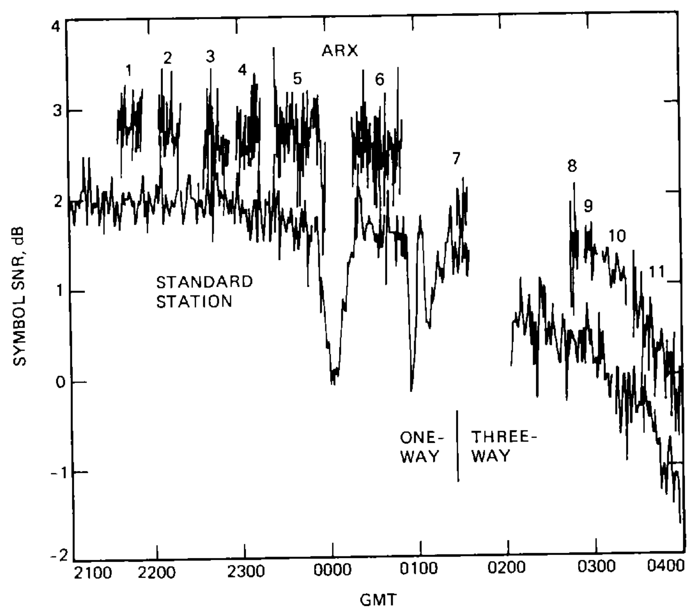

Fig. 5. Symbol SNR versus time, DOY 128

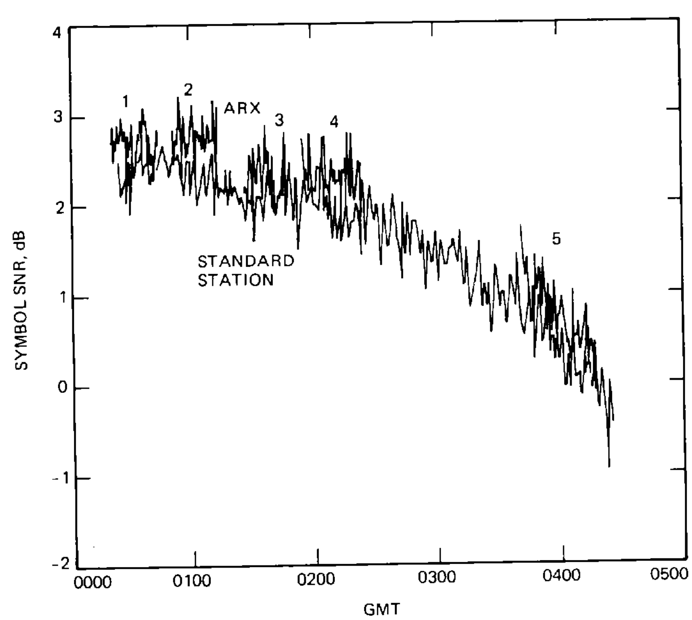

Fig. 4. Symbol SNR versus time, DOY 121

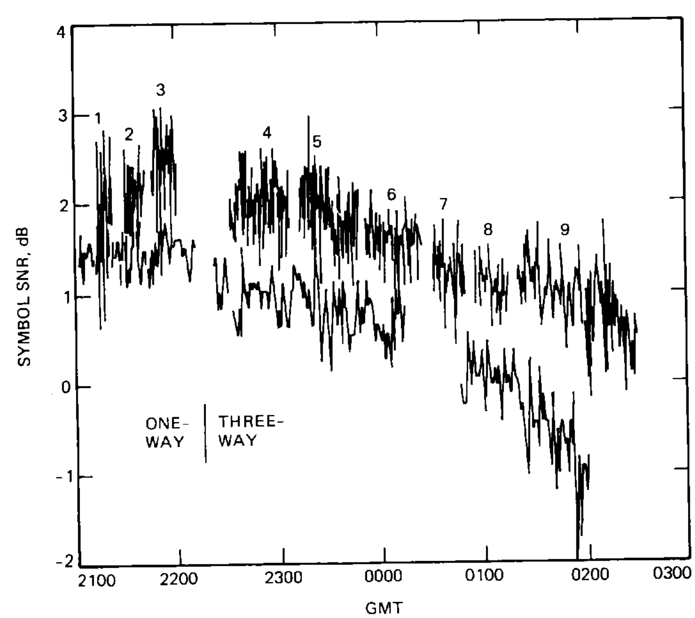

Fig. 6. Symbol SNR versus time, DOY 140

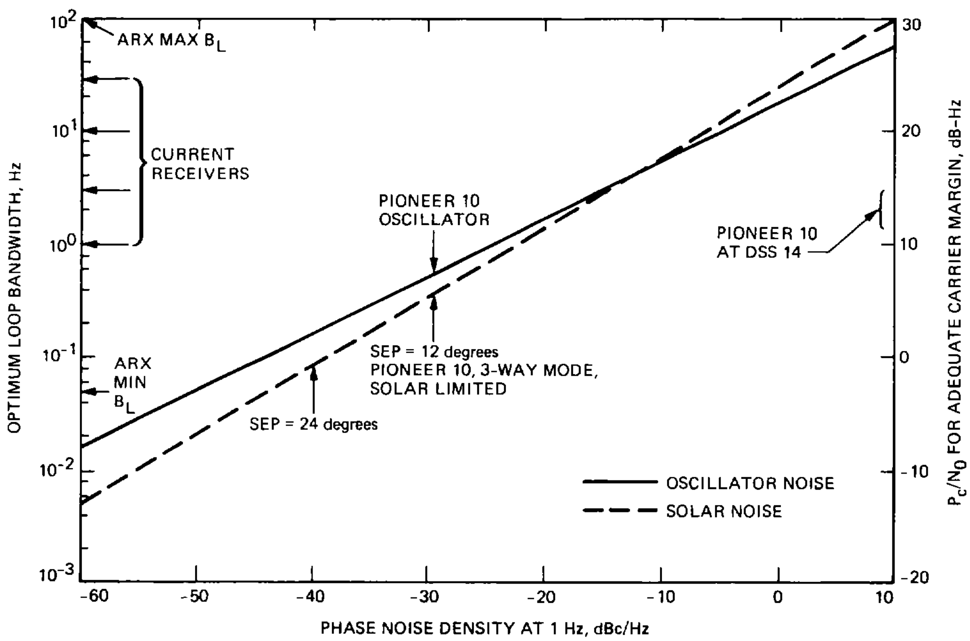

Fig. 7. Carrier loop bandwidth to optimize threshold versus phase noise density