Laboratory and Flight Performance of the Mars Pathfinder (15,1/6) Convolutionally Encoded Telemetry Link

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Compatibility between the Mars Pathfinder spacecraft-generated (15,1/6) convolutional code and the DSN Block III maximum-likelihood convolutional decoder has been demonstrated in the laboratory at all spacecraft data rates. Laboratory tests of the (15,1/6) code (unconcatenated) have found it to be superior to that of the (7,1/2) convolutional code. At 20 bps, the performance gain of the (15,1/6) code over that of the (7,1/2) code is 1.5 dB, and at 1185 to 11,060 bps the performance gain is over 2 dB at a threshold of 5×10^{-3} bit-error rate. In addition, the Mars Pathfinder project has successfully completed a test campaign to measure the in-flight performance of the (15,1/6) convolutional code concatenated with the Reed–Solomon code. It has been found to match the laboratory tests performed prior to launch.

I. Introduction

The Mars Pathfinder project will be the first interplanetary mission to use the constraint length 15 rate 1/6 convolutional code [1] to accomplish its mission objectives. Although the (15,1/6) code was never the baseline design for Mars Pathfinder mission communications needs, the project inherited the code when it chose to use a Cassini-derived telemetry modulation unit. To characterize the performance of this previously untested code, the project initiated a two-part test campaign to verify that the theoretical performance was achievable with the spacecraft hardware and the DSN Block III maximum-likelihood convolutional decoder (B3MCD). Part one of the testing was performed in October and November 1996 at Kennedy Space Center. Part two of the testing took place in January 1997 with the spacecraft en route to Mars. The laboratory configuration tested the (15,1/6) code only. In flight, Mars Pathfinder uses a concatenated inner (15,16) convolutional code and outer Reed–Solomon (252,220) code with interleaving depth 5.

Two important characteristics of the coded link were examined in detail, namely the link threshold and the node synchronization time of the B3MCD. The link threshold was measured at each Mars Pathfinder operational data rate to ensure that the (15,1/6) code exhibited the anticipated gain over the NASA standard (7,1/2) code. The node synchronization time of the B3MCD was of great interest to the Pathfinder mission planners, as thermal constraints during Mars surface operations permit the transmitter to be turned on for only 1 hour at a time. Long acquisition times at low data rates can significantly reduce science data return.

The Mars Pathfinder project commenced normal operations with the (15,1/6) coded link when the B3MCD became fully operational at all deep-space network complexes on April 1, 1997.

II. Laboratory Threshold Testing (Unconcatenated)

An extensive series of compatibility and performance testing was carried out at Kennedy Space Center in October and November of 1996.[1] The objective of the tests was to verify the system loss models used in calculating the threshold for each of the Mars Pathfinder data rates. The system loss models for the (15, 1/6) code[2] had never before been verified in the laboratory.

The Mars Pathfinder spacecraft signal was not used to perform these tests, as time on the spacecraft was unavailable. Instead, the tests were performed closed-loop in the DSN compatibility test trailer (CTT-22) from Monday, October 28, through Wednesday, October 30, 1996. The testing used a (15,1/6) data stream created by the CTT-22 pseudonoise (PN) code generator and test convolutional encoder. This stream was modulated onto X-band (8.4 GHz), turned around by a mock transponder, and run through the Block V receiver (BVR), as shown in Fig. 1. For each of the 20 data rates, the link was configured as specified in Table 1. Using the Y-factor method [2], the E_b/N_0 was set 2 dB above the theoretical threshold determined by Kinman.[3] Kinman's model is a curve fit of the high-rate telemetry loss model for residual carrier binary phase shift keying [3]. The P_t/N_0 was then decreased in 0.5-dB increments using the step attenuator, until the link passed the threshold for a 5×10^{-3} bit-error rate (BER). The E_b/N_0 and BER at each step were recorded. If there were a 5×10^{-3} BER on the unconcatenated link, a negligible number of Reed–Solomon frames would be rejected. This is the point where the Pathfinder mission operates its telemetry link in flight.

Table 1. CTT-22 threshold test parameters.

Parameter	Value
Carrier loop bandwidth	3 Hz
Subcarrier loop bandwidth	1/2 Hz
Subcarrier window	1/4 (unitless)
Symbol loop bandwidth	1/2 Hz
Symbol loop window	1/4 (unitless)
Soft symbol output	Block II MCD (8 bits, variance = 256)
Oscillator	HP 8660 generator

A summary of test results compared to predicts[4] is given in Table 2. In Table 2, bit SNR E_b/N_0 is related to total power-to-noise ratio P_t/N_0 by the expression

$$\frac{E_b}{N_0} = \frac{P_t}{N_0} \sin^2(\Theta_{TLM}) \frac{1}{R_b}$$

[1] L. Harcke, "Mars Pathfinder (15,1/6) Compatibility and Performance Test Report," JPL Interoffice Memorandum 3312-96-047 (internal document), Jet Propulsion Laboratory, Pasadena, California, November 19, 1996.

[2] P. Kinman, *DSN Telemetry System Block-V Receiver*, JPL 810-5, Rev. D (internal document), vol. 1, Module TLM-21, Jet Propulsion Laboratory, Pasadena, California, June 1, 1996.

[3] Ibid.

[4] Ibid.

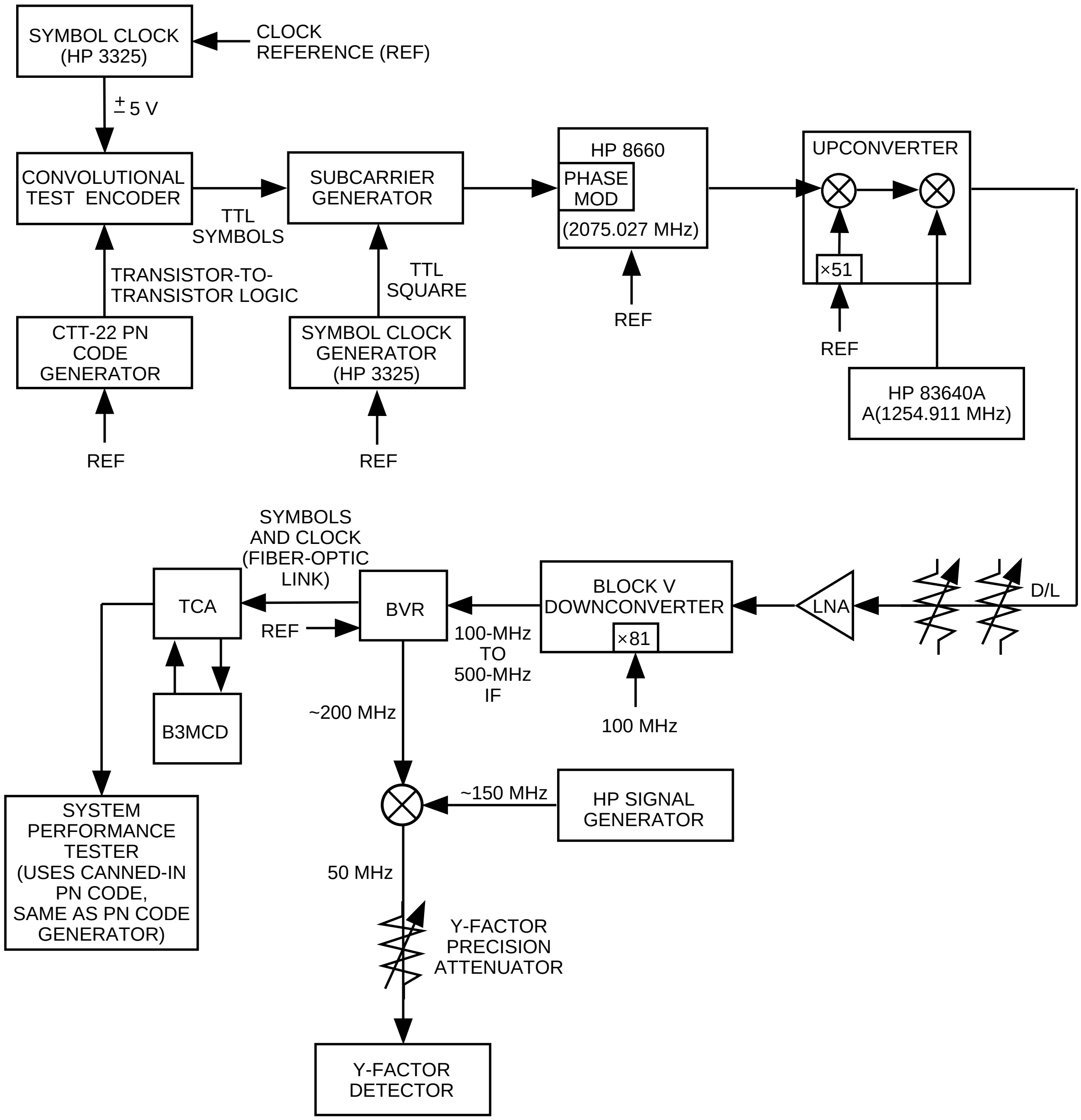

Fig. 1. CTT-22 internal test setup for Mars Pathfinder.

where Θ_{TLM} is the telemetry modulation index in radians and R_b is the channel bit rate in bits per second. The link was found to operate approximately 0.4 dB worse than predicted at the high data rates above 600 bps, near predictions between 600 and 40 bps, and better than predicted at the data rates of 40 bps and below. There was a ±0.3-dB measurement error on all data points due to the Y-factoring process for setting the input signal-to-noise ratio (SNR) in CTT-22. Figure 2 shows BER curves for a range of data rates between 11,060 and 20 bps.

Table 2. Threshold test results for a 5×10^{-3} BER.

Data rate, bps	Measured P_t/N_0 threshold, dB-Hz	Predicted P_t/N_0 threshold,[a] dB-Hz	Measured − Predicted	Modulation index, deg	Measured E_b/N_0, dB-Hz	Measurement error, dB
5	13.9	16	−2.1	37	2.5	±0.3
10	15.4	17.1	−1.7	41	1.7	±0.3
20	17.7	18.5	−0.8	47	2.0	±0.3
40	20	20.2	−0.2	52	1.9	±0.3
79	22.4	22.1	0.3	58	2.0	±0.3
150	24.1	24.1	0	62	1.3	±0.3
300	26.7	26.6	0.1	66	1.1	±0.3
395	27.8	27.6	0.2	69	1.2	±0.3
504	28.9	28.5	0.4	69	1.3	±0.3
600	29.5	29.1	0.4	71	1.2	±0.3
840	31	30.5	0.5	72	1.3	±0.3
1185	32.2	31.8	0.4	73	1.1	±0.3
1659	33.9	33.2	0.7	75	1.4	±0.3
1975	34.5	33.9	0.6	76	1.3	±0.3
2520	35.5	34.9	0.6	78	1.3	±0.3
3555	36.7	36.3	0.4	78	1.0	±0.3
4740	38.1	37.5	0.6	79	1.2	±0.3
6300	39.2	38.7	0.5	80	1.1	±0.3
8295	40.4	39.9	0.5	80	1.1	±0.3
11,060	41.5	41.1	0.4	82	1.0	±0.3

[a] P. Kinman, op cit.

The Cassini program completed a series of laboratory tests with its spare radio frequency subsystem in January 1997.[5] Figure 3 compares the results of the Pathfinder and Cassini tests at two low data rates, 40 and 20 bps. The test parameters for the two data sets differed, as the Cassini testing used slightly different modulation indices and the transponder voltage-controlled oscillator (VCO) rather than a test instrument oscillator. However, the test configurations were similar enough to show that the results of these independently performed tests agree to within several tenths of a dB.

III. Node Synchronization Testing

The purpose of the node synchronization tests was to verify the theoretical node synchronization time for the B3MCD for each of the Mars Pathfinder data rates. The Mars Pathfinder spacecraft signal was not used to perform these tests; instead, a test signal generated internally to CTT-22, as described in the previous section, was used.

During Mars surface operations, the Mars Pathfinder mission plans to turn on its transmitter for 1 hour at a time, three times per day. Mars Pathfinder mission planners need to know the DSN lockup time. They take this time into consideration when allocating downlink (D/L) time slots to different science

[5] A. Makovsky, *Cassini Telemetry Performance: (15,1/6) Testing With the Flight Spare RFS in TDL*, JPL D-14207 (internal document), Jet Propulsion Laboratory, Pasadena, California, January 1997.

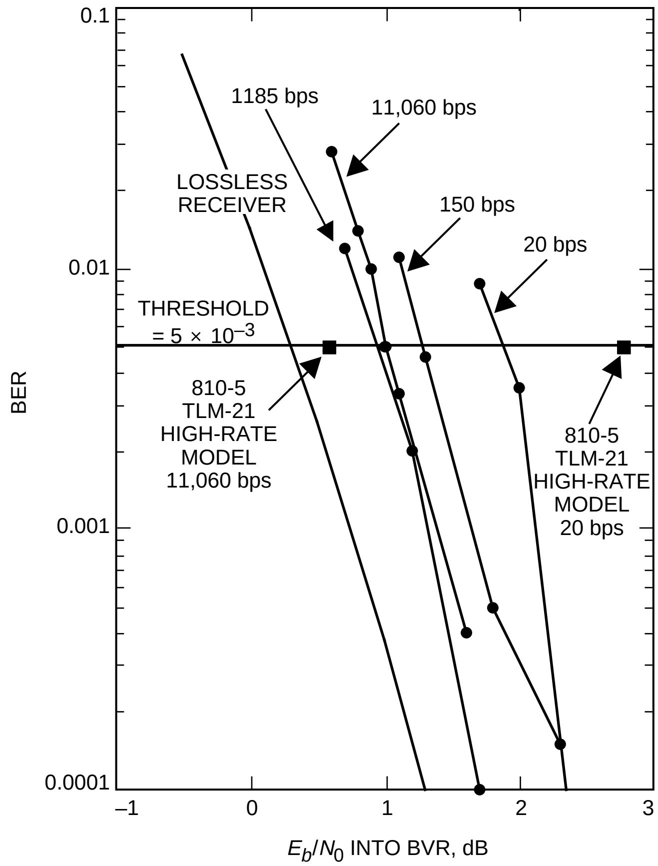

Fig. 2. Mars Pathfinder (15,1/6) convolutional code performance: B3MCD with BVR.

instruments. The DSN lockup time is a composite of the BVR carrier, subcarrier, and symbol lockup times, the B3MCD node synchronization time, and the frame synchronizer subsystem (FSS) lockup time. The lockup times of the BVR and frame synchronizer have been studied and verified in the laboratory. The node synchronization time of the B3MCD had not been verified experimentally prior to this testing, but it should not be the significant component of the lockup time at low data rates, as node synchronization was designed to be 1000 bit times [4], while frame synchronization takes a multiple of 10,112 bit times (the Mars Pathfinder frame length).

The criteria for successful B3MCD acquisition were indications from the B3MCD support computer screen and CTT-22 mock link monitor and control console (LMC) that node synchronization had been achieved.

The node synchronization testing was performed on Thursday, October 31, 1996. The test equipment was configured as shown in Fig. 1. The link was configured to run at 2 dB above the measured threshold for the given data rate in Table 2. Once the BVR indicated it was in lock, the B3MCD was commanded on. The initial time to acquire was noted. The command to drop one symbol was then entered from the LMC. The drop symbol command was then issued several times at each data rate, and the time taken for the B3MCD to resynchronize was recorded. At low data rates, the time for the B3MCD to realize that 1 symbol had been dropped became significant, and these times as reported to the LMC were recorded as shown in Table 3.

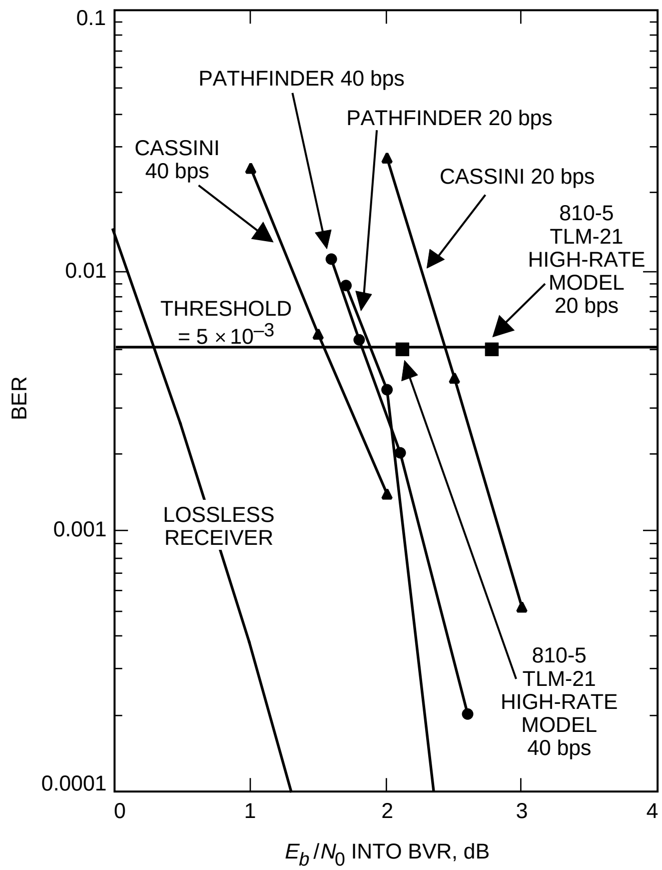

Fig. 3. Comparison of Mars Pathfinder and Cassini B3MCD test data.

At high data rates, the B3MCD support computer was not able to correctly record acquisition times less than 1 s. But at all data rates where the acquisition time was greater than 1 s, the B3MCD acquired in the expected 1000 bit times.

The data in Table 3 show an interesting effect of the B3MCD lock status indicator. The lock status indicator, once it has acquired, correlates 3000 bit chunks of input soft symbols to re-encoded output soft symbols and then compares this number to a known threshold to determine if the in-lock status is still true. Therefore, the B3MCD takes three times as long to determine that it has gone out of lock than to acquire. The actual time to indicate loss of synchronization lies between 3000 and 6000 bit times, as it is most likely for the first correlation of input to output to pass the threshold test if the loss of synchronization did not occur at the beginning of a 3000-bit chunk. See [4] for a description of the threshold test algorithm. This time becomes significant at low data rates such as 10 and 5 bps. The cognizant engineer for the B3MCD algorithms has suggested programming a sliding window into the B3MCD lock status indicator that would shorten the time needed to indicate loss of lock. A detailed discussion of the B3MCD node synchronization process is given in [4].

IV. In-flight Threshold Testing (Convolutional Concatenated With Reed–Solomon)

For approximately 2 weeks in January 1997, the Mars Pathfinder project conducted a series of in-flight tests to verify the performance of the (15,1/6) convolutional code.[6] These tests were coordinated

[6] L. Harcke, "Mars Pathfinder January 1997 In-Flight (15,1/6) Convolutional Code Test Report," JPL Interoffice Memorandum 3312-97-010 (internal document), Jet Propulsion Laboratory, Pasadena, California, February 25, 1997.

Table 3. B3MCD drop and reacquisition times at low data rates.

Data rate, bps	Slip sent, h:min:s	Out of lock, h:min:s	In lock, h:min:s	Time to drop, h:min:s	Time to acquire, h:min:s	Time for 1000 bits, h:min:s
150	0:36:26	0:37:03	0:37:11	0:00:37	0:00:08	0:00:07
150	0:39:04	0:39:35	0:39:42	0:00:31	0:00:07	0:00:07
150	0:41:11	0:41:46	0:41:53	0:00:35	0:00:07	0:00:07
150	0:42:40	0:43:17	0:43:23	0:00:37	0:00:06	0:00:07
79	0:53:42	0:54:55	0:55:08	0:01:13	0:00:13	0:00:13
79	0:55:54	0:57:06	0:57:19	0:01:12	0:00:13	0:00:13
79	0:58:02	0:58:38	0:58:51	0:00:36	0:00:13	0:00:13
79	0:00:01	0:00:49	0:01:01	0:00:48	0:00:12	0:00:13
40	0:02:54	0:04:06	0:04:32	0:01:12	0:00:26	0:00:25
40	0:07:28	0:09:40	0:10:06	0:02:12	0:00:26	0:00:25
40	0:13:10	0:15:14	0:15:39	0:02:04	0:00:25	0:00:25
20	0:27:19	0:29:36	0:30:26	0:02:17	0:00:50	0:00:50
20	0:35:47	0:38:11	0:39:01	0:02:24	0:00:50	0:00:50
10	0:05:49	0:13:33	0:15:13	0:07:44	0:01:40	0:01:40
5	0:36:04	0:46:02	0:49:20	0:09:58	0:03:18	0:03:20

through the Telecommunications and Mission Operations Directorate (TMOD) using the normal project interfaces and network project operations engineers (NOPEs). The prototype B3MCD was installed at the Goldstone site in support of the tests. The 34-m high-efficiency (34-m HEF) antenna DSS 15 provided two-way tracking of the Mars Pathfinder spacecraft for the duration of the test period.

At the beginning of the testing period on January 18, 1997, Mars Pathfinder was only 12.3 million kilometers (0.08 AU) from Earth. At this close range, the total power-to-noise spectral density (P_t/N_0) at the 34-m HEF using the maser low-noise amplifier was approximately 52 dB-Hz. This signal level was 10 dB above the measured threshold for the (15,1/6) code at 11,060 bps, the maximum data rate planned for use during the Pathfinder mission. To test the performance of the code near threshold, it was necessary to degrade the downlink signal by purposely "misconfiguring" the microwave front end of the 34-m HEF. First, the high electron mobility transistor (HEMT) low-noise amplifier (LNA) was used instead of the maser LNA. The system noise temperature of the nondiplexed HEMT is 35.6 K versus 19.7 K for the nondiplexed maser. Second, the antenna was configured for left-hand circular polarization (LCP) rather than right-hand circular polarization (RCP). Finally, noise was injected into the LNA front end using the noise diode assembly. Two noise diodes, 8 and 50 K, were used independently or together, although 50 K is a misnomer, as the noise contribution of the 50-K diode is really 35 K. For all tests, the spacecraft transponder VCO was selected by tracking the spacecraft in the two-way mode with a 2-kW X-band uplink.

We were limited to threshold testing at the 1185-bps data rate since the signal was still very strong (30.5 dB-Hz $P_t/N_0 \pm 2.5$ dB-Hz depending on noise diode setting and spacecraft range) despite the degradation introduced at the front end of the antenna. Table 4 summarizes the threshold test results of the concatenated link. Bit SNR as reported by the B3MCD and symbol SNR as reported by the BVR were averaged over the time interval specified in the last column to form the data in the first two columns of the table. Reed–Solomon frame rejection is given versus the B3MCD-measured bit SNR. A Reed–Solomon frame that is in error is noncorrectable and is thrown away by the ground data processing system.

Table 4. Reed–Solomon (R–S) frame error rate versus the B3MCD reported bit SNR.

B3MCD average bit SNR, dB	BVR average bit SNR, dB	R–S frame error rate, percent	Day of year	Time, UTC
−0.08	0.06	73.44	97-024	07:35–07:45
0.37	0.47	68.07	97-024	07:45–08:05
0.57	0.71	34.79	97-023	08:30–10:30
0.81	0.70	21.71	97-024	06:45–07:30
1.11	2.06	0.00	97-020	07:28–07:43
1.66	1.88	0.00	97-023	10:30–11:00
1.76	2.00	0.00	97-024	08:35–10:00
2.01	2.14	0.00	97-024	08:05–08:35

An annotated plot of bit SNR, symbol SNR, and Reed–Solomon good/bad (in lock/out of lock) indication for one test day is shown in Figure 4. The concatenated (15,1/6) Reed–Solomon link exhibits a very steep approach to threshold, which was found to lie between 0.8 and 1.1 dB bit SNR according to the B3MCD estimator. However, according to the BVR split-symbol moments estimator, the threshold lies between 0.7 and 1.9 dB bit SNR. The BVR split-symbol moments estimator [5] is believed to be more accurate than the input/output soft-symbol correlation algorithm in the B3MCD. Therefore, the exact threshold of the link was not determined to within 1 dB. But the in-flight test does exhibit threshold near the laboratory-measured value of 1 ± 0.3 dB-Hz.

It is important to note that this threshold test analyzed the link performance only at strong carrier loop SNRs. At the 1185 bps P_t/N_0 threshold of 32.2 dB-Hz, the carrier loop SNR is 16.4 dB. In contrast, at the 20-bps threshold of 17.7 dB-Hz, the carrier loop SNR is only 9.6 dB. It was impossible to test the link near the threshold for 20 bps though, because the lowest P_t/N_0 value that could be achieved during the test period was 27.8 dB-Hz. Therefore, no conclusions can be drawn about the in-flight performance of the (15,1/6) convolutional code at weak signal levels.

V. Bit SNR Estimator Performance

The first day and last two days of testing were used to test the strong-signal performance of the (15,1/6) coded link at 4740, 300, and 40 bps. The Reed–Solomon frame error rate remained zero throughout the duration of these tests, but the bit SNR estimator in the B3MCD exhibited poor behavior. Although the B3MCD actually estimates symbol SNR, it reports bit SNR defined as symbol SNR plus $10 \times \log 10(n)$, where $1/n$ is the code rate in bits per symbol. It is believed that the bit SNR estimator ceases to work properly when the actual bit SNR exceeds 23 dB. Table 5 shows how the estimator becomes severely biased and its standard deviation increases as signal strength increases. The authors of [4] intend to report on the performance of this estimator in a future issue of this publication.

VI. Comparison to the (7,1/2) Code

The Mars Pathfinder project did not initiate an extensive testing campaign of the (7,1/2) code performance prior to launch. Instead, a comparison with the Cassini (7,1/2) prelaunch data[7] is made in

[7] A. Makovsky, “Telecommunications Performance With the Cassini Flight RFS-TDL Test Report,” JPL Interoffice Memorandum (internal document), Jet Propulsion Laboratory, Pasadena, California, April 1996.

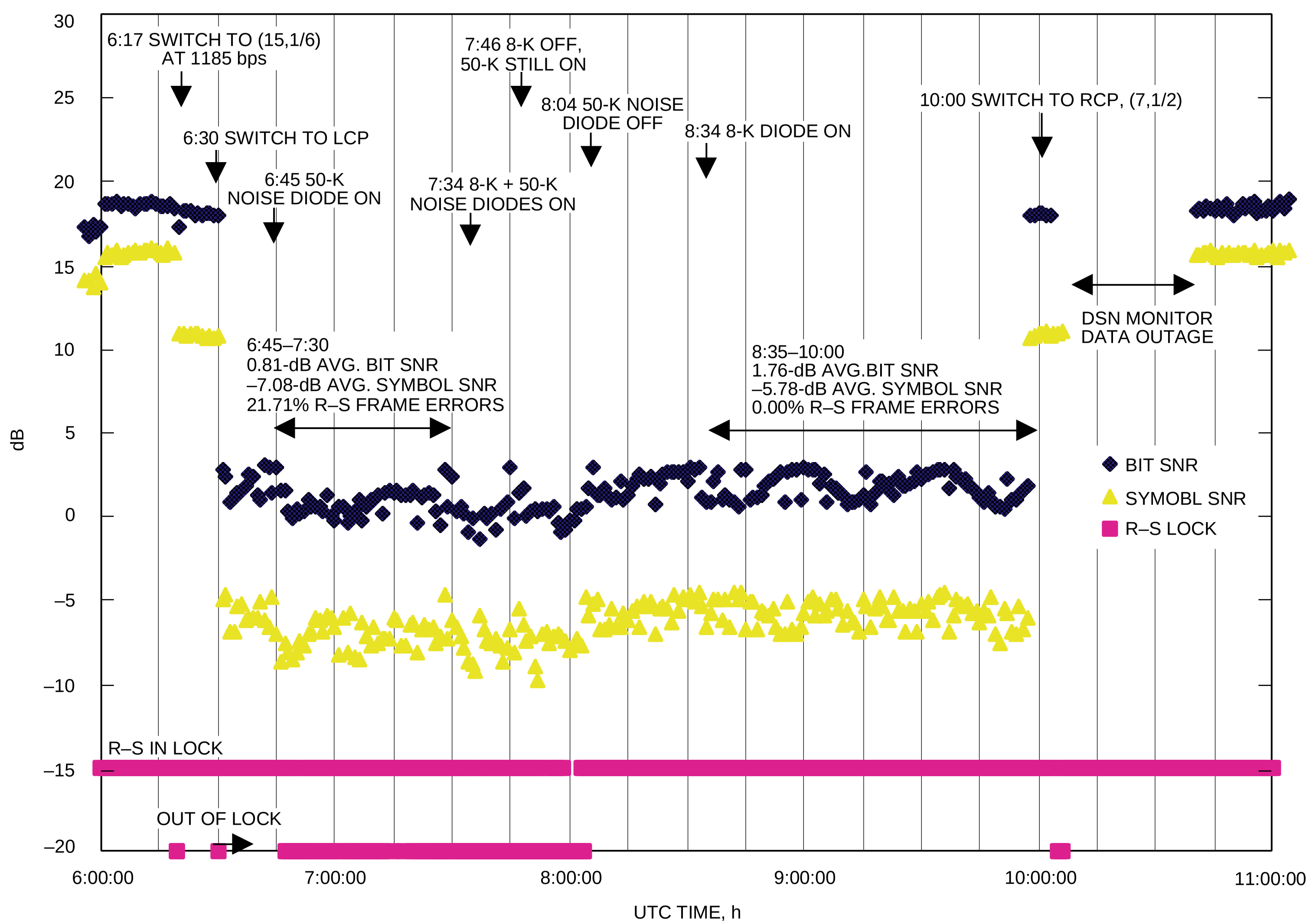

Fig. 4. Mars Pathfinder (15,1/6) convolutional code test, January 24, 1997.

Table 5. B3MCD bit SNR estimator performance.

BVR average symbol SNR, dB	Symbol standard deviation, dB	B3MCD average bit SNR, dB	B3MCD bit SNR standard deviation, dB	R–S frame rejection rate, percent	Day of year	Time, UTC
14.91	0.22	21.96	0.35	0.00	97-028	04:00–04:30
15.48	0.19	17.72	3.70	0.00	97-028	07:00–07:30
22.25	0.32	34.27	5.69	0.00	97-029	04:00–08:00

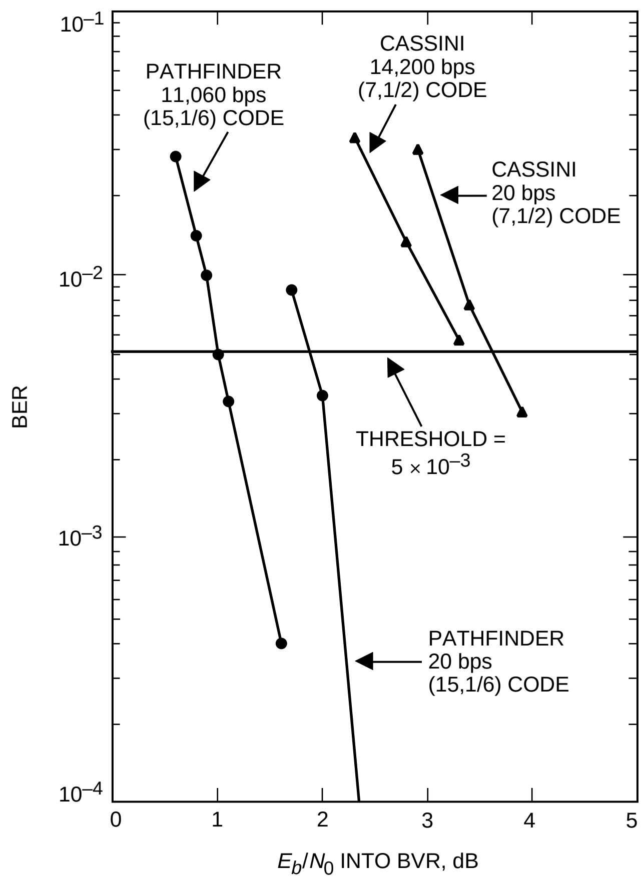

Fig. 5. Comparison of Mars Pathfinder (15,1/6) code test data to Cassini (7,1/2) code test data.

Fig. 5. As can be seen from the BER curves, the (15,1/6) code exhibits a greater than 2-dB gain over the (7,1/2) code at high (10,000-bps) data rates, and over 1.5 dB of gain at low (20-bps) data rates. Again, as mentioned in Section II of this article, the Cassini testing used slightly different modulation indices and the transponder VCO rather than a test oscillator. However, the test parameters were similar enough to allow a valid comparison. As noted by Makovsky,[8] the performance advantage of the (15,1/6) code over the (7,1/2) code is diminished when noisy oscillators, such as the Cassini transponder auxiliary oscillator, are used as the timing reference.

[8] A. Makovsky, January 1997, op cit.

VII. Future Planned Tests

The weak-signal in-flight performance of the (15,1/6) code remains untested. The Mars Pathfinder project plans to test the weak signal performance of the (15,1/6) code after April 1997, when the spacecraft–Earth range will be much greater than it was in January 1997.

Acknowledgments

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