117.6-KILOBIT TELEMETRY FROM MERCURY IN-FLIGHT SYSTEM ANALYSIS[1]

V. L. EVANCHUK
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Summary. This paper discusses very specifically the mode of the Mariner Venus/ Mercury 1973 (MVM'73) telecommunications system in the interplexed dual channel 117.6 kilobits per second (kbps) and 2.45 kbps telemetry. This mode, originally designed for only Venus encounter, was also used at Mercury despite significantly less performance margin. Detailed analysis and careful measurement of system performance before and during flight operations allowed critical operational decisions, which made maximum use of the system capabilities.

Introduction. For the MVM'73 mission the telemetry requirement from Venus was the transmission of 117.6 kbps at an error rate of less than 5 bits in 100. The telemetry requirement for the Mercury encounter was 22.5 kbps with an error rate of less than 5 bits in 100. The goal was 117.6 kbps with an error rate of less than 3.33 bits in 100. All required the simultaneous transmission of a second channel at 2.45 kbps with an error rate of less than 1 bit in 10^4.

Figure 1 is a block diagram of the portion of the system detailing the physical implementation of the Mercury telemetry requirement and goal. From a telecommunications system point of view the implementation consists of:

(1) System design to meet requirements.
(2) Specification of subsystem parameters required by system design.
(3) Specification of subsystem measurements.
(4) Specification of system measurement.
(5) Analysis of measured data.
(6) Estimation of in-flight system performance.
(7) Monitoring and measurement of in-flight performance.
(8) Commitment to the project of the expected performance level for each succeeding critical point.

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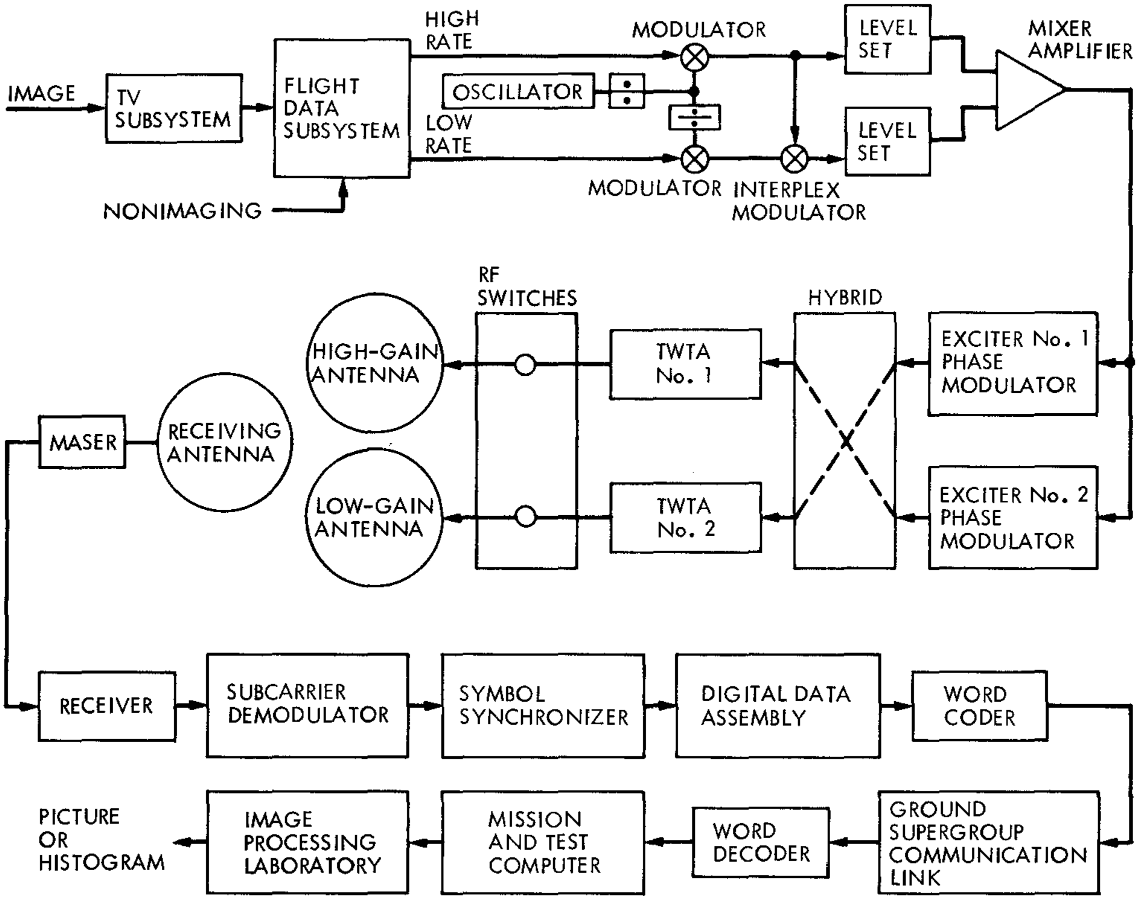

Fig. 1. Block diagram of 117.6-kbps elements

Although the first four items are important, the last four had the greatest impact on the decisions and strategy for the Mercury encounter, and will be discussed in detail. The initial performance estimate indicated that the system marginally met the goals, and only by reducing in-flight measurement uncertainties could accurate performance predicts be made. This was necessary since the very critical decision on which bit rate was to be used at the encounter would be based on these predicts.

Design. The traditional design method at JPL is to design to a sum of adverse tolerances. All separable elements in the telecommunications system are listed with their design values and their worst case tolerances; these tolerances are then added to form a sum of adverse tolerances. If the system performance meets the requirements at the sum of the adverse tolerances, the design is considered acceptable. This can produce a link with a margin of 3 to 5 dB if the system performs at or near its design level. This design method, and the accompanying operational planning, is carried out in a way that takes advantage of performance if the system in-flight performance is at design level or better.

Interplex. The interplex technique (Refs. 1 and 2) was used to increase the efficiency of the low-rate channel. It also benefits the highrate channel in that it allows a higher modulation angle to be used.

Briefly, interplex is a method of premultiplying the low-rate square wave subcarrier and biphase modulated data to achieve a pseudo low-rate channel. The high rate and pseudo low rate are summed together with the appropriate modulation weighting, and then applied to the carrier phase modulator. The modulation process produces a cross product term, usually referred to as the intermodulation product, as well as the two subcarrier side bands. Due to the premultiplication, normal intermodulation product power now appears as the low-rate sideband power, and what would have been the low-rate power appears as the intermodulation power. This swapping of side band power is important when the power levels are not equal, since one can now choose the higher power for the information channel and the lower power for the nonrecoverable intermodulation product. This additional power in the low rate can then be utilized by rebalancing both the high- and low-rate modulation parameters to make the total system more efficient.

Pre-Flight Measurements. During the preliminary analysis of measured data it became apparent that if the new supercooled maser at the Deep Space Station at Goldstone could really achieve a noise temperature of 13.5 Kelvin, and if the spacecraft telecommunications system performance was at its design value, and if the ground station performance was at its design value, 117.6 kbps at Mercury was indeed achievable. Figure 2 displays the prediction of expected bit error rate at the Goldstone 64-meter station on the day of Mercury encounter using preflight measured data. The change in error rate is due to the change in system noise temperature as a function of elevation angle at the station.

In-Flight Measurements. The in-flight measurement of performance was made difficult by the temporary partial failure of the spacecraft S-band high-gain antenna. The track of the Earth vector from the spacecraft required the high-gain antenna feed to go from Sun illuminated to shadowed on December 25, 1973, and from shadow to sunlit on March 4, 1974. The first antenna failure occurred on December 25, and in the succeeding 2 months the S-band downlink varied between 2 dB to 6 dB below design value. The antenna healed on March 4, and with Mercury encounter on March 29 this left little time to make any accurate statistical measurements of the in-flight performance. On March 12, the first 117. 6-kbps performance tests were run using Goldstone and Canberra 64-meter stations configured for minimum noise temperature mode (lownoise temperature maser and no transmission).

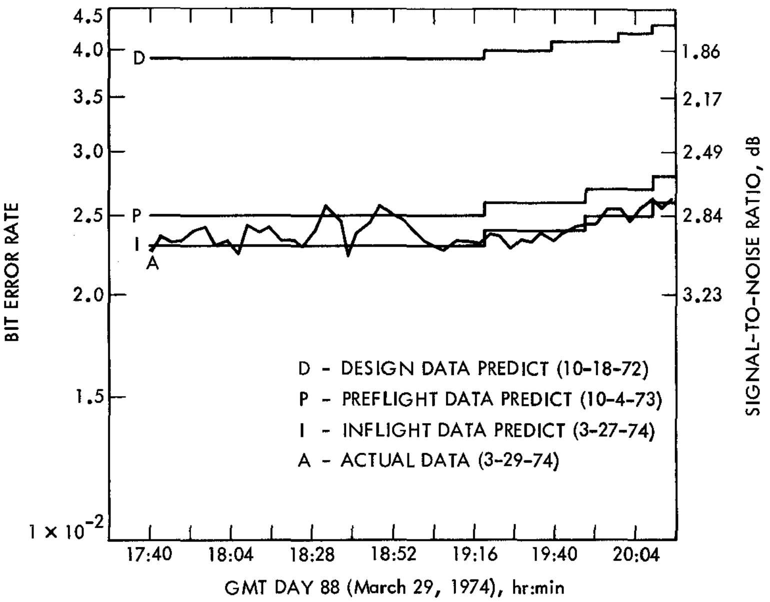

Fig. 2. Bit error rate at Goldstone on March 29, 1974
at 117.6 kbps, compared to predicts

The spacecraft had attitude control difficulties at that time, which placed the high-gain antenna boresight off earth by a significant amount. This effect was calculable and only added a small residual uncertainty. The ground antenna was moved off track to produce a “synthetic” attenuation of the signal from the spacecraft without modifying the noise temperature conditions at the station. Any attempt at putting an attenuator before the first amplifier maser would have increased the system noise temperature and although this effect is theoretically calculable, the residual uncertainty would have been large, of the order of 0.2 dB.

The ground antenna offsets were designed for approximately -2, -3, and -4 dB from the current link conditions. This eliminated, to a large extent, the dependence on absolute values and predicts, and substituted the range distance increase from the test time to encounter, automatically including all nonlinear effects at these signal-to-noise ratios, (SNR.). The range increase would produce a 3.5 dB decrease in received signal level, so a plot of bit error rate (BER) as a function of dB down from current conditions would indicate the expected error rate at encounter within the uncertainty of the measurement of the data points.

Since the total link BER measurement was in question, including the ground data processing system, it was decided to use one of the system “end points” as a measure of BER and convert this value to SNR. The spacecraft TV system was turned off and the Flight Data System was commanded to interrogate the TV at the 117.6-kbps rate. This produces a black picture with a slight amount of residual noise at the spacecraft. The Flight Data System quantifies the elements of the picture into 8-bit pixels. These are then biphase modulated on a high-rate subcarrier, interplexed with the low-rate stream and modulated on the downlink carrier. The end result, after reception, demodulation, synchronization, and dequantization is either an “end point” picture, or a histogram of the decimal values of each pixel. From the histogram it is now possible to measure the total link bit error rate and to eliminate the residual spacecraft noise.

The spacecraft noise will exist in the least significant bits, but the link noise will exist uniformly on all bits. To maximize the confidence level, as many bits as possible must be used. Strong signal tests had indicated that only the two least significant bits would be affected by peak residual noise. This was checked by plotting the derived error rate as a function of the numbers of bits used and correlating this with the total number of bits per picture used to calculate the error rate. Figure 3 is an example of this plot for one particular picture. As can be seen, including the two least significant bits (bits 7 and 8) in the calculation increases the total error rate due to the spacecraft residual noise. The bits used for the link error rate measurement were the six most significant bits.

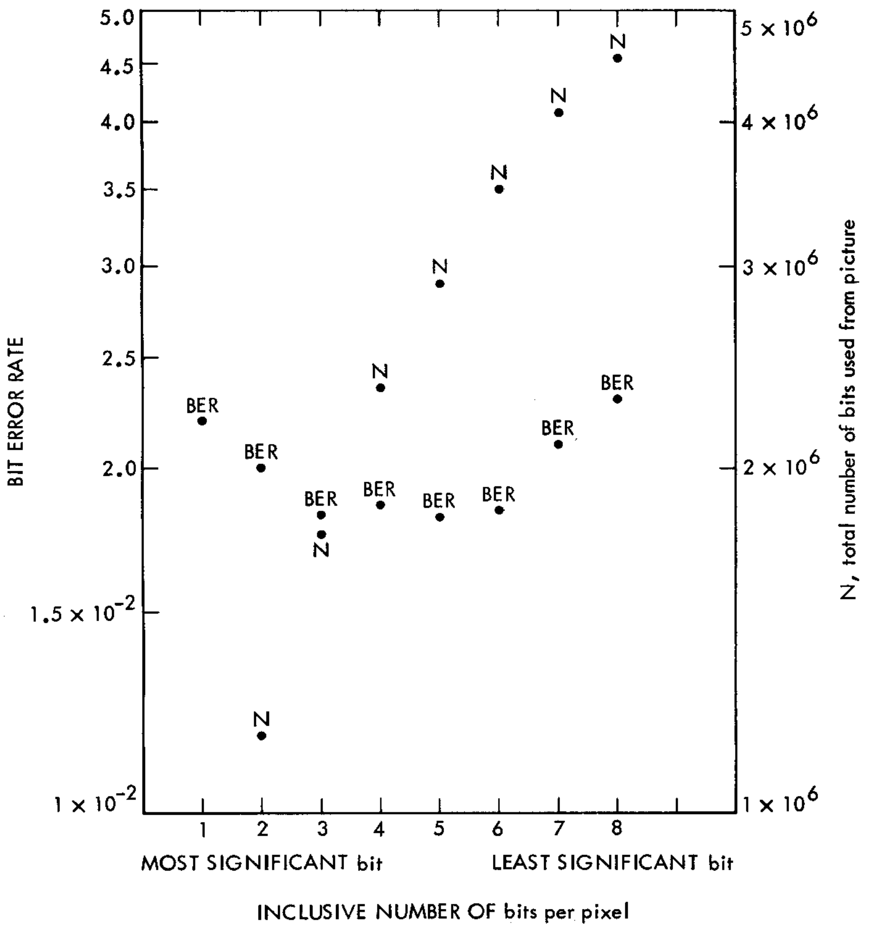

Fig. 3. Bit error rate from picture No. 0129955, March 12, 1974, vs number of bits per pixel used

The result of all of the above was a set of points cross-correlating the bit error rate and the dB decrease in signal. Since dB decrease is related to range increase, which is in turn related to time by the trajectory, one may now plot BER vs time (Fig. 4). Time is deliberately set from right to left to correspond to a loss in dB. The 1 - σ ellipses are SNR estimates converted to error rate in the ordinate and carrier level estimate deltas in the abscissa, together with the tolerances.

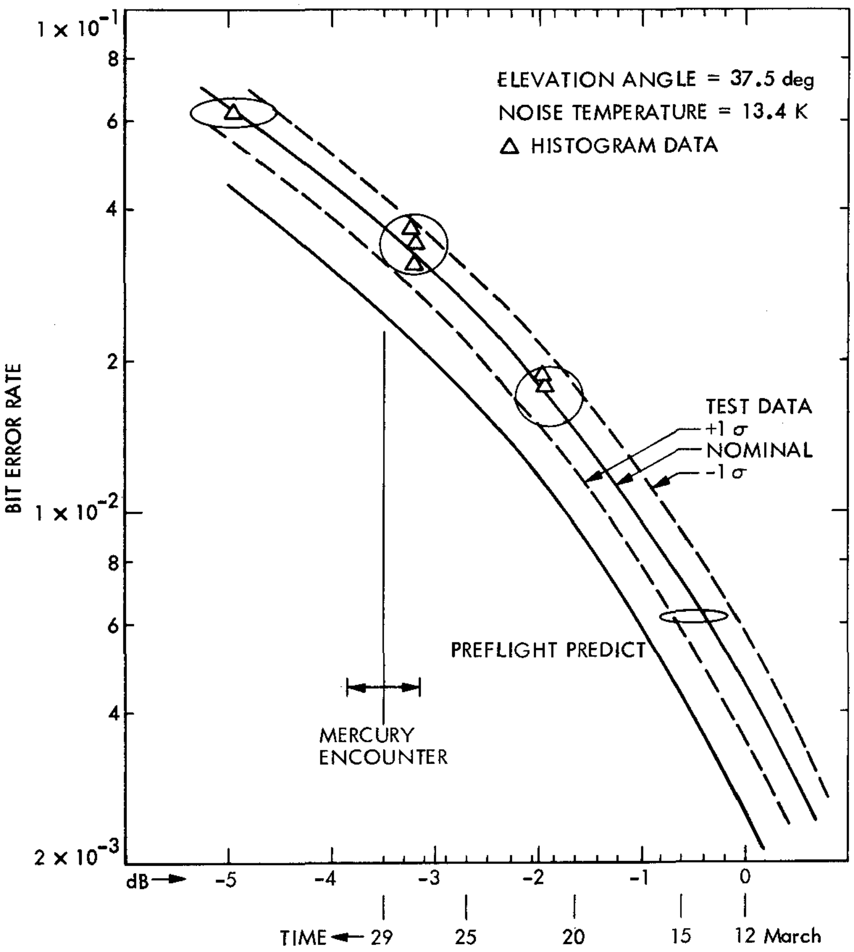

Fig. 4. Goldstone 117.6-kbps test bit error rate, March 12, 1974

The carrier level estimate deltas are the decrease in received carrier power for each offset of the station antenna. These deltas are taken with reference to the peak value at no offset, thereby eliminating the requirement for a perfect AGC (carrier power level) measurement. These deltas are directly equivalent to the data signal power decrease, and since the noise level stays constant the deltas are equivalent to decrease in SNR.

As can be seen, the expected error rate at encounter was 3.8 in 100, while the TV experiment team goal was less than 3.33 in 100. But there were still several considerations that were not included. The first is the elevation angle of the ground antenna. During the test it was peaking at 37.5 degrees but at encounter it would peak at 42 degrees. This is about a 0.1-dB improvement. The second is in the psychology of station operation. During the relatively boring portions of cruise the station calibrations and tuning are not at their best. During tests they are better, but for encounters they are the best. This, although not a measurable number, is probably of the order of 0.2 dB.

The plan at this point was to run short tests at Goldstone and Canberra as we approached Mercury and to compare these to the predicted curve, but in the meantime to commit to a 117.6-kbps/2.45-kbps sequence.

On March 20 a decision was made to switch spacecraft transmitter exciters. This was in response to the Celestial Mechanics and Radio Science team's analysis of the oscillators' phase noise spectrum. They found phase shifts of several degrees that could tend to reduce the validity of any spacecraft generated carrier frequency data from Mercury. The spacecraft has two exciters, each of which contain an oscillator, and a phase modulator. A switch in exciters would also switch to a different telemetry phase modulator. The preflight test data indicated a potential improvement to + 0.1, ±0.3 dB. The improvement was of the order of +0.1 dB.

Table 1 lists the various short tests (10 minutes) during the preencounter. The tests were run at various elevation angles and compared to predicts for that elevation angle and for exciter number 2.

Table 1. 117.6 -kbps tests

Day	Exciter	Mean SNR Deviation from predicts	
		DSS 14	DSS 43
March 12	1	-0.5 dB	
March 13	1		+0.2 dB
March 20	1	-0.4 dB	
March 22	2	+0.0 dB	
March 24	2		+0.3 dB
March 25	2		+0.1 dB
March 26	2	+0.0 dB	+0.4 dB
March 27	2		-0.1 dB
March 28	2	+0.5 dB	
Encounter			
March 29	2	+0.2 dB	-0.1 dB

Performance Level Commitment anci Observed Performance. On March 27 (two days before encounter) the project requested a final error rate predict for the encounter pass at Goldstone. The value given was 2.29 in 100, the equivalent SNR was +3.0 dB at 17:18:59 (hr:min:sec) on March 29, 1974.

The encounter data is shown in Fig. 2. Included are the design predict (10-18-73), preflight predict (10-4-73), and the in-flight predict (3-27-74). The mean deviation over the 2-1/2 hours at encounter was +0.2 dB from preflight data, and 0.0 dB from in-flight data. The mean value of the SNR for the first 10 minutes at 117.6 kbps was +3.0 dB.

Conclusion. The above results indicate that with careful planning and measurement, and with an accurate analytical model, an estimate of system performance can be made that allows critical decisions to be made with high confidence.

References

1. Butman, S., and Timor, U., “Interplex - An Efficient Two-Channel Telemetry System for Space Exploration, “ in Supporting Research and Advanced Development, Space Programs Summary 37-62, Vol. III. Jet Propulsion Laboratory, Pasadena, Calif., April 30, 1970.

2. Butman, S., and Timor, U., “Efficient Multi-Channel Space Telemetry,” in Supporting Research and Advanced Development, Space Programs Summary 37-62, Vol. III. Jet Propulsion Laboratory, Pasadena, Calif., June 30, 1970.