117.6 KILOBIT TELEMETRY FROM MERCURY-A MAJOR DEEP SPACE TELECOMMUNICATION ADVANCE[1]

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Summary. For nearly eight hours on March 29, 1974, Mariner 10 transmitted imaging telemetry in real time at 117.6 Kbps from Mercury. During this time, 562 very high quality frames were received, even though the bit error rate was only about 1 in 40. The transmission of 117.6 Kbps from Mercury is a magnificent telecommunications achievement, which permitted an order of magnitude increase in imaging science data return. The Mariner 10 imaging scientists' requirements, simply stated, were to obtain maximum area coverage at highest spatial resolution. More precisely, they desired photomosaics which were equivalent to the best earth-based pictures on the Moon, i.e., about 1 km resolution. The purpose of this paper is principally to relate the methods by which these "desirements" were translated into measurable telecommunication system requirements and some of the attendant tradeoffs. Additionally, same of the steps taken to achieve their goal are recited.

Introduction. Mariner 10, sixth in a series of interplanetary spacecraft, completed its primary mission on March 29, 1974, by transmitting 562 clear, sharp pictures of Mercury's crater-pocked terrain in real time. The feat represents a remarkable improvement in deep space communications. In the view of the Mariner Imaging Science Team, it represented an order of magnitude increase in data quality and quantity. This was brought about by transmitting the video images in "real time" at 117.6 Kbps at a distance of 1 astronomical unit (150 x 10^6 km). The standard mission plan, based on pre-launch estimates of telecommunication system capability, was to transmit at a rate of 22.05 Kbps. However, by a series of hardware improvements, careful analysis and test of link performance, and detailed analyses and evaluation of picture quality and coverage by the Imaging Team, the full capability of the spacecraft data system was realized with great success. The methods of analysis and test of communications link performance is reported

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in a companion paper by Evanchuk[2] . Here we shall (1) relate in particular how link performance was effectively improved by carefully assessing picture quality and coverage vs. bit rate and bit error rate, and (2) describe the series of improvements, relative to the 1971 Mars Orbiter, Mariner 9.

Imaging Requirements. Broadly stated, the imaging scientist wants to obtain maximum area coverage at the highest spatial resolution. This can be vexing to the telecommunication system designer because it implies, in the limit, an infinite bit rate and zero bit error rate - neither possible. More precisely, the Mariner Venus/Mercury 1973 Imaging Team wanted enough pictures to make mosaics of both the “incoming” and “outgoing” sides of Mercury with “Lick plate” resolution. By this is meant a picture equal to the best earth-based photo of the Moon taken at the Lick Observatory with about 1 km resolution. They further desired sampled coverage at resolutions down to 100 m, In the spring of 1970, at the beginning of the MVM73 Project, members of the Imaging Team, led by B. C. Murray, did a comprehensive tradeoff study of various imaging system, including film and video, under a severe cost constraint and heavily influenced by estimates of Mariner telecommunication capability. Their studies were reported in Ref.[3] . They showed that a very significant improvement in area coverage could be obtained by transforming the standard Mariner method of picture transmission from “record/playback” to “real time” with a bit rate about twice that of the then current mission, Mariner Mars 1971. Their proposal for “real-time” TV was adopted by NASA and the Project management. It included retention of the basic Mariner 9 TV subsystem, but modified by reducing the number of bits per picture element (pixel) from 9 to 8 and replacing the 50 and 500 mm optics by two 1500 mm telescopes (Mariners have two cameras mounted on a two-degree-of-freedom scan platform). The transmission rate then assumed achievable was 29.4 Kbps. Not long after, it was settled at 22.05 Kbps. Importantly, at the time, no consideration was given to raising the standard bit error rate requirement for Mariners, which was 5 in 1000. As it turned out, this became a vital factor in achieving the higher bit rate at Mercury.

Accepting a bit rate at Mercury of the order of 22.05 Kbps meant a drastic under-employment of the combination imaging/data/telecommunication subsystems on the spacecraft. Indeed, it meant reduction of gray levels (discriminability) from 256 to 64 by reducing the number of bits per pixel from 8 to 6, and further reduction of the bits per picture for transmission by a factor of four, either by transmitting only the middle quarter strip of each picture, or transmitting only every fourth pixel in each line, but shifting the

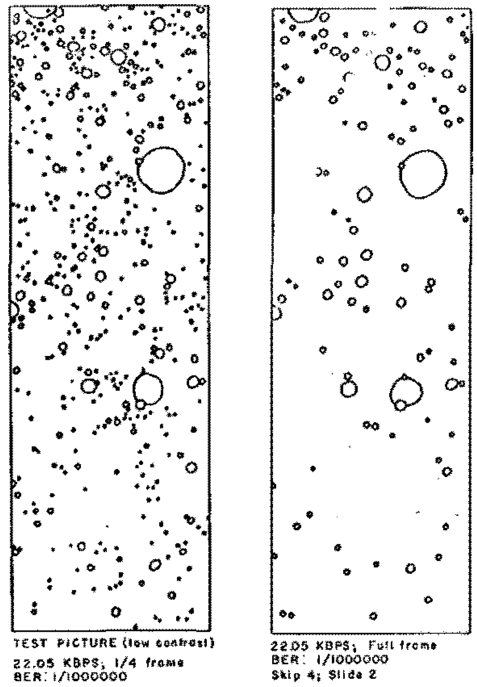
[2] V. L. Evanchuk, “117.6 Kilobit Telemetry from Mercury - In-Flight Systems Analysis,” paper presented at 1974 International Telemetering Conference, International Hotel, Los Angeles, California, October 15-17, 1974.

[3] B. C. Murray, et. al., “Imaging of Mercury and Venus from a Flyby,” ICARUS, Vol. 15, No. 2, October 1971, pp. 153-173.

skipped pixels by 2 on each succeeding line. This was called the “skip 4/slide 2” edit mode. In the first case, using quarter strips, a factor of 4 loss in coverage was incurred. In the second case, though the full frame was retained, a gross loss of resolution was taken. Thus, a coverage-vs.-resolution tradeoff was apparent. To assess this tradeoff, R. Strom of the University of Arizona, an Imaging Team member, initiated a study using a lunar photo as a basic test picture. This was because Mercury was assumed to look much like the Moon, which ultimately proved to be true. Strom’s method of analysis was to count craters using modified reproductions of the test picture made by the Imaging Processing Lab of the Jet Propulsion Laboratory. Comparisons of the quarter frame and “skip 4/slide 2” crater pictures are shown in Figures la and lb. The loss of crater delectability in the skip/slide mode is startlingly evident. At this point, the Imaging Team opted to abandon the skip/slide mode in favor of the quarter strip mode with attendant-loss of area coverage. But this had a serious flaw, i.e., wandering of the picture-to-picture imprint on the planet’s surface due to spacecraft’s attitude limit cycle motion (Figure 2). To mosaic the planet without excessive gores or overlap in coverage, with the very small quarter frames (.12° x .48°), meant an order of magnitude reduction in the attitude orientation stability of the spacecraft. Due to severe project cost constraints, it was deemed infeasible to modify the attitude control subsystem or add a limit cycle compensator. Thus, the only route left was to try to improve telecommunication performance so as to be able to transmit full frame/full resolution pictures from Mercury at 117.6 Kbps. This became the cause celebre. The full frame/full resolution pictures serve very well to fill the gores left by the wandering quarter strips. Just as important, however, is that they permit much greater feature discriminability by allowing 256 gray levels instead of 64. This allows greater contrast stretch enhancement capabilities.

Several methods were investigated to upgrade link performance at 117.6 Kbps. These included adding an X-band TWTA and a telemetry subcarrier to the X-band link, increasing spacecraft antenna size, increasing S-band power output from a nominal 20 to 35 watts, adding a convolutional coder, increasing the sensitivity of the ground receiver by lowering system noise temperature, and finally, increasing the bit errors allowed in the pictures, thus reducing the ST_B/N_0 (signal-to-noise ratio in one bit time) requirement. All but the last two mentioned above were rejected for either cost, schedule, or reliability reasons.

To assess the effect of reducing the ST_B/N_0 requirement on picture fidelity, Strom continued his crater counting analyses using the same lunar test photo, but progressively worsening the bit error rate (BER). He graded a picture with 1 error in 50 as “best possible” and evaluated pictures with 1 in 40 and 1 in 30 bit error rates. The results of these analyses are shown in Figure 3.



1a 1b

Fig. 1. Crater Count Pictures Showing Severe Loss of Crater Detectability for the "Skip 4/Slide 2" Edit Mode

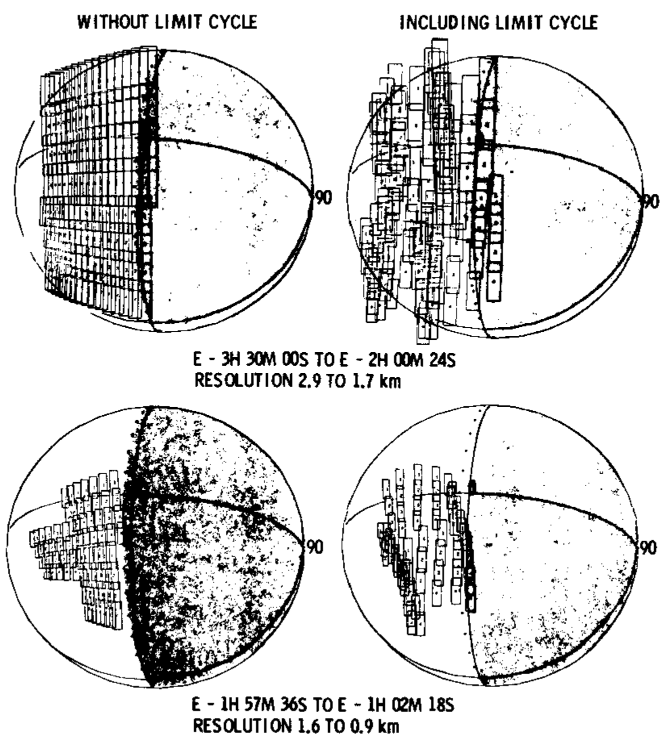


Fig. 2. Effect of Spacecraft Limit Cycle on Picture Imprint Location on Mercury for Quarter Frames

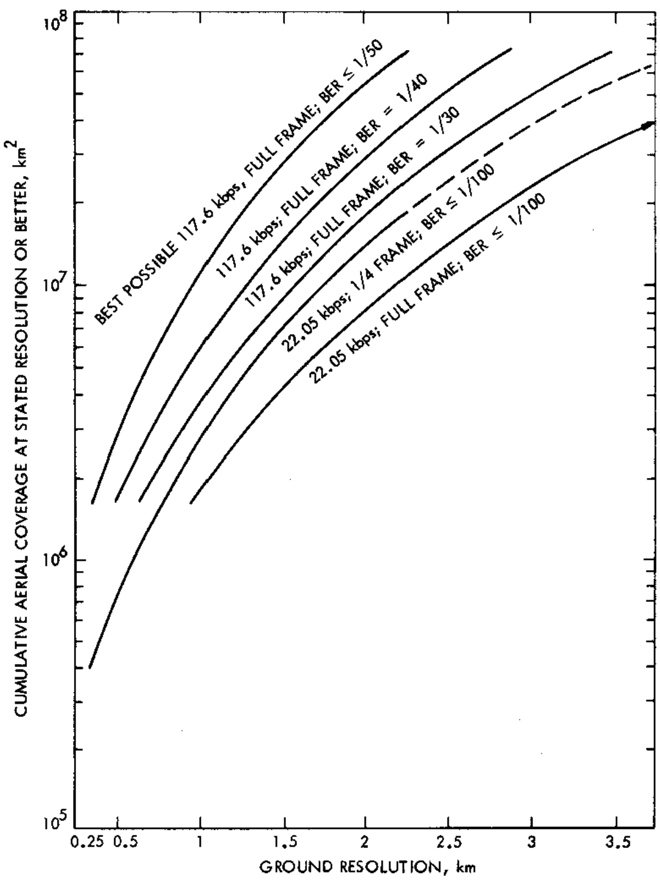


Fig. 3. Cumulative Area Coverage vs. Resolution for Different Bit Rates, Bit Error Rates, and Edit Modes

Here is plotted cumulative area coverage vs. resolution. Note the progressive decrease in area coverage at a stated resolution as BER worsens. For example, at 1 km resolution, area coverage is decreased from 1 x 10^7 to 3.8 x 10^6 km^2 by worsening bit error rate from 1 in 50 to 1 in 30. Also shown are the coverage/resolution curves for the 22.05 Kbps quarter frame and “skip 4/slide 2” full frame modes. Based on this information, the Imaging Team chose 1 in 30 as its “switch point” error rate; i.e., if the bit error rate at Mercury was 1 in 30 or better, they would switch from 22.05 Kbps quarter frame to 117.6 Kbps full frame transmission. The difference between 1 in 50 and 1 in 30 represents a 1-db reduction in ST_B/N_0 in the uncoded 117.6 Kbps channel. To further evaluate the effect of worsened bit error rate, Strom calculated a “resolution loss factor” vs. BER. This is shown in Figure 4.

Note that at about an error rate of 3 in 100, one begins to see false features in the picture.

In addition to determining the worst error rate to permit the lowest ST_B/N_0, an improvement was made in ground station receiving sensitivity. Led by Gerry Levy of the Jet Propulsion Laboratory, two companion efforts were initiated. The first was to reduce the temperature of the maser from 4.4°K to 2.1°K, primarily by installing a new signal

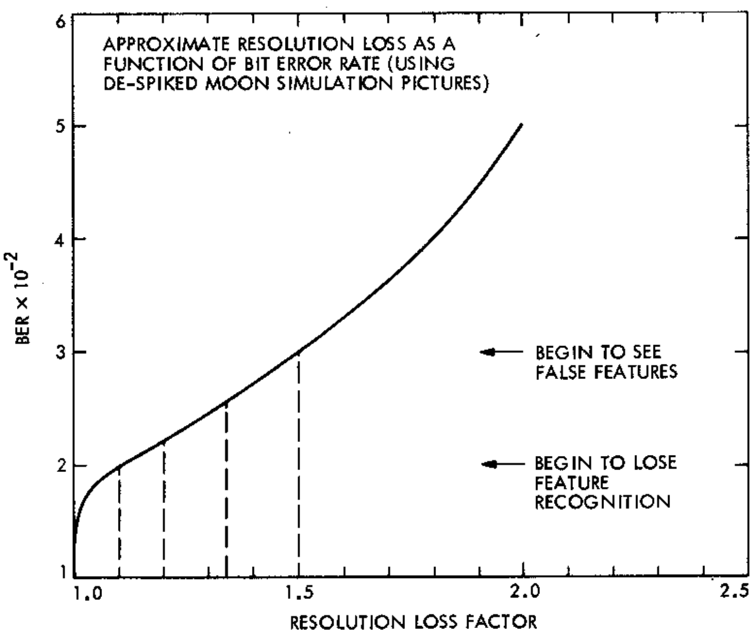


Fig. 4. Resolution Loss Factor vs. Bit Error Rate (BER)

input transmission line which was shorter and colder. This activity has been reported in Ref.[4] . The second was to reactivate the Ultra-Low Noise Cone [5] which was used on the Mariner Mars 1969 Project. This cone was refurbished, retrofitted with the improved maser, and installed in the 64-meter antenna at Canberra, Australia. A second improved maser was installed in the 64-meter antenna at Goldstone, California. The link performance improvements from these actions were 1.6 db at Canberra and 0.7 db at Goldstone. These gains were just sufficient to meet the 1 in 30 "switch point" criteria established by the Imaging Team.

These two methods of effectively improving telecommunication performance stand out because they were deliberate, determined efforts to do so. However, there were other improvements or changes made on Mariner 10 which contribute significantly to the dramatic increase in performance. These are listed in Table I which compares key telecommunication performance factors between Mariners 9 and 10. Notable advantages of Mariner 10 over Mariner 9 were shorter communication distance (+4.0 db), larger

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[4] R. Clauss and E. Wiebe, "Low-Noise Receivers: Microwave Maser Development," Jet Propulsion Laboratory Technical Report 32-1526, Vol. XIX, pp. 93-95, November-December, 1973.

[5] G. S. Levy, et. al., "The Ultra Cone: An Ultra Low-Noise Space Communication Ground Radio Frequency System," IEEE Transactions on Microwave Theory and Techniques, Vol. MIT-16, #9, pp. 596-602, September 1968.

spacecraft antenna, and use of interplex modulation. Also important were the ingenious design of the telemetry and flight data subsystems as reported in Refs.[6] [7].

Conclusion. The outstanding success of the Mariner 10 imaging experiment at Mercury far exceeded pre-flight expectations. This was principally due to the persistence and ingenuity of members of the MVM73 Imaging Team, telecommunication engineers at the Jet Propulsion Laboratory, and Deep Space Network. By iterating, analyzing, and testing requirements and performance factors, seeking methods of improvement, and rising to the challenge, a giant step in deep space telecommunications has been made. Particularly significant was the close definition of picture fidelity characteristics in terms of telecommunication performance factors, and a major improvement in maser design.

Table I
COMPARATIVE IMAGING/DATA/TELECOMMUNICATION FACTORS BETWEEN MARINERS 9 AND 10

COMPARABLE FACTOR	MARINER 9	MARINER 10	MARINER 10 ADVANTAGES
SPACECRAFT			
Antenna Size	40"	54"	M10 had S-X feed lossier.
Antenna Pointing	2 Fixed Positions	2 Deg. of Freedom	Minimum Pointing Loss.
Power Output	20W Nominal	20W Nominal	No Change.
Modulation	Standard Dual	Interplex	Interplex more Efficient.
Modulation Index (Hi-Rate Channel)	65°	72°	More Power in Channel.
Data Rates	16.2 Kbps Block Coded	22.05 Kbps Block Coded. 117.6 Kbps Uncoded.	
Vidicon Readout Rate	132.3 Kbps	117.6 Kbps	
Frame Formats	1. Full Frame Recorded. 2. Full Frame, 88% Pixels Deleted, Real-Time.	1. Full Frame, Real-Time. 2. 1/4 Frame, Real-Time. 3. Full Frame, 75% Pixels Deleted, Real-Time. 4. Full Frame Recorded.	Continuous 42-sec Frames vs. 34 pix each 3.6 hours for Mariner 9.
GROUND			
Antennas	1 - 64 Meter	3 - 64 Meter	New Antennas in Spain and Australia.
System Noise Temperature	15.7°K	13.4°K	Improved Maser Des. (+.7 db)
Feed System	S-Band	S-X Band	New Dichroic Reflector for S-X Reception.
MISSION			
Maximum Communication Distance	237×10^6 Km	149×10^6 Km	4 db Less Space Loss
IMAGING			
Maximum Bit Error Rate Required	5 in 1000	5 in 100	1.8 db Less ST/N_0 Required.
Bits per Picture Element	9	8 (6 for 22.05 Kbps)	Gray Levels Cut 1/2.

[6] J. R. Gilder, "A High Performance Telemetry System for the Mariner Venus-Mercury 1973 Project," IEEE Publication 72CHO-601-5-NTC, Dec. 4-6, 1972.

[7] P. B. Whitehead, "The Mariner Venus-Mercury Flight Data Subsystem," IEEE Publication 72CHO-601-5-NTC, December 4-6, 1972.