DESIGN OF THE MARINER JUPITER/SATURN 1977 TELEMETRY SYSTEM[1]

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Summary. In 1977 NASA will launch two spacecraft to perform scientific investigations of the Jupiter and Saturn planetary systems. The science payload includes a total of 10 instruments to support both the interplanetary cruise and planetary encounter phases. These will be the first launches of a new generation of Mariner-class spacecraft designed for outer-planet missions. The telemetry system design for these missions was especially challenging because of extreme communication ranges (1.5 X 10^9 km), high data rate requirements (up to 115.2 kb/s), and more stringent data quality requirements than previous Mariner missions. This paper discusses the evolution and design of the Mariner Jupiter/Saturn 1977 telemetry system and presents the performance anticipated therefrom.

Introduction. Since 1962 Mariner spacecraft have been exploring the near planets of the solar system. They have carried payloads of various scientific experiments to gather data about the interplanetary medium and to probe nearby planetary systems. Each mission has had progressively greater demands for data return, and design of the telemetry system has evolved accordingly in support of these increasing requirements.

Mariner Jupiter/Saturn 1977 (MJS77), the first Mariner mission to the outer planets, will use gravity-assist at Jupiter to shorten the flight time to Saturn. The spacecraft employed in this mission are new generation Mariners featuring solar independent power sources, X-band transmitters and a large parabolic antenna for high-rate telemetry transmission over communication ranges beyond 1.5 billion km. A fully reprogrammable on-board data system is employed to accommodate changing requirements and capabilities as a function of mission phase. The tracking stations of the Deep Space Network (DSN) are also providing expanded capabilities in support of outer-planet missions in general and MJS77 in particular. X-band receiving capability has been added, and 100-kW S-band transmitters are planned for uplink transmissions. New and sophisticated telemetry decoders are under design to offer improved telemetry performance.

The telemetry system for MJS77 is functionally illustrated in Fig. 1. The system starts with the acquisition of data from science instruments and engineering sensors. The data from

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these sources is sampled and formatted by the Flight Data Subsystem (FDS). Data compression and editing, as well as source error protection coding, may be performed on selected subsets of the data stream. The formatted data is then delivered to either the spacecraft telecommunications subsystems for transmission to Earth or to the spacecraft tape recorder for temporary storage. The DSN, with a world-wide network of tracking stations, receives the spacecraft signal and performs the basic detection of the data stream. The data is then transmitted through the ground communications lines to the Mission Control and Computing Center at Jet Propulsion Laboratory in Pasadena, California. After having synchronized with the data stream, the data is decommutated, error corrections are performed where possible, and the data is displayed for the users. Ultimately the data from each instrument is assembled and delivered to the scientific investigators as experiment data records.

The telemetry design effort for MJS77 has concentrated on finding the best possible match between each of the system elements of Fig. 1 to maximize efficiency within the resources of the project. This required:

(a) The development of realistic user requirements based on the limitations imposed by various elements of the telemetry system.

(b) Optimization tradeoffs at the system level in a form where all areas involved in the design, support, or use of the telemetry system were represented.

Perhaps the most distinguishing aspect of the MJS77 telemetry design effort was the degree of in-depth interaction between designers and users at the earliest stages of the project. This permitted the early evaluation of the impact of many options before decisions were made that could be costly to modify at a later date. In the following paragraphs the requirements determined will be discussed, and the design approaches considered will be explored. That discussion will culminate with a description of the chosen design and its anticipated performance.

Requirements Definition. The requirements imposed on the MJS77 telemetry system arise from the needs of the science payload and those supporting elements of the project whose function is related to either the delivery of science data or the overall conduct of the mission. The totality of requirements for data transmission separate into two categories in support of two distinct mission phases: the interplanetary cruise phase and the planetary encounters.

During the interplanetary cruise phase, science instrument and engineering data will be received at S-band using the 26-m subnet of the DSN. In contrast, the planetary encounter phases require transmission of highrate imaging science data as well as other instrument and engineering data. The planetary encounters will be supported by the 64-m subnet of the DSN with data received at X-band for superior link performance. The specific requirements listed below were formulated to be consistent with the constraints imposed by the tracking stations of the DSN:

(a) The acquisition of instrument and engineering data during cruise at a maximum rate of 2560 b/s with an effective bit error rate of $\leq 5 \times 10^{-5}$. When this is not achievable because of increasing spacecraft range, a lower data rate will be selected consistent with maintaining the channel bit error rate $\leq 5 \times 10^{-5}$.

(b) The continuous acquisition of instrument and engineering data during planetary encounters at a rate of 3600 b/s and an effective bit error rate of $\leq 5 \times 10^{-5}$.

(c) The acquisition and transmission of imaging data during planetary encounters at a maximum rate of 108 kb/ s and a bit error rate of $\leq 5 \times 10^{-3}$. When 108-kb/s real-time transmission is not possible, it is required to store imaging data at 108 kb/ s (for, later transmission at lower rates) or transmit real-time imaging data at one of four selectable lower rates.

Spacecraft Data System Mechanization. The functions of the MJS77 spacecraft data system are to collect and format data from the science payload and spacecraft engineering sensors, perform special-purpose processing (data editing, simple compression and source error protection coding), provide temporary data storage for later non-real-time transmission, and generate control signals to regulate the overall science payload data acquisition process.

Prior to and including Mariner 9, the Mariner data systems were characterized by a totally hardwired logic design capable of generating a fixed number of telemetry modes. Power and mass limitations were instrumental in constraining the number of modes available. Further, this type of implementation required rather early definition of instrument data rates associated with each mode. Once incorporated into the hardware design, changing these requirements was costly. It was apparent that a similar approach for MJS77 would neither be adequate nor practical because the payload had a greater number of instruments and required different data modes for different mission phases. The capability was also needed to adapt to unforeseen scientific opportunities and upgraded ground facilities during the four-year mission lifetime. Accordingly, the MJS77 data system was structured to be essentially fully reprogrammable in flight.

The heart of the data system, the FDS, consists of a highly redundant special-purpose computer. It is constructed predominantly of CMOS logic allowing implementation within low power (16.8-W) and minimum mass (12-kg) constraints. (As a point of reference, it is estimated that a hardwired TTL design capable of generating only the set of telemetry modes defined to date would consume 60 watts and require 27 kg!)

Payload sequencing and data format generation are controlled by programs stored within the computer's memory. Acting upon these programs, the computer issues both serial and pulse commands to each science instrument. Each of two 4096 X 16 bit memories is sufficient to contain at least two separate programs at all times. This provides for expedient transitions between telemetry modes without significantly interrupting the data acquisition and transmission process. Programs required for various phases of the mission will be transmitted to the spacecraft as the mission progresses.

At the present time the need for more than 35 different programs has been determined (Table 1). New programs may be written to accommodate changing scientific priorities or to aid in the diagnosis of in-flight anomalies should they occur. It is also possible to maintain this design to support future missions with significantly different payloads and data return requirements.

The spacecraft's data storage device, a tape recorder based on the Viking Orbiter design, permits acquisition of full-resolution imaging data when real-time transmission is not possible and provides for the storage of science and engineering data during periods when earth communications are interrupted. It features a storage capacity of 5.5×10^8 bits (roughly the equivalent of 95 full-resolution images), two record rates and four playback rates. Telemetry modes are available which permit transmission of playback data only or playback data together with real-time nonimaging science and engineering data.

The MJS77 telemetry formats have been organized to adopt features providing overall simplification of the ground data reduction process. Some of the more important resulting characteristics are: the grouping of data within a particular format into 8-bit or multiples of 8-bit bytes, having all data from a given instrument occur at the same place with a given format, the adoption of a 32-bit synchronization word, the insertion of a nonambiguous time identification word and the transmission of all data with the most significant bit first.

The Microwave Channel. After being formatted and assembled for transmission, the spacecraft data is delivered to the telecommunication subsystems of the spacecraft. There it is coupled to the microwave channel to Earth. All data transmitted is coded using a convolutional code of constraint length 7 and rate 1/2. The data is biphase-modulated on a single subcarrier and phase-modulated on the microwave carrier.

As stated earlier, all cruise phase data requires the same channel quality (bit error rate $\leq 5 \times 10^{-5}$), and data rates are adjusted to maintain that quality throughout the cruise phase of the mission. During the planetary encounter phases, however, there are two different classes of data to transmit with different data quality requirements. Since the imaging data is by far the bulk of the channel, it is desirable to operate the entire channel at a bit error rate of 5×10^{-3} or less as it requires. An error correcting code is then needed to improve the quality of the other science instrument and engineering data to a bit error rate of 5×10^{-5} or less. Since the error correcting code need be applied to only a small percentage of the total data in the channel, the efficiency of the code is not critical. The main criterion is that it be a simple code since it is ultimately concatenated with the convolutional code mentioned earlier. The simpler the code, the more easily it may be coded and decoded. One of the simplest codes available for such application is the Golay (24, 12) code discovered by Marcel Golay in 1949.[2]

The Golay (24, 12) code requires partitioning the binary data to be encoded into 12-bit blocks. To each of these blocks is added 12 paritycheck bits making a codeword of 24 bits (and a code rate of 1/2). The power of this code resides in the fact that, with suitable decoding, any pattern of 3 or fewer channel bit errors occurring within a codeword can be perfectly corrected. Any pattern of 4 errors within a codeword can be detected as erroneous, although correction of 4 errors is not usually possible. (Baumert and McEliece[3] have found techniques of correcting many patterns of 4 errors occurring within a codeword for certain channels.) To illustrate this code consider the following.

Assume that the Golay (24, 12) code is used to transmit data through a channel with a bit error probability of p. Also, assume that the bit errors are random and independent within the channel (as would be the case for an uncoded channel). Then any codeword with 3 or fewer errors will be corrected and any codeword with 4 or greater errors will be erroneously received. The probability of making a codeword error, P_{WE}, is simply the probability of having 4 or more bit errors in a codeword.

Hence

$$P_{WE} = 1 - \sum_{k=0}^{3} \frac{24!}{k!\,(24-k)!} p^k (1-p)^{24-k} \qquad (1)$$

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[2] The (24, 12) Golay code is an extension of the (23, 12) version which has enjoyed extensive discussion in the literature. The only difference between the two is that an additional overall parity bit is added to the (24, 12) version.

[3] Baumert, L. D. , and McEliece, R. J. , “A Golay-Viterbi Concatenated Coding Scheme for MJSI77, 11 Technical Report 32- 1526, Vol. XVIII, Jet Propulsion Laboratory, Pasadena, Calif. , Dec. 15, 1973.

The relation in (1) allows equating the Golay codeword error rate to the channel bit error rate for random and independent bit errors. Now observe that

$$\frac{\text{probability of greater than 4 errors per codeword}}{\text{probability of exactly 4 errors per codeword}} = \frac{1 - \sum_{k=0}^{4} \frac{24!}{k!\,(24-k)!} p^{k} (1-p)^{24-k}}{\frac{24!}{4!\,20!} p^{4} (1-p)^{20}} \tag{2}$$

$$\leq 0.0205 \text{ if } p \leq 0.005$$

Equation (2) shows that for $p \leq 0.005$, nearly all codeword errors contain precisely 4 bit errors. Since we assumed that 4 bit errors cannot be corrected in a codeword, these errors would remain after Golay decoding and, there being 24 bits per codeword, almost all erroneous codewords would have 1/6 of the 24 bits in error. The resultant bit error rate for the Golay decoded data, p*, can then be approximated as

$$p^* \approx \frac{1}{6} P_{WE}$$

$$p^* \approx \frac{1}{6}\left[1 - \sum_{k=0}^{3} \frac{24!}{k!\,(24-k)!} p^{k} (1-p)^{24-k}\right] \tag{3}$$

for $p \leq 0.005$

In the example above, the bit errors in the channel were assumed random and independent. But with a convolutional coded channel, as in MJS77, the bit errors occur in bursts with random lengths. If a burst of 4 or greater bit errors occurred within a codeword, that codeword would not be correctable. In order to reduce the likelihood that a single error burst would destroy a codeword, the Golay coded data is interleaved such that successive bits of a codeword are not adjacent to each other in the data stream transmitted through the channel. The number of separation bits between each codeword bit is referred to as the interleaving depth. The greater the interleaving depth, the longer a single burst must be to cause 4 or more errors in a codeword.

For example, with an interleaving depth of 36, a single error burst must be 3 X 36 + 1 = 109 bits long before a codeword error could occur. It is interesting to note that in order to “whiten” the errors of a bursty channel to the extent that they would appear truly random and independent would require an interleaving depth of infinity. However, even with a moderate interleaving depth it is possible to closely approach the performance indicated in Eq. (3). The task of analyzing the interleaving depth needed for the MJS77 telemetry design was completed by performing laboratory simulation of the concatenated-coded link. A commercially available convolutional decoder was used and various interleaving depths employed for the simulation. A summary of the performance (p* versus p) is shown in

Fig. 2. After examination of that data and consideration of efficient hardware designs, an interleaving depth of 36 was chosen for the MJS77 design.

The performance to be realized from the MJS77 telemetry link is a function of many parameters, including transmitter power, antenna gains, noise temperature and trajectory selection. Although the final values for many of the link parameters are not known at this time, it is still possible to estimate the link performance expected for the nominal mission. This performance appears in Fig. 3, which shows X-band and S-band data rates versus spacecraft range for encounter and cruise quality requirements, respectively.

Concluding Remarks. This paper has discussed the major attributes of the MJS77 telemetry system design. While aimed at meeting rather specific MJS77 requirements, the architecture of the design is structured to be directly applicable to future Mariner-class outer-planet missions. The design represents a significant increase in capability and flexibility and includes a fully programmable data handling computer on-board the spacecraft and a single-channel, convolutional-coded, microwave link. Source error correction coding is performed on subsets of the total data stream to meet varying data quality requirements of the payload. This flexibility allows upgrading of the total mission's data return as improvements in ground facilities occur. This is of particular importance for outer-planet missions where spacecraft operations may extend well beyond five years.

Finally, a sizeable effort was made to integrate the various elements of the system to afford an efficient match between ground and spacecraft capabilities. This effort extended from the initial acquisition of data from the science payload to the final display of the data to users. In a total system sense, the MJS77 telemetry system design represents the largest single extension in interplanetary communications capability undertaken in recent years.

Table 1. Summary of principal MJS77 telemetry modes

Data type	Normal transmission frequency	Data rate	Comments
Real-time engineering only	S-band	1200 b/s	High rate engineering used during launch, memory readouts and anomaly diagnosis
	S-band	40 b/s	Normal rate engineering transmitted at S-band during encounter phases
Real-time cruise science and engineering	S-band S-band S-band S-band S-band S-band	2560 b/s 1280 b/s 640 b/s 320 b/s 160 b/s 80 b/s	Cruise data rate in use selected to match prevailing link capability. Engineering data at 40 b/s included in highest three cruise rates. Engineering data at 10 b/s included in lowest three cruise rates
Real-time encounter science and engineering	X-band	115. 2 kb/s	Full rate, full resolution imaging[a]
	X-band	89. 6 kb/s	3/4 edited imaging[a]
	X-band	67. 2 kb/s	2:1 reduced rate imaging[a]
	X-band	44. 8 kb/s	3:1 reduced rate or 1/3 edited imaging[a]
	X-band	29. 8 kb/s	5:1 reduced rate or 1/5 edited imaging[a]
	X-band	19. 2 kb/s	10:1 reduced rate or 1/10 editing imaging[a]
	X-band	7. 2 kb/s	Encounter nonimaging science and engineering at 3. 6 kb/s coded to 7. 2 kb/s
Real-time non-imaging encounter science, engineering and playback	X-band	67. 2 kb/s	Playback rate = 57. 6 kb/s
	X-band	44. 8 kb/s	Playback rate = 33. 6 kb/s
Playback only	X-band S-band	21. 6 kb/s 7. 2 kb/s	

[a]Coded encounter nonimaging science and engineering at 7. 2 kb/s included.

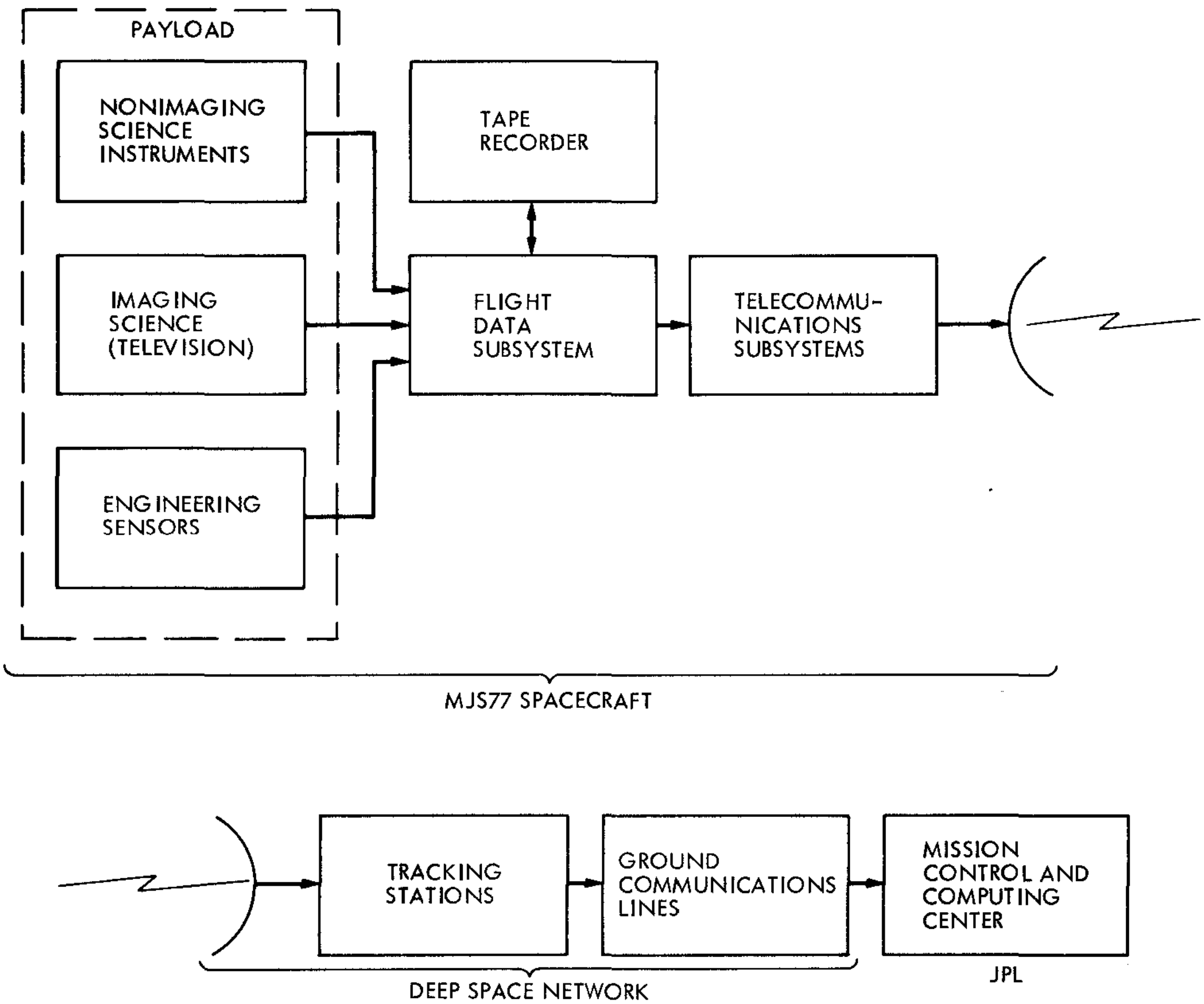

Fig. 1. MJS77 telemetry system block diagram

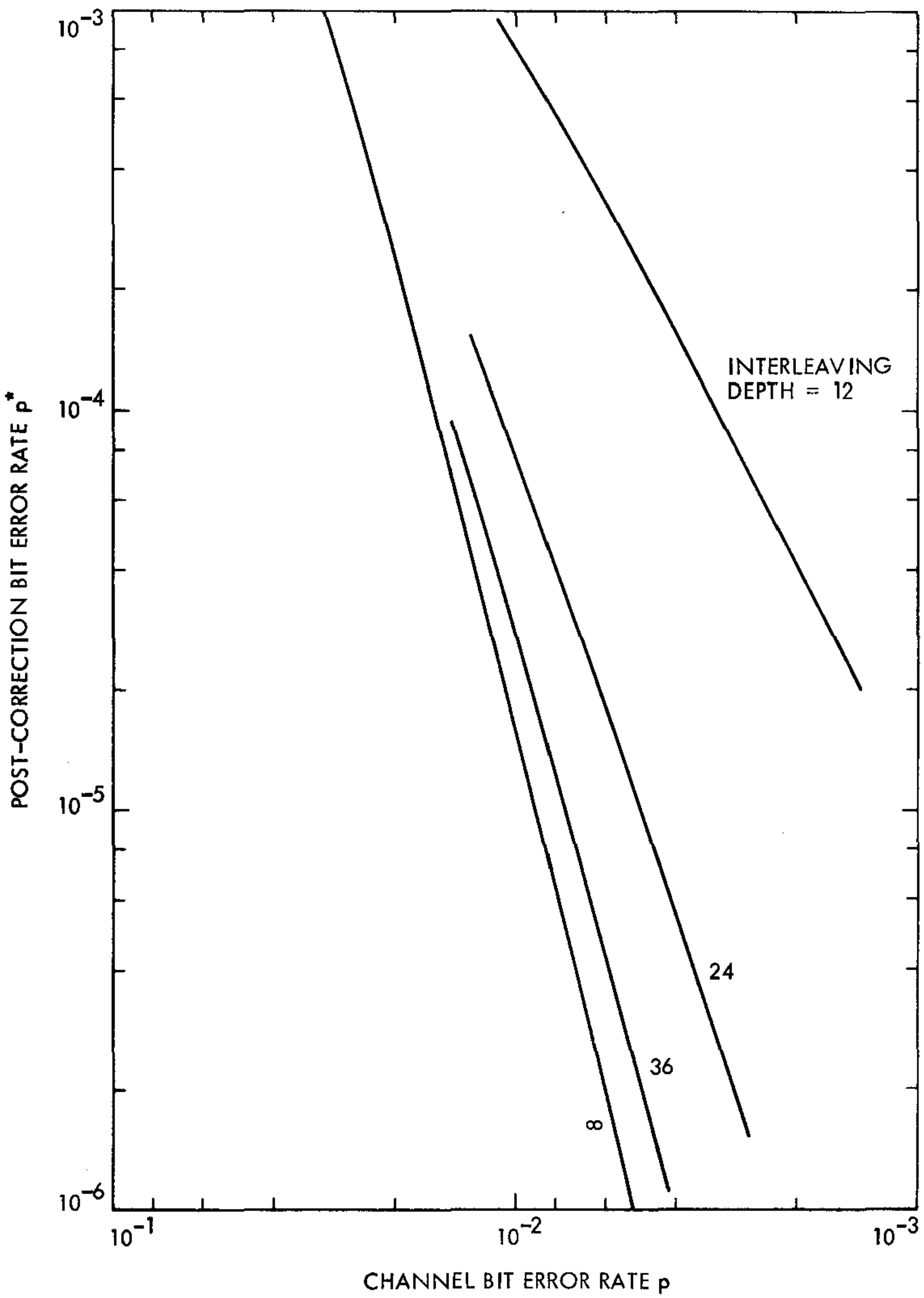

Fig. 2. Error correction performance of MJS77 concatenated coding

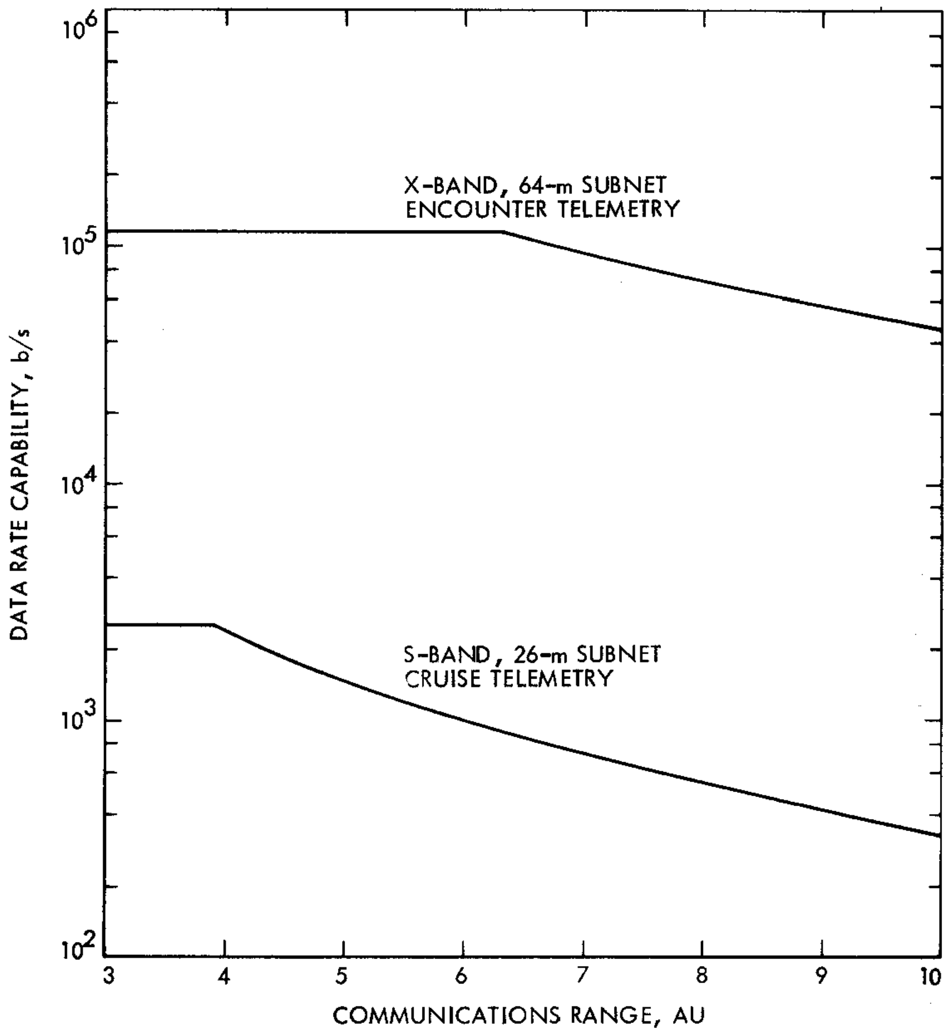

Fig. 3. Nominal data rate capability of the MSS77 telemetry system