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ABSTRACT

An initial communications system design is described that is suitable for a manned twilight Mars flyby mission in 1975. The mission profile assumed is one which provides an Earth-Spacecraft distance at encounter of 0.8 A.U. and a maximum distance of 3.2 A.U. Near Mars encounter several probes are released from the spacecraft and are designed to either land or impact on the Martian surface.

The communications design presented considers the spacecraft-Earth, Earth-spacecraft and probe-spacecraft communications links. The design is generally predicated on present day techniques and is considered to be conservative. Wherever appropriate, trade-offs between antenna size and transmitter output power are presented.

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DATE: July 29, 1966

FROM: R. K. Chen
R. L. Selden

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TECHNICAL MEMORANDUM

I. Introduction

This memorandum contains a description of an initial communication system design that would be suitable for use on a manned spacecraft designed for planetary flyby missions. The mission profile assumed is a twilight flyby of the planet Mars during 1975 where the spacecraft to Earth distance at encounter is 0.8 A.U (6.4×10^7 nm) and 3.2 A.U. (2.56×10^8 nm) at maximum distance.

In the vicinity of Mars, shortly before encounter, several probes are released from the manned vehicle and are either landed on the Martian surface (e.g., automated biological laboratory (ABL) and a geophysical laboratory (Surveyor-like)) or impact the Martian surface (e.g. atmospheric and photographic (Ranger-like) probes). In addition to the probe deployment near encounter, the spacecraft will be equipped with a large telescope that will be used for picture taking, probe targeting, and possibly probe tracking.

The communication requirement assumed for the system design is to provide the manned spacecraft with a transmission capability to earth of at least one megabit per second at encounter. The spacecraft would also have the capability of receiving some or all of the probe data which would be retransmitted to Earth. Any remaining probe data would be transmitted to Earth directly.

II. Spacecraft-Earth Communications Link

Several prudent assumptions can be made at the outset in the design of the Spacecraft-Earth link. Among these are:

(1) The earth-based deep-space tracking network will be similar to that which exists today. The network by 1975 is assumed to be updated with at least three 210' diameter antenna systems similar to the one now in operation at the JPL facility at

[redacted]

Goldstone, California. All stations are assumed to be equipped with cooled maser rf amplifiers, exhibiting a maximum system noise temperature of 50°K. (This is well within the present state-of-the-art and is a conservative assumption.)

(2) The frequencies used will be in the S-band (2100-2300 MHz).

(3) The system will be of the "unified" type similar to that used for deep space unmanned vehicles and Apollo.

(4) The miscellaneous losses in the ground network and the spacecraft (including modulation and demodulation losses) are assumed to be 10dB.

(5) The desired maximum bit error for the data received at Earth is 10^{-3}.

The assumed parameters for subsequent calculations are summarized in Table 1.

Using the one-way transmission equation

$$\frac{S}{N} = \frac{P_t \ G_t \ G_r}{K \ T_{eff} \ B \ L_{fs} \ L_{syst}}$$

where: S/N = signal-to-noise ratio

P_t = transmitter power

G_t = transmitter antenna power gain

G_r = receiver antenna power gain

K = Boltzman's constant

T_{eff} = receiving system effective noise temperature

B = bandwidth

L_{fs} = free space path loss

L_{syst} = miscellaneous system losses and the assumptions made, the antenna gain-transmitter power product (G_tP_t) required for transmitting 10^6 bps from the manned spacecraft to Earth during encounter is 65.6 dbw. Some of the possible spacecraft antenna size and transmitter power combinations are:

Antenna Size	Antenna Gain (2300 Mc)	Transmitter Power
10 ft.	34 db	1450 watts
15 ft.	38 db	575 watts
20 ft.	40 db	363 watts
30 ft.	44 db	145 watts

The primary tradeoff for determining the antenna size and RF power combination to be used on the spacecraft is to minimize the weight, i.e., does a 30' antenna and 145 watt transmitter with its prime power supply weigh more than a 20' antenna system and 363 watt transmitter.

A few comments are in order here relative to the size of the antenna on the spacecraft. The antenna can be of light weight construction and deployed after injection into the Mars flyby orbit has been accomplished. Typical weight of a 30' antenna is estimated to be 200-400 pounds (a 200 pound, 30' reflector is being considered for the Advanced Technology Satellite (ATS) program). The erectable 10' antenna which will be used on the lunar surface in the Apollo program weighs only 15 pounds.

In addition to reducing the amount of power required for the spacecraft-to-Earth communications system, the advantage of using the largest practicable antenna on the spacecraft is to increase the Earth-to-spacecraft communications capability. The effect of spacecraft antenna sizes on the Earth-to-spacecraft communications capability during Mars encounter is shown as follows.

Antenna Size	Communications capability	
	PCM System*	Conventional FM System (IF Bandwidth)
10 ft.	1×10^7 bps	5.37×10^6 Hz
15 ft.	2.7×10^7 bps	1.35×10^7 Hz
20 ft.	4.3×10^7 bps	2.14×10^7 Hz
30 ft.	1×10^8 bps	5.37×10^7 Hz

At maximum distance from Earth the system capability would be reduced by a factor of 16. At first glance, enhancement of the Earth to spacecraft link does not seem to be a big advantage. However, in a mission of this duration, approximately two years, it would be highly desirable to provide crew entertainment (e.g. television) from Earth.

An alternate approach to this system design is to assume a rigid antenna construction whose size is determined by the maximum diameter structure that can be stacked within the launch vehicle. Prime power is then allocated based on the overall spacecraft power budget. An example of the systems capabilities that would be available based on this design approach would be as follows:

Maximum Antenna Diameter	20'
Antenna Gain	+40dB
Prime Spacecraft Power Allocated to Transmission System	2.0kw
Transmitter Output Power at 2.3GHz	0.65kw (28.1 dBw)
Antenna Gain Transmitter Power (G_tP_t)	+68.1dBw
Data rate capability at encounter	1.85×10^6 Bits/Second

III. Communication Systems with Probes

Various probes have been suggested for use during the manned Mars flyby mission and they present different requirements for getting the scientific information back to the manned spacecraft or to the Earth. The basic differences of all the probe designs from the communications viewpoint are twofold, the information rate and the life time of the probes. In general, it is desirable to keep the communications system design on the

*Bit error rate of 1×10^{-3}

probe as simple as possible. To facilitate this design approach requires that the spacecraft system(s) used to communicate with the probes employ high gain antenna(s) and low noise receiving systems.

The relative advantages of collecting the probe information by relay from the manned spacecraft or directly to the Earth can be estimated by considering the differences in receiving capabilities of the spacecraft and the Earth and the communication distances involved. For any probe design, calculations can be made to determine the "break-even" point in terms of "days-after-encounter" where the receiving capability of the manned spacecraft and the Earth stations are equal for different receiving system designs on the manned spacecraft. Before the break-even point, the spacecraft would have higher receiving capability than the Earth, and after the break-even point the reverse would be the case. Using the parameters given in Table I for the receiving systems, the break-even points, calculated for several antenna sizes on the manned spacecraft, are as follows:

Spacecraft Antenna Size	Break-even Point (Days after encounter)
10 ft.	3 days
15 ft.	5 days
20 ft.	6 days
30 ft.	10 days

It should be noted that the above comparison is based on the utilization of S-band frequencies on both the probe-spacecraft and probe-Earth links. Inasmuch as there is no requirement for the probe-spacecraft link to remain in the S-band frequencies, a change to C-band for this transmission link would increase the break-even point shown above by a factor of two (e.g. a 20 foot diameter spacecraft antenna would provide an enhanced receiving capability for about 12 days after encounter.)

Three representative probes presenting different information rate and life time requirements are used in the following to give some indication of the communication systems requirements for probe communications. These probes are briefly described as follows:

A. Ranger-type Photographic Probe

The probe is assumed to be a Ranger-type vehicle which would be launched four or five days prior to Mars encounter and precede the spacecraft time of encounter by approximately one hour. Information transmitted is assumed to be analog television with a baseband of 300 KHz during a ten minute period prior to the destruction of the probe in the Martian atmosphere.

B. Lander Photographic Probe

This probe is assumed to be a lander similar to the Russian Luna 9 vehicle. The camera on the lander would survey the Martian terrain for a period of 12 hours after touchdown during the Martian day. It is desirable to obtain a 360° panoramic view of the surrounding terrain at least once per hour so that similar pictures will be taken throughout the Martian day at various sun angles. It is expected that the lander would lose its line-of-sight with the flyby spacecraft shortly after touchdown, therefore, the picture information would need to be recorded on video tape to be transmitted approximately 12 hours after touchdown when line-of-sight is reestablished with the spacecraft. Video information is continuously recorded for twelve hours at a 420 Hz rate and is assumed to be transmitted to the spacecraft at twice the recording rate.

C. Long Life Landers

It is anticipated that certain types of long life lander probes, because of the nature of their intended scientific experiments, would not have a requirement to transmit at a high information rate. These landers would include the Automated Biological Laboratory (ABL) and the Geophysical Laboratory. It is assumed that the landers would continuously collect information at the rate of 250 bits per second (bps). Since approximately 50% of the time the landers will be out of sight of Earth, some of the information would need to be recorded. Transmission to Earth then, would be at twice the recording rate. A relatively simple lander design could be mechanized to provide a long duration communication capability; its prime power could be obtained from a solar array source.

Table II summarizes some of the characteristics of the probes which are pertinent to the communication system designs. The receiving system on the spacecraft is assumed to have a 20 ft. antenna and an uncooled parametric amplifier system which has an effective system noise temperature of 300°K.

For the purpose of this memorandum, the video information from the photographic probes will be assumed to be transmitted by a conventional FM method, and the data from the long life lander probes will be transmitted by a coherent PCM method. In order to obtain the desired baseband performances, the design of the FM system would be as follows.

	Baseband SNR	Modulation Index	IF SNR	IF Bandwidth
Ranger Photographic Probe	40 db p-p/rms	3.5	10db	3.0 MHz
Lander Photographic Probe	40 db p-p/rms	3.5	10db	10.0 KHz

Table II provides the performance calculations from the probes to the spacecraft or Earth receiving stations. The criteria established is the combined transmitter power and transmitting antenna gain or effective radiated power (ERP) requirements of the probes. Various combinations of these two parameters can be made, the following represent a reasonable set of numbers:

	ERP Required	Antenna Size	Antenna Beamwidth	Transmitter Power
Ranger Photographic Probe	32 dbw	1 ft.	32°	100 w
Lander Photographic Probe	30.8 dbw	1 ft.	32°	50 w
Long Life Lander Probe	38.8 dbw	4 ft.	8°	20 w

Other probes, such as an atmospheric and a surface sample retriever probe, may also be incorporated in a Manned Mars Flyby mission, but are not discussed here. However, it is reasonable to assume that the information rate from these probes would be less than the probes discussed above, and the spacecraft or Earth would be able to receive them with the communication systems reviewed here.

The probe deployment strategy or sequence was not considered in the discussion. The implication is that the probes will be deployed sequentially so that the same communication system on the spacecraft would be able to communicate with the probes on a time sharing basis. It is highly probable that two separate antenna systems would be needed on the spacecraft in order to communicate with the Earth and the probes simultaneously. In addition to providing simultaneous probe-spacecraft and spacecraft-Earth communications, two antenna systems would provide redundancy in the antenna system.

It should be noted that directional antennas are used for all the probes, therefore, antenna pointing capabilities would be needed in all cases with the exception of the Ranger Photographic Probe. The Ranger probe would be active for a limited duration (10 minutes) and its angular relation with respect to the spacecraft is well within the beamwidth of the antenna. The antenna pointing of the lander probes could be accomplished by command links from the spacecraft or Earth. The capabilities of the command links to the lander probes with omnidirectional command receive antennas are calculated in Table IV. It is seen that the command capability from Spacecraft to Lander Photographic Probe is 630 bits per second and from Earth to Long Life Lander Probe is 115 bps.

IV. Summary

A summary of spacecraft and probe system parameters is provided in Table V. Note that all of these designs use S-band frequencies, which would allow redundancy in the required communications equipment. Additionally, the design approach used here is conservative. FM receiver thresholds are based on present day conventional discriminators, on board data processing (e.g., compression) and coded communications techniques are not included. Improvements in performance could be obtained by using some of these techniques, such as FM with feedback receivers and orthogonal codes for digital data transmission, at the expense of design and equipment complexity. Increasing the operating frequencies from S-band to C-band would also improve the communications performance by approximately 6 db.

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Attachments
Tables I-V

TABLE I

Communication System Parameters Assumed for

Earth - Spacecraft Links Calculations

Earth transmitter power	100 Kw
Earth Antenna gain, transmit (2100 GHz)	60.5 db
receive (2300 GHz)	61.0 db
Path loss (0.8 A.U. at 2.3 GHz)	261.2 db
Ground receiver system noise spectral density (T_{eff}=50°K)	-211.6 dbw/Hz
Spacecraft receiver system noise spectral density (uncooled parametric amplifier, T_{eff}=300°K)	-203.8 dbw/Hz
Miscellaneous system losses	10 db
Signal-to-noise ratio required	
coherent PSK modulation, 10^{-3} bit error rate (in a bit rate bandwidth)	7 db
conventional FM (in an I.F. bandwidth)	10 db

	Ranger Photographic Probe	Lander Photographic Probe	Long Life Lander Probe
Frame rate	0.4 frame/sec	1 frame/hour	---
Horizontal Resolution	1200 elements	6000 elements	---
Vertical Resolution	1200 elements	500 elements	---
Video Bandwidth	300 KHz	840 Hz	---
Digital Data Rate	4.0×10^6 bps	11.0×10^3 bps	500 bps
S/N Required (Analog)	31 db rms/rms (40 db p-p/rms)	31 db rms/rms (40 db p-p/rms)	---
Digital Bit Error Rate (maximum allowed)	10^{-3}	10^{-3}	10^{-3}
Information Transmitted to:	Spacecraft	Spacecraft	Earth
Life Time (communication)	10 minutes	one day	six months
Receiving Antenna Size	20 ft. (40 db gain)	20 ft. (40 db gain)	210 ft. (61 db gain)
Receiving System Noise Temperature	300°K	300°K	50°K
Maximum Distance	20,000 nm	300,000 nm	2.3 A.U.

TABLE II - Summary of Probe Characteristics for Communications

	Ranger Photographic Probe	Lander Photographic Probe	Long Life Lander Probe
Receiving System Noise Power per Hz	-203.8 dbw/Hz	-203.8 dbw/Hz	-211.6 dbw/Hz
Noise Bandwidth	64.8 db (3 MHz)	40.0 db (10 kHz)	27.0 db (500 Hz)
Total Noise Power	-139.0 dbw	-163.8 dbw	-184.6 dbw
Signal to Noise Ratio Required	10.0 db	10.0 db	7.0 db
Receiving Signal Power Required	-129.0 dbw	-153.8 dbw	-177.6 dbw
Path Loss	-191.0 db (20K.N.mi.)	-214.6 db (300 K.N.mi.)	-270.4 db (2.3 AU)
Total System Losses	- 10.0 db	- 10.0 db	- 7.0 db
Receiving Antenna Gain	40.0 db	40.0 db	61.0 db
Net Loss	-161.0 db	-184.6 db	-216.4 db
ERP Required (Combined Transmitter Power and Transmitting Antenna Gain)	32 dbw	30.8 dbw	38.8 dbw

TABLE III - Performance Calculations for Probe Communications Systems

Probe to Spacecraft or Earth

	Lander Photographic Probe (From Spacecraft)	Long Life Lander Probe (From Earth)
Transmitter Power	25.6 dbw (363 watts)	50 dbw (100 KW)
Transmitting Antenna Gain	40.0 db	61.0 db
Path Loss	-214.6 db	-270.4 db
Receiving Antenna Gain	- 3.0 db	- 3.0 db
Total System Losses	- 10.0 db	- 7.0 db
Total Received Signal Power	-162.0 dbw	-169.4 dbw
Receiver System Noise Power per Hz	-200.0 dbw/Hz	-200.0 dbw/Hz
Signal to Noise Ratio Required (Coherent PCM for 10^{-5} Bit Error Rate)	10.0 db	10.0 db
Available Bandwidth	28 db or 630 bps	20.6 db or 115 bps

TABLE IV - Command Link Capabilities to Lander Probes from Spacecraft or Earth

	Spacecraft	Ranger Photo Probe	Lander Photo Probe	Long Life Lander Probe	Earth
Transmitter Power	363 w	100 w	50 w	20 w	100 Kw
Antenna Size	20 ft.	1 ft.	1 ft.	4 ft.	210 ft.
Receiver System Noise Temperature	300°K	---	725°K	725°K	50°K
Data Transmission to Earth	10^6 bps (encounter) 62.5 Kbps (Maximum distance)	---	---	500 bps (Maximum distance)	---
Data Received From Earth	4.3×10^7 bps (encounter) 2.7×10^6 bps (Maximum distance)	---	---	115 bps (Maximum distance)	---
Data Transmission to Spacecraft	---	300 KHz video	840 Hz video	---	---
Data Received From Spacecraft	---	---	630 bps	---	---

TABLE V - Summary of Communications Parameters for Manned Mars Flyby Mission