IAA-L-0507

MARS RELAY SATELLITE: KEY TO ENABLING & ENHANCING LOW COST EXPLORATION MISSIONS

Rolf Hastrup[*], Robert Cesarone[**], Albert Miller[†], and Robert McOmber[‡]

ABSTRACT

Currently there is a renewed focus on Mars exploration both by NASA and the international community. This renewed interest appears to be manifesting itself in numerous low-cost missions employing small, lightweight elements. A formidable problem facing these low-cost missions is communications with Earth. Providing adequate direct-link performance has very significant impacts on spacecraft power, pointing, mass and overall complexity. Additionally, there are serious connectivity constraints, especially at higher latitudes. A Mars relay satellite can enable and enhance low-cost missions to Mars, and the multi-mission application of a Mars relay satellite is especially attractive. Key attributes of a Mars relay nelwork architecture are presented, including: *in-situ* and Mars-Earth connectivity, performance and operational benefits for the mission elements and the Deep Space Network. In addition, the paper illustrates that a variety of orbits may be employed for relay support, including orbits also suitable for the multi-functional role of remote sensing.

INTRODUCTION

This paper is based on a portion of the studies that NASA's Office of Space Communications has been sponsoring to understand the efficient and effective utilization of planetary data relay networks to increase the science mission return, while concurrently reducing associated operational life-cycle costs. The Jet Propulsion laboratory has been serving as the project and contract manager for this effort. Stanford Telecommunications, Incorporated has been awarded a contract to deliver a study on Mars relay network technical analyses.

Recent renewed focus on Mars exploration by both NASA and the international community has led to a wide variety of proposed scientific missions. The thrust of this renewed interest is manifested in numerous low-cost missions which employ small, lightweight subsystems which implement advanced technologies such as integrated microcircuits and sophisticated software schemes. Candidate scenarios of potential international Mars missions were developed by the International Mars Exploration Working Group (IMEWG) in January, 1994.[1,2] An example scenario is shown in Figure 1.

A formidable task facing these low-cost missions is the transfer of telemetry, command, and scientific data to and from the spacecraft. If a direct communications link is proposed, link margin and data rate requirements place very significant constraints on spacecraft transmission power, antenna pointing, launch mass, and overall system complexity. Additionally, for flight systems at or near the. surface of Mars, serious connectivity constraints (especially at higher Martian latitudes) could significantly reduce the "Earth view" for up to many months at a time.

This paper discusses the role a Mars relay satellite (MRS) system could play in enabling and enhancing low-cost missions to Mars by overcoming the serious deficiencies of a direct link architecture., which are manifested by reduced scientific data rates and increased power and mass requirements for the

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scientific payload. The potential for a series of concurrent low-cost Mars exploration missions makes the multi-mission application of a Mars relay satellite. infrastructure especially attractive. Based on recent studies by NASA, a representative set of key characteristics has been compiled, and is summarized in Table 1, for potential Mars mission elements.[3,4] The data of Table 1 are believed to represent reasonable bounds for the concept development and tradeoff analyses which are discussed in this paper,

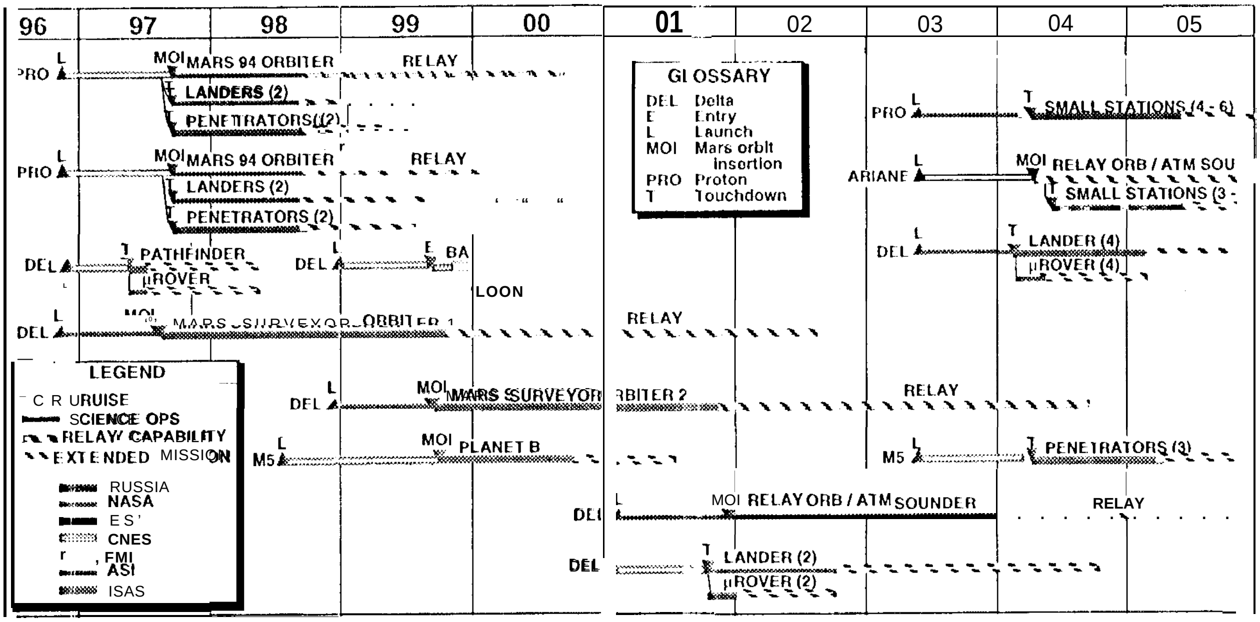

Figure 1. Example Mars Mission Set Scenario (IMEWG)

Table 1. Potential Supported Mission Element Characteristics

	Full Science Lander	Geoscience Lander and/ or Rover	Mini-Met Lander	Balloon	Penetrator
Science Instrumentation	Seismology Geoscience (1) (Incl. µrover) Meteorology	Geoscience (1) (Incl. µrover) Meteorology	Meteorology only	Meteorology Imaging and spectrometry	Meteorology Geochemistry
Lifetime at Mars	2 to 6 yr	1 to 12 mo	2 to 6 yr	1 to 12 mo	1 to 24 mo
Frequency of MRS contacts (per lander)	~1 /sol (2)	~1 /sol	~1 /mo (3)	~1/sol	~1 /sol
Data return volume (per lander)	10 Mb/sol	1 Mb/sol	1 Mb/mo	1 Mb/sol	1 Mb/sol
Command volume (per lander)	1 kb/sol	1 kb/sol	<100 b/sol	200 b/sol	200 b/sol

1) Geoscience includes: imaging, spectrometry, and chemical analysis
2) sol = Mars day (24.6 hr)
(3) Mini-met has limited power and utilizes infrequent communication periods

In the following paragraphs, the communications issues for Mars missions using a direct link with an Earth-based network are described. The comparable issues are discussed for a Mars relay network concept. The paper concludes with the. presentation of possible additional functions which could be performed on the relay platform, and conclusions relative to the advantages and disadvantages of using a Mars relay network to enable low-cost exploration missions.

DIRECT-LINK COMMUNICATIONS ISSUES

The reliance on direct-link communications between individual exploration mission elements at Mars and the ground antennas at Earth involves several potential constraints, which could significantly reduce science data return. These include connectivity constraints, telecommunications performance, and operations complexity. Each of these is briefly outlined below.

Connectivity Constraints

Mars' relational axis is inclined 25° from the ecliptic causing polar regions of Mars' surface to be out of view from Earth for many months at a time. This connectivity constraint is illustrated in Figure 2, for which an elevation mask of 20° is assumed for an element on Mars' surface. These connectivity constraints present particular limitations for direct-link polar exploration missions and global network missions involving high latitude stations. Note that loss of contact alternates between the North and South polar regions over the Earth-Mars synodic period of about 25 months.

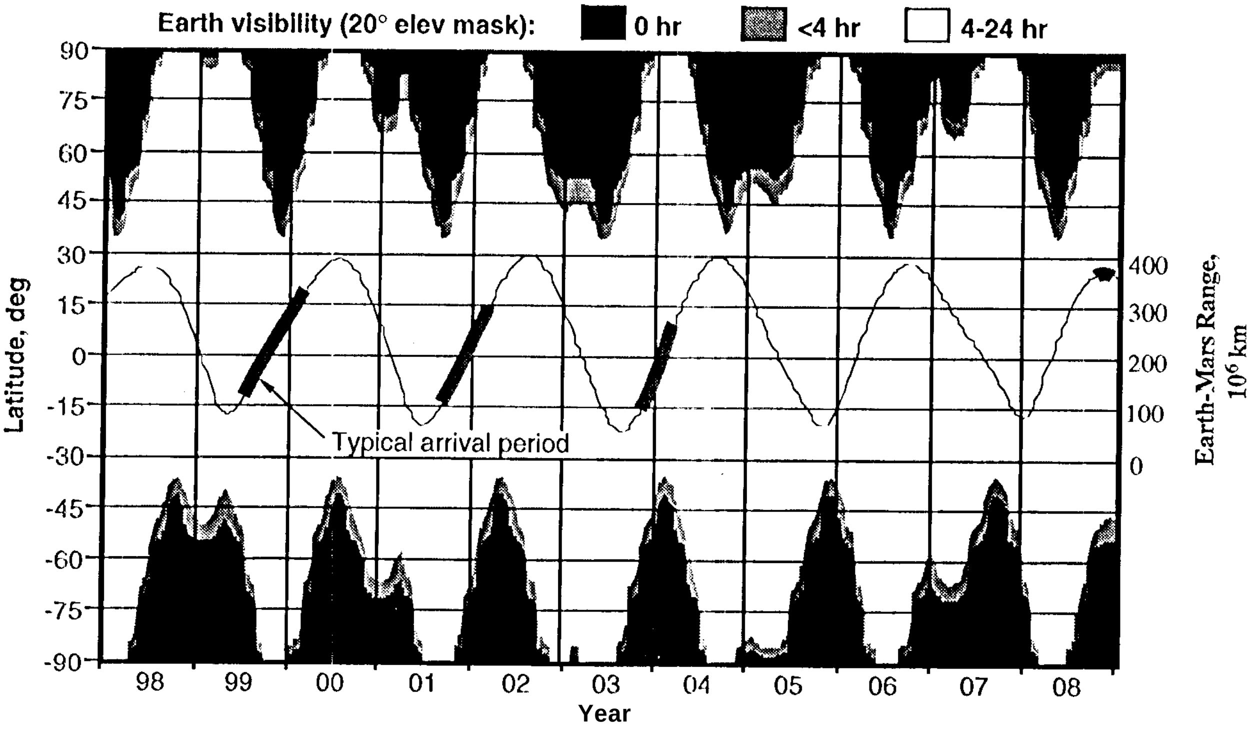

Figure 2. Mars-Earth Connectivity Constraints

Direct-Link Performance

The required performance for direct transmission from Mars at a specified data rate depends on the Mars-Earth range, radiated (RF) power, antenna gain of the transmitting and receiving stations, and the radio frequency band employed,

Figure 2 also depicts the variation of Mars-Earth range over the several synodic periods. Also shown are typical arrival windows for mission launch opportunities based on modest launch energy and arrival velocities ($C3 \leq 13\ km^2/s^2$, arrival $V_\infty \leq 8$ km/s). Typically, arrival is seen to occur after Mars-Earth closest approach, with communications range increasing as the mission progresses. Note that no arrival period is shown for 2005-06 because both the type I and II trajectories for that opportunity require very high launch energy ($C3 > 15\ km^2/s^2$).

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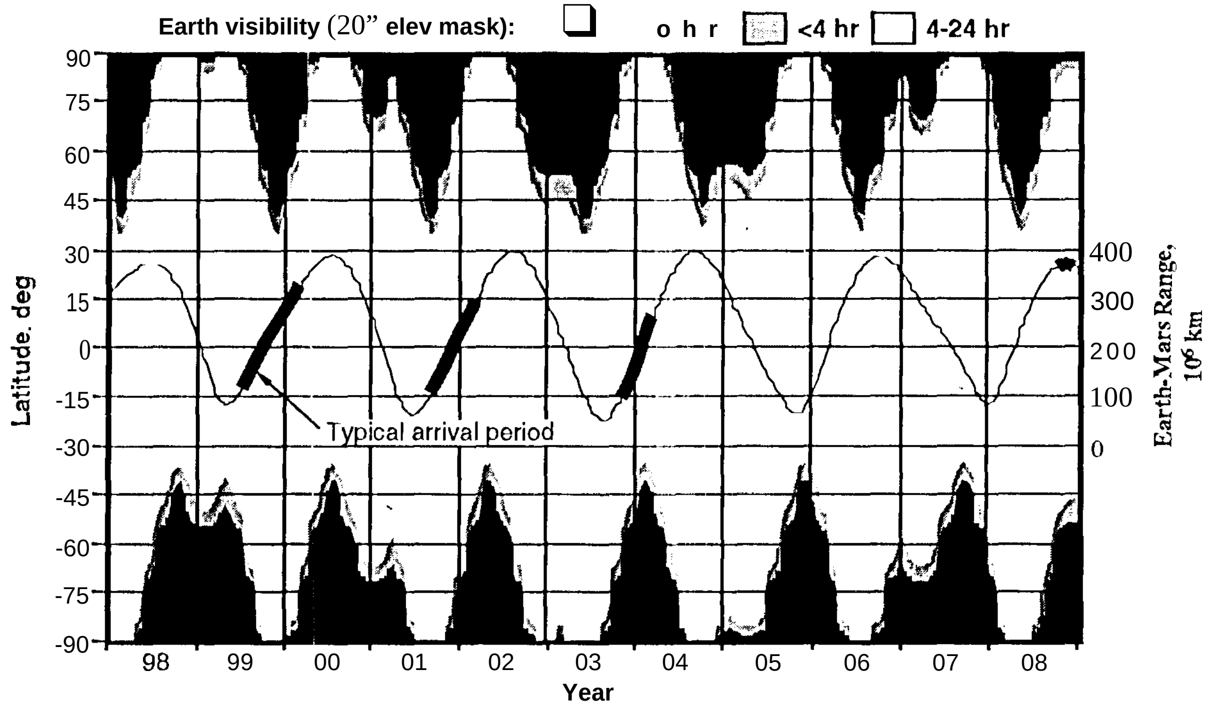

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A representative portion of the Mars-Earth direct link performance trade space is shown in Figure 3. Transmit RF power vs antenna gain are depicted for selected values of data rates and range. Antenna pointing accuracy for a fixed 1-dB pointing loss is also shown (dashed line). The data of Figure 3 are based on X band and a 34-m high efficiency (HEF) Deep Space Network receiving antenna. Use of a 70-m DSN antenna would provide approximately 6-dB improvement, or four times the data rate compared with a 34-m antenna. However, design for use of the 70-m antennas should only be considered for short term coverage (or contingency operations) during critical events because of limited availability. The Mars Pathfinder design point (13 W RF power, 24.9 dB boresight antenna gain) is indicated in Figure 3 for reference. Mars Pathfinder does plan to make limited use of the 70-m antenna subnet for the critical landing and post-landing sequences.

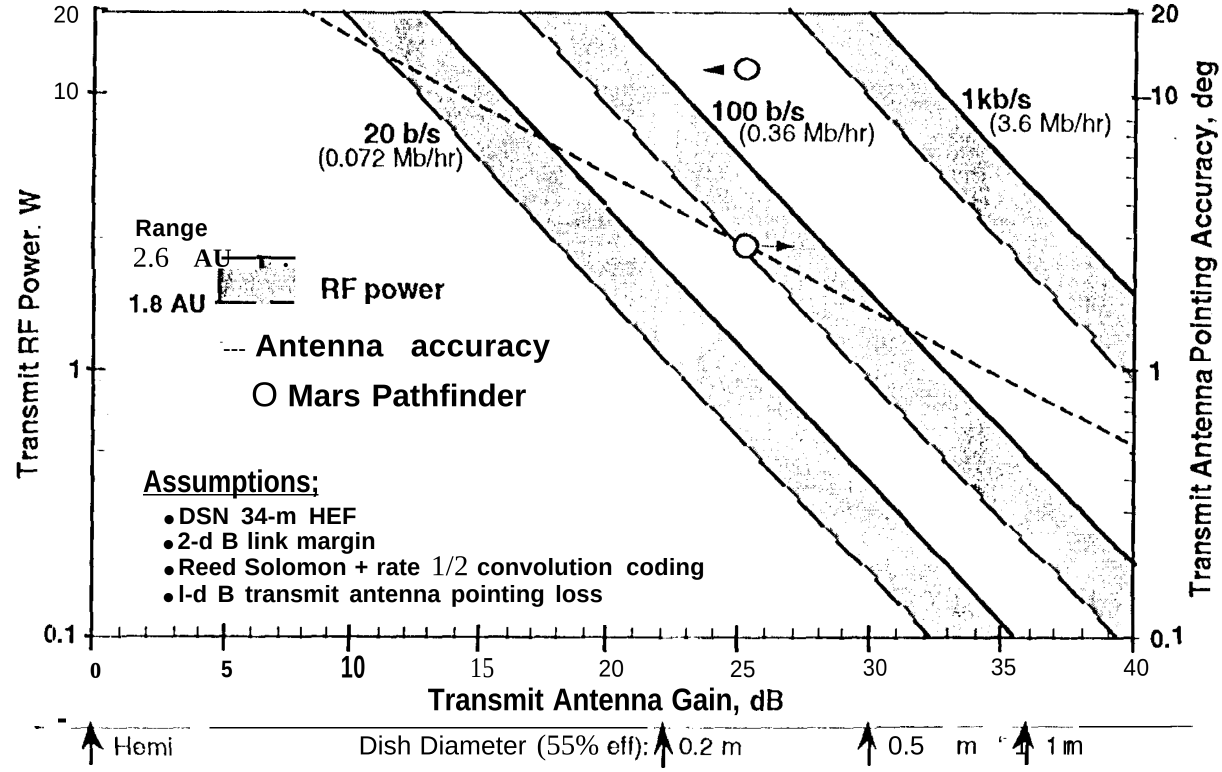


Figure 3. Mars-Earth Direct Link Performance Parameters (X band)

S band has been used for earlier Mars missions (e.g., Mariner 71 and Viking); however, X band provides approximately 11-dB improvement in link performance relative to S band, but X band requires a factor of 3 to 4 improvement in pointing accuracy to achieve this benefit. Ka-band downlink capability may be available in the future, and could provide 3- to 6-dB improvement over X band.

For X band, the communications input power can be expected to be about three times the transmit RF power indicated in Figure 3.

As indicated in Figure 3, even for missions with low data rates (- 100 b/s), use of a direct link with reasonable power levels requires that the transmitting antenna be designed to be pointed (either mechanically or electronically), which is an additional challenge when in the harsh environment of Mars' surface.

Direct-Link Operations

As indicated above, direct-link communications entails the operations burden of ensuring continued proper pointing of the antenna toward Earth. In addition, the power required to support direct-link communications typically is significant enough that it must be carefully accounted for in conducting spacecraft activities.

Mars-Earth direct-link communications requires that Earth tracking stations be scheduled to support each transmitting element. For multiple elements distributed over Mars' longitude, as in the case of a science network, this can result in substantial Earth tracking operations. In addition, critical activities and marginal performance could result in appreciable demands on the 70-m DSN subnet.

ENABLING AND **ENHANCING ATTRIBUTES OF A RELAY NETWORK**

Connectivity Benefits

Utilization of a Mars relay network can extend the regions of potential lander operations to the entire surface of Mars. Also, the MRS orbit can be tailored to enhance mission operations by ensuring contact with mission elements at desired times relative to the Mars day/night cycle.[5] End-to-end connectivity between the landers and Earth depends on both *in-situ* landers-MRS connectivity and MRS-Earth connectivity. By operating the MRS in a store-and-forward mode rather than a simple bent-pipe mode, the landers-MRS and MRS-Earth communications links become independent processes that can each be optimized for best overall mission performance.

In-situ connectivity from a lander to the MRS depends on both the lander position and the parameters of the MRS orbit (e.g., eccentricity, altitude, and inclination). In general, circular MRS orbits ensure greater uniformity of surface coverage with longer lander contact times provided by the higher altitude orbits. Figure 4 provides a comparison of contact time landers could expect for selected MRS orbit types. For each MRS orbit type, the figure illustrates minimum achieved contact over one sol to any surface point either across the entire surface of Mars or within the ± 45° latitude band. As indicated, not all orbits examined guarantee contact to all points on the surface of Mars each sol. Such gaps in coverage can significantly impact data storage requirements for landers as well as slow the operations for elements (such as surface rovers) requiring commands from Earth. In fact, for optimum rover operations, multiple MRS contacts per sol are desirable to enable timely cycles consisting of rover data return, Earth-based analysis, and commanding from Earth.[6] Many of the circular, sun-synchronous orbits listed in the figure provide such multiple contacts to every location on the surface of Mars.

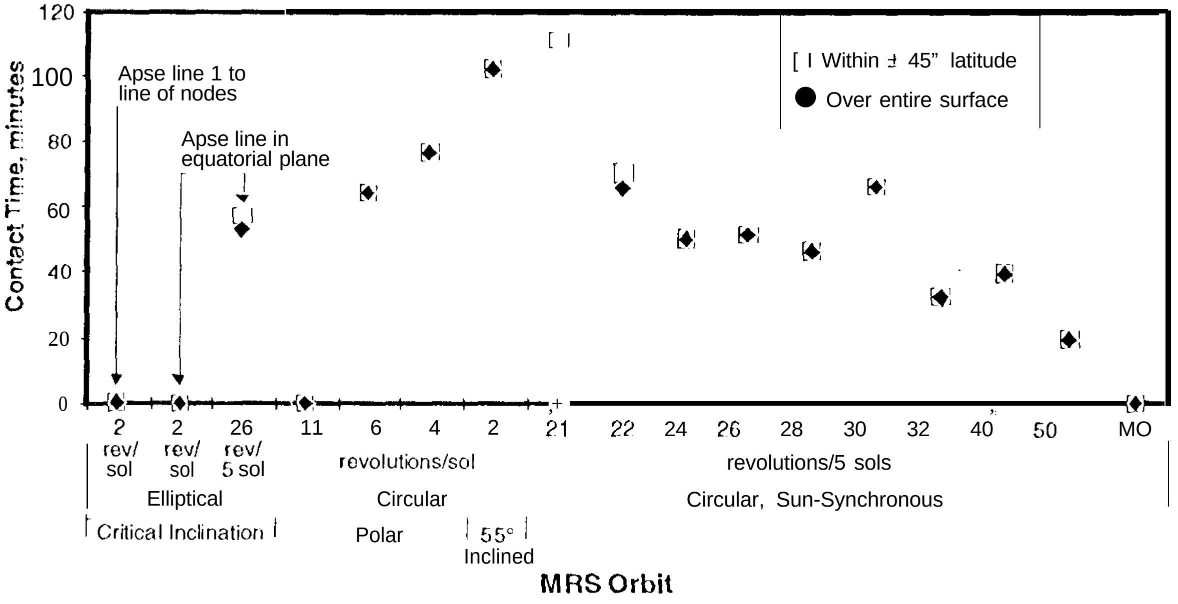


Figure 4. Surface Coverage Capability of Various Orbit Types

Table 2 illustrates the average contact time and number of contacts per sol achieved at various latitudes for several of the circular, sun-synchronous orbits under examination. The table confirms the multiple contacts per sol attainable with the 22- and 50-revolution per 5-sol orbits. The orbit planned for the Mars Observer (MO) mission is optimized for planetary imaging and does not guarantee contact to each point on the surface of Mars each sol but, over a 2-sol period, contact to any surface location on Mars is assured. While not optimum from a relay contact time and operations perspective, the MO orbit may provide a good compromise between the need for planetary imaging and data collection from a few landers on the surface of Mars.

Table 2. Communications Coverage Characteristics for Selected Sun-Synchronous Orbits

Orbit Type (Sun Synchronous)	**Minimum Contact Time/sol,** Averaged over 5 sols (Lander at 0°, 45°, 90°)	**Contacts per sol** **(1** Lander at 0°,45°, 90°)
MO/Mars Global Surveyor Orbit	4 min, 5 min, 75 min	1 per 2 sols, 1, 12
50 Revolution/5 sol Orbit	**20,35,** 140	2-3, 2-4, 10
22 **Revolution/5 sol Orbit**	130, 165,90	2-4, 34,4-5

Connectivity between the MRS and Earth is primarily limited by the frequency of occultations of the MRS-to-Earth link by Mars. In general, very low-altitude MRS orbits will experience some occultation each sol as the orbiter passes behind Mars as seen from the Earth. These outages do not prevent data collection by the orbiters as long as the store-and-forward capability described above is implemented; however, the outages do restrict the times at which data return to the Earth by the MRS can occur. Link occultations can be minimized or eliminated by using a circular, sun-synchronous orbit of sufficient altitude and having an ascending, node properly aligned with the day/night terminator on Mars. Such orbits, completing between 22 and 50 revolutions over a 5-sol period, maximize operational flexibility by greatly reducing constraints on MRS-Earth communications opportunities.

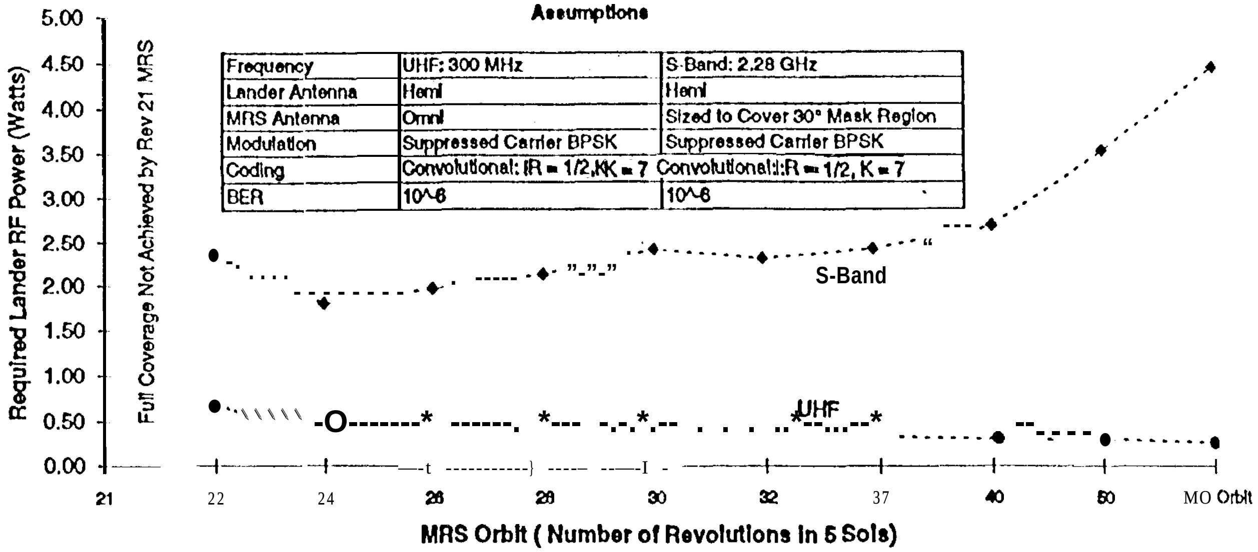
An additional factor impacting connectivity between the Mars and Earth is intervention of the sun. Near superior conjunction, communications between the. Mars and Earth may not be possible for from several days up to a week due to blockage/interference by the sun. The length of outage depends on the communications frequency, with shorter outages occurring for the higher frequencies.

Surface Element Performance Benefits

Very dramatic relaxation of the surface element communications system performance requirements is possible by the use of a Mars relay network and elimination of the Mars-Earth direct link. The communications range from landers to an MRS will be a factor of 20,000 to 200,000 times smaller, compared to the, maximum Mars-Earth range of -2.6 AU. Since achievable data rate varies as the square of communications range, the impact of this decrease in range on the lander implementation can be quite significant. While these performance differences impact both the forward and return communications paths, the. return path, with its higher data rates and constraints on available EIRP (effective isotropic radiated power), tends to drive the implementation, and is the subject of the discussions below.

Considering the lander-to-MRS link, Figure 5 shows the lander transmitted RF (radio frequency) power needed to assure data return of 10 Mb/sol, averaged over a 5-sol period, for a lander anywhere on the surface of Mars. The figure includes results for several circular, sun-synchronous orbits having ground tracks that repeat after 5 sols as well as the originally planned MO orbit. At UHF, it is possible to attain an average data return of 10 Mb/sol/lander using less than 0.5 W of lander RF power even though simple low-gain hemispherical or omnidirectional antennas are used on both the MRS and the landers. At S band, significantly more power is required for the landers even if a higher gain antenna is used on the MRS. In the figure, the MRS antenna for S band has been sized to provide. coverage to all lander locations which see the MRS at an elevation angle greater than 30°. For lower altitudes, it is the decrease in MRS antenna size (to provide increased beam width) that results in worse. performance for these cases.

Table 3 compares lander communications requirements using a relay link (from Figure 5) to the direct-to-Earth link requirements at a Mars-Earth range. of 1.88 AU. Note that the significant increase in required lander power and the high-gain lander antenna needed for direct-to-Earth communications both tend to increase. the amount of mass that must be delivered to the surface of Mars. Additionally, the requirement for antenna steering when no MRS is present has significant implementation and operations impacts. Finally, note that the 1.88 AU range used in the table is the median Mars-to-Earth distance.; to maintain communications performance at a range of -2.6 AU, a lander using direct communications to Earth requires approximately twice the listed power levels.



Frequency	UHF: 300 MHz	S-Band: 2.28 GHz
Lander Antenna	Hemi	Hemi
MRS Antenna	Omni	Sized to Cover 30° Mask Region
Modulation	Suppressed Carrier BPSK	Suppressed Carrier BPSK
Coding	Convolutional: R = 1/2, K = 7	Convolutional: R = 1/2, K = 7
BER	10^-6	10^-6

Figure 5. Required Surface Element-Transmit Power for Data Return via Relay Link

Table 3. Relay vs Direct-to-Earth Lander Telecommunications Performance Comparison

Parameter	Relay	Direct to Earth
RF transmit power	<0.5 W (UHF)	-5.5 W (X band)
Transmitter input power	-1 W	~15 W
Antenna	4 }Hemispherical coverage	0.2-m dish
Antenna pointing	None	-4° accuracy (to Earth)
Data return volume	10 Mb/sol	2.88 Mb/sol (8-hr Dins)

The link from the MRS back to Earth must carry the return science data from all mission elements. Based on the mission model presented earlier, the aggregate data quantity per sol which must be returned to Earth has been estimated to peak at -125 Mb/sol around the year 2004. Using the MRS and DSN parameters given below in Table 4, this data can be returned to Earth at a data rate. of 4.4 kb/s in a single 8-hour DSN communications pass. For the direct-to-Earth communications implementation described earlier, an individual lander can return a significant amount of data to the DSN in 8 hours, but the total DSN service time needed by all landers is much greater. For example, with multiple landers globally dispersed on the surface of Mars, the direct-to-Earth link contacts to the DSN can occur throughout the day so continuous support from the DSN may be required.

Table 4: Sample MRS-to-Earth Link Parameters

Frequency band	X band
MRS antenna	1.25 m dish
MRS RF transmit power	10 W
DSN antenna	34-m (HEF
Modulation	BPSK
Coding	Concatenated Reed-Solomon & convolutional (rate 1/2
Achievable data rate	4.4 kb/s
Achieved bit error rate	« 10^{-6} with 2-dB margin

Integrated Radio Metrics for Navigation

An MRS can also provide lander position determination through the use of radio metric data collected during communications opportunities with the landers. By taking Doppler and range measurements cm the lander return link signals, lander positions relative to Mars can be computed. The resultant accuracy depends on whether or not the landers implement a coherent turn-around capability (e.g., transmit a carrier coherently related to the carrier sent by the MRS) but, using multiple communications opportunities, estimates of absolute lander position are possible with accuracies of ≤ 2 km (1σ) 7. Once lander positions have been determined, the MRS can use in-situ radio metric measurements to autonomously establish its own orbit ephemeris. Such autonomous navigation can be one significant factor in reducing overall systems operations complexity, which is further discussed in the paragraphs below.

Automated in-situ link operations

Design of the *in-situ* operations concept used by the MRS for communications with the landers must take into account the needs of the landers as well as Earth-based operations. The key considerations for the landers are assurance of command reception and science data return while maintaining low operational complexity. Autonomous *in-situ* command and data collection operation.s between the MRS and landers are desired to reduce the Earth-based operations. Additionally, the operations concept must take into account the existence of both relatively capable full science landers with high data volume requirements, and mini-met landers having small amounts of return data but facing significant power restrictions.

A relatively simple operations concept has been defined that meets these various requirements. The MRS continuously broadcasts a single forward link (command) channel containing commands unique to each lander as well as data (such as MRS ephemeris and return link channel status) shared by all landers. Higher capability landers can leave their receiver on continuously - using the MRS forward link channel as the signal to initiate communications. For mini-met stations that do not have sufficient power for continuous receiver operation, the MRS ephemeris can be used by the landers to predict the approximate MRS communications opportunities, thus minimizing the lander receiver "on" time needed to verify MRS presence. Once MRS presence has been detected, the lander begins to transmit an acquisition sequence into a previously assigned MRS receive channel.

Because of the potentially large number of landers on the surface of Mars, the MRS design includes multiple (up 10 eight) receiver channels that are active at all times. Once a signal from a lander has been acquired, the MRS sends a message on the command link indicating readiness to receive the lander science data. On reception of this message, the lander initiates science data transmission, continuing until all stored data has been returned, or until loss of the communications link occurs. Loss of the communications link can occur at either the MRS or lander receiver. If the MRS receiver loses lock, a channel status message on the MRS command link is used to tell the lander to terminate transmission. Loss of the MRS command link by the lander also terminates communications.

POTENTIAL NON-RELAY SUPPORT FUNCTIONS

The Mars relay function can be combined with other objectives in a multi-functional spacecraft. These functions include serving as a platform for remote sensing science and serving as a carrier for delivery of mission elements to Mars.

Remote Sensing Platform

As has been shown above, a remote sensing mapping orbit (e.g., the Mars Observer orbit) can provide acceptable global relay support. Furthermore, remote sensing pointing requirements are very compatible with relay antenna pointing needs. Mars Observer is an excellent example of this, in that a Mars balloon relay package was included as part of the. nadir-pointed payload.[8]

NASA's FY95 budge.(submittal includes funding for an aggressive Mars exploration program. The preliminary program requirements document[9] calls for a "Mars Surveyor Program, consisting of orbiters and landers to be launched at every launch opportunity over the next decade starling with the. 1996 opportunity." It also specifics that "all orbiters should early a relay link which is compatible with all US landers as well as international landers." The request for proposal for the first orbiter specifics at least 5 years orbits life in order to provide a relay support resource beyond the 2-year period of prime remote sensing science operations. [10]

A relay satellite supporting a network of globally distributed meteorology stations on the surface, can play an additional role by carrying an atmospheric sounder instrument. The atmospheric sounder would provide global profiles of atmospheric data as an important complement to the concurrent surface meteorology data.

Delivery Carrier

A relay satellite can also serve as a carrier for delivery to Mars of mission elements such as landers, balloons or penetrators. Deployment can either be during Mars approach or out of orbit, as was the method used for the Viking landers. Providing the carrier function for the surface elements would afford an additional telecommunications benefit in that these elements would not require separate provisions for communications with Earth during interplanetary cruise, as would be the case for free-flying elements. Thus, the landers delivered by a carrier relay orbiter would only need a UHF system to be used for the *in-situ* relay link. The free flyers would require an additional S- or X-band system, since a UHF system would not suffice for the cruise link to Earth.

RELIABILITY AND COST ISSUES

A relay network architecture will provide the greatest benefits and cost savings to the landed elements by enabling the supported elements to rely entirely on relay communications and avoid the added power, mass, complexity and cost associated with direct link communications with Earth. Much of the advantage to be gained from a relay network would be sacrificed if, for example., a direct link were required for backup or emergency. Thus, the relay network should be robust, consisting of more than one relay satellite., The example scenario of Figure 1 provides such relay satellite redundancy by including relay capability on the remote sensing orbiters launched in 1996-98, and later, when larger numbers of landers are deployed, by launching orbiters more dedicated to the relay function, but which include atmospheric sounders and deliver small surface stations, as mass delivery capability permits.

Larger numbers of surface elements will become affordable for Mars global exploration as the combined benefits of micro-technology and multi-mission relay support permit substantial reductions in power, mass and complexity. Thus, multi-mission relay satellites will become cost effective for the Mars surface exploration program as their cost can be amortized over an increasing aggregate of surface elements.

Consideration of the cost effectiveness of a relay network system should take into account all of the offsetting savings as well as scientific return enabled by such a system. In addition to direct savings in the cost of developing and manufacturing of the surface elements, there are the following potential savings: lower launch costs of smaller and lighter surface elements; lower operational costs of surface elements with no antenna pointing, greatly reduced power duty cycle, and all communications links autonomously controlled by the relay orbiter; and reduced Earth-based communications network operations costs with all data flow between Mars and Earth funneled through the daily 4- to 8-hr 2-way link between the relay satellite and Earth.

The cost effectiveness of the relay network concept should be enhanced through evolution toward longer life relay satellites with extended multi-mission application. Important factors which can contribute to longer relay satellite life are the. maturing of space qualified micro-electronics, and the. family of highly stable, "frozen" sun-synchronous orbits previously discussed.

CONCLUSIONS

There are various strategies for meeting the telecommunications requirements of the missions comprising a Mars exploration program. Ideally, this function should be provided by means of efficient systems and workable interfaces for the total mission set, The challenge to the designers is to select the. architecture which maximizes the benefits-to-cost ratio for the. Mars exploration program. The.

use of relay satellites at Mars can yield significant performance and cost benefits for exploration of that planet. In summary, these include: 1) increased ability to provide connectivity to landed elements which would otherwise be out of view of Earth-based antennas for many months; 2) a potential 500-1000 fold increase in science. data volume; 3) a decrease in the power and pointing requirements for landed elements with a corresponding decrease in their launch mass, landed mass, complexity and cost; 4) the potential to additionally utilize the relay satellite as a delivery system for landed elements; **5) the** potential to additionally utilize the relay satellite as an orbital platform for concurrent remote sensing observations, and; 6) efficient utilization of Earth-based communications resources.

ACKNOWLEDGMENT

The authors wish to thank J. R. Hall, Plans Manager for the JPL Telecommunications and Data Acquisition Office, and Aaron Weinberg, Vice President of Communications Sciences, Stanford Telecommunications, Inc., for their many contributions to this study. The authors also gratefully acknowledge the valuable technical contributions of Richard A. Cook, Mission Design Manager for the JPL Mars Pathfinder Project, Gary K. Noreen and Charles J. Ruggier, members of the. technical staff of the JPL Telecommunications Systems Section, and Paul Sutton, Flight System Manager for the JPL Mars Surface Exploration Pre-Project.

Research described in this document was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration, and by Stanford Telecommunications, inc. under Subcontract No. 958741.

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