G. MARCONI ORBITER AND THE MARS RELAY NETWORK

Gary Noreen, Tomas Komarek, Charles Edwards, Roger Diehl and Stuart Kerridge, JPL; Cesare Dionisio, Massimiliano Marcozzi and Riccardo Collina, Alenia Spazio; and Enrico Flamini, ASI

Abstract

A Mars relay network is being built using relay radios on nearly every Mars orbiter. Mars relay network performance has been limited because Mars orbiters are usually designed to support science missions from low, near-polar orbits; their relay functions are of secondary importance in spacecraft and mission design. The ASI/NASA G. Marconi Orbiter (GMO) will be the first Mars orbiter designed primarily for relay support; science experiments on GMO are secondary. Combining a high performance relay with a custom relay orbit, GMO can increase the data returned from in-situ missions by an order of magnitude. GMO will increase connectivity to in-situ missions from a few minutes (typical of other orbiters) to hours at a time, offering much greater operational flexibility and resilience and enabling new relay services.

Introduction

Relay radios on orbiters at Mars facilitate communications between ground stations on Earth and spacecraft, landers, rovers, and other in-situ mission elements at Mars. Relay links also provide navigation and timing services.[4]

This paper reviews the Mars relay network and future relay users. It describes the ASI/NASA G. Marconi Orbiter (GMO)[5], which will have a primary relay payload and a secondary science payload, and how GMO is being designed to augment the Mars relay network. The paper then compares the performance of several candidate GMO orbits.

The paper shows that GMO can benefit in-situ Mars missions by:

- Increasing the data returned to Earth by an order of magnitude.
- Increasing communication opportunities from minutes at a time to hours, resulting in greater operational flexibility and resilience.
- Providing new relay services enabled by GMO's greater connectivity, such as rover traverse monitoring.

Mars Relay Network

The Mars relay network currently consists of relay radios on two NASA orbiters at Mars. These will be joined by a Japanese orbiter in 2003, a European orbiter in 2004, another NASA orbiter in 2005, and GMO and a French orbiter in 2008.[6] All except the Japanese Nozomi orbiter have relay radios (Table 1).

The NASA orbiters are all in low, near-polar orbits as needed for their global mapping objectives. They all

Orbiter	*Mars Global Surveyor*	*Mars Odyssey*	*Mars Express*	*Mars Reconnaissance Orbiter (MRO)*	***G. Marconi Orbiter (GMO)***	*Premier*
Agency	NASA	NASA	ESA	NASA	**ASI/ NASA**	CNES
Mars Arrival	1999	2001	2004	2006	**2008**	2008
Relay Band	UHF	UHF	UHF	UHF	**UHF & X-Band**	UHF
Relay Protocol	Mars Balloon Relay	CCSDS Proximity-1	CCSDS Proximity-1	CCSDS Proximity-1	**CCSDS Proximity-1**	CCSDS Proximity-1
Relay Radio	MBR[1]	CE 505[2]	MELACOM[3]	Electra	**Electra**	Electra
UHF EIRP	2 W	2 W	4 W	6 W	**50 W**	6 W
UHF G/T	-27 dB/K	-27 dB/K	-27 dB/K	-30 dB/K	**-15 dB/K**	-30 dB/K
Mars Orbit					(Reference)	
Perigee	373 km	400 km	294 km	207 km	4450 km	500 km
Apogee	435 km	400 km	10,103 km	296 km	4450 km	500 km
Inclination	93°	93°	-86°	93°	-130°	93°
Node crossing	1 p.m.	5 p.m.		3 p.m.	2 p.m.	Noon

Table 1: Mars Orbiters with Relays

have nadir-pointed low gain UHF antennas for relay communications.

There has been a high degree of international cooperation in the development of relay communications infrastructure at Mars beginning with the Mars Balloon Relay on Mars Global Surveyor, which was provided to NASA by the French space agency, Centre National d'Etudes Spatiales (CNES). It was recognized early on that with so many missions from different countries going to Mars, there was a need for an international relay standard to ensure compatibility between orbiting relays and relay users and to minimize duplication of effort. This recognition prompted the development of the Consultative Committee for Space Data Systems (CCSDS)[7] Proximity-1 Space Link Protocol. The Proximity-1 protocol was first implemented on Mars Odyssey and will be on all later Mars orbiters.

International cooperation will be extended further with the development of the Electra relay radio by NASA, which will be flown on the CNES Premier orbiter as well as on GMO and the Mars Reconnaissance Orbiter.

Relay Users

Orbiting relay radios at Mars will support proximity links to in-situ Mars missions including two NASA Mars Exploration Rovers and the European Beagle II lander arriving in 2004, four CNES NetLanders in 2008 and the NASA Mars Smart Lander (MSL) rover in 2010. Many other potential relay user missions are being proposed for NASA's Mars Scout Program, which is in the midst of a competitive selection process. These may include additional landers, airplanes, balloons or orbiters. In the long term, NASA is studying a sample return mission that would make ample use of relay orbiters, along with various other in-situ missions.

Our focus in this paper is on relay users that would be serviced by GMO, which arrives at Mars in 2008, such as the NetLanders, the MSL rover and Mars Scout missions. NetLander and MSL rover communication systems and relay needs are briefly described below.

NetLanders

Four NetLanders under development by a European consortium led by CNES will land on Mars in 2008.[8] They are designed to last one Earth year after Mars arrival.

The NetLanders will be able to communicate with Earth only through UHF relays on Mars orbiters. Each NetLander will be limited to no more than 20 minutes transmission time each day, preferably near local noon. A minimum of 3 Mb/sol* and 100 Mb/week is to be relayed from each NetLander.

Each NetLander will have a UHF radio with a 5 W transmitter operating at data rates of 8, 32 and 256 kbps. The NetLander UHF antenna has 0 dBi peak gain (-3 dB at 20° elevation angle).

The NetLanders are typical of other small Mars landers. Given their limited transmit time, minimizing the energy required per transmitted bit is all-important. These missions are often best served by relays in low orbits, resulting in minimum slant range but short coverage periods. Global longitudinal coverage is desired, though the latitude of the NetLanders will be between ±30°.

Mars Smart Lander (MSL) Rover

The Mars Smart Lander (MSL) will deploy a single rover on the surface of Mars in late 2010.

MSL is to be capable of precision landing virtually anywhere on Mars, but will probably be sent to a landing site under 45° latitude.

The rover may traverse as much as 9 km on Mars. It is expected to last as long as 1000 sols if nuclear powered, and will traverse under 10 km.

The rover will support X-band communications with a 0.75 m diameter High Gain Antenna (HGA) and a 50 W transmitter. This antenna must be steered. The rover will also have a 10 W UHF radio and an omni-directional UHF antenna.

The current rover communications plan calls for a Direct-To-Earth (DTE) link at X-band one hour each morning and another hour each evening for monitoring and control. At the maximum Mars range from Earth, the rover can send 5.6 kbps to a 34 m Deep Space Station on Earth, which adds up to 40 Mb/sol. Most of the rover's science data would be sent to Mars orbiters through UHF relay links at much higher data rates.

The MSL rover is typical of other proposed large Mars landers and rovers, which frequently have X-band DTE communication systems as well as UHF relay radios and which can normally transmit for long periods of time. Such landers and rovers are typically best served by relays in high orbits with long coverage periods.

Mars Scout

NASA recently released a Mars Scout Announcement of Opportunity (AO) for competitively selected

* A sol is a Martian day, which lasts 24 hours and 37 minutes.

missions to Mars.[9] The Mars Scout missions are intended to complement the major strategic missions in NASA's Mars Exploration Program. They can cost no more than $325 million. Mars Scout missions could include Mars Orbiters, landers, rovers, or even aerial systems like airplanes and balloons. If a Mars Scout orbiter is designed to last more than a year in orbit, it is required to include an Electra radio so that it can provide relay communication services.

In the fall of this year, NASA plans to select up to four of the proposals submitted in response to the Mars Scout AO for Phase A studies. NASA plans to make a final selection in the summer of 2003 of at least one Mars Scout mission for launch in 2007.

G. Marconi Orbiter

The G. Marconi Orbiter (GMO) is a joint ASI-NASA mission. ASI (Agenzia Spaziale Italiana, the Italian space agency) will provide the spacecraft, which will be built and operated by Alenia Spazio. NASA is responsible for the Electra relay radio, a camera, the launch vehicle and navigation services. GMO will be tracked by NASA's Deep Space Network and by an Italian ground station in Sardinia.

The NASA camera is designed to detect an orbiting sample canister from a Mars sample return mission.

GMO will be launched on a Delta III, Soyuz-2/Fregat or Japanese H-II in August, 2007. It will be injected into a Type II trajectory to Mars, then inserted into a Mars orbit in July, 2008. GMO is designed for a 6-year lifetime in orbit, with enough consumables for 10 years.

The Electra relay radio on GMO receives at UHF or X-band and transmits 10 W at UHF. There will be two relay antennas: a 12 dB gain UHF Medium Gain Antenna (MGA) and a 0.5 m diameter X-band relay MGA (receive-only), both mounted on a gimbaled platform (Figure 1).

GMO UHF relay performance will be more than an order of magnitude better than that of any of the other Mars relay orbiters (Table 1). These orbiters typically have a nadir pointed relay Low Gain Antenna (LGA) mounted on a platform shared with scientific instruments that interfere with the relay LGA, significantly degrading relay performance. The GMO relay MGAs will be mechanically steered towards a relay user during each tracking pass, maximizing relay antenna performance.

The GMO Earth link will use an X-/K_a-band High Gain Antenna (HGA) on the order of 3 m in diameter. This antenna will support both X-band two-way communications and a K_a-band downlink to Earth using a 35 W K_a-band TWTA. The HGA will be attached directly to the body of the spacecraft, which is derived from the new version of the Alenia PRIMA bus. Downlink data rate is expected to be about 400 kbps at maximum Mars range.

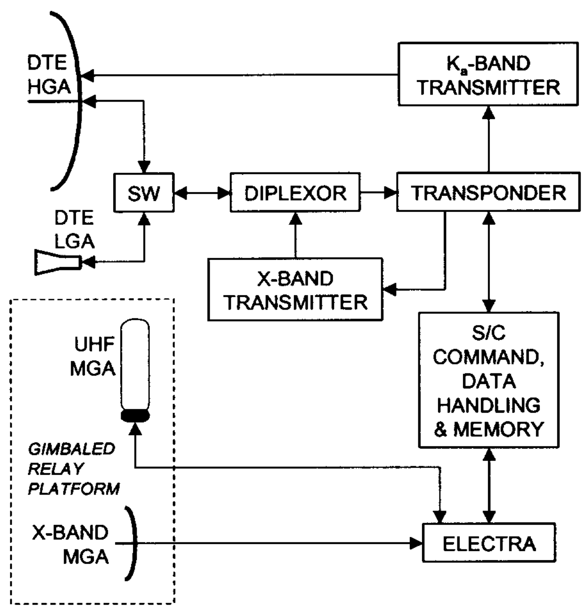

Figure 1: Simplified GMO RF Diagram

GMO Design Process

GMO is in the midst of an iterative design process. The design has focused initially on serving the NetLanders and the MSL rover because these are GMO's most certain users. The GMO design team has worked directly with the NetLander and MSL rover design teams to understand their requirements. Once the initial Mars Scout selection has been made, the GMO design team will interact with Mars Scout teams as well. It may be possible for fundamental decisions about GMO design, such as its orbit, to be made at that point if they can be shown to satisfy all the parties. However, final decisions may have to await the final Mars Scout selection. In any event, since GMO is to continue to provide relay services long after the NetLander, MSL and initial Mars Scout missions have ended, the design must be flexible to accommodate other likely future missions.

Fortunately, the NetLanders and MSL are each representative of a broad range of missions. The NetLanders are typical of small landers that store energy from sunlight in batteries and transmit for a few minutes each day, preferably in sunlight. Multiple widely distributed small landers are frequently proposed for global in-situ measurements. MSL and its rover, on the other hand, are more typical of larger landers and rovers which are less energy-limited and which can thus transmit for long periods of time. Since they are large, they are relatively expensive to send to Mars and thus they will be sent to only one or two locations during any given Mars launch opportunity.

The GMO design team has identified design options – principally orbit options at this stage – and evaluated how GMO would serve the NetLander and MSL missions based on each design option. These evaluations are being reviewed with the NetLander and MSL teams, following which the design options will be refined, reevaluated and reviewed again with GMO users.

Since GMO is one of a network of orbiting relays, we need to determine how to best complement relay services provided by other Mars orbiters. We thus have compared our design options with the services provided by the other orbiters throughout the design process.

Orbit Design

The value of GMO to each potential user depends to a large extent on the orbit in which GMO is placed. NetLander-class missions generally can communicate for only a very brief period. They wish that period to be at low altitude near local noon, and require global coverage (at least in longitude). MSL-class missions, on the other hand, desire long contact periods, generally requiring a high orbit, and because they are inherently large and expensive, will probably be at no more than two sites during a given Mars exploration opportunity.[†] The trick is to find an orbit that can satisfy the conflicting requirements of NetLander and MSL, while being flexible enough to accommodate future missions with less well-known requirements. Several candidate orbits are described and analyzed below.

The analysis estimates the data returned from NetLanders and from the MSL rover for each candidate orbit, and compares these estimates to the data returned from MRO and Premier, the two other Mars orbiters most likely to be operating for a large portion of the time GMO is providing relay services. The analysis then compares the connectivity for each of the candidate GMO orbits to MRO and Premier connectivity.

Equatorial Orbits

Equatorial orbits (inclination i= 0°) are of interest for GMO, in spite of the fact that they do not provide coverage of high latitudes. Most other Mars orbiters are polar orbiters, ensuring extensive coverage of high latitudes. Furthermore, currently approved Mars missions (i.e. the NetLanders and MSL) are not likely to end up at high latitudes.

Equatorial orbits provide extended coverage of equatorial regions, which are less well covered by the near-polar orbiters, and thus an equatorial orbit may enable GMO to provide coverage complementary to that of the other orbiters.

We consider here two equatorial orbits: areostationary and ½ sol Apogee at Constant time-of-day Equatorial (ACE).

Areostationary

If the orbiter is in an equatorial circular orbit with a period of 1 sol, it remains fixed over a given equatorial location. At Mars, this is referred to as an areostationary orbit – akin to geostationary orbits around Earth. Areostationary orbit altitude is 17,030 km.

The areostationary orbit enables continuous coverage, but of only a portion of one hemisphere. Polar regions are excluded. The high altitude results in low data rates for UHF relay links, and the unchanging relative positions of the orbiter and landed elements precludes Doppler navigation.

½ Sol ACE (Apogee at Constant time-of-day Equatorial) Orbit

An equatorial orbit previously proposed for satellite communications at Earth[10] has potential use at Mars. In an Apogee at Constant time-of-day Equatorial (ACE) orbit, the line of apsides rotates at sun-synchronous rate so that all points of the orbit always overfly a specific longitude on Mars at a fixed time of day. This requires a specific combination of semi-major axis a and ellipticity e, and is generally highly elliptical.

The GMO design team has characterized a ½ sol ACE orbit with the line of apsides aligned with the sun so that apogee is always between the sun and Mars (Figure 2). The orbit is set up so that the orbiter is at apogee at nearly the same time that MSL is at local noon, maximizing daytime coverage of MSL and its rover. As ACE orbits are prograde, the orbiter "follows" MSL as it comes from behind Mars, catches up to it at apogee at noon, and then goes back behind Mars when MSL is in darkness. The orbiter is visible to MSL during the entire time MSL is in sunlight.

† Orbital mechanics generally limits the times at which probes can be sent to Mars to a brief period every 26 months.

Other advantages of this orbit are that since it is highly elliptical, a relatively low ΔV is needed to enter it and slant range to landers is reduced considerably during portions of its orbit. Landed elements needing only brief communications periods, like NetLanders, can wait until the slant range is low before communicating. The principal disadvantage of this orbit is that it provides limited coverage of Mars, as illustrated in Figure 3.

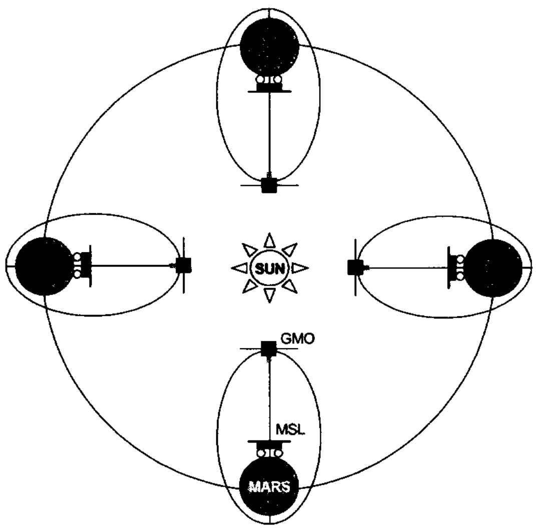

Figure 2: ½ sol ACE orbit with Noon Apogee

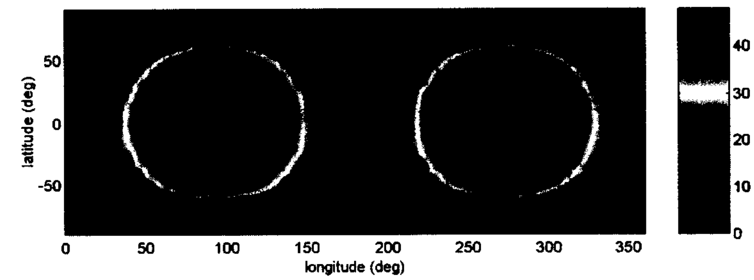

Figure 3: Percent of Time Mars Orbiter in ½ Sol ACE Orbit is Visible as a Function of Ground Location

Sun Synchronous Orbits

The line of nodes of an orbit regresses due to the oblateness (J2) of the central body. In a sun-synchronous orbit, the nodes regress at a constant rate equal to the mean motion of the sun in the sky. The orbit then maintains its orientation with respect to the Sun during a Martian year. This requires a specific combination of semi-major axis a, eccentricity e and inclination i. Sun synchronous orbits can be circular or elliptical. They may eliminate eclipses, depending on the specific orbit selected. Figure 4 shows sun synchronous orbits at Mars as functions of apoapse (hmax), periapse (hmin) and inclination.

The 4450 km sun synchronous circular orbit has some desirable attributes: it has a high probability of

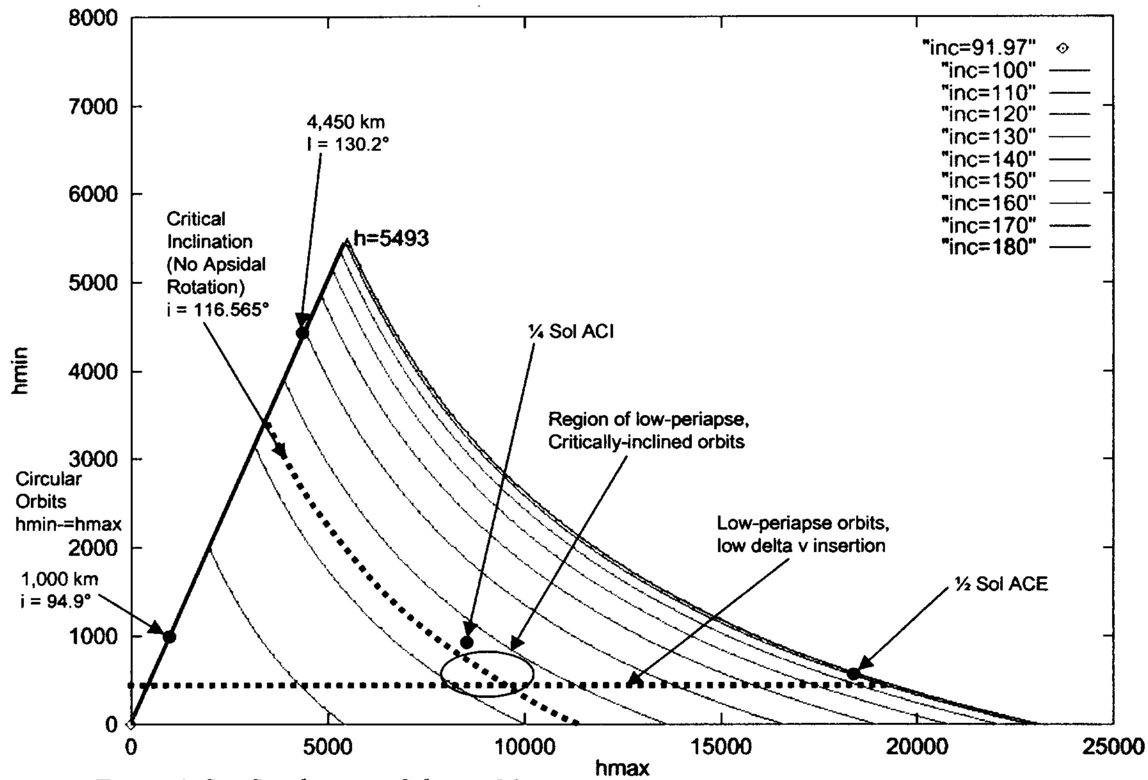

Figure 4: Sun Synchronous Orbits at Mars

being able to "see" critical events of user missions due to its large footprint. Also, it has an almost uniform data throughput capability as a function of user surface latitude and longitude, assuming the lander can communicate at any time of Martian day. The 4450 km sun synchronous circular orbit and the more highly inclined 1000 km sun synchronous circular orbit were selected as candidate orbits for analysis.

¼ Sol ACI (Apogee at Constant time-of-day Inclined) Orbit

At the critical inclination (i = 116.6° or 63.4°), the line of apsides stays approximately fixed in inertial space; a and e can be freely chosen to satisfy other requirements (e.g., sun-synchronous, resonant). Resonance is considered with respect to fixed locations on the surface of Mars, so overflight patterns repeat over fairly short time periods: an integral number of revolutions occur in an integral number of sols. A slight modification to the critically inclined orbit can cause the line of apsides to rotate 360° per year so that apogee occurs at constant time of day, just as for an ACE orbit. We consider here a ¼ sol Apogee at Constant time of day Inclined (ACI) orbit. The apogee of this orbit can be set so that it stays between Mars and the sun, maximizing sunlit coverage – also just as for the ACE orbit. This orbit has greater coverage area than the ½ sol ACE orbit, but less daytime MSL coverage.

Orbit Analysis

The following orbits are analyzed herein (Table 2): ½ sol ACE and ¼ sol ACI orbits, each with apogee at local noon over MSL; an areostationary orbit at the MSL longitude; and 1000 km and 4450 km circular sun synchronous orbits. The orbit parameters were selected to optimize coverage of the four NetLanders and MSL at their reference locations.

These orbits are shown graphically in Figure 5 (except areostationary). We compare below the data returned from GMO in each orbit. We also compare the connectivity of each orbit, i.e. the times when the orbiter is in view of a landed element.

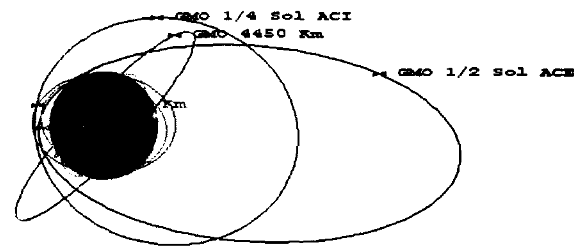

Figure 5: GMO Candidate Orbits

Data Return

The amount of data that can be sent from a relay user to a relay orbiter depends on the data rate at which the data is sent and on the amount of time the data is sent. The data rate depends on the slant range between the relay user and the orbiter and on the antenna gain on the orbiter as shown in Figure 6.

Because of the low altitude of the science orbiters, the slant range to them is quite low. Thus a lander could send data to a science orbiter at 64 kbps (Figure 6) even though the science orbiter has a low performance antenna.

An orbiter like GMO in a mid-altitude orbit, for example the 4450 km circular sun synchronous orbit, can support only a lower data rate (16 kbps in Figure 6), even if it has a much higher gain antenna like the 12 dB MGA on GMO.

GMO can make up for the relatively low data rate that can be sent to it in a high orbit by enabling relay users to transmit for a longer period of time. The science orbiters are in view only for a few minutes above any particular location; GMO may be in view for hours, depending on which orbit is selected.

Orbit	Mars Reconnaissance Orbiter (MRO)	CNES Premier Orbiter	*GMO 1000 km Circular Sun Sync*	*GMO 4450 km Circular Sun Sync*	*GMO ¼ Sol ACI*	*GMO ½ Sol ACE*	*GMO Areostationary*
a, km	3,648.606	3,897	4,397.0	7,847.0	8,150.5	12,890	17,030
Eccentricity	0.012176	0	0	0.0	0.47	0.691614	0
Inclination	93°	93°	94.9°	130.2°	116.565°	0°	0°
Node crossing	3 p.m.	Noon	6 p.m.	2 p.m.	Noon	N/A	N/A
Apogee, km	207	500	1,000	4,450	923	578	17,030
Perigee, km	296	500	1,000	4,450	8,584	18,408	17,030

Table 2: MRO & Premier orbits and GMO Candidate Orbits

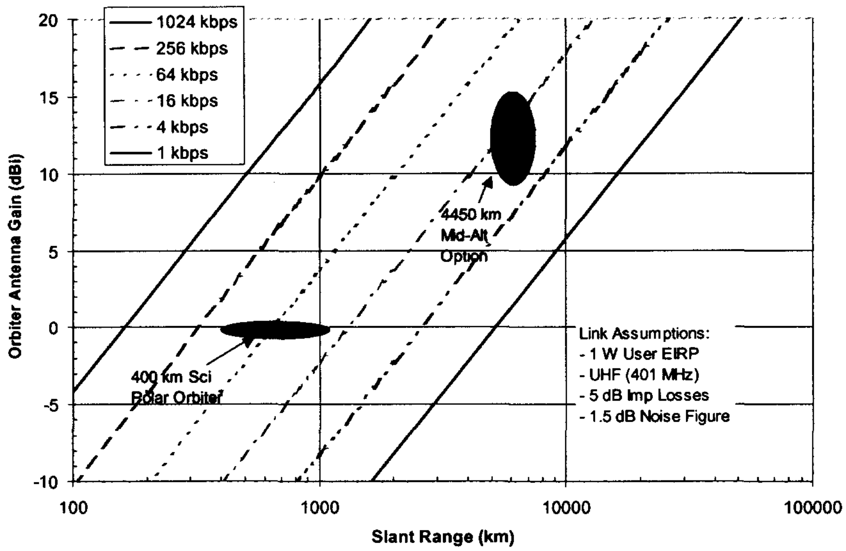

Figure 6: Data Rate vs. Antenna Gain & Range

To determine how much total data volume could be supported through each orbiter, Aerospace Corporation ran, under a JPL contract, 72 day simulations of links to NetLanders and to Smart Lander. Figure 7 shows the total data volume sent by each NetLander. It is assumed that each NetLander is using only a single orbiter to send all its data. The range in data volume is due to the different locations of the four NetLanders.

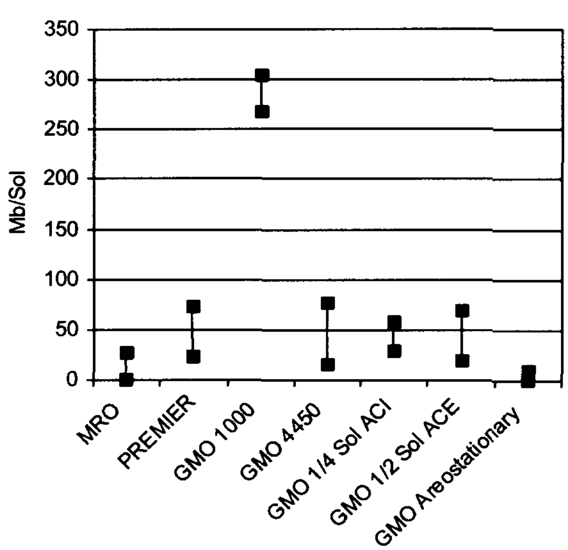

Figure 7: NetLander Data Return

Note that data volume returned by GMO from the 4450 km, ¼ sol ACI and ½ sol ACE orbits is comparable to that sent through the Premier orbiter. This is because while each NetLander can transmit for 20 minutes, a longer period of time than Premier is in view, it is not a large enough period of time to significantly increase the overall data return and the GMO slant ranges are longer than for Premier. GMO would meet the basic NetLander requirements from any of these orbits. The 1000 km GMO orbit is quite a bit better, due to the much lower slant range than the other GMO orbits. The 12 dB MGA on GMO and the longer contact times more than make up for the greater slant range relative to Premier. Neither GMO in an areostationary orbit nor MRO are able to communicate with all of the landers each day in sunlight, so neither can alone meet the minimum NetLander requirement of 3 Mb/sol per day.

Data return through the MSL rover is quite different. Since the rover can send data for hours, it can take advantage of the long contact times offered by GMO to send back much more data than otherwise possible. It can also use the high performance X-band link to GMO to increase the data rate to 2 Mbps.

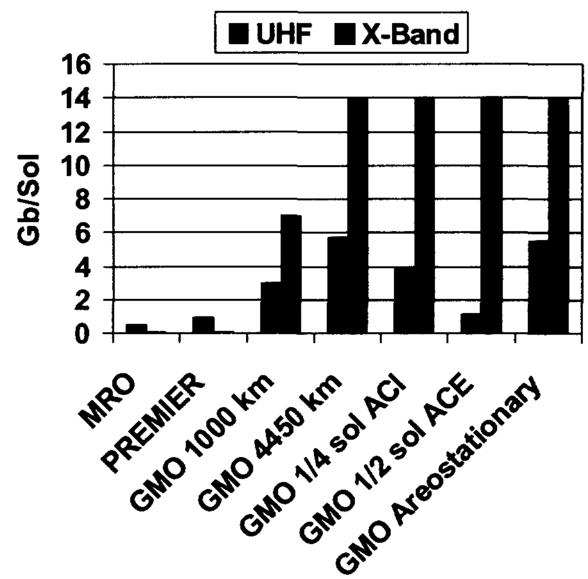

Figure 8: MSL Rover Data Return

In Figure 8, it is assumed that the X-band transmitter on the MSL rover sends data through GMO for two hours per day rather than over a Direct-To-Earth link. Note that GMO will increase MSL rover data volume by an order of magnitude above what could be returned through any of the other orbiters.

Connectivity

GMO will dramatically increase the amount of time that landed elements can communicate. If GMO is in a ½ sol ACE orbit, MSL could communicate through GMO 11 hours a day – much longer than the time during which it is in sunlight (Figure 9).

The roles of UHF and X-band links could be reversed when the MSL rover uses GMO. Instead of using an X-band DTE link for monitoring and control, a UHF link to GMO could provide these functions far more frequently and easily. Bulk science data could be sent through the GMO X-band link rather than through a much lower data rate and shorter duration UHF link to another orbiter.

The very long contact times possible through GMO in some candidate orbits have several other potential benefits for in-situ Mars missions:

1) Operational flexibility – the ability to communicate when convenient from an operational perspective rather than only for brief periods dictated by orbital mechanics.
2) Continuous monitoring – with GMO in a ½ sol ACE orbit, a landed element could be monitored continuously during the sunlit hours. For example, a rover could be continuously monitored throughout a daytime traverse.
3) Rapid response time – it may be possible for relay user mission operations teams to respond in under an hour to new conditions observed by an in-situ element, though there are both technical and organizational obstacles to implementing such a capability. Without GMO, the minimum time between contacts is usually many hours.

The greater connectivity provided by GMO can increase the resilience of in-situ missions by improving the ground team's knowledge of what is happening to the in-situ elements and by enabling ground teams to respond in a more timely manner.

Entry, Descent and Landing (EDL) Coverage

To ensure that NASA can reconstruct any future failure, NASA's Mars Exploration Program requires all missions to Mars to communicate during every critical event. The most critical event for missions landing on Mars is Entry, Descent and Landing (EDL). Such missions can usually best meet the EDL tracking requirement through relay orbiters.

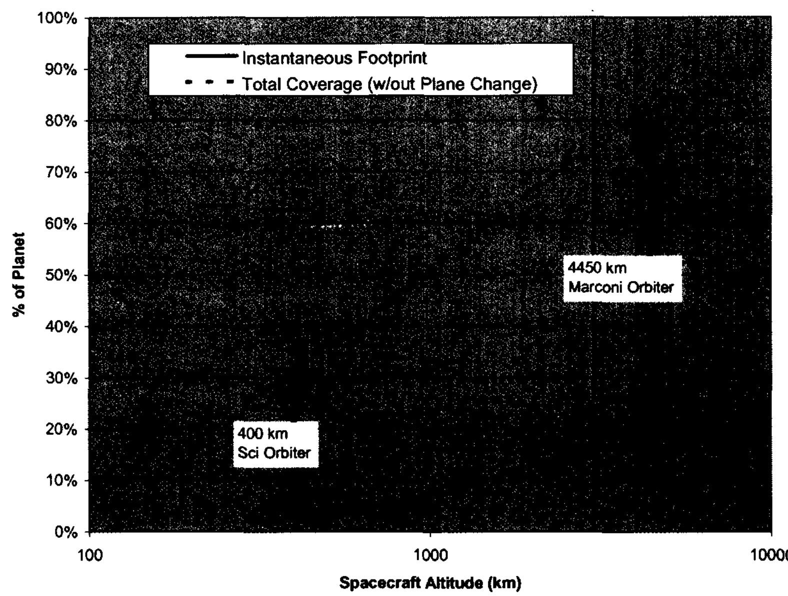

Figure 10: Orbiter Footprint

Unfortunately, low altitude science orbiters are often poorly positioned to track incoming spacecraft. Figure 10 shows that they have relatively small instantaneous footprints and total coverage, which limits the areas in which the landers can be tracked through EDL and hence limits possible landing sites. The much larger coverage of GMO in a higher orbit greatly increases potential landing areas for which EDL tracking is possible.

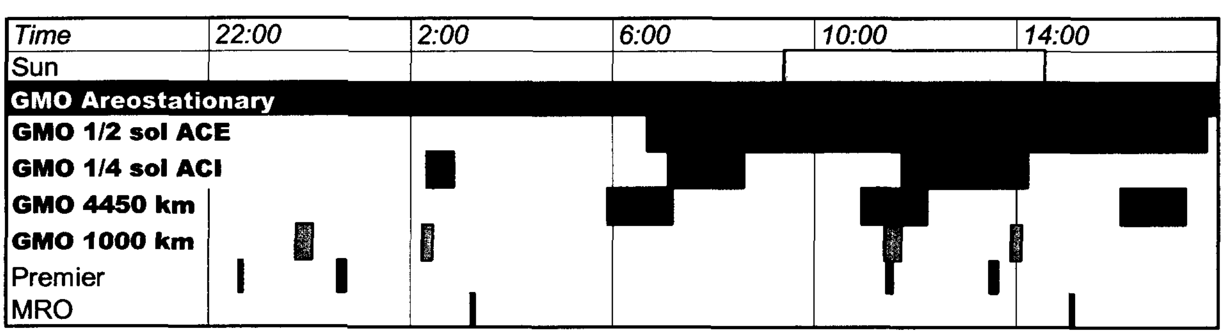

Figure 9: MSL Coverage Chart (times when elevation angle > 20° over MSL at 41° S location)

Conclusion

By combining an orbit optimized for relay services and a high performance relay payload, GMO will enable a dramatic increase in the data return and connectivity of in-situ Mars missions. GMO will enable fundamentally new Mars relay network services that could significantly improve the operation and resilience of in-situ Mars missions.

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