

TELECOMMUNICATIONS SYSTEMS EVOLUTION FOR MARS EXPLORATION

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ABSTRACT

This paper describes the evolution of telecommunication systems at Mars. It reviews the telecommunications capabilities, technology and limiting factors of current and planned Mars orbiters from Mars Global Surveyor to the planned Mars Telecommunications Orbiter (MTO).

INTRODUCTION

Mars orbiters with relay radios are enabling exciting in-situ missions to the Red Planet.

The British Beagle 2 lander will relay all its communications through Mars orbiters after it lands on Mars on the day after Christmas – first through NASA’s Mars Odyssey orbiter, then through ESA’s Mars Express orbiter, which is carrying Beagle 2 to Mars. Spirit and Opportunity, NASA’s twin Mars Exploration Rovers, will be tracked by NASA’s Mars Global Surveyor (MGS) orbiter as they arrive at Mars and will relay data to Earth through both Odyssey and MGS after landing on January 4th and 26th, respectively.

NASA added relay radios to Mars Global Sur-

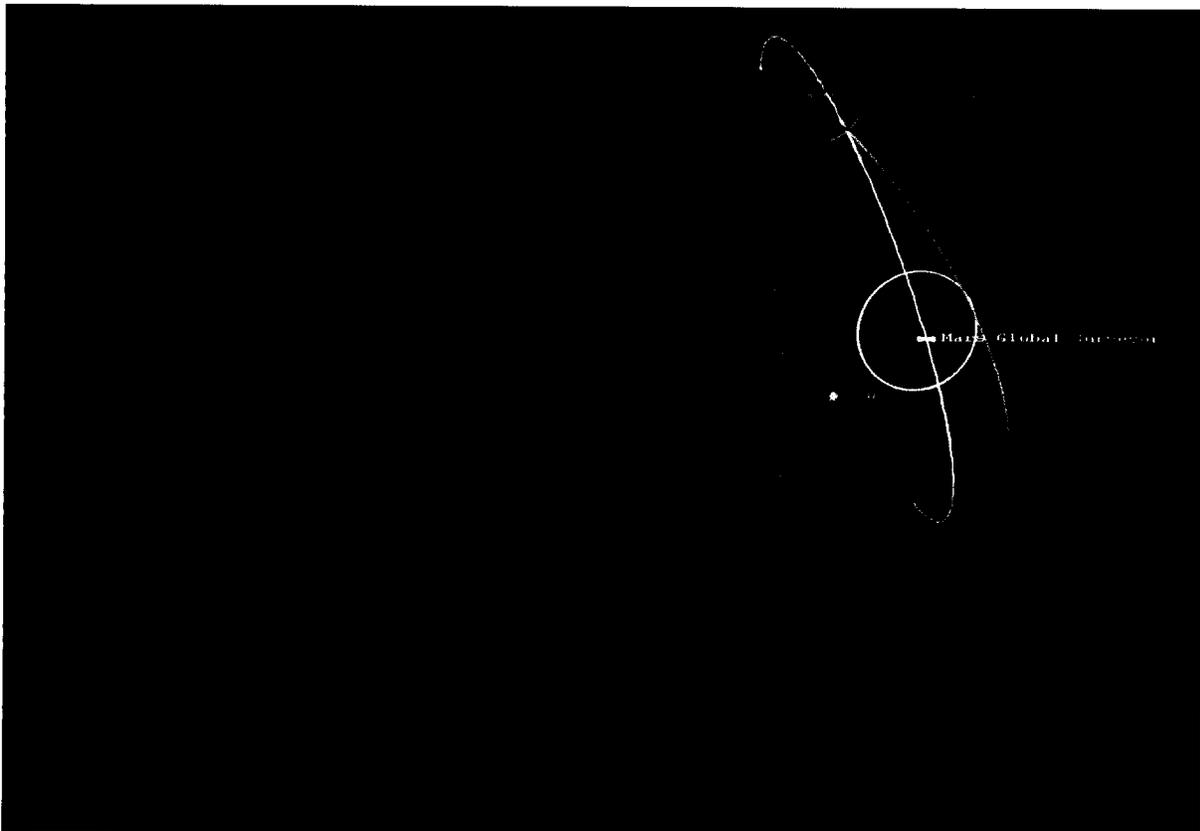


Figure 1. Mars Network before MTO

veyor and Mars Odyssey specifically to provide relay services to other missions. As such, the relay radios are part of a new way of exploring other planets: through a long term program, with each mission building on others to establish an interplanetary internet¹ for the support of future missions.

NASA will add Mars Reconnaissance Orbiter (MRO) to the Mars Network in 2005.² MRO will carry the first Electra³, a frequency-agile software relay radio, and will have high rate X-band and K_a-band Direct-To-Earth links.

While the Mars Network of science orbiters with relay radios (Figure 1) has greatly improved our ability to navigate and communicate with Marscraft (landers, rovers aerobots and orbiters in the vicinity of Mars), its capabilities are limited because it has been constructed by adding relay radios to orbiters optimized for science missions rather than for communications. NASA will augment the Mars Network in 2010 with the Mars Telecommunications Orbiter (MTO), the first interplanetary spacecraft optimized for relay communications services. MTO will be placed into a high orbit selected specifically for its relay mission. MTO will have the most advanced communications system ever put on an interplanetary spacecraft, with high performance X- and K_a-band links to Earth, high performance UHF and X-band relay links to other

Marscraft, and an experimental laser communications payload for Direct-To-Earth (DTE) communications.

MTO will dramatically increase both the data return from other missions sent to Mars and the amount of time and frequency of contacts to Mars missions, fundamentally improving our ability to monitor and control Marscraft and leading to more flexible and reliable operations.

MARS NETWORK

The Mars Network consists of Mars orbiters with radios capable of relaying communications to and from other Marscraft and ground stations on Earth. The Mars Network currently consists of the NASA Mars Global Surveyor (MGS) and Mars Odyssey orbiters.

The origin of the Mars Network can be traced to a French Mars balloon mission: Jacques Blamont of CNES proposed to send balloons to Mars on what eventually became the ill-fated Russian Mars '96 spacecraft. To communicate with these balloons – which would have had no DTE capability – CNES developed the Mars Balloon Relay (MBR)⁴. A CNES MBR was first sent to Mars on another ill-fated spacecraft in 1992: NASA's Mars Observer. A CNES MBR successfully reached Mars on MGS in 1996 (Figure 2).

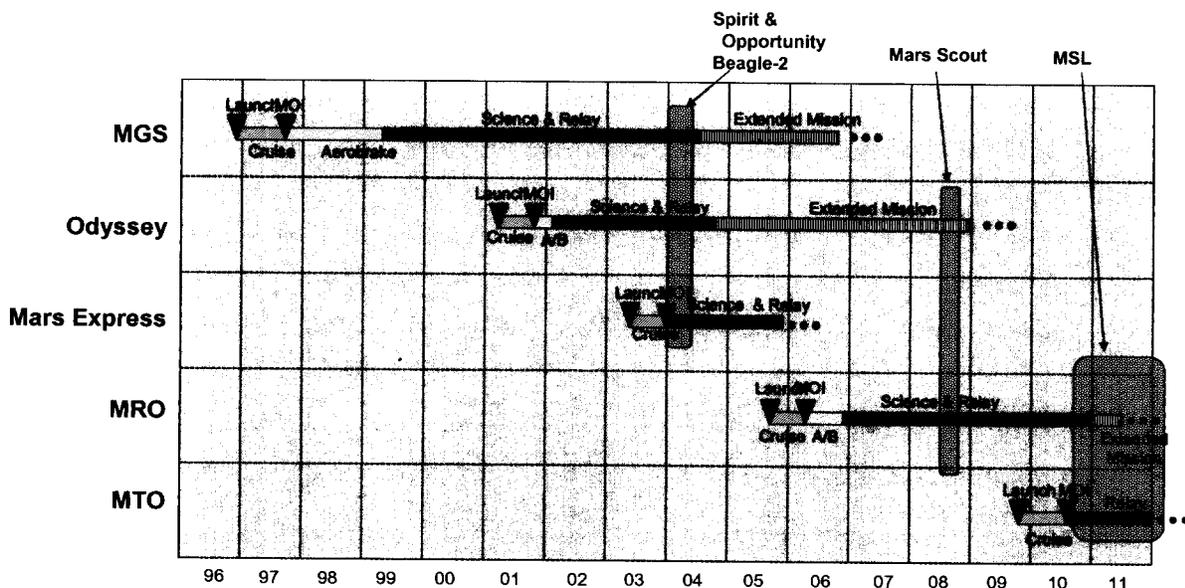


Figure 2. Mars Network Development

Table 1. Mars Orbiter Relays

Orbiter	MGS	Odyssey	Mars Express	MRO	MTO
Relay Protocol	Mars Balloon Relay	CCSDS Proximity-1	CCSDS Proximity-1	CCSDS Proximity-1	CCSDS Proximity-1
Relay Radio	Mars Relay	CE 505	MELACOM	Electra	Electra + X-band
Relay Antenna	Nadir-pointed	Nadir-pointed	Nadir-pointed	Nadir-pointed	Steered
Forward Link					
ERP	2 W	2 W	4 W	6 W	50 W
Frequency	437.1 MHz	437.1 MHz	437.1 MHz	390-450 MHz	390-450 MHz
Data Rates	Tones only	8-256 kbps	2 & 8 kbps	1 to 1024 kbps	1 to 1024 kbps
Return Link					

The international interest in relay communications at Mars led to the development of a space relay radio standard by the Consultative Committee on Space Data Standards (CCSDS): the Proximity-1 standard⁵. Proximity-1 is a flexible bi-directional protocol providing several operating modes and levels of service. While initially developed for Mars missions, it is intended to be used for other space missions as well.

The CE 505 relay radio⁶ sent to Mars on the NASA Mars Odyssey orbiter in 2000 was the first to implement the CCSDS Proximity-1 protocol. This was followed by the MELACOM⁷ radio on Mars Express now on its way to Mars, also compatible with CCSDS Proximity-1 (Table 1).

MGS, Odyssey and MRO have nadir-pointed UHF Low Gain Antennas for relay communications. The platforms on which each of these LGAs is placed are shared with several scientific instruments, resulting in irregular, poor performance patterns (Figure 3).

Mars Telecommunications Orbiter (MTO), to be launched in 2009, will have high performance steered X-band and UHF relay antennas

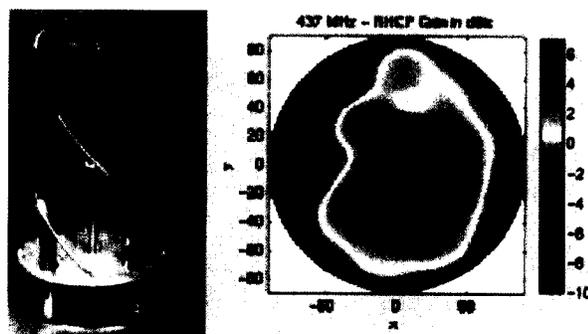


Figure 3. Odyssey UHF Antenna & Pattern

on a dedicated relay antenna platform. Because these antennas are steered, they will normally operate near their peak gain – unlike the UHF relay antennas on other Mars orbiters.

High rate telecommunications from Mars to Earth will begin with MRO (Table 2, next page), which will have a 3 m diameter High Gain Antenna and 100 W X-band and 35 W K_a -band transmitters. MTO will have a similar RF capability, and will augment this with a Laser Communications Demonstration.

Table 2. Mars Orbiter Direct-to-Earth Links

Orbiter	MGS	Odyssey	Mars Express	MRO	MTO
Antenna Diameter	1.5 m	1.3 m	1.6 m	3 m	3 m
RF Power X-Band	25 W	13.8 W	65 W	100 W	100 W
K _a -Band				35 W	35 W
Laser					5 W
Data Rate X-Band	33 kbps	14 kbps	97 kbps	526 kbps	526 kbps
K _a -Band				526 kbps	526 kbps
Laser				526 kbps	1 Mbps

Network Users

The Mars Network will be used for the first time this year by Spirit and Opportunity (the two NASA Mars Exploration Rovers) and by the British Beagle II lander, all now on their way to Mars. It will also be used by the Phoenix Mars Scout mission in 2007. In 2010, the NASA Mars Science Laboratory (MSL) mission will use the Mars Network. Users after 2010 are not yet known, but are likely to include large landers and rovers like MSL as well as small landers like the proposed CNES Netlanders.⁸

Small landers typically have only a limited amount of energy available for each communications session. They thus generally send their data in short communications periods. The CNES Netlanders, for example, would transmit for no more than 20 minutes per sol.

Large landers like MSL, on the other hand, typically generate enough energy each day to communicate for hours at a time.

Orbits and Performance

Low, near-polar sun synchronous orbits such as those used by MGS, Odyssey and MRO (Table 3) provide global coverage at low range

* RF link capabilities to 34 m DSN antenna at maximum range of 2.67 AU. Actual rates are generally lower due to spacecraft hardware implementations.

and at sun angles optimized for science observations. Contact times are inherently short – typically under 10 minutes. From a relay communications perspective, these orbiters have good energy efficiency due to their low range when communicating with Marscraft on the surface of Mars (Figure 4).[†] They provide excellent coverage in polar regions with frequent contacts, but infrequent (once or twice per sol) contacts in mid-latitude regions. This

polar bias translates into much higher data volume capability at the poles than in mid-latitude areas, illustrated in Figure 5 (next page) for Odyssey and MRO links from MSL.

Table 3. Mars Orbiter Orbits

Orbiter	MGS	Odyssey	Mars Express	MRO
Periapse Alt.	373 km	400 km	294 km	207 km
Apoapse Alt.	435 km	400 km	10,103 km	296 km
Period	118 min.	118 min.	420 min.	113 min.
Inclination	93°	93°	-86°	93°
Node Cross.	2 p.m.	5 p.m.	Variable	3 p.m.

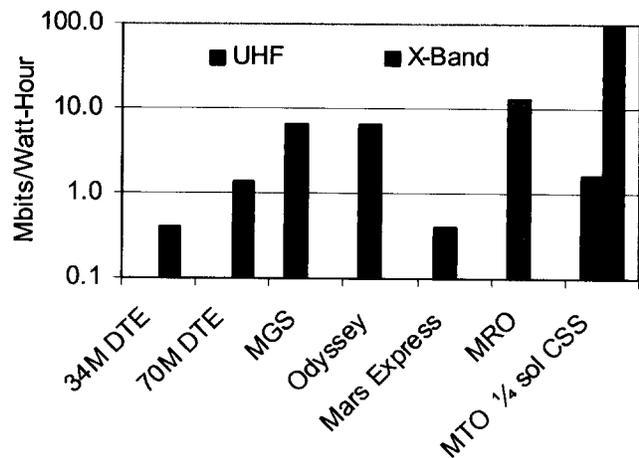


Figure 4. MSL Return Link Power Efficiency

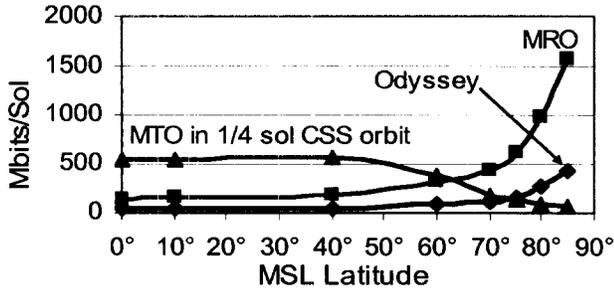


Figure 5. MSL UHF Relay Data Volume as a Function of MSL Latitude

The relatively high orbit of MTO results in greater path loss than for NASA's other Mars orbiters, but for large landers like MSL, this greater path loss is more than made up for by the higher gain relay antenna and the much greater contact times possible with MTO. The overall data volume that MSL could send through MTO from its challenge landing site is 3 times greater than through MRO at UHF and more than 2 orders of magnitude greater at X-band (Figure 6).

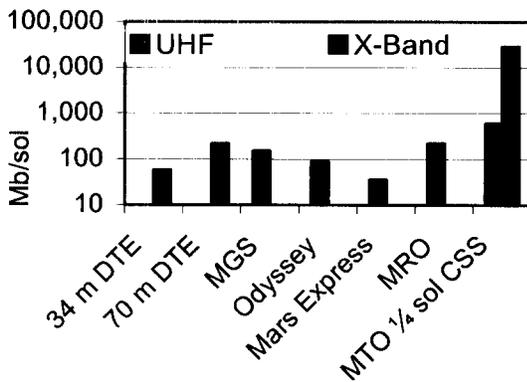


Figure 6. Potential Data Volume from MSL at 41.45° N, 286.5° W

Table 2. Candidate MTO Orbits

Orbit type	Period, hours	Inclination	Apoapse Alt.	Periapse Alt.
4450 km Circular Sun Synchronous (non-repeating ground track)	5.9	130°	4,450 km	4,450 km
1/4 sol Circular Sun Synchronous (CSS)	6.165	136.683°	4,722 km	4,722 km
1/4 sol Apoapse at Constant time of day Critically Inclined (ACCI)	6.165	116.565°	8,483 km	953 km
1/2 sol Apoapse at Constant time of day Equatorial (ACE)	12.321	0°	18,397 km	583 km

† Based on MSL at its challenge location: 41.45° N, 286.5° W. MTO data is for the 1/4 sol Circular

Orbits currently under consideration for MTO include the four candidate orbits identified in Table 4 and illustrated in Figure 7 (next page). Three of these are daily repeat-groundtrack orbits⁹ that cover the same areas at the same time each day, a desirable attribute from the perspective of Mars relay users.

MTO should provide coverage which is complementary to relay coverage of the other Mars orbiters. However, because these other orbiters have shorter planned lifetimes than MTO and arrive at Mars earlier (or are already there), global coverage capability for MTO may be needed to ensure polar coverage of future missions.

The value of complementary orbits can be seen from Figure 5, which shows the amount of data which could be relayed over a UHF link from MTO in the 1/4 sol Circular Sun Synchronous (CSS) candidate orbit as a function of MSL latitude. Note that the return of data from MSL through MTO in this orbit is best if MSL is at a low latitude, while performance through Odyssey and MRO is much better near the poles, as previously noted.

Figure 8 (next page) shows the amount of data which could be relayed over a UHF link from MSL to MTO in the 1/4 sol CSS candidate orbit as a function of MSL longitude as well as latitude. The latitudinal inhomogeneities are due to the repeating ground track nature of this orbit.

Sun Synchronous (CSS) candidate orbit.

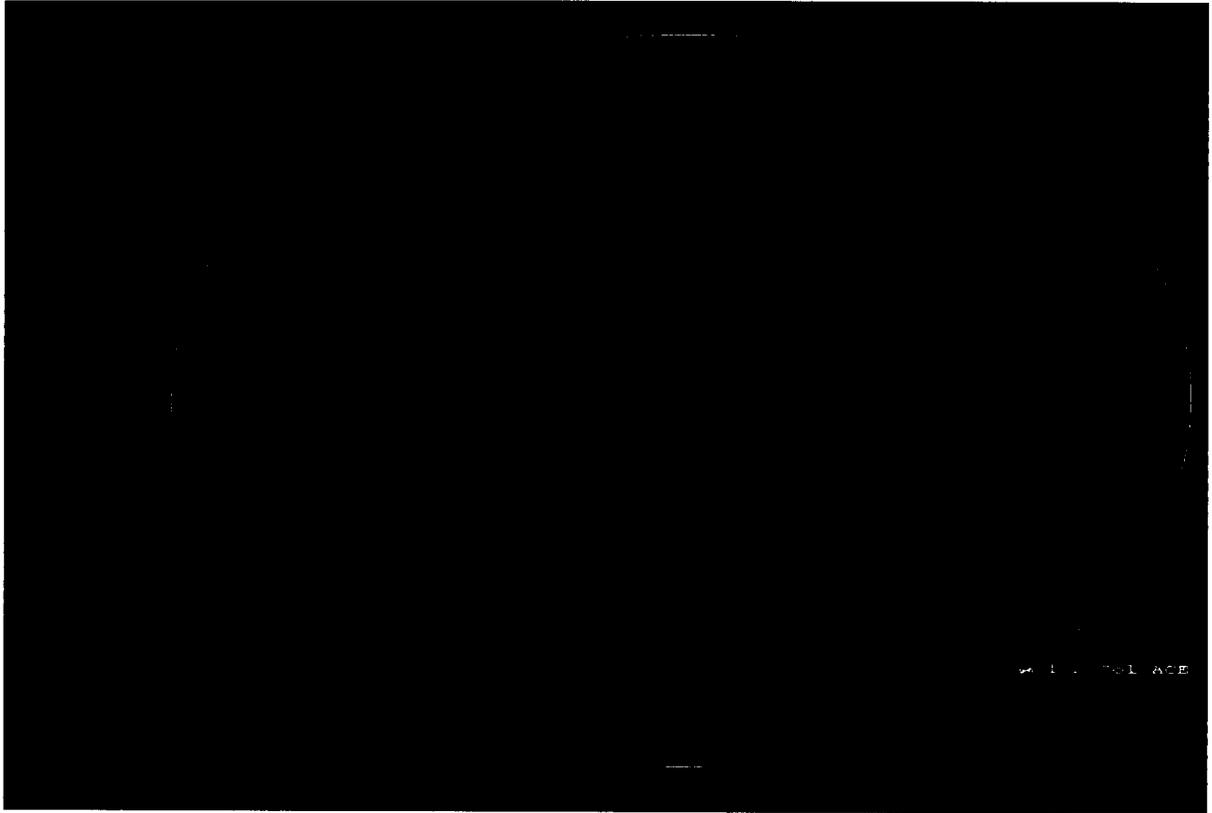


Figure 7. Candidate MTO Orbits

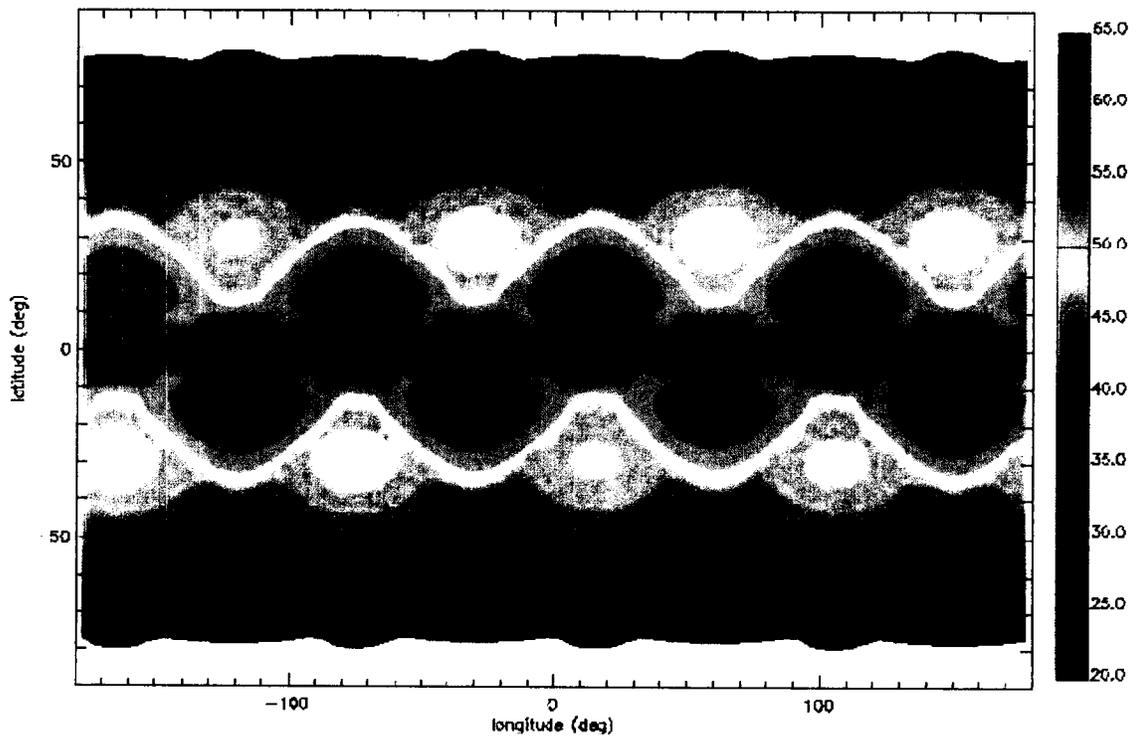


Figure 8. MSL UHF Data Volume to MTO in $\frac{1}{4}$ sol CSS candidate orbit, Mb/Sol/W

Figure 9 shows the times in which various orbiters and the Sun are in view of MSL at its challenge site. The contact times for MRO, Odyssey and MRO are very short (ten minutes or less) and infrequent, typical of low altitude near-polar orbiters covering mid-latitude regions.

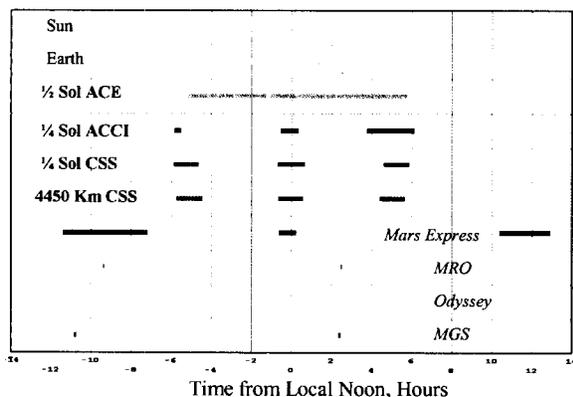


Figure 9: MSL View Periods

The long contact times made possible by MTO enable important new monitor and control services. For example, a rover or aerobot with a low power UHF transmitter could be continuously monitored all the time it is in motion and could be commanded at convenient times

through MTO.

Final selection of the MTO orbit will be made following analysis of the ΔV required to get into candidate orbits as well as further evaluation of the relative benefits of these and other orbits.

MTO SPACECRAFT

The MTO spacecraft will be built by an industry contractor. This section describes the reference spacecraft design developed by JPL (Figure 10).

The MTO spacecraft is scheduled to be launched in 2009. It will be inserted into a highly elliptical orbit about Mars in 2010. At least two propulsive ΔV maneuvers, a periapse raise followed by an apoapse lower, will place MTO into its final orbit.

MTO carries two principal payloads: 1) an Electra transceiver which, together with steerable UHF and X-band proximity antennas, provide data relay services and navigation support to Marscraft and 2) a telescope and associated laser and electronics that will be used to demonstrate high data rate communications with Earth at optical wavelengths.



Figure 10. JPL Artist Conception of Mars Telecommunications Orbiter

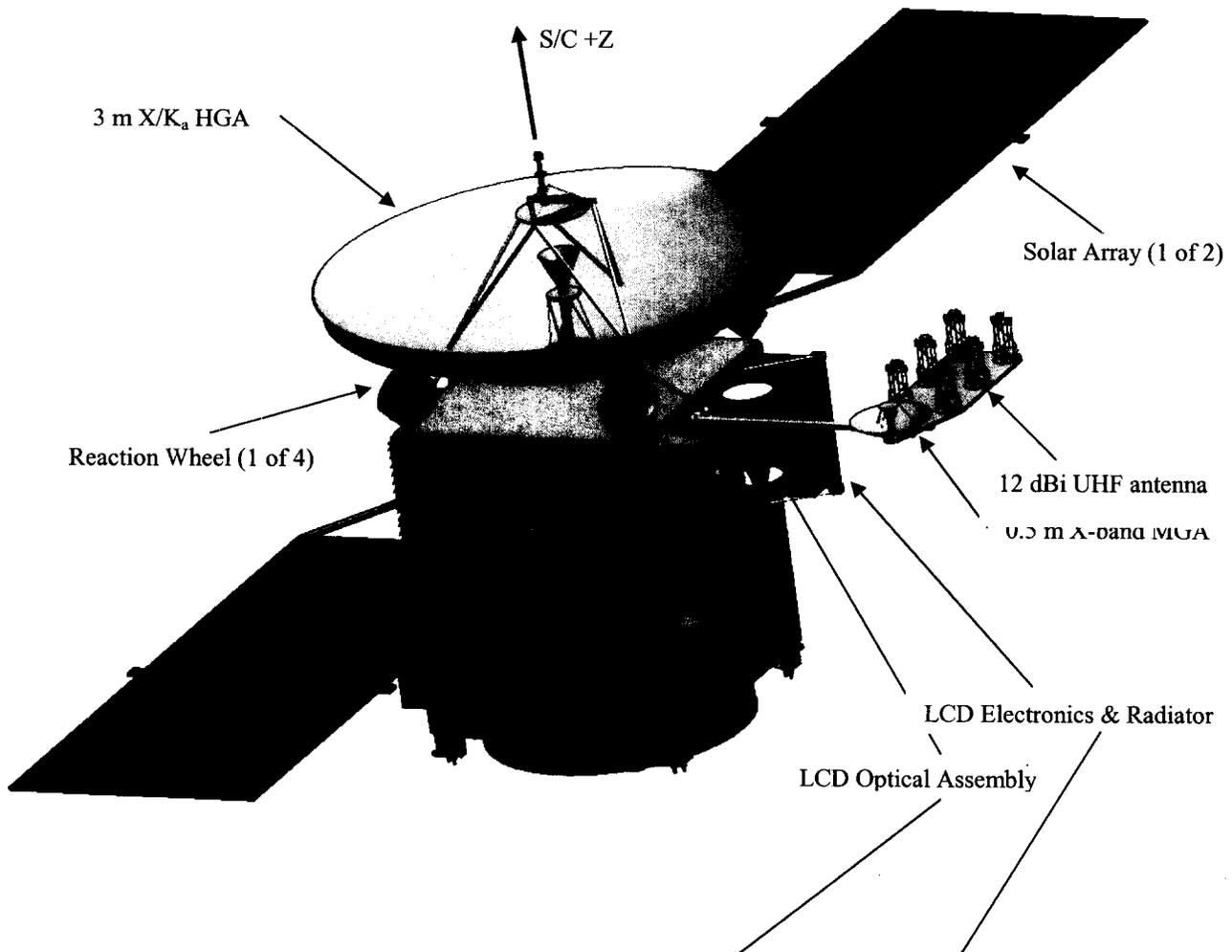


Figure 11. JPL Reference MTO Configuration

In JPL's reference design, both the Laser Communications Demonstration payload and a 3 meter diameter X-/K_a-band High Gain Antenna (HGA) are mounted body-fixed with their boresites co-aligned (Figure 11, previous page). The nominal attitude of the spacecraft is with these boresites Earth-pointed. Body-fixed solar arrays, oversized to account for the up to 47° sun off-point that would occur with the HGA always Earth-pointed, further simplify the design and mission operations. So that an Earth-point attitude can be maintained during data relay operations with other Marscraft, 12 dBi UHF and 0.5 m X-band relay antennas are mounted at the end of a gimbaled boom that is deployed shortly after launch.

MTO Links

Figure 12 illustrates MTO's communications link capabilities.

MRO will demonstrate K_a-band DTE operations at Mars,¹⁰ but MTO will be the first spacecraft to rely on K_a-band communications as a fully operational capability at Mars. MTO plans to use weather predictions to generate an optimal K_a-band link profile for each pass.¹¹

MTO will employ the selective retransmission capability of the CCSDS File Delivery Protocol (CFDP) on all DTE links to ensure reliable delivery of data even if bits are lost due to bad weather or other adverse conditions. This protocol operates efficiently by automatically re-sending only those frames which did not get through successfully.

Orbiting relays before MTO do not change data rates during a relay pass: the data rate for each pass is chosen in advance based on predicted link conditions. As there is generally some uncertainty about link conditions, a large margin – typically 6 dB – is normally added to ensure reliable link performance. Also, because of the irregular patterns of the relay antennas on the science orbiters and the large range changes between the orbiter and relay user during each relay pass, there is a large variation in link performance during the pass.

MTO will be able to make real-time data rate changes during a relay pass based on measured link performance. As a result, MTO will be able to optimize the link performance continuously during each pass, and can minimize margin. MTO will rely on the automatic retransmission capability of the CCSDS Prox-

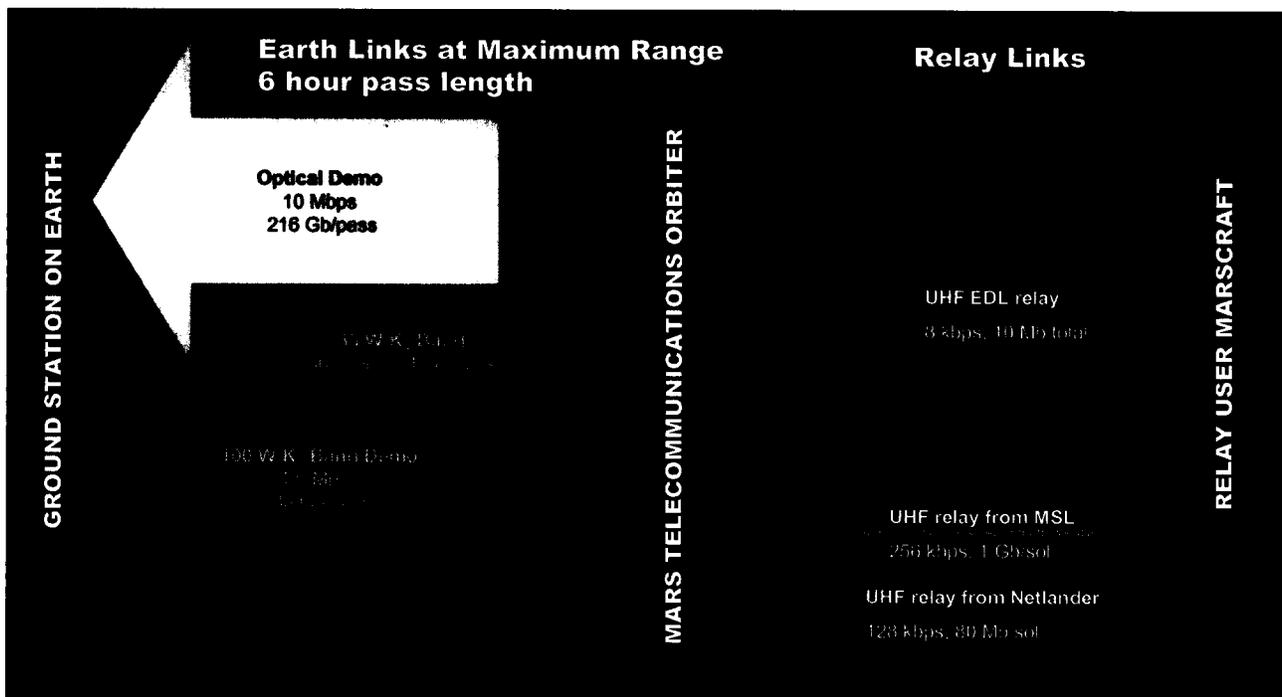


Figure 12. MTO Return Links

imity-1 protocol to ensure reliable delivery of data even with small, changing margin. This strategy should result in a large additional increase in MTO relay performance relative to all previous relays orbiting Mars.

MTO operations are described in another paper at this Congress.¹²

MTO Laser Communications Demonstration

Demonstrating deep space laser communications (lasercom)¹³ is a primary MTO objective. The MTO lasercom demonstration will send information using beams of light and optical elements, such as a telescope, rather than RF signals, amplifiers, and antennas. Near-Earth lasercom systems have already been demonstrated (GeoLITE in the U.S. and SILEX in Europe), and the technology has the potential to revolutionize deep space communications.

Deep space laser communications systems are expected to provide a substantial performance improvement over comparable RF systems and may eventually require less spacecraft mass. For example, an optical link with a 4 meter receiver on Earth will provide roughly the same performance as an RF link at K_a-Band using a 34 meter DSN antenna; with a 10 meter optical receiver, optical performance is 6 times better.

Presently, the flight terminal is expected to provide a continuous data link of between 1 and 100 Mbits/second from Mars to Earth, depending on the instantaneous distance. The 100 Mbits/second data rate will be a significant performance increase over today's RF systems and will be largely due to the use of efficient signaling, detection architectures, and near-capacity achieving error-correcting codes. The flight terminal includes a 30.5 cm telescope, a 5 W average/300 W peak power laser in a Master Oscillator Power Amplifier configuration operating at 1.06 μm, and an inertial reference subsystem. Flight terminal mass is about 70 kg and power consumption is expected to be about 130 W. A high performance stabilization and pointing subsystem will

be built through the use of passive stabilization and active tracking of an uplink beacon.

The Mars Lasercom Demo team is considering various options for the Earth receive terminals and beacon terminals. Critical technologies for receiving the deep space signal include low-cost large collection apertures and low-noise photon-counting detectors. Transmitting an uplink beacon through the turbulence in the atmosphere is another challenging problem that will have to be overcome. The team is investigating what is possible by using existing astronomical telescopes as well as what is required to be built to allow operations near the sun. The current plan is to have at least one high performing ground terminal since Mars spends much of the year within several 10s of degrees of the sun as seen from Earth. A future ground-based operational system will require more terminals than the existing RF Deep Space Network since lasercom links are easily obscured by clouds. Putting the Earth-based infrastructure in space, like NASA's Tracking and Data Relay Satellite System, may be an alternative approach.

It is theoretically possible to use laser communications throughout the solar system with better performance than RF systems. Laser communications will enable bandwidth-hungry instruments, such as hyperspectral imagers, and instruments with high definition in spectral, spatial or temporal modes to be used in deep space exploration. However, significant detailed engineering analysis, design, and tests have to be conducted before recommending that a laser communications system be used instead of a conventional RF system as a mission critical component. NASA needs to understand the best approach to do signal acquisition and tracking over interplanetary distances and to develop the appropriate infrastructure. However, it is not unreasonable for mission planners to consider using laser communications from the outer planets in the next decade. The Mars Laser Communications Demonstration project will provide much needed engineering insight.

CONCLUSION

The Mars Network, mankind's first interplanetary infrastructure, has laid the groundwork for the intensive robotic exploration of Mars now under way. Its development has been a truly international endeavor, with the first relay radio contributed by the French, the first and several succeeding orbiters and additional relay radios from the United States, and an orbiter and relay radio from the European Space Agency.

NASA's Mars Telecommunications Orbiter will bring revolutionary capabilities to the Mars Network. MTO will increase the data returned from other Mars missions by orders of magnitude, fundamentally change our connection to the red planet, and demonstrate interplanetary laser communications for the first time.

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