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THE MARS TELECOMMUNICATIONS ORBITER A KEY ASSET IN THE MARS NETWORK[†]

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The Mars Telecommunications Orbiter (MTO) to be launched in 2009 will play a key role in the Mars Network since it will be the first interplanetary mission whose primary objective is to provide communications to existing and upcoming Mars missions. This paper presents a basic description of the primary mission and provides trajectory information for the Mars Telecommunication Orbiter. This overview of the MTO mission should be considered preliminary. (Note from the author: The MTO project was cancelled in July 2005).

Nomenclature

ACCI	=	Apoapse at Constant Time of Day, Critically Inclined
C_3	=	Injection Energy Per Unit Mass (V_∞^2), km^2/s^2
CCAFS	=	Cape Canaveral Air Force Station
CSS	=	Circular Sun-Synchronous
DLA	=	Declination of the Launch Asymptote, deg
DSN	=	Deep Space Network
DV	=	Delta-V / ΔV
EDL	=	Entry, Descent, and Landing
ESA	=	European Space Agency
ESS	=	Elliptical Sun-Synchronous
JAXA	=	Japanese Space Agency
MAV	=	Mars Ascent Vehicle
MEX	=	Mars Express
MGS	=	Mars Global Surveyor
MLCD	=	Mars Laser Communications Demonstration
MOI	=	Mars Orbit Insertion
MRO	=	Mars Reconnaissance Orbiter
MTO	=	Mars Telecommunications Orbiter
ODY	=	Mars Odyssey
OSC	=	Orbital Sample Canister
RAN	=	Rendezvous and Autonomous Navigation
RLA	=	Right Ascension of the Launch Asymptote
TCM	=	Trajectory Correction Maneuver
UTC	=	Universal Time Coordinated
V_∞	=	Hyperbolic Excess Velocity, km/s

Introduction

The Mars Network currently consists of the Mars Global Surveyor (MGS), Mars Odyssey (ODY), and Mars Express (MEX)[1]. The Network will grow with the addition of the Mars Reconnaissance Orbiter (MRO) in 2006. The orbits of these spacecraft were selected to optimize the return of remote science. On the other hand, MTO will be placed into an orbit optimized for spacecraft telecommunications relay support. MTO will feature the most advanced communications system ever put on an interplanetary spacecraft, with high performance X-band and Ka-band links to Earth, high performance UHF and X-band relay links to other spacecraft, and an experimental laser

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communications payload (MLCD) for Earth communications. While MTO will provide fundamental communications infrastructure at Mars, MTO will also provide critical event coverage for Entry, Descent, and Landing (EDL), approach navigation (via Doppler data collection) for improved landing precision and demonstrate the ability to detect and track an orbital sample released from the orbiter and tracked with its narrow angle camera.

Reference Launch Period and Trajectories

The MTO mission will be launched during the 2009 Mars opportunity using a Type II Earth-to-Mars interplanetary ballistic trajectory. The mission will launch from either the Cape Canaveral Air Force Station (CCAFS) in Florida or Vandenberg Air Force Base (VAFB) in California. The launch dates and arrival dates for MTO must be coordinated with those of the Mars Science Laboratory (MSL) which tentatively is scheduled to be launched in the 2009 opportunity or any other Mars mission that will share the launch date space. The requirement for MTO to provide critical event coverage for MSL constrains the arrival of MTO at Mars to allow for orbit commissioning. The current reference launch period for MTO is 20 days in length and extends from 22 September 2009 to 11 October 2009 as seen in Table 2.1. The required injection energy per unit mass as a function of the launch date and the arrival date is illustrated in a typical pork-chop plot[2,3] in Fig. 2.1

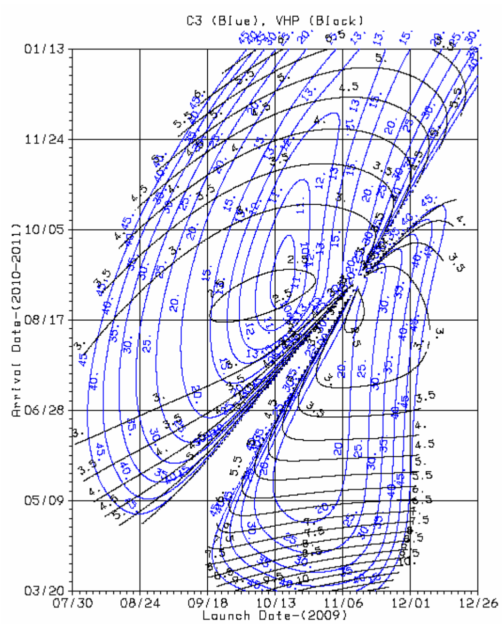


Figure 2-1. Earth to Mars 2009 Type I/II Trajectories

Launch Day	Launch Date (mm/dd/yy)	Arrival Date (mm/dd/yy)
1	09/22/09	08/19/10
2	09/23/09	08/19/10
3	09/24/09	08/21/10
4	09/25/09	08/21/10
5	09/26/09	08/21/10
6	09/27/09	08/23/10
7	09/28/09	08/23/10
8	09/29/09	08/25/10
9	09/30/09	08/25/10
10	10/01/09	08/25/10
11	10/02/09	08/27/10
12	10/03/09	08/27/10
13	10/04/09	08/27/10
14	10/05/09	08/29/10
15	10/06/09	08/29/10
16	10/07/09	08/29/10
17	10/08/09	08/31/10
18	10/09/09	08/31/10
19	10/10/09	08/31/10
20	10/11/09	08/31/10

Table 2-1. Reference Launch Period

Launch Vehicle Targeting

The Targeting Interface Point (TIP) is the time when the interplanetary target conditions are achieved by the launch vehicle. The Earth relative target conditions are defined by the launch energy (C3), the declination of the launch asymptote (DLA) and the right ascension of the launch asymptote (RLA). High launch declinations have a penalty in performance and are usually avoided. The period of launch dates listed in Table 2.1 have C_3 values that range between 10 and 14 km^2/sec^2 and DLA values which range between 15° and 20°. The Earth departure conditions for the opening and closing of the launch space are shown in Table 3.1

Launch of the MTO spacecraft will be conducted using an intermediate-class Evolved Expendable Launch Vehicle (EELV). As stated before, MTO will be launched from either the Eastern or the Western Range. From a performance point of view, launching from the Cape is preferred due to launch azimuth restrictions of the Western Range and the resultant effect on launch vehicle inertial velocity. Due to the fact that launches of two different missions in the 2009 Earth to Mars opportunity is anticipated, MTO may launch from the Western Range to avoid launch scheduling conflicts[4].

The candidate launch vehicles include the Boeing Delta IV 4240 and the Lockheed Martin Atlas V 401 and 411.

	Open	Close
Injection Date (ET)	22-Sep-2009 00:00:00.00	11-Oct-2009 00:00:00.00
Arrival Date (ET)	19-Aug-2010 00:00:00.00	31-Aug-2010 00:00:00.00
Hyperbolic Departure Elements, Earth Centered, Equator & Equinox of Epoch		
Radius (km)	6563.2	6563.2
Inclination (deg)	28.5	28.5
True Anomaly (deg)	0	0
C_3, Energy (km^2/sec^2)	13.949	10.361
DLA, Declination of V_∞ (deg)	15.729	19.126
RLA, Right Ascension of V_∞ (deg)	123.553	114.128
Cartesian Elements, Earth Centered, Earth Equator & Equinox of J2000 (Long-Coast Parking Orbit, Ascending Node Hyperbolic Injection)		
X (km)	5972.875	5219.83
Y (km)	-2719.767	-3923.879
Z (km)	48.906	-656.737
V_x (km/sec)	4.200508	6.524261
V_y (km/sec)	9.324561	7.782493
V_z (km/sec)	5.551936	5.356738
Cartesian Elements, Earth Centered, Earth Equator & Equinox of J2000 (Short-Coast Parking Orbit, Descending Node Hyperbolic Injection)		
X (km)	5507.117	4886.059
Y (km)	-2013.838	-3173.717
Z (km)	-2948.03	-3021.374
V_x (km/sec)	3.046525	5.564741
V_y (km/sec)	11.073605	9.939051
V_z (km/sec)	-1.873413	-1.441094

Table 3-1. Heliocentric Injection Conditions

Cruise

The MTO mission will use a Type-II trajectory between Earth and Mars. The trajectory at the open (22-Sep-2009) and close (11-Oct-2009) of the reference launch period is shown in Fig. 4.1 and Fig. 4.2 respectively.

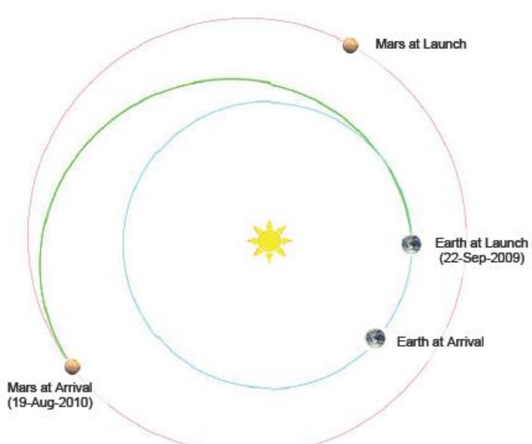


Figure 4-1. Earth to Mars 2009 Open Launch

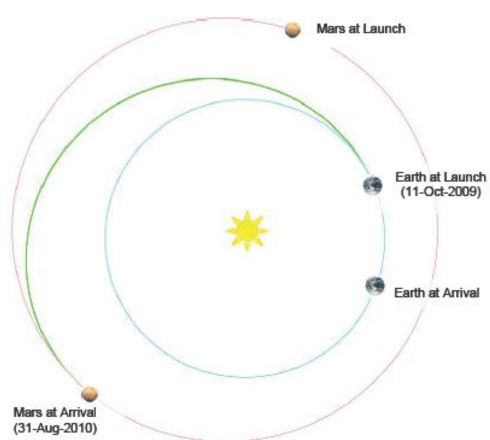


Figure 4-2. Earth to Mars 2009 Close Launch

These trajectories are purely ballistic, i.e. no deep space maneuvers (broken plane maneuvers) during the interplanetary transfer. Three Trajectory Corrections Maneuvers (TCMs) during the cruise phase are scheduled to correct launch vehicle dispersions, remove planetary protection biasing, and control the cruise and approach to Mars. TCM-1 is scheduled to occur 15 days after launch; TCM-2 is tentatively scheduled to be executed 90 days after launch. TCM-3 will be performed 60 days before Mars Orbit Insertion (MOI). The heliocentric conditions for the interplanetary transfer are shown in Table 4.1.

	Open	Close
Injection Date (ET)	22-Sep-2009 00:00:00.00	11-Oct-2009 00:00:00.00
Arrival Date (ET	19-Aug-2010 00:00:00.00	31-Aug-2010 00:00:00.00
Classical Orbital Elements at Injection, Sun Centered, Earth Equator & Equinox of J2000		
Semi-major Axis (km)	193452987.190	193643790.632
Eccentricity	0.235879	0.229847
Inclination (deg)	22.979	23.213
Node Angle (deg)	0.021	-0.182
Arg. Of Periapsis (deg)	22.292	25.009
True Anomaly (deg)	-14.158	-4.370
Cartesian Elements at Injection, Sun Centered, Earth Equator & Equinox of J2000		
X (km)	150138952.220	142300048.46
Y (km)	-2416655.984	41613048.201
Z (km)	-1048180.523	18039884.270
V_x (km/sec)	-1.940824	-10.7661
V_y (km/sec)	30.224688	28.715954
V_z (km/sec)	12.816858	12.300567

Table 4-1. Heliocentric Injection Conditions

The interplanetary B-plane targets for an unbiased injection for a Northern and Southern approach for the open and close of the reference launch period are shown in Table 4.2.

	Open	Close
Injection Date (ET)	22-Sep-2009 00:00:00.00	11-Oct-2009 00:00:00.00
Arrival Date (ET	19-Aug-2010 00:00:00.00	31-Aug-2010 00:00:00.00
Hyperbolic Arrival Elements, Mars Centered, Equator and Equinox of Epoch (North Approach)		
B•T (km)	-5151.667	-5203.435
B•R (km)	-6095.791	-6154.500
Periapsis Radius (km)	3646.2	3646.2
B Plane Angle (deg)	-130.201	-130.213
True Anomaly (deg)	0	0
V_∞ (km/sec)	2.489	2.459
Declination of V_∞ (deg)	-0.490	-1.351
Right Ascension of V_∞ (deg)	229.933	230.728
Hyperbolic Arrival Elements, Mars Centered, Equator and Equinox of Epoch (South Approach)		
B•T (km)	-5151.667	-5203.435
B•R (km)	6095.791	6154.500
Periapsis Radius (km)	3646.2	3646.2
B Plane Angle (deg)	130.201	130.213
True Anomaly (deg)	0	0
V_∞ (km/sec)	2.489	2.459
Declination of V_∞ (deg)	-0.491	-1.351
Right Ascension of V_∞ (deg)	229.933	230.728

Table 4-2. Unbiased Injection Interplanetary B-Plane Targets

Approach and Orbit Insertion

Following the execution of TCM-3, two more TCMs are scheduled to fine-tune the approach trajectory. The selection of a Northern or Southern approach is still pending. Mars Orbit Insertion (MOI) will be performed using a pure chemical propulsive burn. No aerobraking or aerocapture will be used to capture around Mars. The magnitude of the MOI ΔV for the reference launch date is approximately 676 m/s. The MOI maneuver will be targeted to capture into a 250km by 5 sol orbit. MTO will then follow a series of maneuvers to achieve the initial service orbit which will provide EDL coverage to upcoming spacecraft and relay services to missions on Mars. Following MOI, a maneuver will be executed at apoapse to raise periapse in order to match the periapse of the service orbit. When reaching periapse, MTO will again execute a propulsive burn to lower apoapse to the final apoapse altitude. Since the initial capture orbit has a high altitude apoapse, the size of this maneuver may be too large. Currently, the size of this maneuver is constrained to be less than or equal to the magnitude of MOI. If the magnitude of the apoapse lowering maneuver is larger than the magnitude of MOI, this maneuver will simply be broken into two different maneuvers so that the apoapse altitude of the service orbit is reached. This maneuver strategy is illustrated in Fig. 5.1 for a Northern approach.

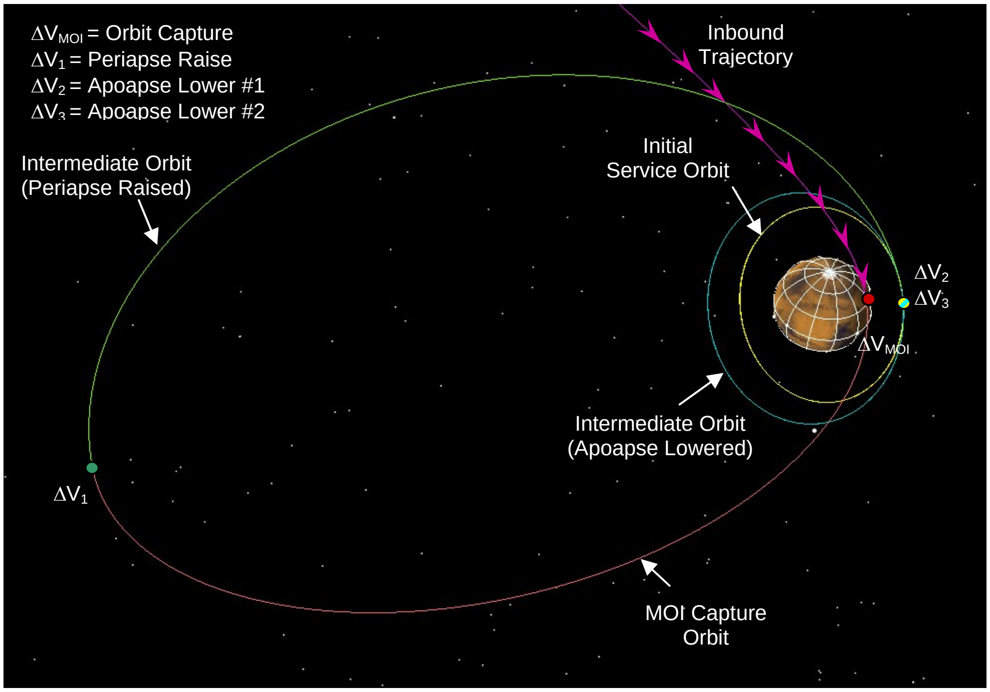


Figure 5-1. MOI Geometry, North Approach to Initial Service Orbit

Fig. 5.2 shows the incoming trajectory, MOI and the sequence of maneuvers scheduled to be executed as they will occur as seen from the Earth.

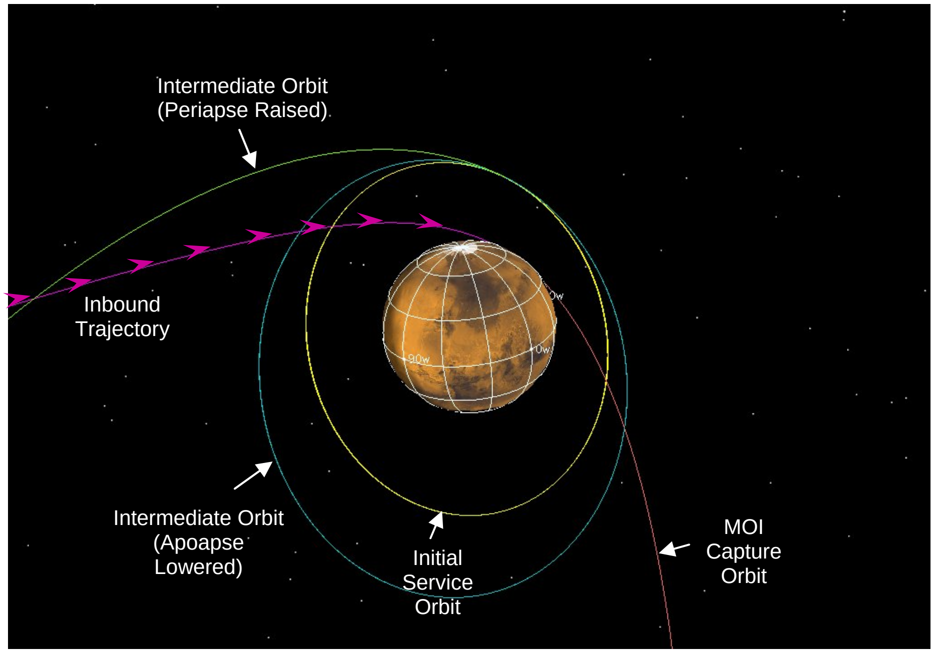


Figure 5-2. MOI Geometry, North Approach to Initial Service Orbit, View from Earth

Candidate Orbits to Support Relay

Over 200 orbits have been characterized and evaluated as the initial service orbit to provide EDL coverage and support relay. The orbit selection criteria are based on the specific needs of the potential spacecraft customers which include the following: Number of contacts per sol, maximum communication gap per sol, maximum data rates, and total data throughput per sol for UHF and X-Band among others. The performance of the different orbit candidates depends on the orbital characteristics of the orbit, mainly semi-major axis, eccentricity and inclination. The LMST of the orbit would shift Eastwards or Westwards the pattern of a particular metric and the local times when the passes occur. A variation in the true anomaly of the orbit would only shift the pattern of a particular metric. The orbit selection process considers a number of factors: Higher altitudes are preferred to allow longer passes and larger footprints, intermediate inclinations are favored to ensure global access (MTO must be able to provide relay services to any spacecraft). Sun-Synchronous orbits are beneficial from a power and thermal point of view, and Ground Track Repeat (GTR) orbits allow passes over the same latitude/longitude every sol[4].

Currently three orbit candidates have been chosen as the reference orbits for the initial service phase. These orbits including Northern and Southern approaches are listed in Table 6.1.

Orbit Parameter	Orbit Candidates					
	North Approach			South Approach		
	1/4-sol CSS (Natural Nodes[5])	1/4-sol ACCI (Apsides at Equator)	1/5-sol ESS (Natural Nodes[5])	1/4-sol CSS (Natural Nodes[5])	1/4-sol ACCI (Apsides at Equator)	1/5-sol ESS (Natural Nodes[5])
Semi-Major Axis (km)	8117.93	8114.013	6992.277	8117.93	8114.013	6992.277
Altitude (km)	4721.7	948.6 - 8487.0	3176.5 - 4015.6	4721.7	948.6 - 8487.0	3176.5 - 4015.6
Eccentricity	Circular (e=0)	Eccentric (e=0.464532)	Eccentric (e=0.06)	Circular (e=0)	Eccentric (e=0.464532)	Eccentric (e=0.06)
Inclination (deg)	136.754	116.565	115.398	136.754	116.565	115.398
Nodal Period (sol) (1 sol=88775.244 s)	0.2500	0.2500	0.2000	0.2500	0.2500	0.2000
Node Sun-Synchronous	YES	YES	YES	YES	YES	YES
Ground-Track Repeating	YES	YES	QUASI	YES	YES	QUASI

Table 6-1. MTO Reference Candidate Orbits

It is important to note that MTO is expected to provide EDL and relay services for 10 years (last 4 years as part of the projected extended mission) to multiple users. Depending on the needs of future users of the Mars Network, MTO will modify its initial service orbit to satisfy these needs. The ΔV budget has allocated 200 m/s for plane changes and 50 m/s for phasing maneuvers which widens the spectrum of coverage of MTO to support multiple users with various needs[5,6]. Table 6.2 lists the ΔV budget for MTO which includes orbit insertion and orbit commissioning.

ΔV Allocation	ΔV Magnitude (m/s)
MOI	676
TCMs	60
Peri Raise	66
Apoapse Lower 1	600
Apoapse Lower 2	261
Plane Changes	200
Phasing	50
Rendezvous	50
Reserve	87
TOTAL	2050

Table 6-2. MTO Projected ΔV budget

MTO Primary Objectives

A. Telecommunications Relay

MTO is equipped with a telecommunications relay payload called Electra similar to the one that the Mars Reconnaissance Orbiter (MRO) carries. MTO is also equipped with Ka-band Direct-to-Earth (DTE) which features high data rates and also X-band Direct-to-Earth with lower data rate capabilities but with higher tolerance to signal degradation due to weather effects. Proximity links are accomplished via UHF and X-band frequencies. Figure 7.1 illustrates the telecommunications relay between MTO, spacecraft and Earth. The Electra payload will provide both forward and return proximity links to and from surface assets for command and science data return.

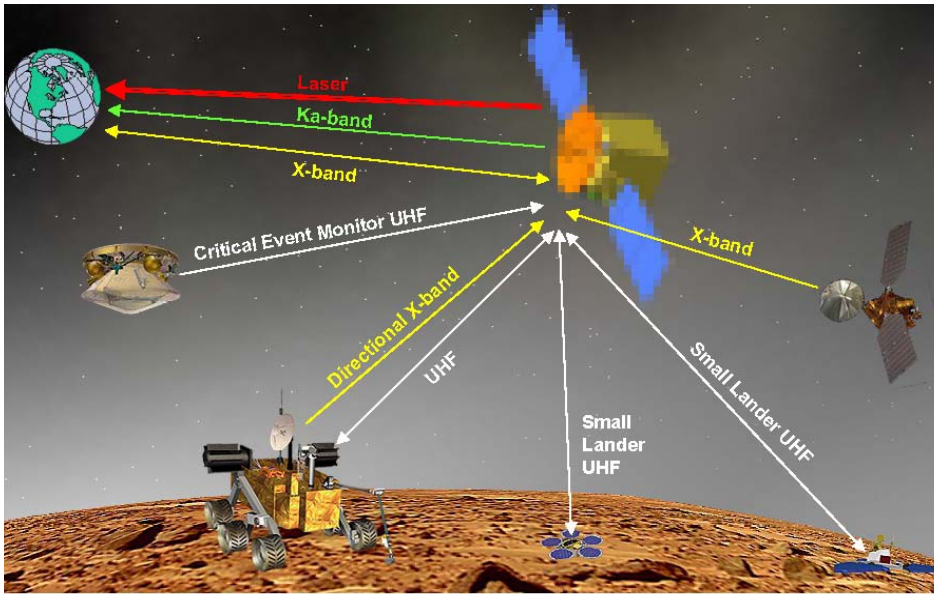


Figure 7-1. Telecommunications Relay between MTO, spacecraft and Earth

Table 7.1 lists the telecommunication characteristics of current Mars orbiter and upcoming missions which include MRO and MTO[7].

	MGS	Odyssey	Mars Express	MRO	MTO
Mars Orbiter Relays - Forward Link					
EIRP	2 W	2 W	4 W	6 W	50 W
Data Rates	Tones Only	8-256 kbps	2 & 8 kbps	1 to 1024 kbps	1 to 1024 kbps
Mars Orbiter Relays - Return Link					
Data Rates	8 & 128 kbps	8-256 kbps	2-128 kbps	1 to 1024 kbps	1 to 4096 kbps
Mars Orbiter Direct-to-Earth Links					
X-Band Data Rate	33 kbps	14 kbps	97 kbps	526 kbps	526 kbps
Ka-Band Data Rate				526 kbps	526 kbps
Laser					1 Mbps

Table 7-1. Telecommunications Characteristics for different Mars Orbiters

B. Precision Navigation and Timing

Electra features an ultra-stable oscillator with a deviation of better than 10^{-12} sec on a 10 seconds count. This oscillator is also used as a reference for timing services by maintaining an onboard Mars time base to within 10 milliseconds or better of UTC.

Traditionally, tracking of spacecraft has been enabled by the Earth-based DSN Doppler. MTO will dramatically improve the knowledge of a spacecraft incoming trajectory. B-plane uncertainties of better than 1 km can be achieved as compared to the 13 km using DSN data. Precision Navigation is illustrated in Figure 7.2.

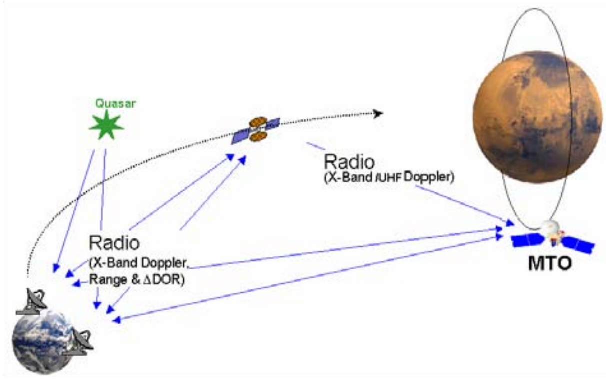


Figure 7-2. MTO Precision Navigation

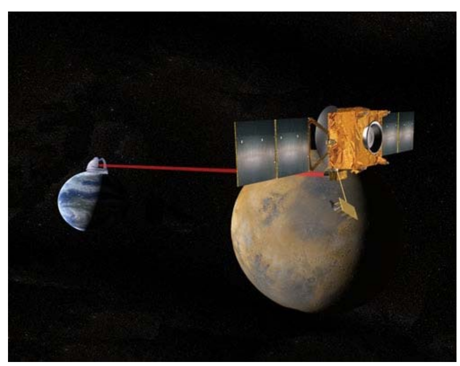
C. Critical Event Coverage

Events such as orbit insertion of a Mars orbiter (MOI), Entry, Descent and Landing (EDL) of a lander and launch from the Martian surface of a Mars Ascent Vehicle (MAV) are considered critical events that require direct line of sight between the spacecraft and MTO. The orbit selection process optimizes the initial service orbit to cover these critical events. MTO will support many customers; therefore, phasing maneuvers executed in advance of a critical event will be required. The current ΔV budget has allocated enough ΔV to cover these critical events. Different maneuver strategies will be followed to cover these events which include plane changes, node phasing and true anomaly phasing.

MTO Technology Demonstrations

A. Mars Laser Communications Demonstration (MLCD)

The MLCD payload will demonstrate for the first time deep-space optical communications link. This demonstration is scheduled during the interplanetary transfer between Earth and Mars and during the first year after orbit commissioning. The MLCD project is managed by NASA Goddard Space Flight Center and requires an Earth-based infrastructure which includes an extensive ground system and a telescope array to enable forward and return laser communications. A mobile ground system is also projected to avoid data dropouts due to weather conditions at the target telescope array. Downlink communications will feature a data transmission rate of 10 Mbps with a goal of 30 Mbps with a minimum of 1Mbps. Upload communications will feature a data transmission rate of 10 bps[8].



B. Rendezvous and Autonomous Navigation (RAN) Demonstration

This demonstration is composed of two main elements. An experiment to support a future Mars Sample Return Mission and a demonstration to support extensive autonomous navigation (AutoNav) in Mars orbit. The rendezvous element will search, detect and track an Orbiting Sample Canister (OSC) using both optical and radio detection released by the MTO spacecraft. The AutoNav element will demonstrate autonomous precision approach and orbital navigation using Mars landmarks and Martian moons Phobos and Deimos[9].

C. 100W Ka-Band Traveling-Wave Tube Amplifier (TWTA) Demonstration

This demonstration is a key driver for future deep-space missions since this technology will support robust data rates enabling high data volume. It is not planned to use the TWTA simultaneously with other relay or demonstration operations although when operating, the TWTA will be used instead of the MTO's Ka-band power amplifier.

MTO Customers 2010-2020

It is anticipated that the Mars Science Laboratory (MSL) will be the first customer that MTO will support. Following MSL, one of the more ambitious missions within NASA's Mars Exploration Program is the Mars Sample Return mission (MSR) to be launched in the 2013 or 2016 opportunity. During the next decade, several Mars Scouts missions and other Mars missions managed by the European Space Agency (ESA) and the Japanese Space Agency (JAXA) will potentially benefit of the advanced capabilities that MTO offers.

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