NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Mars Exploration Program

Mars Relay Description for Discovery 2010 Proposals

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1 Introduction

The Discovery 2010 Announcement of Opportunity (AO) solicits proposals for planetary science missions to be launched no later than the end of calendar year 2016. The AO includes the opportunity to propose missions destined for Mars. Accordingly, this document provides information on telecommunications relay services available for use by applicable Mars Discovery missions, based on the relay capabilities that are planned to be in place as part of the continuing NASA Mars Exploration Program. Specifically, this guide outlines the orbital, communications and radiometric characteristics of each orbiting relay asset as needed to predict relay performance. It also presents guidelines on how to design Mars missions that will employ orbiting relays at Mars.

In cases where this guide conflicts with the AO, the AO takes precedence.

Section 2 of this document describes the overall Mars Relay infrastructure that has been established by NASA's Mars Exploration Program to support exploration of the Red Planet, as well as future planned augmentations to that infrastructure that are relevant in the time frame of a Mars Discovery mission proposed in reponse to the this AO.

Section 3 presents a number of Guidelines regarding the design, implementation, and operation of relay links that would utilize services provided by the Mars Relay infrastructure.

Sections 4, 5, 6, and 7 provide specific details regarding, respectively, the relay capabilities and constraints of the Odyssey, Mars Reconnaissance Orbiter, 2013 MAVEN, and 2016 ExoMars/Trace Gas Orbiter missions.

Section 8 describes multimisison relay processes involved in the planning and execution of relay services.

Section 9 discusses specific lessons-learned from relay support to the 2003 Mars Exploration Rovers (Spirit and Opportunity) and to the 2007 Phoenix Lander.

2 Mars Relay Infrastructure Overview

Recognizing the value of relay communications for enabling and enhancing Mars exploration, the Mars Exploration Program has established a strategy of including relay communications capabilities on each Mars science orbiter [1]. For Mars *in situ* spacecraft (such as landers, rovers, penetrators, and aerobots), severe mass, volume, and power constraints can severely limit or preclude the ability to transmit significant amounts of data over conventional direct-to-Earth telecommunications links. For such missions, relay communication offers an attractive and, at times, enabling option. Rather than establishing a link over the long distance to Earth (up to ~400,000,000 km), a user spacecraft can instead communicate with a relay-capable orbiter as it passes overhead, over a slant range of just hundreds or thousands of kilometers. The short communications distance allows high instantaneous data rates, even with simple, omnidirectional radio links, increasing data volume while reducing the energy-per-bit required to transmit those data. The relay orbiters, typically equipped with larger, higher-directivity antennas and higher power transmitters, can then take on the burden of communicating over the long haul link back to Earth. In addition to the advantages of data volume and energy efficiency, relay orbiters also enable communications with surface spacecraft at times when Earth is not in view (e.g., during the Martian night). Finally, these relay telecommunciations links can also be configured to acquire radio metric observables (e.g., Doppler) which can provide position, navigation, and timing information for user spacecraft.

At the time of arrival of the Spirit and Opportunity rovers at Mars in January 2004, the Mars Global Surveyor (MGS) and Odyssey spacecraft were in orbit, each equipped with Ultra-High Frequency (UHF) relay communications payloads. The two rovers included both an X-band direct-to-Earth communications system as well as a UHF system for relay communications with Mars orbiters. Due to the data volume and energy advantages cited above, the rovers quickly adopted an operational strategy of returning the bulk of their data via the relay links. To date, 98% of the science and engineering data obtained from Spirit and Opportunity have been returned via relay links, with each rover returning an average of 88 Mb/sol. In addition to this surface relay support, MGS also provided communications support during the terminal phase of Entry, Descent, and Landing (EDL) for Spirit and Opportunity, gathering high-rate (8 kbps) engineering telemetry that would have been used to diagnose any anomalies that might have led to a loss of the spacecraft during this critical phase of the mission.

The relay infrastructure was augmented by the launch of the Mars Reconnaissance Orbiter (MRO) in 2005. In addition to its science payload suite, MRO includes the Electra Proximity Link Payload, a next-generation UHF radio system for relay services at Mars. After the loss of MGS in 2006, Odyssey and MRO both provided relay services to the 2007 Phoenix Lander mission. Unlike Spirit and Opportunity, Phoenix had no direct-to-Earth communications capability and hence was entirely dependent on UHF relay communications for all command and telemetry services once the lander separated from its interplanetary cruise stage shortly prior to atmospheric entry. Both Odyssey and MRO acquired critical event telemetry from the Phoenix spacecraft during its EDL phase. And over its 151-sol surface mission, the Phoenix Lander returned 25.6 Gb of data, corresponding to an average of 251 Mb/sol. (The higher average data return of Phoenix relative to Spirit and Opportunity was due to its high latitude, which permitted more frequent relay contacts from the near polar orbits of Odyssey and MRO.)[1]

[1] While this document focuses on NASA relay orbiters, it should be noted that the European Space Agency's Mars Express Orbiter is also equipped with an interoperable UHF relay payload, and has been successfully used to perform a number of demonstration relay passes with Spirit, Opportunity, and Phoenix, and to provide redundant tracking of the Phoenix UHF carrier signal during Entry, Descent, and Landing.

Odyssey and MRO continue to support Spirit and Opportunity today, and both are planned to be used for support of the 2011 Mars Science Laboratory (MSL) mission, arriving at Mars in late 2012, with a nominal primary surface mission duration of one Mars year (or roughly two Earth years.)

In the time frame of a Mars mission proposed in response to the Discovery 2010 AO, both Odyssey and MRO could potentially still be in operation and available to provide relay services. Both orbiters have sufficient propellant reserves to maintain operation in their current orbits until 2020 or beyond. However, depending on the final landing site selected for MSL and the actual MSL launch day, it may be necessary to modify the orbits of one or both orbiters in order to position them to enable visibility of MSL during its EDL phase. Such orbit changes could require significant propellant use, resulting in a reduced propellant lifetime. MRO, with its large remaining propellant budget, would still retain sufficient propellant to operate beyond 2020, but Odyssey's propellant life could be significantly reduced, with propellant runout as early as 2014. The final MSL EDL strategy, and the corresponding implications on Odyssey propellant lifetime, will likely not be fully known until MSL launch in Oct-Dec, 2011. Needless to say, both orbiters will also be operating well beyond their nominal design lifetime in the post 2016 time frame.

To augment this relay infrastructure, MEP plans to include a UHF relay payload on the 2013 Mars Atmosphere and Volatile Evolution Mission (MAVEN). After MAVEN completes its primary science phase in Oct 2015, it would be available to provide relay services to user missions at Mars. Unlike Odyssey and MRO, which operate in low-altitude near-circular orbits, MAVEN will operate in a highly elliptical orbit matched to its science objectives, with a low periapsis altitude of 150 km and an apoapsis altitude of over 6000 km. The resulting orbit results in substantial variability in overflight geometry, with an impact on the frequency of relay contacts and the slant range (and corresponding data rate) at which individual contacts are supported. (Detailed MAVEN orbit characteristics will be presented in Section 6.) Nonetheless, MAVEN plays an important role in the overall MEP relay strategy, providing an additional redundant relay asset and providing a high likelihood that at least one relay orbiter would be available in the 2016-2020 time frame.

One other emerging mission concept could have applicability to a Mars Discovery mission proposer. At the current time, ESA and NASA are in the early planning stages for a joint ESA/NASA Mars orbiter mission which would be launched early in 2016. The ExoMars/Trace Gas Orbiter , the first mission proposed under the Mars Exploration Joint Initiative announced in 2009 by NASA and ESA, would conduct orbital science investigations from a low-altitude circular orbit and would carry a UHF relay payload to provide telecommunications relay services to other Mars spacecraft.

To enable interoperability among the various Mars relay orbiters and to provide a standardized service interface to user spacecraft, each Mars relay orbiter supports relay communications in conformance with the Consultative Committee on Space Data Systems (CCSDS) Proximity-1 Space Link Protocol [2,3,4]. User missions are responsible for implementing a relay communications system that conforms to this standard in order to access Mars Relay services. One option that users should consider is to implement their UHF relay system based on the Electra-Lite UHF Transceiver that is planned to be flown on the 2011 Mars Science Laboratory mission. The Electra-Lite radio system is compatible with the CCSDS Proximity-1 Space Link Protocol and is inherently interoperable with the NASA Mars Relay infrastructure [5].

3 Recommended Guidelines

3.1 Relay Link Design

Relay link designers should carefully and clearly enumerate all link parameters associated with their side of the communications link and include sufficient margin to ensure reliable link performance. Proposals should include representative link budgets and should quantify their link margin assumptions and justify them based on the nature, complexity and scope of the telecommunications link design uncertainties as well as the criticality of the data transmitted.

3.2 Critical Event Coverage

Critical event coverage can be provided by Mars infrastructure relay orbiter(s) provided the coverage meets the guidelines referenced in this guide. Mars Scout proposers can also use DSN assets (including the 70-m network) for providing critical event coverage. Proposers are also free to propose a combination of relay orbiter(s) and DSN coverage.

3.3 Orbiter Redundancy

The availability of multiple relay orbiters increases the likelihood that at least one relay orbiter will be operational at the time that a user mission requires relay services. The proposed mission design should be compatible with using any of the available relay assets planned for operation at the time services are needed. Ideally, mission objectives should be achievable if any one of the redundant orbiters is available; the proposer may also wish to discuss the enhancement in science return if multiple orbiters are in fact available.

3.4 Relay Cost

There is no direct cost to Mars Discovery missions for using Mars infrastructure relay orbiter(s). However, Discovery missions must pay for the amount of DSN tracking of Mars infrastructure relay orbiters needed to relay Discovery telemetry and command data. Tracking costs are given in "NASA Mission Operations and Communications Services" in the Mars Discovery library. Proposers should also budget for an appropriate level of project staffing required to interface with the relay orbiter missions for Mars relay planning and coordination efforts.

3.5 Relay Tests

Each relay orbiter will have a ground-based system for conducting compatibility tests with user relay radios. Testing is required at two levels: (1) radio compatibility and (2) end-to-end relay compatibility, including flight and ground system interfaces. Each Discovery mission using relay services must include relay compatibility testing in its schedule and pay for its part of the tests.

Much of the remainder of this guide provides information about the individual relay orbiter orbits, services, radios, and antenna patterns to help proposers meet these guidelines.

The guide also gives information about the Earth link capabilities of the orbiters. At the end are sections on the use of orbiters by the Mars Exploration Rovers and some lessons learned from that mission.

4 Odyssey

4.1 Orbit

Odyssey operates in a sun-synchronous, near-circular orbit, with an inclination of approximately 93 deg. The orbit node is currently oriented such that the mean local solar time of the ascending node is approximately 3:45 am. Keplerian orbit elements for the Odyssey spacecraft, at the epoch of Jan 1, 2010, are presented in Table 4.1-1.

Table 4.1-1: Odyssey orbit elements

Orbit Element	**ODYSSEY**
Periapsis Radius (km)	3762.0
Apoapsis Radius (km)	3827.8
Semi-major Axis (km)	3794.9
Eccentricity	0.0087
Inclination (deg)	93.0
Ascending Node (deg)	124.4
Arg of Periapsis (deg)	-89.0
Time from Periapsis (sec)	-3535.9
Epoch	2010-001T00:53:10
Related data	
Periapsis altitude / location	390 km / South pole
Apoapsis altitude / location	454 km / North pole
Local Mean Solar Time (LMST), ascending node	3:47 am
LMST, descending node	3:47 pm
Orbit period	1 hr 59 min

(Mean Keplerian orbit elements, Mars-centered, Mars mean equator and Earth mean equator, J2000, IAU 1991 Coordinate System)

Odyssey's low-altitude orbit results in short geometric contacts, with average pass durations of roughly 10 min during which the orbiter is visible above 10 deg from a given spot on the Martian surface. For low-latitude sites within 30 deg of the equator, a user will typically have 2-4 contact opportunities each sol, clustered around the 3:45 am and 3:45 pm nodal crossings. At higher latitudes, additional passes will be available, up to a maximum of 12-13 passes per sol for near-polar sites.

It is possible that the LMST of the Odyssey descending node may need to be adjusted in order to support communications with the Mars Science Laboratory during its Entry, Descent, and Landing in Aug-Sep, 2012. Depending on the size of the required plane change, it may not be possible to return the orbiter to a fixed LMST of ~3:45 PM for the descending node. Hence Discovery proposers should assume that Odyssey's node may vary from the value shown in Table 4.1-1 in the time frame of a Mars Discovery mission.

4.2 Relay Proximity Link Specifications

The Odyssey UHF transceiver (CE-505, built by L-3 Cincinnati Electronics) is compatible with the CCSDS Proximity-1 Space Link Protocol. Proximity-1 transfer frames are sent on both the forward link (from the orbiter to the surface vehicle) and on the return link (surface back to the orbiter) using the Proximity-1 protocol link management in either reliable (retransmission) or expedited (no retransmission) mode. In retransmission mode, an ARQ protocol is utilized to request retransmission of any proximity frames that are not received error-free.

Odyssey also provides an unreliable bit stream mode of service that does not utilize the Proximity-1 protocol (i.e, the radio operates as a simple bit stream modem without any additional link layer frame processing).

Figure 4.2-1 is a block diagram of the Odyssey UHF subsystem.

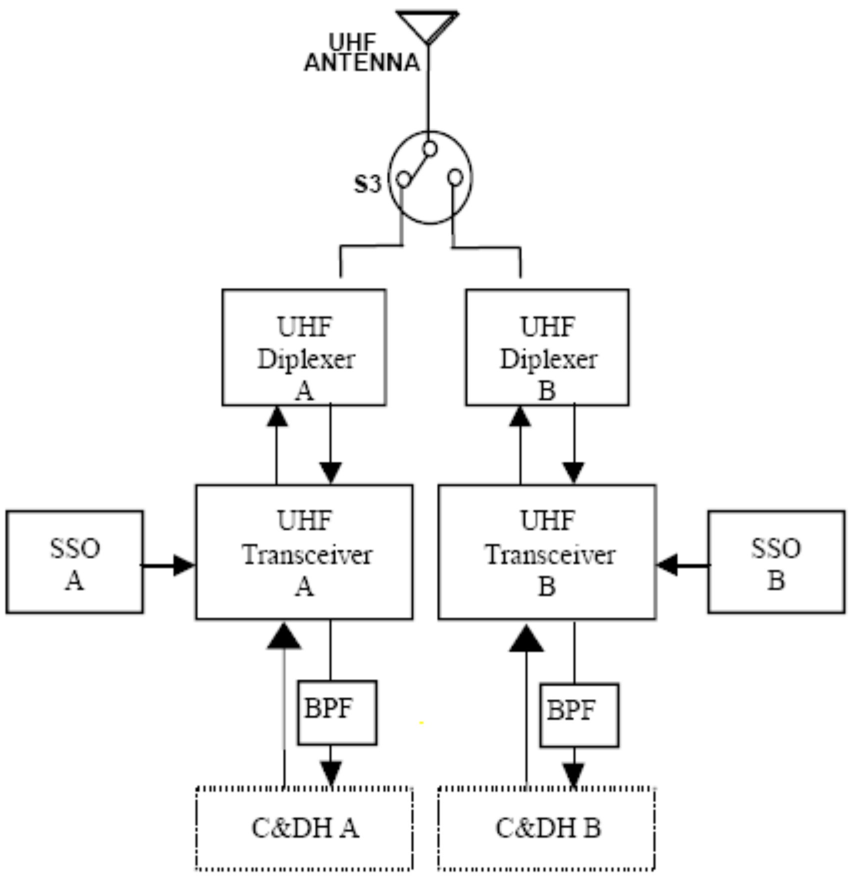


Figure 4.2-1 Block diagram of Odyssey UHF subsystem

The transceivers and the SSOs (sufficiently stable oscillators) are block redundant. However, there is no cross-strapping between the Odyssey CD&H and the transceivers and between the transceivers and the SSOs. A single antenna will provide transmitting and receiving capability and a switch will connect it to the active UHF radio.

Table 4.2-1 summarizes the Odyssey services, and which ones can be provided simultaneously (that is, within a single relay session).

Table 4.2-1 Odyssey Available Data Services and Concurrency

Odyssey service	**Service capabilities within one session**		
Proximity-1 data (Reliable or expedited)	X		
Unreliable bit stream (Raw Data Mode)		X	
Doppler	X	X	
Open Loop Record (Canister Mode)			X

Proximity-1 data: Odyssey supports both Reliable mode and Expedited mode of Proximity-1 data services. The Reliable mode employs an ARQ retransmission protocol to provide complete, gap-free data delivery across the relay link, in accordance with the CCSDS Proximity-1 protocol. Odyssey Proximity-1 data services are an operational subset of those supported by the later orbiters (MRO, MAVEN, ExoMars/TGO). There are several differences in the service names that Odyssey uses and there are constraints on the Odyssey Proximity-1 settings.

Under the Odyssey project, the Reliable (Retransmission) mode is called Reliable Bit Stream or Sequence Controlled mode. The Expedited mode is called Message-Bypass mode.

For Odyssey Proximity-1 operations, the Proximity-1 data packet size is not directly user-selectable, but is rather a fixed function of the combination of user-specified Rx and Tx data rates. For the Reliable mode, the Odyssey Go-Back-N value is fixed to a value of 2 frames. These Odyssey CE-505 radio fixed settings are "tuned" for efficient link operation with a second CE-505 lander radio. (The Electra radio data frame size and Go-Back-N values can be user set to accommodate efficient operations with a CE-505 radio. Thus an Electra-equipped lander can be tuned to efficiently interoperate with a the CE-505 based Odyssey orbiter.)

Unrealiable bit stream mode: In this mode, the frame layer protocol is not used. The Odyssey transmit buffer needs to have data ready to send, otherwise the transmitter is shutdown and the link dropped.

Doppler data: The difference between a phase locked carrier and a reference frequency can be measured and recorded by the Odyssey CE-505 radio Doppler function. The reference frequency can be derived from the oscillator internal to the transceiver or from the Odyssey sufficiently stable oscillator (SSO).

Doppler measurements are put in fixed length packets containing the strobe-enabled time (seconds and subseconds), the zero-cross counter and the time counter.

Canister mode: In Canister mode, the Odyssey CE-505 creates an open-loop sampling of the incoming baseband signal at a rate of 83.6 kHz and with a 1-bit analog-to-digital (A/D) conversion. The center frequency of the open loop record is always at the nominal 401.585625 MHz receive center frequency. No other sample rates or A/D conversion bit widths are possible. Due to Odyssey flight software constraints, the precision of the time-stamp is 20 ms.

The Canister mode data are put in fixed length packets, like the Doppler data packets, but with the raw RF data replacing the Doppler counter data.

Table 4.2-2 defines the major operating modes, functions and constraints for Odyssey.

Table 4.2-2 Odyssey UHF Modes, Functions and Performance

Capability	**Values**
Protocol	Proximity-1
Carrier frequency	437.1 MHz forward 401.585625 MHz return
Frequency reference	Sufficiently stable oscillator (SSO), with Allan deviation better than $1*10^{-11}$ for integration times between 1 and 1000 sec.
RF output power	40.5 dBm (11.2 W) nominal
Antenna gain	Figure 11 (437.1 MHz) Figure 12 (401.6 MHz)
Transceiver to antenna circuit loss	-1.0 dB at 437.1 MHz (forward) -1.8 dB at 401.6 MHz (return)
Receiver noise figure	2.5 dB
Carrier modulation modes	PCM / bi-phase-L (Manchester) / PM (60 deg mod index) FSK NRZ
Rx and Tx data rates	8, 32, 128, 256 kbps
Encoding	Uncoded, (k=7, r= 1/2) convolutional
Decoding	Uncoded, , (k=7, r= 1/2) convolutional (3 bit soft decode)
Acquisition and tracking	Acquires +/- 8 kHz off center frequency

Table 4.2-3 defines the Odyssey signal level thresholds for coded and uncoded data. The table assumes the use of transceiver SN001 (Odyssey Side A). Thresholds are at the antenna connector, same as for MRO.

Table 4.2-3 Odyssey coded and uncoded receive signal thresholds

Bit rate, kbps	Threshold Power at Antenna (dBm) (Coded data)	Threshold Power at Antenna (dBm) (Uncoded data)
8	-119.2	-116.8
32	-114.7	-110.8
128	-108.5	-104.8
256	-104.6	-101.6
• BER = $1*10^{-6}$		

- Code is k=7, r=1/2, 3-bit soft decision.
- Symbol rate = 2*symbol rate for coded data.
- Mars noise temperature = 210 K at antenna.

A link with Odyssey is initiated by Odyssey sending a Proximity-1 Hail at 8 kbps. The Hail includes “Set Transmit” and “Set Receive” directives that described the configuration of transceivers at both ends of the link. Information about the intended communications mode, data rates, coding, and modulation are all contained in this Proximity-1 Hail data frame.

The Odyssey relay antenna is a body-mounted UHF helix that is right circular polarized (RCP) for both the forward and return link.

Figures 4.2-2 and 4.2-3 show the antenna gain as a function of angle from boresight. In each figure, the solid curve is the average gain over cuts made in the orthogonal axis (clock or phi). The dotted curves above and below the solid curve are the gains for the best-case and worst-case clock cut, respectively.

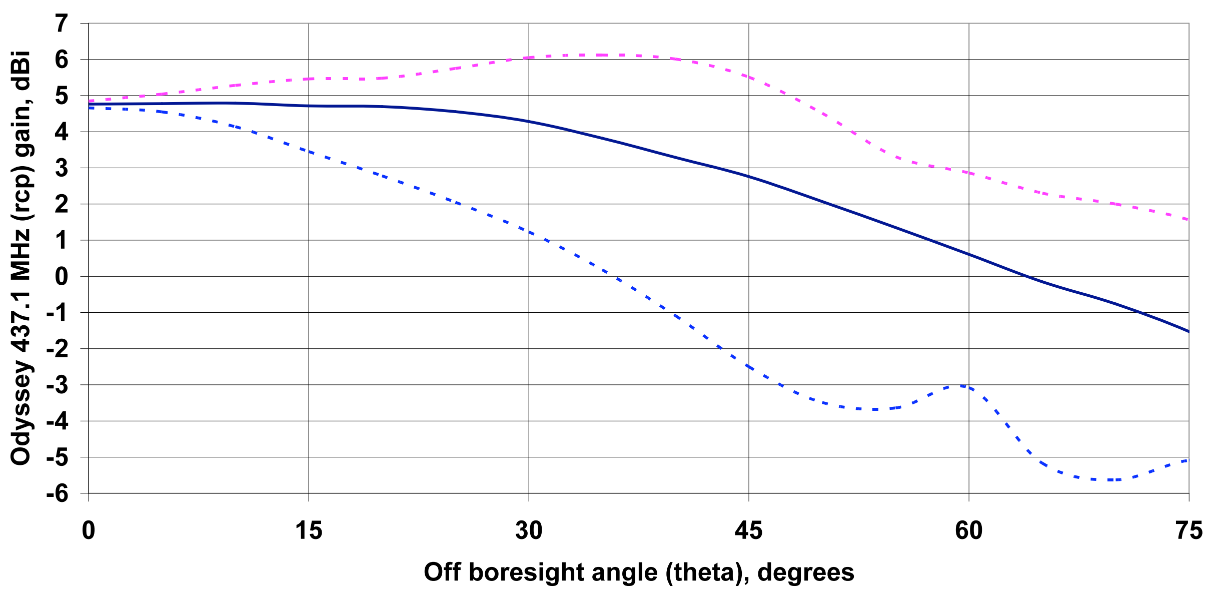


Figure 4.2-2 Odyssey 437.1 MHz (rcp) gain pattern

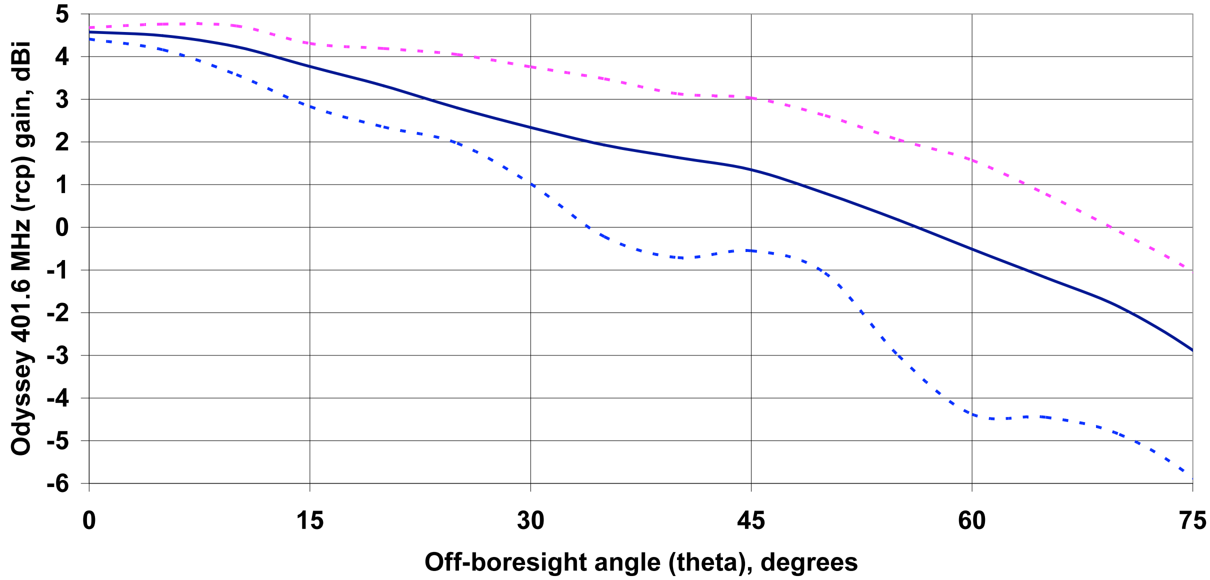


Figure 4.2-3 Odyssey 401 MHz (rcp) gain pattern

4.3 Deep Space Link Performance

The performance of the deep space link impacts forward and return link latencies for end-to-end relay services. Odyssey communicates with Earth over an X-band link, with a 1.3 m High Gain Antenna and a 15 W Solid State Power Amplifier. At maximum Earth-Mars distance, Odyssey achieves a downlink data rate of 14.22 kbps to a 34m DSN antenna, and 39.816 kbps to a70m DSN antenna. Higher data rates can be obtained at reduced Earth-Mars separation, up to a maximum supported data rate of 124.425 kbps.

The nominal uplink data rate from Earth to Odyssey is 1 kbps.

4.4 Operational Considerations

The Odyssey relay antenna is not articulated, nor will the spacecraft be steered prior to or during a relay pass. The Odyssey spacecraft nadir deck is pitched 17 deg behind nadir, opposite the direction of flight, as illustrated in Fig 4.4-1. The cant angle is the angle between the orbiter y-axis and the velocity vector. The UHF antenna boresight is along the –x axis. The antenna is pointed off nadir by the cant angle. This fixed offset between nadir and the antenna boresight must be taken into account when using the Odyssey antenna patterns and when planning relay passes.

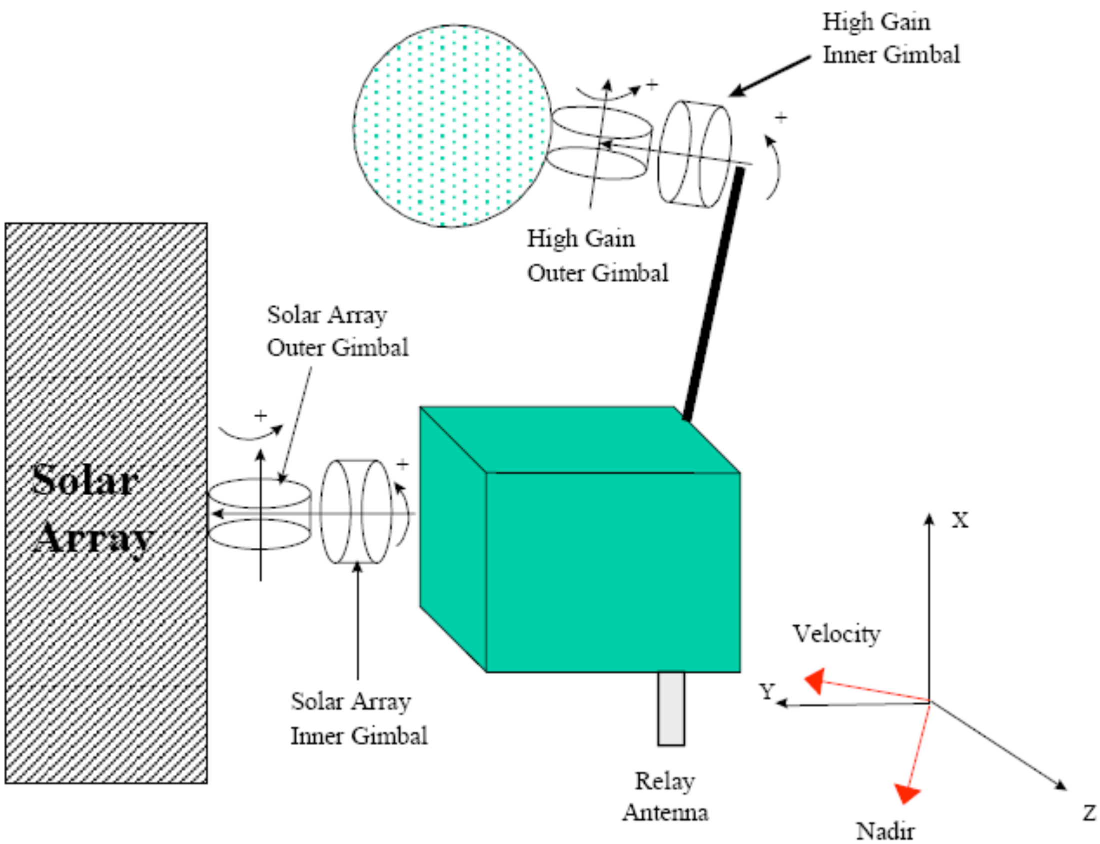


Figure 4.4-1 Odyssey and UHF antenna geometry

5 Mars Reconnaissance Orbiter

5.1 Orbit

MRO operates in a sun-synchronous, near-circular orbit, with an inclination of approximately 92.6 deg. The orbit node is currently oriented such that the mean local solar time of the ascending node is approximately 3:04 pm. Keplerian orbit elements for the MRO spacecraft, at the epoch of Jan 1, 2010, are presented in Table 5.1-1.

Table 5.1-1 MRO Orbit Elements

Orbit Element	**MRO**
Periapsis Radius (km)	3626.4
Apoapsis Radius (km)	3688.6
Semi-major Axis (km)	3657.5
Eccentricity	0.0085
Inclination (deg)	92.6
Ascending Node (deg)	-66.2
Arg of Periapsis (deg)	-89.4
Time from Periapsis (sec)	-3344.6
Epoch	2010-001T00:42:09
Related data	
Periapsis altitude / location	252 km / South pole
Apoapsis altitude / location	317 km / North pole
Local Mean Solar Time (LMST), ascending node	3:04 pm
LMST, descending node	3:04 am
Orbit period	1 hr 52 min

MRO's low-altitude orbit results in short geometric contacts, with average pass durations of roughly 7 min during which the orbiter is visible above 10 deg from a given spot on the Martian surface. For low-latitude sites within 30 deg of the equator, a user will typically have 1-3 contact opportunities each sol, clustered around the ~3:00 am and ~3:00 pm nodal crossings. At higher latitudes, additional passes will be available, up to a maximum of 13-14 passes per sol for near-polar sites.

It is possible that the LMST of the MRO descending node may need to be adjusted in order to support communications with the Mars Science Laboratory during its Entry, Descent, and Landing in Aug-Sep, 2012. In particular, the ascending node may be moved as early as 1:45 PM LMST, depending on the selected MSL landing site and launch/arrival strategy. However, MRO has sufficient propellant reserves to support a prompt return to a 3:00 PM LMST ascending node within 180 sols, so proposers may assume that the MRO orbit would be restored to that sun-synchronous configuration by the time of a Mars Discovery mission.

5.2 Relay Proximity Link Specifications

Figure 5.2-1 is a block diagram of the MRO Electra Proximiy Link Payload. The Electra UHF Transceivers (EUTs) and Ultra-Stable Oscillators (USOs) are redundant. The diagram shows the restrictions on allowable combinations of use with the MRO command and data handling (C&DH) subsystem and solid state recorder (SSR).

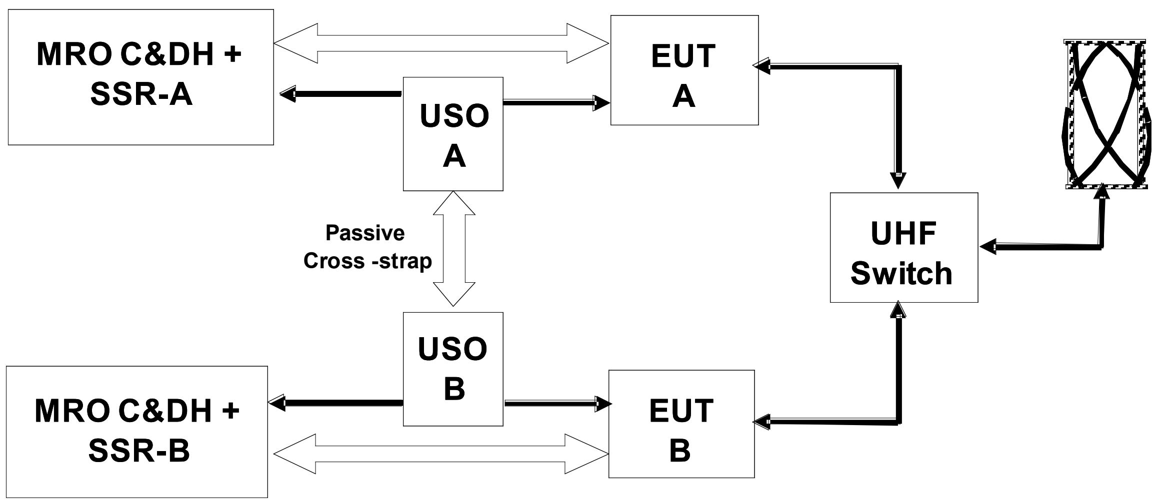


Figure 5.2-1 MRO/Electra UHF subsystem block diagram and interfaces with C&DH and SSR

The MRO Electra Payload supports the following services:

- Forward and return link communications
- Surface asset position determination
- Orbit determination
- Tracking during critical events such as entry, descent, and landing (EDL)

Electra services are compatible with the CCSDS Proximity-1 protocol. The MRO Electra radio provides one basic time service (time stamps) which can be used for event timing and reconstruction, clock correlation, and 1-way ranging.

Table 5.2-1 lists the MRO services, and indicates which ones can be provided simultaneously (that is, within a single relay session).

Table 5.2-1 MRO Available Data Services and Concurrency

MRO service	Service capabilities within one session		
Proximity-1 data (reliable or expedited)	X		
Proximity-1 time stamp	X		
Raw data		X	
Phase-power (Doppler)	X	X	
Open loop record			X

Proximity-1: Typically the MRO Electra will initiate a Proximity-1 session by sending a string of "hail" data packets while looking for a response from the specific lander identified in the hail packet. This standard operating procedure can be reversed, that is, lander-initiated relay sessions are possible.

The hail includes information describing the session operating mode for both the forward and return link directions. This includes operating frequency, data rate, and channel coding mode, to name a few important things. The current software implementation on the MRO Electra allows for only a single data rate per Proximity-1 session. Future software upgrades intended for support of the MSL mission will include the ability to dynamically sense link power and performance metrics and automatically negotiate a change in data rate to accommodate the change in channel capacity. Proposers may assume that this capability is present at the time of a proposed Discovery mission.

In Proximity-1 reliable mode, data frames with bit errors are automatically detected and retransmitted via a standard Go-Back-N protocol scheme.

In Proximity-1 expedited mode, data frames with bit errors are discarded on the receive end. All that remains is a record of the data frame number missing from the frame sequence accounting.

The MRO Electra radio has a number of commandable timer settings that allow it to flywheel over short link drop outs or that force automatic link reacquisition after longer signal drop out periods. These functions are built into the MRO Electra Proximity-1 session management to maximize data return in a relay link environment with variable link performance.

Proximity-1 sessions are terminated by timed sequenced command or by the time out of a dropped signal count down timer.

Time Stamp packets: Time stamp data consists of snapshots of the local Electra clock corresponding to the ingress or egress times of Proximity-1 Frame sync markers. Thus time stamp data may only be collected in conjunction with Proximity-1 mode operations. The time stamps are paired with the corresponding Proximity-1 frame sequence numbers and noted as arriving or departing frames. These can be processed on the ground in conjunction with similar remote asset Proximity-1 time stamp data to achieve user-to-MRO Electra clock correlation.

Electra can time tag the trailing edge of the last bit of the attached frame sync marker of any incoming or outgoing Proximity-1 transfer frame to an accuracy of 60 nanoseconds RMS relative to the Electra clock.

Raw data: In Raw data mode there is no hailing or link establishment protocol, nor is there any session data management or accounting protocol. A link is established by time sequence transmissions and reception at both ends of the link. For example, the MRO orbiter is sequenced to begin listening for a signal at time X and another vehicle is sequenced to begin sending at time X+delta.

In addition to coordinated sequence timing, both sides of the link must agree beforehand to the same data link mode settings, for example frequencies, data rates and coding.

While the raw data sent from the surface may have its own internal format, Electra and MRO know nothing of these native data structures and treat the received data as a continuous bit stream that is subsequently partitioned into 32-byte boundary data units that are passed to the ground.

Phase & Power data: MRO's Electra transceiver can sample and record phase signal power of a phase locked received carrier signal. This radiometric information is highly accurate on two accounts. First, the phase information is relative to the phase of the Electra USO signal with stability of better than 1 part in 10^{-12}. Second, the capture of successive samples is tied directly to the USO based local clock to achieve a highly stable inter-sample time period. In effect, this data forms the basis for a Doppler metric. Each sample contains phase, AGC power, I amplitude, Q amplitude, and a USO based time tag.

The Electra radio has a minimum accumulated Doppler phase measurement interval of 1 second, with the capability to command the output rate to integer multiples of the minimum (5, 10, 20, 60 sec, etc.) The Electra can time tag the accumulated Doppler phase measurement with a minimum accuracy of 60 nanoseconds relative to the MRO spacecraft clock.

Open Loop Data: Open loop data consists of high rate in-phase and quadrature (I & Q) samples of the digital representation of the down-converted signal given a fixed receive center frequency and no closed loop signal tracking. It is required of the user to specify a data collection rate, data collection filter bandwidth and data collection center frequency that will achieve the capture of the intended received signal bandwidth. The user is also required to specify the fixed receiver gain setting that effectively defines the peak-to-peak signal amplitude range into MRO. Electra provides 8 bits/sample for the I channel and the Q channel, corresponding to signal level range of 51 dB.

Sample collection timing is based on a highly stable USO synchronous internal clock. Available sampling rates range in powers of 2 from about 1.15 Hz to about 150 kHz. Data may be collected with or without time tags.

Table 5.2-2 defines the major operating modes, functions, and constraints for the MRO Electra payload.

Table 5.2-2 MRO Electra Modes, Functions and Performance

Capability	Values
Protocol	Proximity-1 (Reliable and Expedited Link Layer protocols)
Frequencies	See next section (including Table 5.2-5)
Modes of Operation	Half duplex[2] Rx and Tx (no Proximity-1 protocol in half duplex) Full duplex transceiver
Full duplex carrier modes	Coherent, noncoherent
Transceiver RF output power	5.0 W full duplex, 7.0 W half duplex
Transceiver to antenna circuit loss	-0.42 dB
Antenna gain	Figure 5.2-2 (437.1 MHz) and Figure 5.2-3 (401.6 MHz)
Carrier modulation modes	Suppressed carrier, residual carrier (60 deg mod index)
Modulation types	Residual carrier BPSK with bi-phase-L (Manchester) Suppressed carrier BPSK
Frequency reference	Ultra stable oscillator
Rx and Tx symbol rates	1, 2, 4, 8, 16, 32, 64, 128, 256, 512, 1024, 2048 ksps. Also, adaptive data rate mode
Received signal power range	-140 to -70 dBm
Encoding	Uncoded, (k=7, r= 1/2) convolutional, differential symbol coding
Decoding	Uncoded, (k=7, r= 1/2) convolutional (3 bit soft decode)
Scrambling / Descrambling	V.38
Acquisition and tracking loop	Second-order PLL, with loop bandwidth 10 Hz to 10 kHz (for received signal from -140 dBm to -70 dBm)
Tracking range and rate	+/- 20 kHz, +/- 200 Hz/sec

Table 5.2-3 and Table 5.2-4 define the MRO signal level thresholds for convolutionally coded data and uncoded data, respectively. The threshold values in both tables assume the following MRO mode and link conditions.

- BPSK, full duplex: 0 dB margin, mod index 60 degrees. The tables assume residual carrier mode operation. At the higher data rates, suppressed carrier modulation may be considered for more power-efficient operation.
- Nominal filter losses and noise figure, Mars noise temperature 210 K.
- Threshold power (dBm) is defined at the input to the antenna connector at 401.6 MHz.
- **Thresholds do not include potential performance impacts due to Electromagnetic Interference (EMI) from MRO science instruments. See Section 5.4 for a discussion of the impact of EMI.**

[2] The term "full duplex" is used by MRO in the conventional sense of simultaneous forward and return link capability at separate frequencies. The term "half duplex" means that Electra's transmitter and receiver are not on simultaneously even though the forward and return links may be on separate frequencies.

- Add additional link margin per your design requirements.

Table 5.2-3 MRO coded receive signal configuration and threshold data

Bit rate, kbps (coded)	Threshold Power, dBm (at Antenna Connector)
1	-130.8
2	-127.8
4	-124.8
8	-121.8
16	-118.8
32	-115.8
64	-112.8
128	-109.7
256	-106.7
512	-103.3
1024	-99.6
Performance is based on use of a 16,384 bit Proximity-1 frame length. Code is k=7, r=1/2, 3-bit soft decision. Data rate = 0.5*symbol rate. BER = 4.53*10-7, Proximity-1 FER = 1.0*10-3, Threshold Eb/No = 5.5 dB	

Table 5.2-4 MRO uncoded receive signal configuration and threshold data

Bit rate, kbps (uncoded)	Threshold Power, dBm (at Antenna Connector)
1	-126.0
2	-123.0
4	-119.9
8	-116.9
16	-113.9
32	-110.9
64	-107.9
128	-104.8
256	-101.7
512	-98.5
1024	-94.9
2048	-91.1
Performance is based on use of a 1,000 bit Proximity-1 frame length. Uncoded data. Data rate = symbol rate. BER = 1.08*10-6, Proximity-1 FER = 1.0*10-3, Threshold Eb/No = 10.5 dB.	

MRO Electra implements frequency agility and swappable transmit and receive bands. While complying with Proximity-1 channel definitions for eight frequency pairs, MRO Electra supports the 16 preset frequency pairs, defined in Table 5.2-5.

Table 5.2-5 Proximity-1 "Blue Book" channel numbers and frequencies

Channel Number	CCSDS Forward Frequency (MHz)	MRO Preset Forward Frequency (MHz)	CCSDS Return Frequency (MHz)	MRO Preset Return Frequency (MHz)
0	437.1	437.1	401.585625	401.585625
1	435.6	435.6	404.4	404.4
2	439.2	439.2	397.5	397.5
3	444.6	444.6	393.9	393.9
4	435 to 450	436	390 to 405	401.4
5	435 to 450	438	390 to 405	402
6	435 to 450	440	390 to 405	402.6
7	435 to 450	441	390 to 405	403.2
8		442		391
9		442.5		392
10		443		393
11		445		395
12		446		395.5
13		447		396
14		448		399
15		449		400

In addition to these 16 preset pairs, the MRO Electra radio has the capability to tune its Tx and Rx frequency across the entire 390 MHz to 450 MHz band, thus any frequency pair combination within this band is possible. For half duplex operation, any pair of frequencies will work as an operational pair. For full duplex operation, the Tx frequency must be chosen in the range of 435 MHz to 450 MHz and the Rx frequency must be chosen in the range of 390 to 405 MHz.

Figures 5.2-2 and 5.2-3 present the RCP antenna gain patterns for the MRO Electra UHF quadrifilar helix antenna at 437.1 MHz and 401.6 MHz, respectively.

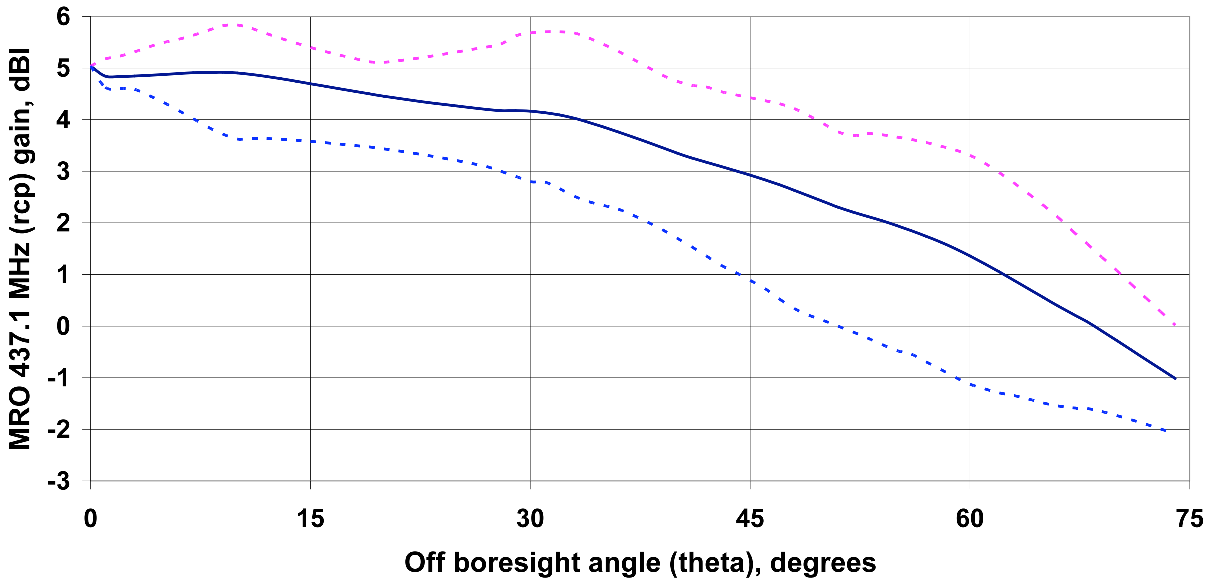


Figure 5.2-2 MRO 437.1 MHz (rcp) gain pattern

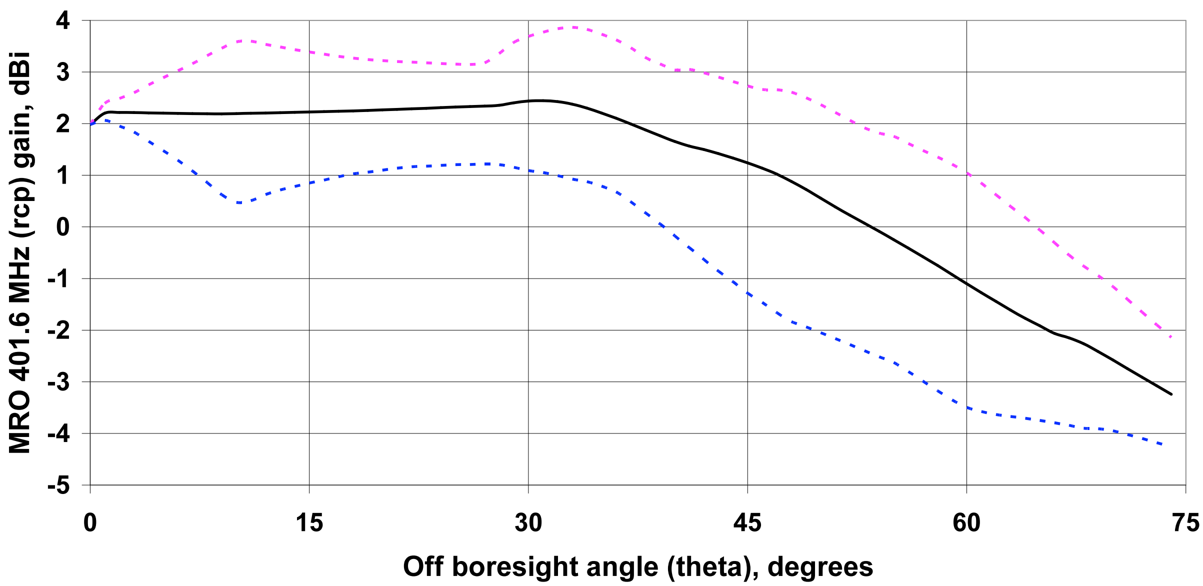


Figure 5.2-3 MRO 401.6 MHz (rcp) gain pattern

5.3 Deep Space Link Characteristics

MRO utilizes a very capable deep space telecommunications link, due to the high data volume generated by its science instrument suite. The high downlink data rate reduces the time for delivery of return link relay data to Earth.

MRO nominally communicates with Earth via an X-band link using a 3m High Gain Antenna and a 100 W Travelling Wave Tube Amplifier. The nominal uplink data rate from Earth to MRO is 2 kbps. At maximum Earth-Mars distance, MRO can achieve a downlink data rate to Earth of 500 kbps to a 34m DSN antenna, and 2.6 Mbps to a 70m DSN antenna. Higher data rates can be supported at shorter Earth-Mars range, up to a maximum of 5.2 Mbps.

5.4 Operational Considerations

Several of the MRO science instrument generate radiated emissions in the Electra UHF receive band, which lead to degradation in the Electra receive thresholds presented in Section 5.2. The EMI impact to Electra performance was observed to be 6.4 – 7.3 dB degradation in link threshold for the 8k, 32k, and 128k coded return link data rates utilized during support to the Phoenix Lander in 2008. However, at this point EMI degradation has only been assessed at 401.585626 MHz (Channel 0 in the Proximity-1 specification) and only at these three data rates.

In-flight testing on MRO will be conducted prior to MSL arrival to characterize EMI impacts at other UHF channel frequencies and over the full range of Electra supported data rates. **For now, it is recommended that proposers apply an across-the-board degradation of 7.3 dB to all MRO Electra thresholds to account for this EMI degradation.**

6 Mars Atmosphere and Volatile Evolution Mission (MAVEN)

The MAVEN mission is the second Scout mission in the Mars Exploration Program. Consistent with the requirements of the Scout Announcement of Opportunity, MAVEN incorporates an MEP-provided Electra payload and will serve as an additional relay asset after completion of its primary science phase.

MAVEN launches in Nov-Dec, 2013, arriving at Mars in Sep, 2014. After a three-week orbit transition phase, the mission will begin a one-year primary science mission, investigating the current state of the Martian atmosphere and the various processes that have contributed to its evolution over time. During this primary science phase, MAVEN will not be used for relay services, assuming that Odyssey and/or MRO are still operational. If both of those legacy assets were not available, MAVEN could provide contingency relay services, constrained to a maximum of one relay service per sol.

In Oct, 2015, upon completion of the primary science mission phase, MAVEN enters an extended mission phase during which full relay services would be available, with a capability of supporting up to 4 relay passes per sol.

6.1 Orbit

To support its aeronomy science objectives, MAVEN operates in a highly elliptical orbit, with a low periapsis altitude of 150 km to dip below the exobase of the Martian atmosphere each orbit, and an apoapsis altitude of over 6000 km to enable measurements of the solar wind upstream of the bow shock. The resulting orbit, with 4.5-hr period and a 75-deg inclination, exhibits precession of both the ascending node and the line of apsides, leading the periapsis to migrate over latitude and local time over the course of the mission.

Table 6.1-1 provides a representative set of orbital elements for MAVEN. While the basic orbit characterstics (semi-major axis, eccentricity, and inclination) are accurate, there may be significant changes in the ascending node and argument of periapsis based on future mission design considerations. In addition, at some point after the completion of the primary science phase, it is likely that a small periapsis raise maneuver will be executed, raising the periapsis to 250 km in order to reduce propellant utilization and extend mission lifetime. Analysis indicates that this small change has minimal effect on average relay characteristics.

Table 6.1-1: MAVEN orbit elements

Orbit Element	MAVEN
Periapsis Radius (km)	3553.5
Apoapsis Radius (km)	9605.3
Semi-major Axis (km)	6579.4
Eccentricity	0.459907

Inclination (deg)	75.05167
Ascending Node (deg)	328.22406
Arg of Periapsis (deg)	147.32635
Time from Periapsis (sec)	295.568
Epoch	2015-274T13:42:06
Related data	
Orbit period	4 hr 30 min

(Mean Keplerian orbit elements, Mars-centered, Mars mean equator and Earth mean equator, J2000, IAU 1991 Coordinate System)

The highly elliptical orbit leads to significantly different geometries for relay contacts, relative to the low-altitude, circular, sun-synchronous orbits of Odyssey and MRO. Near-equatorial users within a +- 30 deg latitude range will typically have 1-4 geometric contacts per sol, depending on latitude and varying with time as the line of apsides precesses. At higher latitudes, from 30-75 deg north or south latitude, contact statistics range from 1-6 passes per sol, with a small region near the pole (well above +- 75 deg latitude) where users can go for long periods with no passes when MAVEN's periapsis has precessed near that pole.

Relay pass durations and the slant ranges over which the relay link operates are also highly variable based on MAVEN's orbit. Passes supported from near MAVEN periapsis have short durations, low slant ranges, and can support high instantaneous data rates, similar to Odyssey and MRO. However, passes supported from near MAVEN apoapsis can have geometric contact durations of over 2 hrs, with slant ranges exceeding 8000 km. Such passes will be required to use much lower instantaneous data rates to account for the large slant range; the longer pass duration can partially compensate, although some users will be limited in the maximum pass duration they can support due to energy constraints. In particular, whereas Odyssey and MRO in their low altitude orbits have typically utilized uncoded 8kbps forward links, with MAVEN it will likely be necessary to use lower rate, coded forward links in order to close the forward relay link from portions of the orbit near apoapsis.

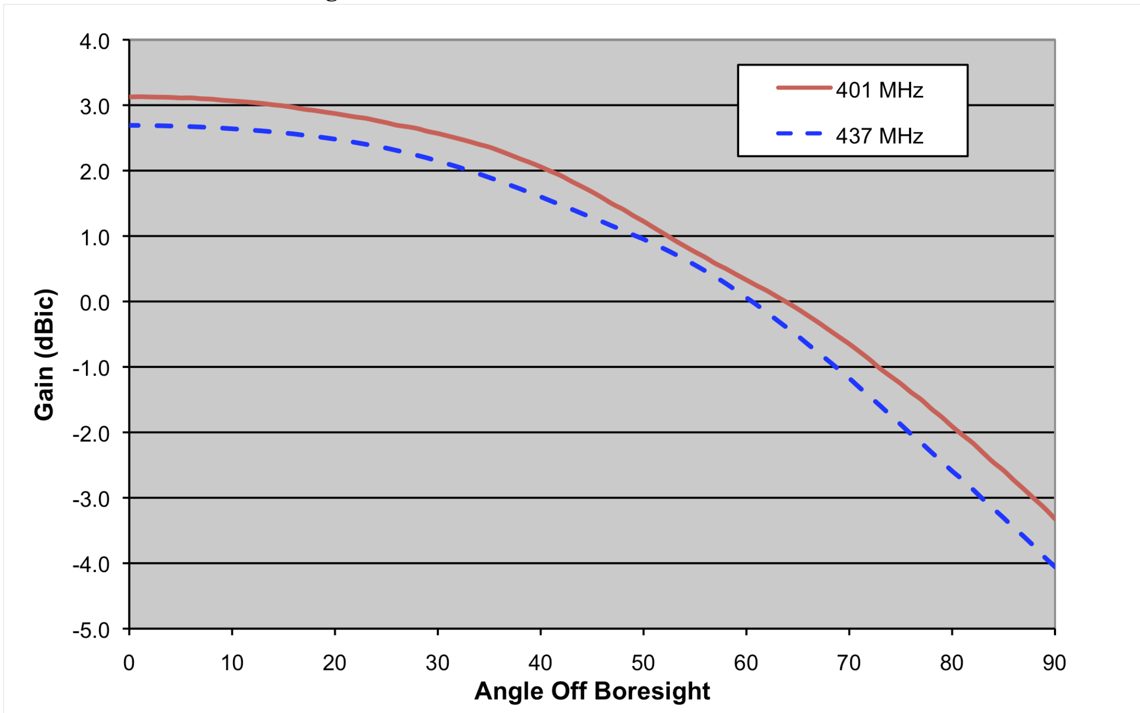
6.2 Relay Proximity Link Specifications

MAVEN will implement a single-string version of the Electra Proximity Link Payload for provision of relay services. The Electra UHF Transceiver will have the same performance specifications as the Electra UHF Transceiver of MRO; see Section 5.2 for details.

MAVEN will not include an external Ultra-Stable Oscillator. Rather, the Electra UHF Transceiver will include an internal Temperature Controlled Crystal Oscillator for its frequency reference.

MAVEN's relay payload will use a different UHF antenna than MRO, based on a new helix design that will be used for the 2011 Mars Science Laboratory mission. Figure 6.2-1 presents the RCP gain pattern of the planned helix at 401 MHz and 437 MHz.

Fig. 6.2-1: MAVEN UHF Antenna Gain Pattern



6.3 Deep Space Link Characteristics

The MAVEN spacecraft communicates with Earth over an X-band uplink and downlink. A 2 m High Gain Antenna coupled with a 100 W Travelling Wave Tube Amplifier provides a downlink data rate capability of 271 kbps to a 34m DSN antenna at maximum Earth-Mars distance. Uplink via the HGA is supported at 2 kbps.

6.4 Operational Considerations

During nominal science operations, MAVEN operates primarily in a spacecraft attitude that orients the HGA boresight towards the sun; in this attitude high-rate communications with Earth are not available. In addition, the relay antenna boresight can at times be pointed more than 90 deg from a surface user spacecraft.

For a supported relay pass, MAVEN will provide deep space link opportunities shortly before and after the supported relay contact, slewing the spacecraft to steer the HGA to Earth and enable high-rate communications with the DSN. The deep space link session prior to the relay service allows uplink from Earth to MAVEN of any files intended for forward link delivery to the user during the relay pass, while the deep space link session after the relay service supports downlink from MAVEN to Earth of all user data transmitted on the return link during the relay pass, along with any Electra phase and power data, Electra time stamp data, Electra open loop recordings, and Electra engineering telemetry.

During the relay service itself, the spacecraft attitude will be adjusted to orient the UHF antenna boresight for the relay pass. While several pointing options are under consideration, it is recommended at this time for users to assume that the UHF boresight will be pointed in the nadir direction during the relay pass.

Because MAVEN's solar arrays are fixed, and co-aligned with the HGA, the periods of modified spacecraft attitude impact the solar array illumination and the resulting power generation. To mitigate the potential impact on the MAVEN energy balance, proposers should assume that the duration of supported relay passes will be limited to no more than 30 min.

7 ExoMars/Trace Gas Orbiter Mission

NASA and ESA have recently announced a Mars Exploration Joint Initiative (MEJI), envisioning a series of collaborative missions to explore the Red Planet. The first mission as part of this initiative is the 2016 ExoMars/Trace Gas Orbiter (TGO) Mission. While technical planning is at a very early stage, a joint ESA-NASA engineering working group has established an initial mission concept, described here.

The 2016 ExoMars/TGO mission will consist of an ESA-provided orbiter bus, launched on a NASA launch vehicle, and carrying a suite of NASA- and ESA-provided science instruments including investigations of trace gas constituents of the Mars atmosphere. On approach to Mars, the primary spacecraft will release an ESA-provided Entry, Descent, and Landing Demonstrator payload, which will demonstrate EDL technologies for ESA. In addition, NASA will provide a relay payload, based on the Electra UHF Transceiver flying on MRO and planned for flight on MAVEN.

The current mission timeline calls for launch in Jan, 2016. The spacecraft would arrive at Mars in Oct, 2016, releasing the EDL Demonstrator several days prior to Mars arrival, and then performing a Mars Orbit Insertion maneuver to enter an initial 4-sol capture orbit. Subsequent maneuvers will reduce the orbit period to 1 sol, and in Nov, 2016, the spacecraft will begin a period of aerobraking to further reduce orbital period and lower apoapsis. Aerobraking will be completed sometime in the May-Aug 2016, and after a 1 month checkout period, the primary science mission will commence. Relay services can be provided during the primary science phase, in parallel with planned science observations. The one Mars year primary science mission will complete in Jul-Oct, 2019; subsequently the mission enters an extended data relay phase nominally extending through the end of Dec, 2022.

7.1 Orbit

Upon completion of aerobraking, ExoMars/TGO will be in a 400 km circular orbit with an inclination of 74 deg. As desired by the mission's trace gas science objectives, this is a non-sun-synchronous orbit, so the local time of the orbit node will precess, moving earlier each day, and thus the contact times for relay service will drift. Due to uncertainties in the duration of the aerobraking phase, the specific orbit node at the beginning of the primary science phase is uncertain, so users should be capable of supporting an arbitrary initial orbit node.

7.2 Relay Proximity Link Specifications

ExoMars/TGO will implement a dual-string version of the Electra Proximity Link Payload for provision of relay services. The Electra UHF Transceiver will have the same performance specifications as the Electra UHF Transceiver of MRO; see Section 5.2 for details.

ExoMars/TGO will include external, redundant Ultra-Stable Oscillators, with performance similar to the USOs flown on MRO.

The initial concept for the ExoMars/TGO UHF antenna is a pair of nadir-oriented UHF patch antennas with an on-boresight gain of 8.5 dBic. An preliminary estimate of the antenna pattern is provided in Figure 7.2-1.

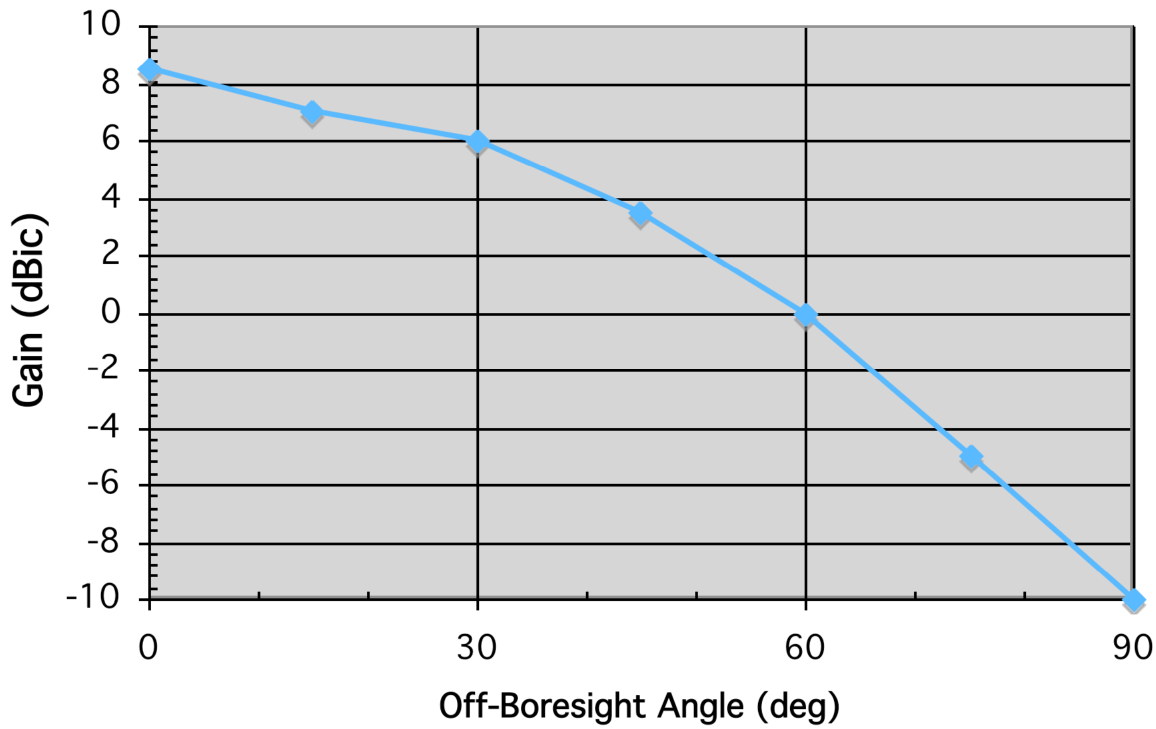


Figure 7.2-1: Preliminary ExoMars/TGO UHF Antenna Gain Pattern

7.3 Deep Space Link Characteristics

The ExoMars/TGI orbiter will communicate to Earth via a 2.2 m High Gain Antenna and a 65 W Travelling Wave Tube Amplifier, enabling a downlink data rate of 150 kbps to a 34m DSN antenna at maximum Earth-Mars distance.

(The orbiter may include a Ka-band downlink for increased downlink performance, but detailed specifications for this Ka-band option are not yet available.)

8 Relay Operations

8.1 Multimission Relay Coordination

Coordination of relay opportunities among service-providing relay orbiters and users of relay services is performed via a set of processes and tools led by the Multimission Relay Operations Lead, jointly supporting the MEP Chief Telecommunications Engineer and the Multi-Mission Ground Systems and Services Program Office (MGSS).

Early in the mission lifecycle of a relay service user mission, a Memorandum of Agreement is established with the orbiter relay service providers to document the high level aspects of the planned relay services. The MOA will establish the broad parameters of support, including the timeframe in which relay services are required, the types of service (data transfer, time services, Doppler tracking, open loop recording, etc.) and the quantity of service (e.g., anticipated number of relay passes per sol).

Subsequently, a more detailed Interface Control Document is established with each relay orbiter service provider to define ground data system interfaces, provide more detailed descriptions of specific service configurations (e.g., list of specific Proximity-1 channels , data rates, frames sizes, etc.), and establish schedule plans for cross-project interoperability testing and relay operations testing.

During flight operations, the Multimission Relay Operations Lead coordinates the detailed planning, scheduling and execution of operational relay services. Figure 8-1 illustrates the current multimission relay process. Every four weeks, as part of the long-range coordination process, each project (including the orbiters) provides ephemeris predictions, as well as known non-relay periods, to MGSS as part of the coordination process. On a bi-weekly basis, for near-term coordination planning, the projects update this information and provide specific “requested” overflights. Relay opportunities are assigned as part of the MGSS’s short-range coordination process.

An improved set of relay planning tools is under development for support of the 2011 Mars Science Laboratory mission and will be in place in the time frame of a Discovery Mars mission. The Mars Relay Operations Service (MaROS) system will provide centralized web-based tools to support relay planning, user relay service requests, orbiter relay service commitments, standardized interfaces for the submission of user forward-link products, and integrated service monitoring and assessment.

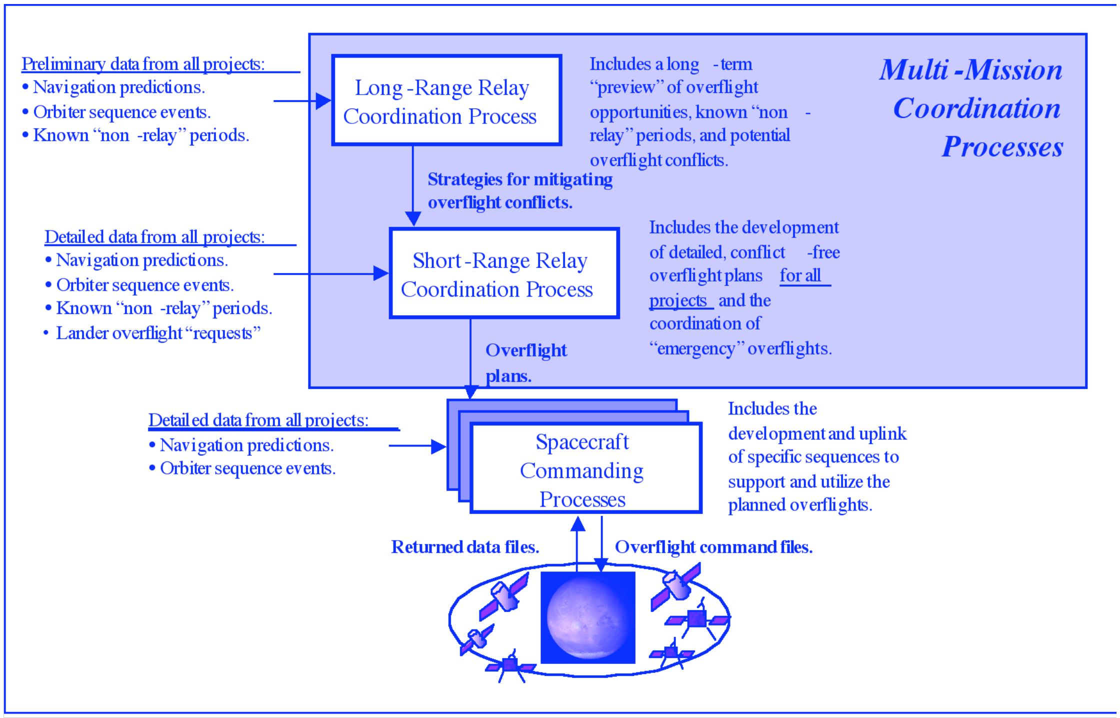


Figure 8-1 Multi mission Mars relay coordination process

8.2 *Latency*

Sending data through orbiters takes more time than sending it directly to or from Earth due to the store-and-forward nature of the link. Relative to the time that a given telemetry file onboard a Discovery spacecraft is ready to be sent to Earth via a relay orbiter, contributors to the end-to-end relay latency include:

- time until the next relay pass,
- relay pass duration,
- time until DSN coverage for the relay orbiter,
- potential Mars occultation of the orbiter-to-Earth link,
- time duration to transmit the relay data on the orbiter's deep space downlink,
- one-way light time between Mars and Earth
- ground processing time to deliver the data to the Discovery mission's ground data system.

Similarly, for delivery of commands to a Discovery spacecraft via a relay orbiter, contributions to the end-to-end latency include:

- ground processing time to deliver the command file to the relay orbiter's ground data system
- time to process the command file into an orbiter command product
- time until DSN coverage for the relay orbiter

- time to radiate the command to the relay orbiter
- potential Mars occultation of the Earth-to-orbiter link
- one-way light time between Mars and Earth
- time until the next relay contact between the orbiter and Discovery spacecraft
- relay pass duration.

When DSN coverage is scheduled to overlap with relay contacts, end-to-end latencies of less than 1 hour can be achieved.

Deterministic protocols greatly enhance the ability to predict these latencies. As part of the coordination process, the orbiter projects generate weekly predictions of forward- and return-link latency.

8.3 EDL considerations

For critical events like Entry-Descent-Landing (EDL), on-orbit relay assets can adjust their orbit phasing (that is, adjust the true anomaly of the orbit). Orbit phasing moves the timing of the orbiter forward or backward in its orbit so that when a spacecraft arrives at Mars, the relay orbiter will be in a good orbit position to provide telecom and navigation support for critical events surrounding EDL. Assuming that the desired orbit phasing is known several months in advance, the phasing can be adjusted at very low propellant cost.

By contrast, changes in the orientation of the orbit plane (e.g., changing the local time of the ascending node) typically have much greater propellant costs. In general, users should not assume that orbit plane adjustments can be accommodated. In any event, any such orbit change will need to be carefully negotiated in light of the orbiter propellant budget, the magnitude of the required plane change, and the time over which that change can be implemented.

The antenna placement on an arriving/descending vehicle and that vehicle's attitude relative to the orbiter are critical in order to maintain communication during EDL. It may be possible to provide enhanced orbiter pointing for special one-time events such as EDL in order to improve critical event telemetry support.

Plasma outages may occur on UHF relay links during the hypersonic phase of entry, depending on the spacecraft's approach angle and velocity.

8.4 Compatibility Testing of User Radios

Radio-to-radio compatibility testing and end-to-end information system testing between the user mission testbed and the orbiter mission testbed are essential in order to ensure successful relay operations. While each orbiter mission maintains the ground test systems necessary to support compatibility testing, the user mission is responsible for the costs of such tests.

The spacecraft testbed testing verifies the exact relay modes and command sequences used on both spacecraft for planned flight operations.

9 Lessons Learned

Relay operations in support of the Mars Exploration Rovers and the Phoenix Lander have provided a number of lessons learned, applicable to future relay support scenarios:

- Early transceiver-level compatibility testing should be performed to validate interoperability between the user and orbiter UHF transceivers.
- Full end-to-end data flow tests should be performed early as well, in order to validate the entire data flow path, including flight and ground elements of both the user project and the orbiter relay project.
- Operational Readiness Tests should be scheduled and performed to fully exercise the user and orbiter relay operations teams prior to flight relay operations.
- Limiting the number of distinct modes that a user requires can significantly reduce relay test costs. To that end, users should establish the minimum required set of Proximity-1 configurations (e.g., data rates, frame sizes, ARQ parameters, frequency channels) to support their relay needs.
- Interoperability testing should be as flight-like as possible. For instance, transceiver behavior should be characterized under both favorable and adverse link characteristics, and system level testing should simulate representative processing loads on flight system processors and data buses.
- UHF link performance can be adversely affected by electromagnetic interference (EMI) from other spacecraft elements, including science instruments and flight avionics. Early attention to EMI considerations, including subsystem level design and test, system level grounding, and system level testing, are critical to meeting EMI requirements. In some cases, specific flight rules may be required to constrain the use of certain payloads during relay operations in order to eliminate sources of EMI.

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