NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Mars Exploration Program

Mars Relay Description for Discovery 2014 Proposals

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1 Introduction

The Discovery 2014 Announcement of Opportunity (AO) solicits proposals for planetary science missions to be launched no later than the end of calendar year 2021. 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 radio metric 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 response 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), the 2007 Phoenix Lander, and the 2011 Mars Science Laboratory mission's Curiosity rover.

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. 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 telecommunications 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, over 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.) Odyssey and MRO continue to support Opportunity today.[1]

[1] While this document focuses on NASA relay orbiters as well as the 2016 ESA ExoMars/Trace Gas Orbiter, 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

	ODY	MRO	Total
Total # Passes	618	656	1274
Total Data Return (Gb)	45.6	148.9	194.5
Average # Passes/sol:	1.7	1.8	3.6
Average Return Data Vol/Sol (Mb)	128	417	545
Average Return Data Vol/Pass (Mb)	74	227	153

Table 2-1: Curiosity data return metrics during the first year of surface operations.

On Aug 6, 2012, the Mars Science Laboratory (MSL) mission arrived at Mars. Both MRO and Odyssey were positioned to be in view of MSL's EDL trajectory, acquiring critical event telemetry during the first use of MSL's "skycrane" EDL system. Since landing, MSL's Curiosity Rover has returned nearly all of its science and engineering telemetry via relay links to ODY and MRO. Over the first year of Curiosity surface operations, rover data return averaged well over 500 Mb/sol, based on an average of 3 to 4 relay contacts each sol. Table 2-1 summarizes Curiosity data return over its first year of surface operations. The significant increase in data return for this mission is largely due to performance on the Curiosity-MRO link, leveraging new capabilities of the Electra and Electra-Lite relay transceivers onboard MRO and Curiosity, respectively. These new capabilities include support of higher instantaneous data rates and more efficient modulation, as well as implementation of a new Adaptive Data Rate algorithm that allows the data rate to be adjusted throughout each relay pass to always operate at the highest supportable data rate as a function of time.

To augment this relay infrastructure, MEP has included an Electra UHF relay payload on the 2013 Mars Atmosphere and Volatile Evolution Mission (MAVEN), scheduled to arrive at Mars on Sep 22, 2014. After MAVEN completes its primary science phase in Oct 2015, it will be available to provide relay services to user missions at Mars. Unlike Odyssey and MRO, which operate in low-altitude near-circular orbits, MAVEN nominally plans to 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.)

In addition, the European Space Agency (ESA) plans to launch the ExoMars Trace Gas Orbiter (TGO) mission in January, 2016. NASA and ESA have established a Memorandum of Understanding, under which NASA will provide redundant Electra

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relay passes with Spirit, Opportunity, and Phoenix, and Curiosity, and to provide redundant tracking of the Phoenix and MSL UHF carrier signal during Entry, Descent, and Landing. Given the age of Mars Express in the timeframe of an applicable Discovery mission, we have not included it in this guide.

UHF transceivers for flight on TGO, and TGO will provide relay services to both ESA and NASA landed assets. ExoMars/TGO arrives at Mars in October 2016, and completes aerobraking to a circular orbit by November 2017, at which point TGO will begin its primary science mission and also be available for scheduled relay services.

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. 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 currently operating on the Mars Science Laboratory mission's Curiosity Rover. The Electra-Lite radio system is compatible with the CCSDS Proximity-1 Space Link Protocol and is inherently interoperable with the NASA Mars Relay Network infrastructure.

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. (See Section 8.3 for additional discussion of EDL support considerations.) 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, proposers should 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 prior missions and some of the lessons learned from them.

4 Odyssey

4.1 Orbit

Odyssey operates in a sun-synchronous, near-circular orbit, with an inclination of approximately 93 deg. Currently the orbit node is being reoriented for science purposes, with the ascending node slowly drifting to a Local Mean Solar Time of 6:45 AM. The node will reach this orientation in November 2015, at which time Odyssey will execute an orbit trim maneuver to re-establish a sun-synchronous orbit which will leave the ascending node at this value for the remainder of the mission lifetime. Keplerian orbit elements for the Odyssey spacecraft, at the epoch of Jan 1, 2016, are presented in Table 4.1-1.

Table 4.1-1: Odyssey orbit elements

Orbit Element	**ODYSSEY**
Periapsis Radius (km)	3761.5
Apoapsis Radius (km)	3828.1
Semi-major Axis (km)	3794.8
Eccentricity	0.0088
Inclination (deg)	93.2
Ascending Node (deg)	237.0
Arg of Periapsis (deg)	269.1
Time from Periapsis (sec)	-1767.2
Epoch	01-JAN-2016 01:25:43 UTC
Related data	
Periapsis altitude / location	388 km / South pole
Apoapsis altitude / location	457 km / North pole
Local Mean Solar Time (LMST), ascending node	6:45 AM
LMST, descending node	6:45 PM
Orbit period	1 hr 58 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 6:45 am and 6:45 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.

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.

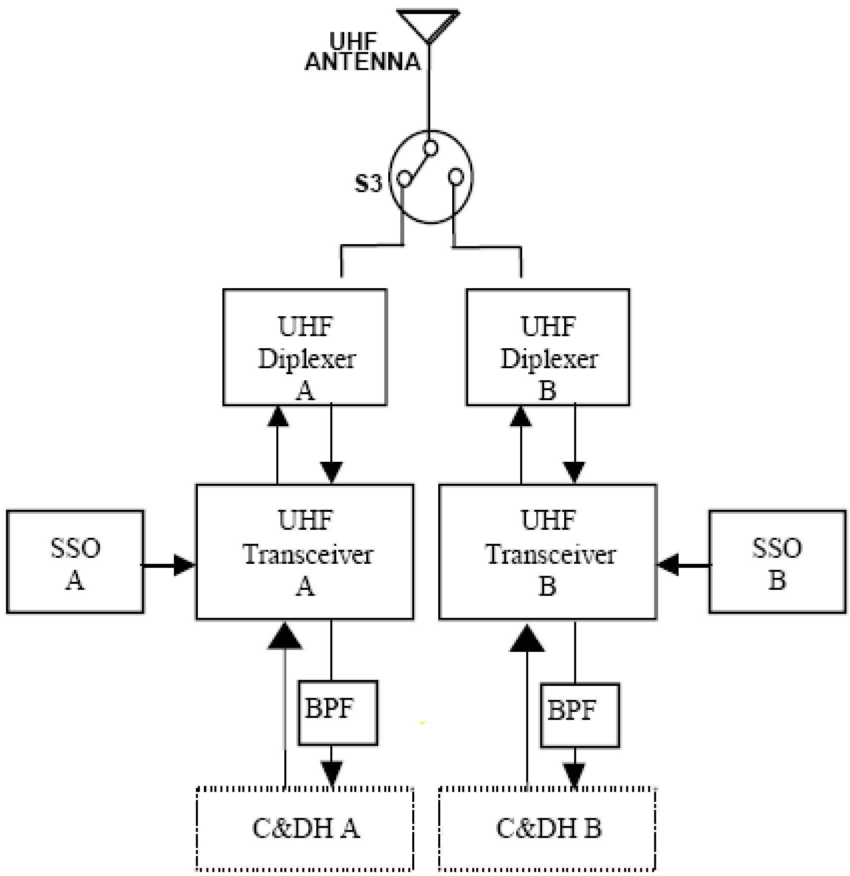

Figure 4.2-1 Block diagram of Odyssey UHF subsystem

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 4.2-3 defines the Odyssey signal level thresholds.

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 describe 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.

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	See Figure 4.2-2 (437.1 MHz) and Figure 4.2-3 (401.6 MHz)
Transceiver to antenna circuit loss	-1.5 dB at 437.1 MHz (forward) -2.3 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 Odyssey receive signal thresholds

Bit rate, kbps	Coded Threshold Power (dBm)
8	-122.9
32	-116.8
128	-110.5
256	-106.5

- BER = $1*10^{-6}$
- Threshold defined at transceiver input port
- Code is k=7, r= ½, 3-bit soft decision.
- Mars noise temperature = 210 K at antenna.

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.

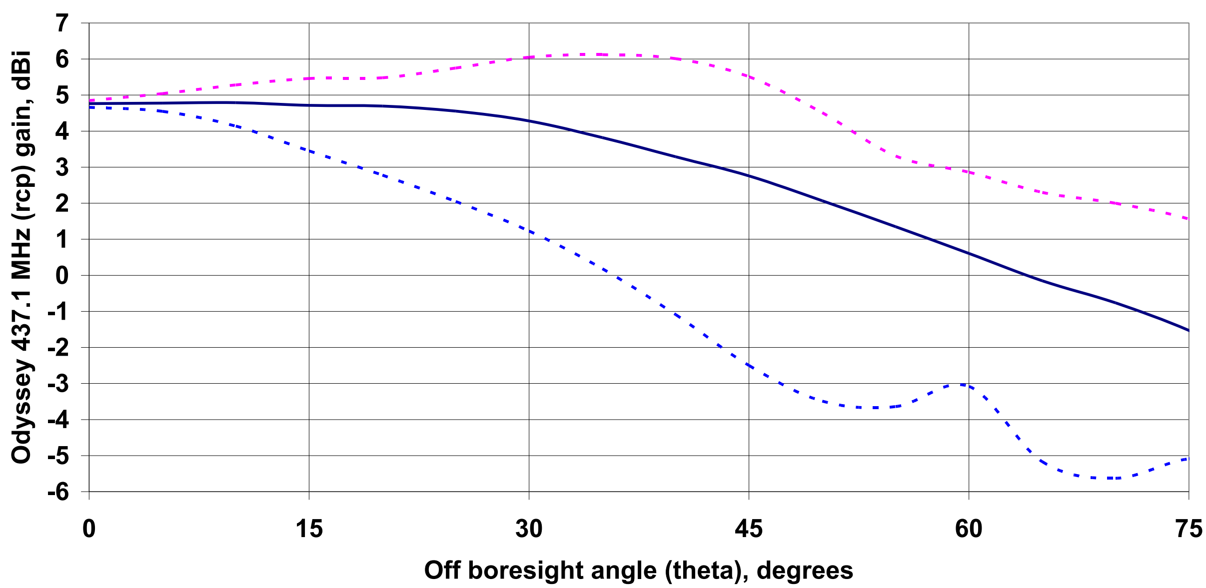

Figure 4.2-2 Odyssey 437.1 MHz (rcp) gain pattern

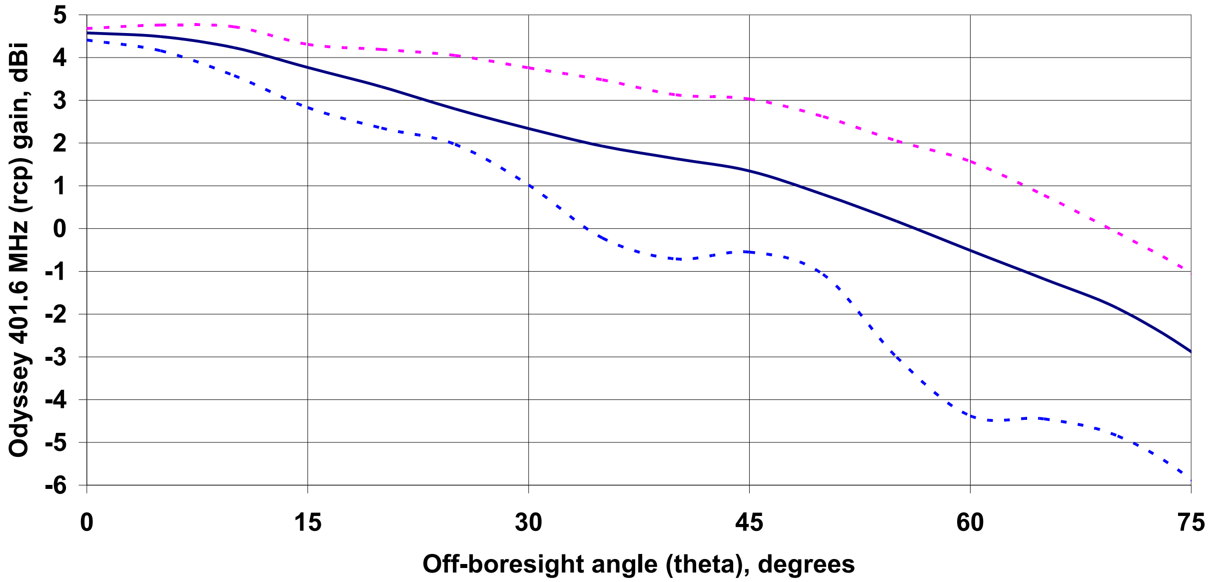

Figure 4.2-3 Odyssey 401 MHz (rcp) gain pattern

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 a 70m 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.

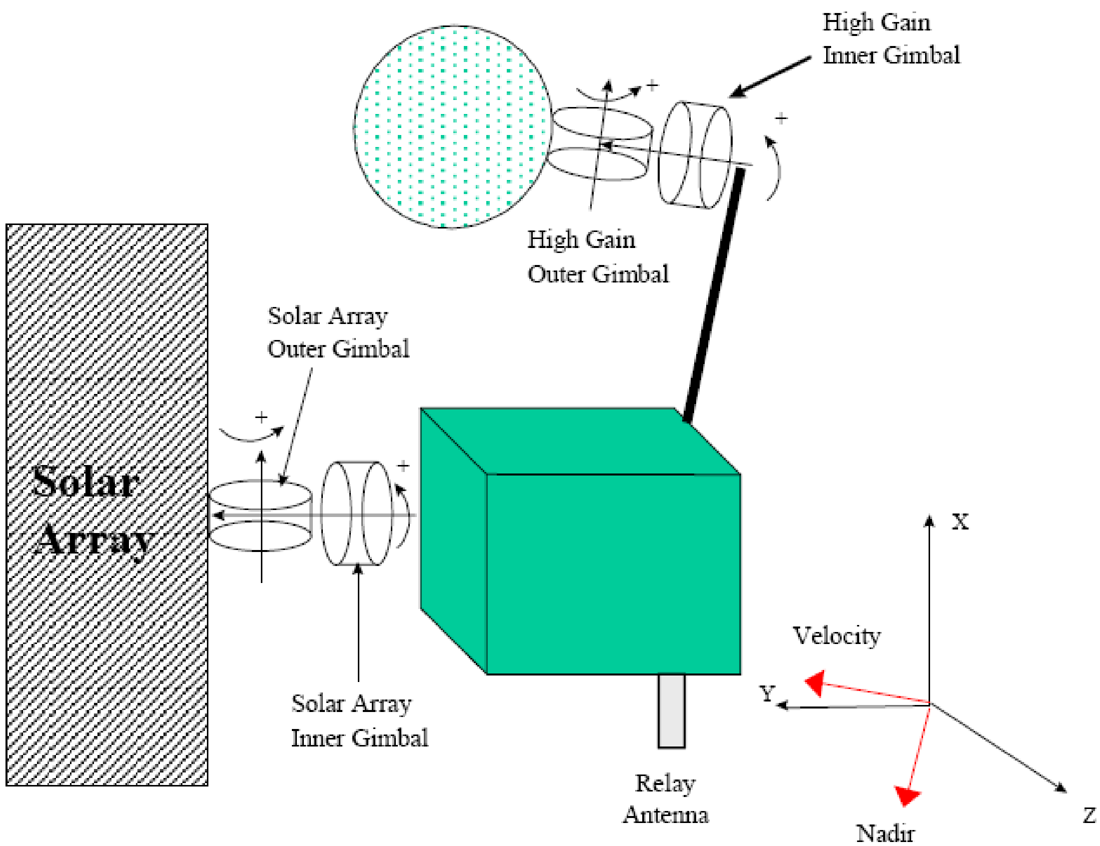

Figure 4.4-1 Odyssey and UHF antenna geometry

In the time frame of a mission selected in response to the 2014 Discovery AO, Odyssey will be far beyond its nominal design lifetime. The orbiter continues to operate today as a fully functional relay orbiter, providing services to the Curiosity and Opportunity rovers. It is estimated that the remaining orbiter propellant could sustain ongoing operations beyond 2025, at current usage rates. However, a number of factors could lead to a shorter operational life. Any increase in the rate of spacecraft safe mode events would increase the propellant usage rate. One of Odyssey's reaction wheels failed in 2012, forcing activation of the spare skew wheel. Another reaction wheel failure would force transition to an all-thruster mode of attitude control, reducing the remaining propellant lifetime to 1-3 yrs. A number of other components are also approaching or exceeding their design lifetimes. Finally, continued operation in the post-2020 time frame is contingent on future NASA programmatic decisions to continue to extend Odyssey flight operations, in the context of the agency's Senior Review process.

5 Mars Reconnaissance Orbiter

5.1 Orbit

Similar to ODY, MRO also operates in a sun-synchronous, near-circular orbit, with an inclination of approximately 93 deg. The orbit node is typically oriented such that the mean local solar time of the ascending node is approximately 3:00 pm. Keplerian orbit elements for the MRO spacecraft, at the epoch of Jan 1, 2016, are presented in Table 5.1-1.

Table 5.1-1 MRO Orbit Elements

Orbit Element	**MRO**
Periapsis Radius (km)	3625.1
Apoapsis Radius (km)	3690.1
Semi-major Axis (km)	3657.6
Eccentricity	0.0089
Inclination (deg)	92.6
Ascending Node (deg)	360.9
Arg of Periapsis (deg)	270.4
Time from Periapsis (sec)	1516.3
Epoch	01-JAN-2016 04:55:34 UTC
Related data	
Periapsis altitude / location	252 km / South pole
Apoapsis altitude / location	317 km / North pole
Local Mean Solar Time (LMST), ascending node	3:00 PM
LMST, descending node	3:00 AM
Orbit period	1 hr 52 min

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

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.

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).

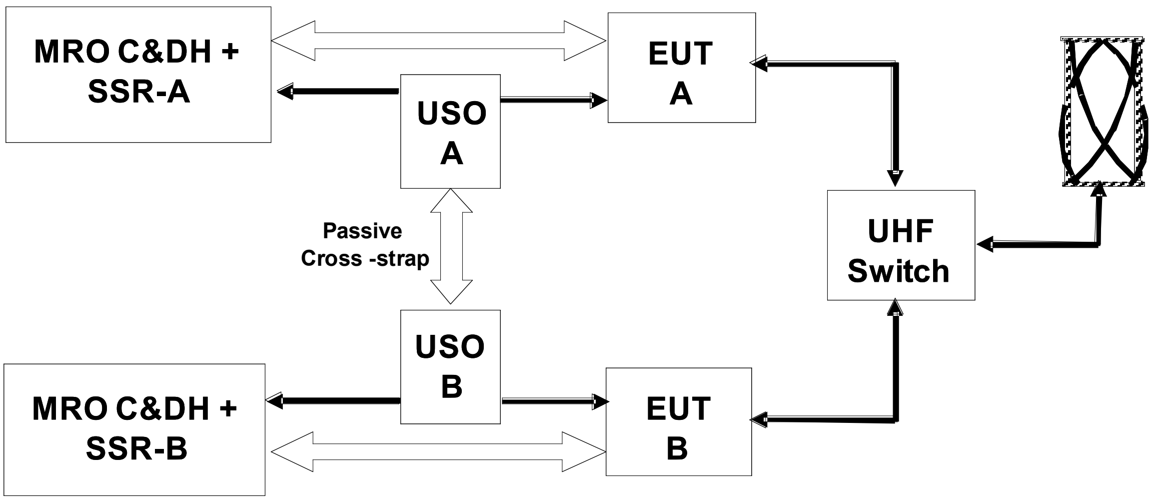

Figure 5.2-1 MRO/Electra UHF subsystem block diagram and interfaces with C&DH and SSR

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. 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.

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 can also specify a fixed receiver gain setting that effectively defines the peak-to-peak signal amplitude range into MRO, or can enable Electra's Automatic Gain Control

Table 5.2-2 MRO Electra Modes, Functions and Performance

Capability	**Values**
Protocol	Proximity-1 (Reliable and Expedited Link Layer protocols)
Modes of Operation	Simplex Rx or Tx Full duplex
Frequencies	Simplex: 390-450 MHz Full Duplex: 390-405 MHz rcv; 435-450 MHz txmt
Full duplex carrier modes	Coherent, noncoherent
Transceiver RF output power	5.0 W full duplex, 7.0 W simplex
Transceiver to antenna circuit loss	-0.42 dB
Antenna gain	See Figure 5.2-2 (437.1 MHz) and Figure 5.2-3 (401.6 MHz) for gain pattern
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

to dynamically adjust the receive signal gain. Electra provides 8 bits/sample for the I channel and the Q channel, corresponding to signal level dynamic 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 ~1.15 Hz to ~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 5.2-3 defines the MRO signal level thresholds for convolutionally coded data, both for residual carrier and suppressed carrier modulation modes. The threshold values in both tables assume the following MRO mode and link conditions.

- Residual carrier corresponds to a 60 deg mod index; suppressed carrier is supported at higher data rates for more power-efficient operations.
- Nominal filter losses and noise figure, Mars noise temperature 210 K.
- Threshold power (dBm) is defined at the transceiver input.
- **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.**
- Listed thresholds do not include any link margin; add additional link margin per your design requirements.

MRO Electra implements frequency agility and swappable transmit and receive bands. The MRO Electra radio has the capability to tune its Tx and Rx frequency across the

Table 5.2-3 MRO coded receive signal thresholds

Bit rate, kbps	Coded Threshold Power, dBm Residual Carrier	Coded Threshold Power, dBm Suppressed Carrier
1	-133.2	-
2	-130.2	-
4	-127.1	-
8	-124.1	-
16	-121.1	-
32	-118.1	-119.3
64	-115.1	-116.3
128	-112.1	-113.3
256	-109.1	-110.3
512	-105.6	-106.9
1024	-101.9	-102.9
2048	-	-99.3

- Threshold power defined at transceiver input
- Code is k=7, r=1/2, 3-bit soft decision. Data rate = 0.5*symbol rate.
- BER = 1×10^{-6}

entire 390 MHz to 450 MHz band. 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.

Electra also supports an Adaptive Data Rate capability, in which the MRO Electra monitors the symbol signal-to-noise-ratio (SSNR) on the return link from the lander throughout the relay overflight and, based on the measured SSNR value, sends directives to the lander spacecraft to raise or lower its transmit rate, allowing the lander to always operate at the optimal data rate. This feature is being uses routinely in MRO's relay

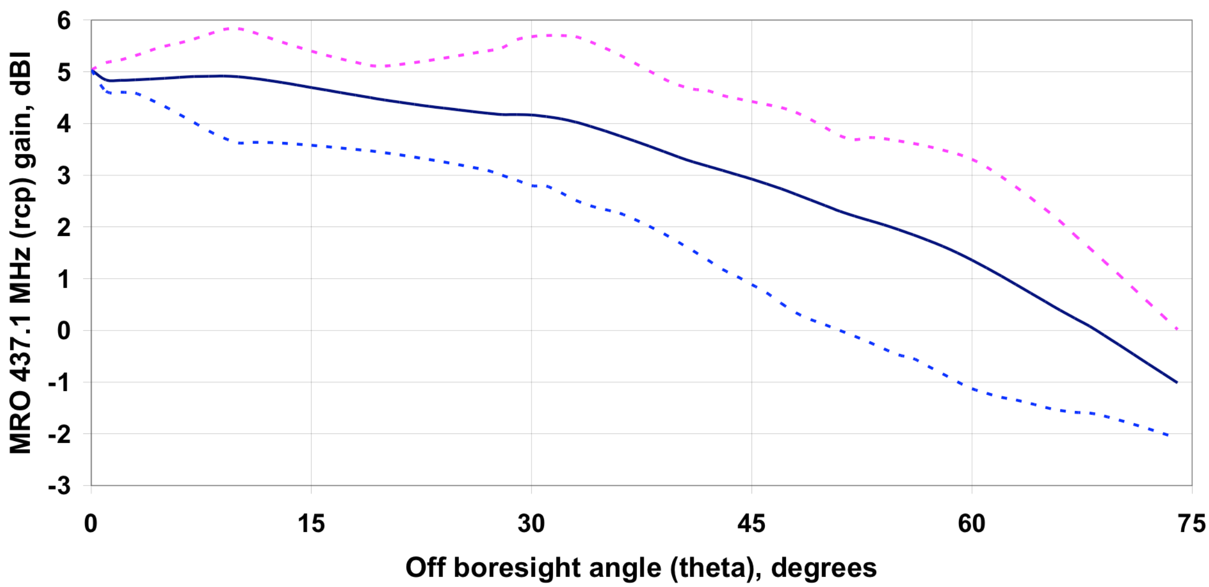

Figure 5.2-2   MRO 437.1 MHz (rcp) gain pattern

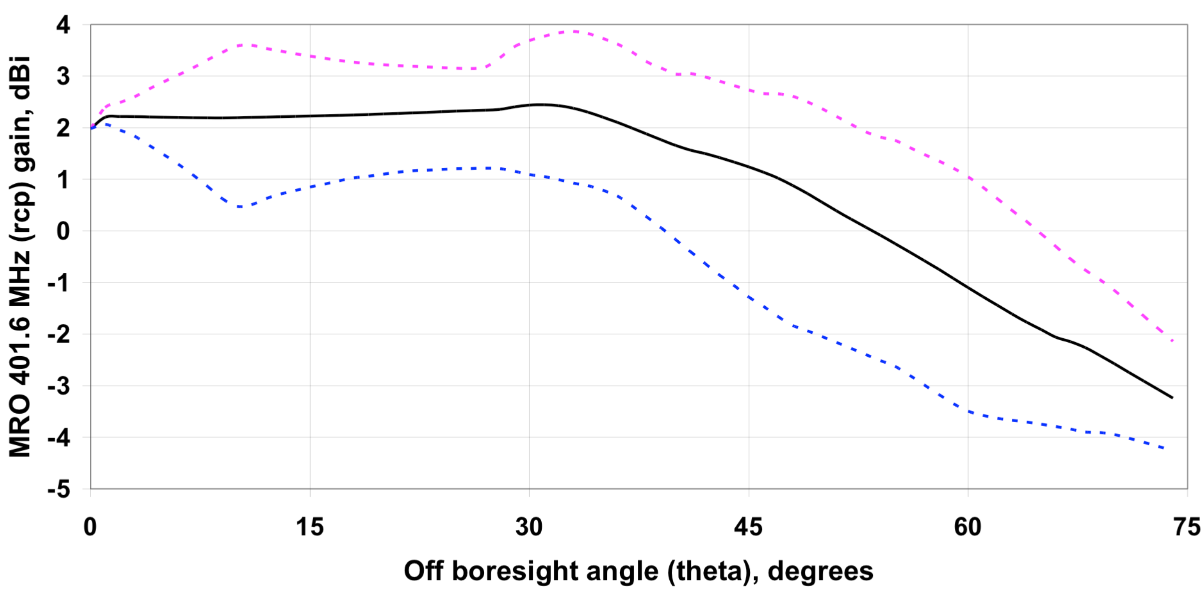

Figure 5.2-3   MRO 401.6 MHz (rcp) gain pattern

support to the Curiosity rover. The current ADR implementation effectively raises the data rate by a factor of two when the link margin grows to more than 3 dB above the current data rate threshold, and lowers the data rate by a factor of two when the link margin becomes negative relative to the current data rate threshold. At each data rate change, there is a short gap of up to 5 sec to allow the link to re-acquire at the new rate; the reliable CCSDS Proximity-1 Link Protocol ensures that no data are lost due to this gap.

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.

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 ~7 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 and in ongoing support to the Opportunity rover, both of which operate at a fixed return link frequency of 401.585626 MHz (Channel 0 in the Proximity-1 specification).

The Mars Science Laboratory's Curiosity rover utilizes an Electra-Lite UHF Transceiver that can select a return link channel anywhere in the range 390 – 405 MHz. Prior to MSL arrival at Mars, in-flight tests on MRO were conducted to quantify EMI impacts across this frequency band. Based on these tests, Curiosity has chosen to operate at a return link frequency of 391.0 MHz, at which the EMI degradation is reduced to ~4 dB.

For special short-term events, such as critical events or support of the first few sols on the surface, MRO can power off the science instruments that are the primary sources of EMI.

In this configuration, MRO recommends that users still include 1 dB of EMI degradation to account for possible low-level spurious signals generated by the spacecraft avionics.

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 successfully launched on Nov 18, 2013, and is scheduled to perform Mars orbit insertion on Sep 22, 2014. After a five-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, nominal MAVEN relay services are not planned, under the assumption that Odyssey and/or MRO are still operational. However, if needed, MAVEN could provide contingency relay services, constrained to a maximum of one relay service per sol, during the primary mission.

In November 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 a ~4.5-hr period and a ~74-deg inclination, exhibits precession of both the ascending node and the line of apsides, causing 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 ~200 km in order to reduce propellant utilization and extend mission lifetime. Analysis indicates that this small change has minimal effect on average relay characteristics. It is also possible that more significant orbit modifications may be made after the MAVEN primary science phase is completed, including options that would use aerobraking to significantly reduce the apoapsis altitude. Final decisions regarding the long-term MAVEN orbit strategy will likely not be made until the primary science phase is completed.

Proposers should use the orbit characteristics shown in Table 6.1-1 to evaluate aggregate relay performance metrics (e.g., average data return per sol). However, due to the uncertainty in the long-term orbit evolution strategy, it is not currently possible to definitively assess relay coverage for a discrete event at a specific epoch (e.g., critical event relay support for EDL) in the time frame of a proposed Discovery mission. Users with such a need should describe the required coverage geometry for evaluation by the Mars program.

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.

Table 6.1-1: MAVEN orbit elements

Orbit Element	MAVEN
Semi-major Axis (km)	6556.270734
Eccentricity	0.4608135
Inclination (deg)	74.068671
Ascending Node (deg)	63.122542
Arg of Periapsis (deg)	206.485674
Time from Periapsis (sec)	295.568
Epoch	01-NOV-2015 02:05:38 UTC
Related data	
Orbit period	4 h 28 m 37 s

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

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. Detailed specifications are presented in Table 6.2-1. We highlight here the minor differences between the MAVEN and MRO Electra implementations.

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. The different reference oscillator results in slightly different open-loop sampling rates, with support for powers of 2 up to ~128 kHz.

The MAVEN Electra implements a new Low Density Parity Check (LDPC) error correcting code, offering improved performance relative to the heritage (7,½) convolutional code. (Use of this code requires that the user transceiver implement an LDPC encoder.) Table 6.2-2 provides the detailed receiver thresholds for the MAVEN Electra UHF Transceiver for various modulation and coding options.

Table 6.2-1 MAVEN Electra Modes, Functions and Performance

Capability	**Values**
Protocol	Proximity-1 (Reliable and Expedited Link Layer protocols)
Modes of Operation	Simplex Rx or Tx Full duplex
Frequencies	Simplex: 390-450 MHz Full Duplex: 390-405 MHz rcv; 435-450 MHz txmt
Full duplex carrier modes	Coherent, noncoherent
Transceiver RF output power	5.0 W full duplex, 7.0 W simplex
Transceiver to antenna circuit loss	-2.0 dB
Antenna gain	On-boresight gain: 2.8 dBic @ 437 MHz, 3.1 dBic at 401 MHz; see Fig 6.2-1 for gain pattern
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	Internal Temperature Controlled Crystal 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), (k=1024, r=½) Low Density Parity Check
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 6.2-2 MAVEN coded receive signal thresholds

Data Rate	Residual Carrier – Convolutional Coded	Suppressed Carrier – Convolutional Coded	Suppressed Carrier – Coded LDPC
1 kbps	–133.1 dB		
2 kbps	–130.1 dB		
4 kbps	–127.1 dB		
8 kbps	–124.1 dB		
16 kbps	–121.1 dB		
32 kbps	–118.1 dB	–120.3 dB	-122.75 dB
64 kbps	–115.1 dB	–117.25 dB	-120.0 dB
128 kbps	–112.1 dB	–114.35 dB	-116.85 dB
256 kbps	–109.1 dB	–111.25 dB	-114.0 dB
512 kbps	–105.6 dB	–108.0 dB	-111.0 dB
1024 kbps	–101.9 dB	–105.2 dB	-107.75 dB
2048 kbps	NA	–101.6 dB	1.2 -104.25 dB

NOTE: *Threshold is measured at the transceiver. Threshold values reflect performance of the FEC implementation and were measured under ambient temperature (+20C to +30C). Data rates are measured at the input of the encoder. Actual throughput, e.g., user data bits per second, will be lower due to link layer overheads such as ASM, Proximity-1 Link Layer header, and the efficiency of the go-back-N ARQ algorithm that is operating point dependent. Front end losses from antenna output to radio input is 2dB.*

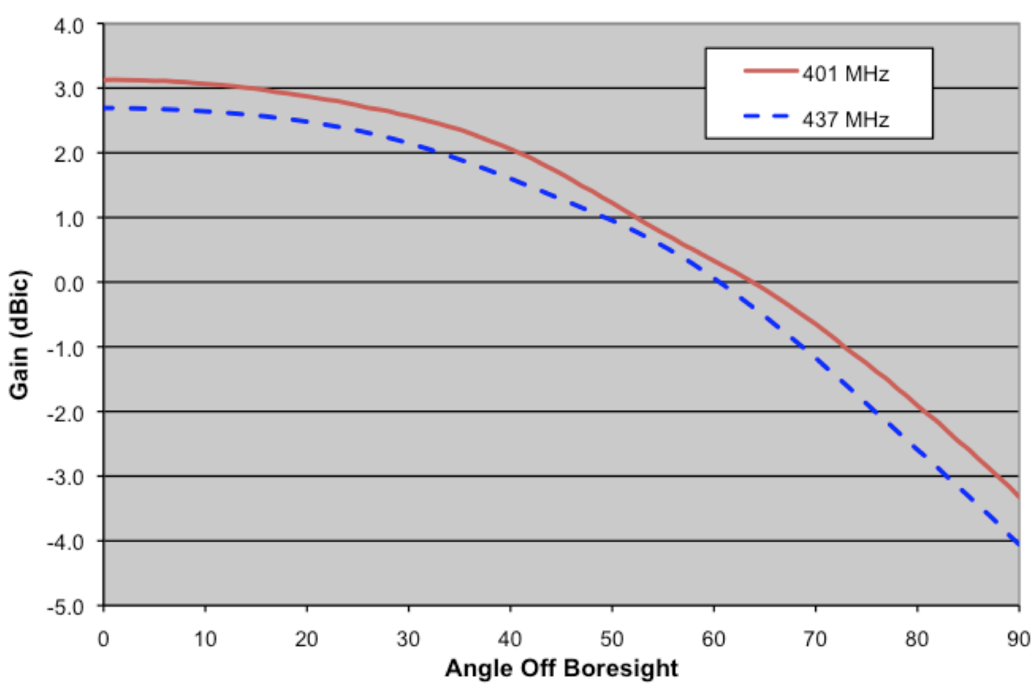

Fig. 6.2-1: MAVEN UHF Antenna Gain Pattern

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

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 in the nadir direction for the duration of 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

The European Space Agency has established the ExoMars program, consisting of a series of missions exploring the Mars environment and demonstrating technologies in preparation for a future Mars sample return mission. The first element in this program is the 2016 ExoMars/Trace Gas Orbiter (TGO), consisting of an ESA-provided orbiter bus, launched on a Roskosmos launch vehicle, and carrying a suite of ESA- and Roskosmos-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 Module, a short-lived lander that will demonstrate EDL technologies applicable to future ExoMars landers. In addition, NASA is providing a dual-string Electra UHF Transceiver payload, with the Electra design effectively identical to the Electra transceiver on MAVEN.

The current mission timeline calls for launch in January 2016. The spacecraft would arrive at Mars on 19 Oct, 2016, releasing the EDL Demonstrator three 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 November 2016 the spacecraft will begin a period of aerobraking to further reduce orbital period and lower apoapsis. Aerobraking will be completed by ~November 2017, at which time 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 ~November 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. Detailed orbit parameters are not yet finalized, as alternative ground track strategies are considered. One representative candidate orbit state is summarized in Table 7.1-1.

ESA plans to use ExoMars/TGO to provide critical event communications support for the entry, descent and landing event of their 2018 ExoMars Rover mission. Depending on final landing site selection for that mission, ESA may need to slightly modify the TGO orbit elements to modify the nodal precession rate in order to establish good geometric coverage of that EDL event. As a result, the detailed TGO nodal orientation in the time frame of a prospective Discovery mission is currently uncertain. Users with a need for a certain nodal orientation at a specific epoch (e.g., for relay support during a critical event such as EDL) should document the required nodal orientation, to support feasibility assessment by the Mars program.

Table 7.1-1: Candidate ExoMars/TGO orbit elements

Orbit Element	TGO
Semi-major Axis (km)	3797
Eccentricity	0
Inclination (deg)	74.0
Ascending Node (deg)	105.6
Arg of Periapsis (deg)	n/a
Time from Periapsis (sec)	0
Epoch	13-NOV-2017 00:00:00 UTC

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

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 is essentially identical to the MAVEN implementation; relay service specifications are listed in Table

Table 7.2-1 ExoMars/TGO Electra Modes, Functions and Performance

Capability	Values
Protocol	Proximity-1 (Reliable and Expedited Link Layer protocols)
Modes of Operation	Simplex Rx or Tx Full duplex
Frequencies	Simplex: 390-450 MHz Full Duplex: 390-405 MHz rcv; 435-450 MHz txmt
Full duplex carrier modes	Coherent, noncoherent
Transceiver RF output power	5.0 W full duplex, 7.0 W simplex
Transceiver to antenna circuit loss	-0.8 dB
Antenna gain	On-boresight gain of 4.7 dBic; see Fig 7.2-1 for pattern.
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	Internal Temperature Controlled Crystal 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), (k=1024, r=½) Low Density Parity Check
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

7.2-1, and coded threshold performance in Table 7.2-2.

Each Electra UHF Transceiver on ExoMars/TGO will be connected to a nadir-oriented helix UHF antenna with an on-boresight gain of 4.7 dBic. A preliminary estimate of the antenna pattern is provided in Figure 7.2-1.

Table 7.2-2 ExoMars/TGO coded receive signal thresholds

Data Rate	Residual Carrier – Convolutional Coded	Suppressed Carrier – Convolutional Coded	Suppressed Carrier – Coded LDPC
1 kbps	–133.1 dB		
2 kbps	–130.1 dB		
4 kbps	–127.1 dB		
8 kbps	–124.1 dB		
16 kbps	–121.1 dB		
32 kbps	–118.1 dB	–120.3 dB	-122.75 dB
64 kbps	–115.1 dB	–117.25 dB	-120.0 dB
128 kbps	–112.1 dB	–114.35 dB	-116.85 dB
256 kbps	–109.1 dB	–111.25 dB	-114.0 dB
512 kbps	–105.6 dB	–108.0 dB	-111.0 dB
1024 kbps	–101.9 dB	–105.2 dB	-107.75 dB
2048 kbps	NA	–101.6 dB	1.1 -104.25 dB

NOTE: *Threshold is measured at the transceiver. Threshold values reflect performance of the FEC implementation and were measured under ambient temperature (+20C to +30C). Data rates are measured at the input of the encoder. Actual throughput, e.g., user data bits per second, will be lower due to link layer overheads such as ASM, Proximity-1 Link Layer header, and the efficiency of the go-back-N ARQ algorithm that is operating point dependent. Front end losses from antenna output to radio input is 0.8 dB.*

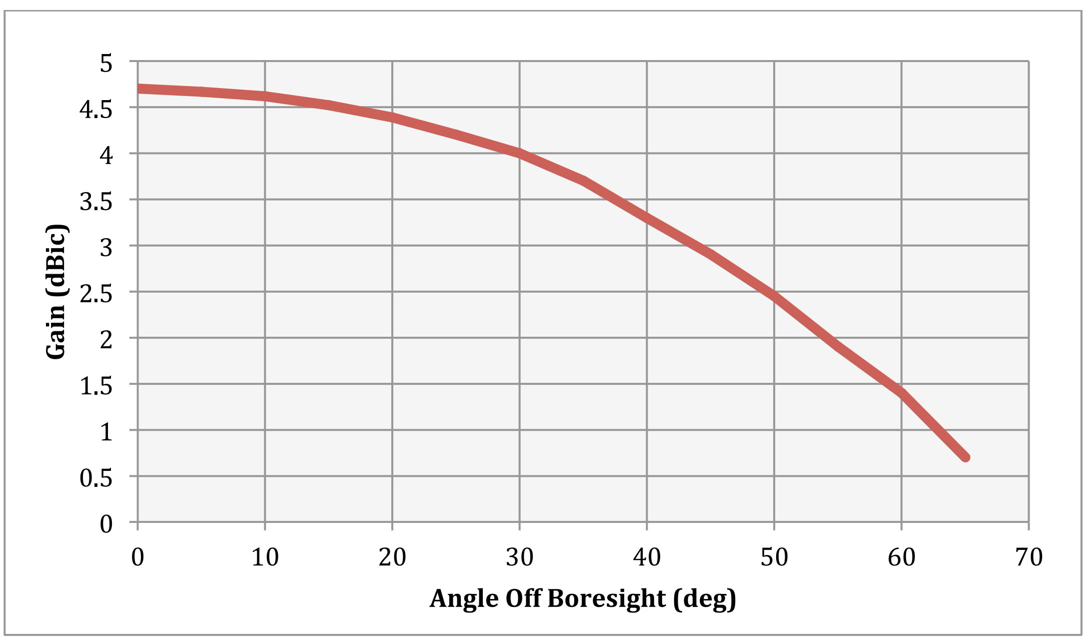

Figure 7.2-1: Preliminary ExoMars/TGO UHF Antenna Gain Pattern

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.

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 Mars Relay Network Service Agreement is documenting the planned relay services that the operational set of relay orbiters will provide to the user. The Service Agreement 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 between the user mission and 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.

Supporting all aspects of relay operations, the Mars Relay Operations Service (MaROS) system provides a centralized web-based toolset 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.

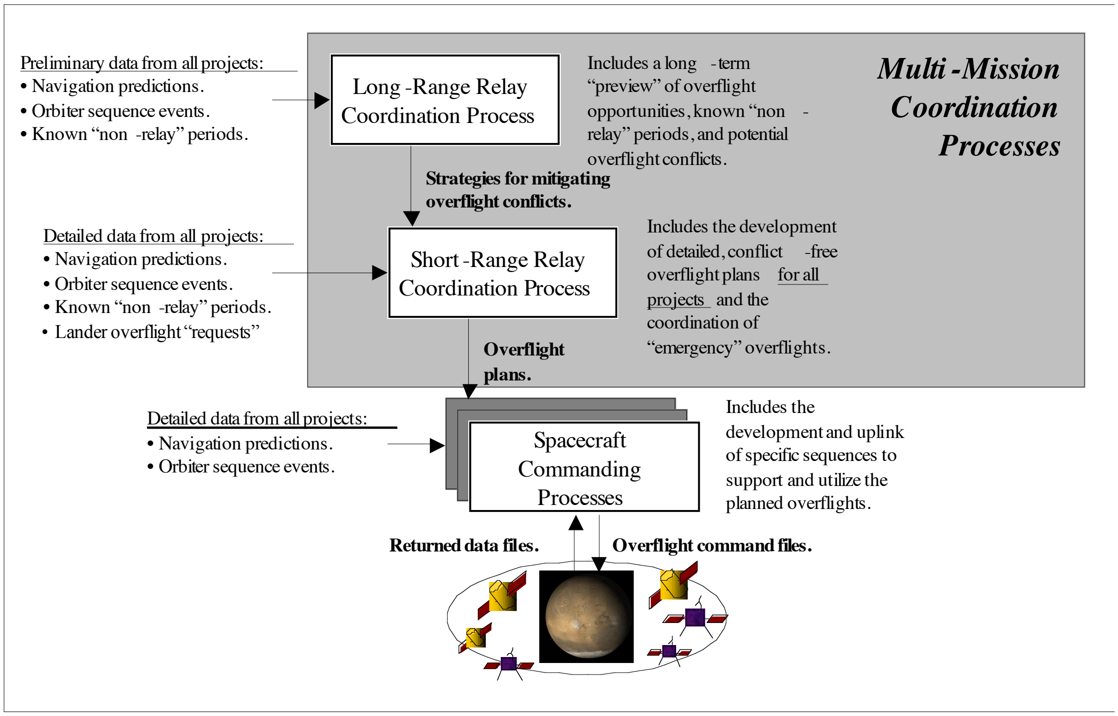

Figure 8-1 Multi mission Mars relay coordination process

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 typically be achieved.

Deterministic protocols greatly enhance the ability to predict these latencies. As part of the coordination process, predictions of forward- and return-link latency are calculated and posted within the MaROS system.

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, Phoenix Lander, and Curiosity Rover 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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