NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Mars Exploration Program

Mars Relay Description for Discovery 2019 Proposals

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1 Introduction

The Discovery 2019 Announcement of Opportunity (AO) solicits proposals for planetary science missions to be launched no later than the end of calendar year 2026. 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 Network 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 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 Network infrastructure.

Sections 4, 5, 6, and 7 provide specific details regarding, respectively, the relay capabilities and constraints of the Mars 2001 Odyssey Orbiter, the Mars Reconnaissance Orbiter (MRO), the Mars Atmosphere and Volatile Evolution (MAVEN) orbiter, and the 2016 ExoMars Trace Gas Orbiter (TGO).

Section 8 describes multimission 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, the 2011 Mars Science Laboratory mission's Curiosity rover, and the 2018 InSight lander.

2 Mars Relay Network 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 relay service 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 antennas, 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 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. 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 relay service user spacecraft.

At the time of arrival of the Spirit and Opportunity rovers at Mars in January 2004, the Mars Global Surveyor[1] (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. Over 99% of the science and engineering data obtained from Spirit and Opportunity were 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 UHF Transceiver (EUT), a next-generation UHF radio system for relay services at Mars. 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

[1] Mars Global Surveyor was lost in late 2006. All other orbiters mentioned herein remain operational at the time of this writing.

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.)[2]

On 6 August 2012, the Mars Science Laboratory (MSL, or Curiosity rover) 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 Odyssey 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 UHF transceivers onboard MRO and Curiosity, respectively. These new capabilities include support of higher instantaneous data rates, more efficient modulation, and a new adaptive data rate (ADR) selection algorithm that allows the data rate to be adjusted throughout each relay session to always operate at the highest supportable data rate as a function of signal strength.

To augment this relay infrastructure, MEP included an EUT on the 2013 Mars Atmosphere and Volatile Evolution Mission (MAVEN), which arrived at Mars on 22 September 2014. Unlike Odyssey and MRO, which operate in low-altitude near-circular orbits, MAVEN operates in a highly elliptical orbit matched to its science objectives, with a low periapsis altitude of ~150 km[3] and an apoapsis altitude of ~4500 km. The resulting orbit results in substantial variability in orbiter-to-lander view 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) launched the ExoMars Trace Gas Orbiter (TGO) mission in January, 2016. NASA and ESA established a Memorandum of Understanding, under which NASA provided redundant EUTs for flight on TGO, and TGO provides relay services to both ESA and NASA landed assets. ExoMars/TGO arrived at Mars in October 2016.

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[2] 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 relay sessions with Spirit, Opportunity, Phoenix, and Curiosity. It also provided redundant tracking of the Phoenix and MSL UHF carrier signal during their respective EDL. Given the expected lifetime of Mars Express in the timeframe of this AO, we have not included further information about the relay services offered by the project in this guide.

[3] By the time NASA's Mars 2020 Rover arrives in early 2021, the MAVEN project will have raised the periapsis of the orbiter to above 180 km.

	Odyssey	MRO	MAVEN	TGO	TOTAL
Total Number of Sessions	3220	3290	23	9	6542
Total Data Return (Gb)	252.8	727.9	8.7	4.9	994.3
Average Number of Sessions per Day	2.2	2.3	N/A	N/A	4.5
Average Return-Link Data Volume per Day (Mb)	173.0	498.2	N/A	N/A	671.3
Average Return-Link Data Volume per Session (Mb)	78.5	221.2	378.3	542.7	N/A

Table 2-1: Curiosity data return metrics during the first 5 years of surface operations. Note that MAVEN and TGO came online later and only recently have begun primary relay service provision.

To enable interoperability among the various Mars orbiters that act as relay service providers and to provide a standardized service interface to relay service user spacecraft, each relay orbiter supports relay communications in conformance with the Consultative Committee on Space Data Systems (CCSDS) Proximity-1 Space Link Protocol. Relay service user missions are responsible for implementing a relay communications system that conforms to this standard in order to access Mars Relay Network services. One option that users should consider is to implement their UHF relay system based on the Electra-Lite UHF Transceiver (ELT) that is currently operating on the Mars Science Laboratory mission's Curiosity Rover. The ELT 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 relay planning and coordination efforts.

3.5 Relay Tests

Each relay orbiter will have a ground-based system for conducting UHF compatibility tests with relay service user 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. Its ascending node corresponds to a Local Mean Solar Time (LMST) of 6:45 AM. 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)	3765.4
Apoapsis Radius (km)	3825.1
Semi-major Axis (km)	3795.3
Eccentricity	0.00786
Inclination (deg)	93.0
Ascending Node (deg)	142.8
Argument of Periapsis (deg)	270.0
Time from Periapsis (sec)	3537.9
Epoch	10-APR-2019 00:14:00 UTC
Related data	
Periapsis altitude / location	392 km / South pole
Apoapsis altitude / location	454 km / North pole
Local Mean Solar Time (LMST), ascending node	6:43 AM
LMST, descending node	6:43 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 session 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 relay service user spacecraft 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 sessions will be available, up to a maximum of 12-13 sessions 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 (from the surface vehicle to the orbiter) using the Proximity-1 protocol, with 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.

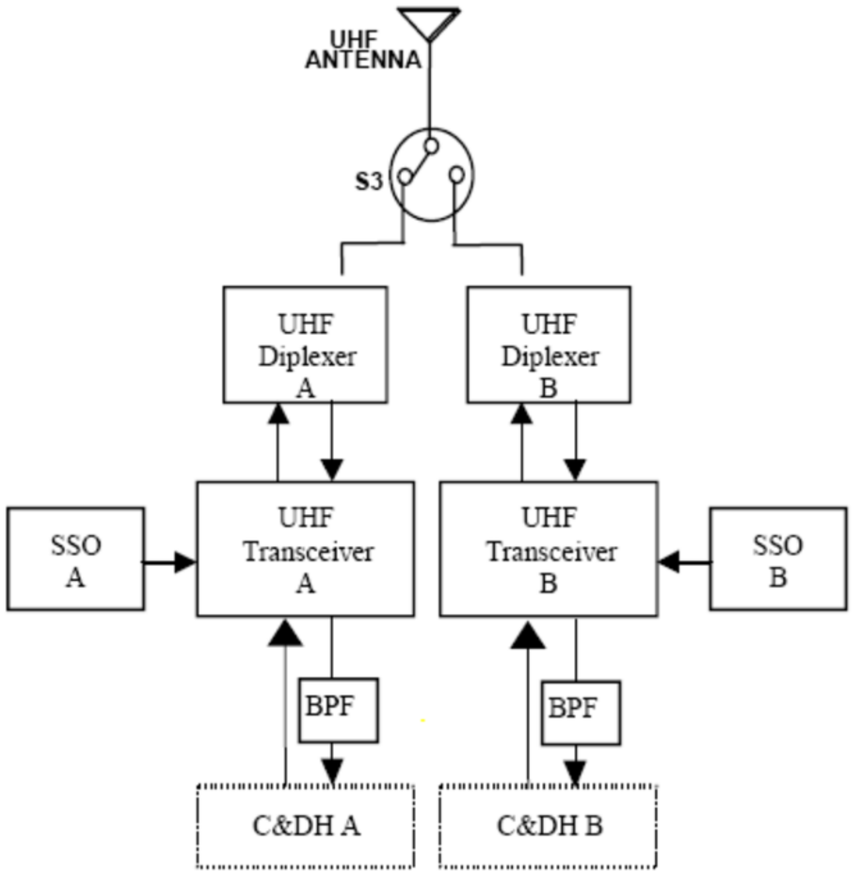

Figure 4.2-1 Block diagram of Odyssey UHF subsystem

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 provides transmitting and receiving capability and a switch connects 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).[4]

For Odyssey Proximity-1 operations, the Proximity-1 data packet size is not directly user-selectable, but is instead 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. (By contrast, 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.)

Unreliable 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 shut down and the link is terminated.

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 recording is always at the nominal

[4] 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.

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 relay session with Odyssey is typically 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 (401.585625 MHz)
Transceiver to antenna circuit loss	-1.5 dB at 437.1 MHz (forward) -2.3 dB at 401.585625 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.

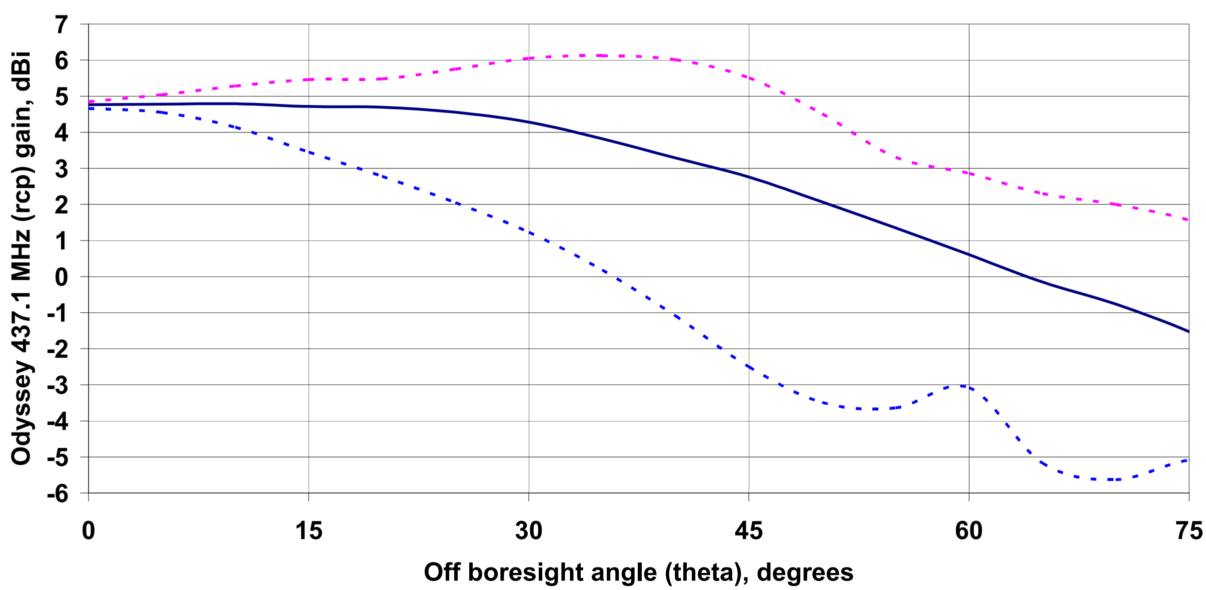

Figure 4.2-2 Odyssey 437.1 MHz (RCP) gain pattern

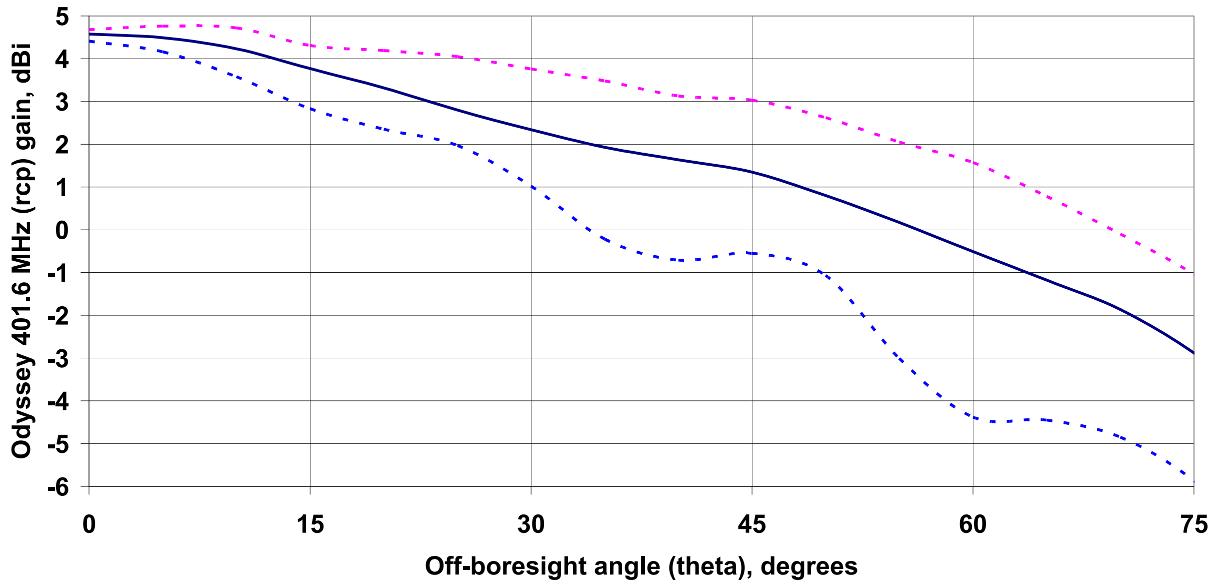

Figure 4.2-3 Odyssey 401 MHz (RCP) gain pattern

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 (HGA) and a 15 W Solid State Power Amplifier (SSPA). 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, regardless of the Earth-Mars range.

4.4 Operational Considerations

The Odyssey relay antenna is not articulated, nor is the spacecraft steered prior to or during a relay session. The Odyssey spacecraft nadir deck is seasonally 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 sessions.

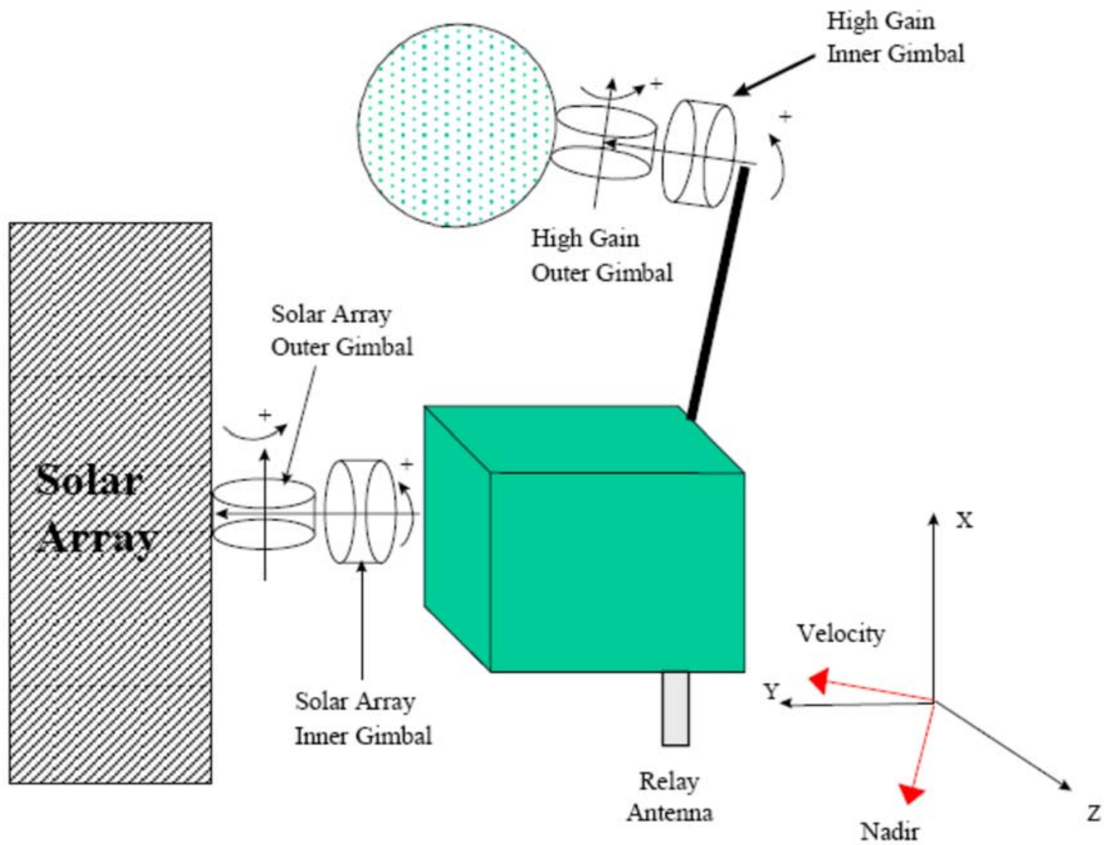

Figure 4.4-1 Odyssey and UHF antenna geometry

In the time frame of a mission selected in response to the 2019 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 rover and InSight lander. 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. For example, 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.

5 Mars Reconnaissance Orbiter

5.1 Orbit

Similar to Odyssey, MRO operates in a sun-synchronous, near-circular orbit, with an inclination of approximately 93 deg. The orbit node is typically oriented such that the LMST 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)	3633.0
Apoapsis Radius (km)	3694.0
Semi-major Axis (km)	3663.7
Eccentricity	0.0083
Inclination (deg)	92.7
Ascending Node (deg)	260.6
Argument of Periapsis (deg)	272.6
Time from Periapsis (sec)	2197.8
Epoch	01-APR-2019 00:05:15 UTC
Related data	
Periapsis altitude / location	252 km / South pole
Apoapsis altitude / location	317 km / North pole
Local Mean Solar Time (LMST), ascending node	2:52:58 PM
LMST, descending node	2:52:58 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 session durations of typically 10 minutes during which the orbiter is visible above 10 deg from the local horizon. For low-latitude sites within 30 deg of the equator, a relay service user spacecraft 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 sessions will be available, up to a maximum of 13-14 sessions per sol for near-polar sites.

5.2 Relay Proximity Link Specifications

Figure 5.2-1 is a block diagram of the MRO Electra Proximity 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).

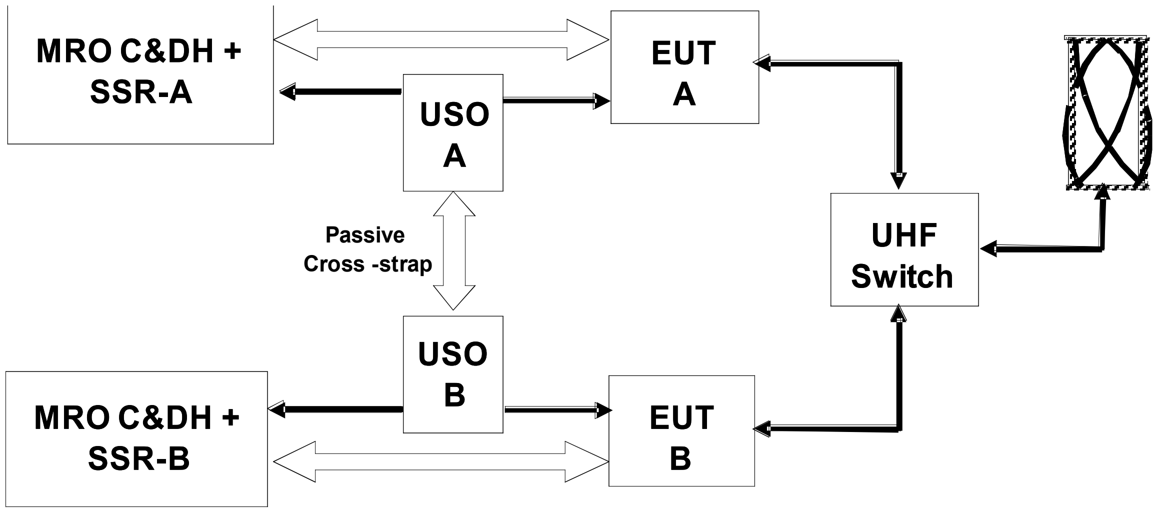

Figure 5.2-1 MRO/Electra UHF subsystem block diagram and interfaces with C&DH and SSR

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 EUT 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 EUT initiates 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 EUT 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 onboard MRO are terminated by a timed, sequenced command.

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.

The MRO EUT 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 a timed, sequenced transmission and reception at both ends of the link. For example, the MRO orbiter could be sequenced to begin listening for a signal at time X and another vehicle could be 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, such as 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.

Phase & Power data: MRO's EUT can sample and record phase signal power of a phase locked received carrier signal. This radio metric information is highly accurate on two accounts. First, the phase information is relative to the phase of the Electra USO signal with stability 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 EUT 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 EUT 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 relay service 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 may also specify a fixed receiver gain setting that effectively defines the peak-to-peak signal amplitude range into MRO, or may enable the EUT's Automatic Gain Control to

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 (401.585625 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; optionally with ADR on the return-link when operating in full duplex 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

dynamically adjust the receive signal gain. The EUT provides 8 bits/sample for the I channel and the Q channel, corresponding to a signal level dynamic range of 51 dB. Available sampling rates range in powers of 2 from ~1.15 Hz to ~150 kHz. Data may be collected with or without time tags, though, for high sample frequencies, time stamps are usually only collected on the first 5 samples.

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, with a Mars noise temperature of 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; relay service users should add additional link margin per the user's design requirements.

MRO's EUT implements frequency agility and swappable transmit and receive bands.

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 x 10^{-6}

The MRO EUT has the capability to tune its Tx and Rx frequency across the 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.

The EUT also supports an adaptive data rate (ADR) selection capability, in which the EUT monitors the symbol signal-to-noise-ratio (SSNR) on the return-link from the lander throughout the relay session 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

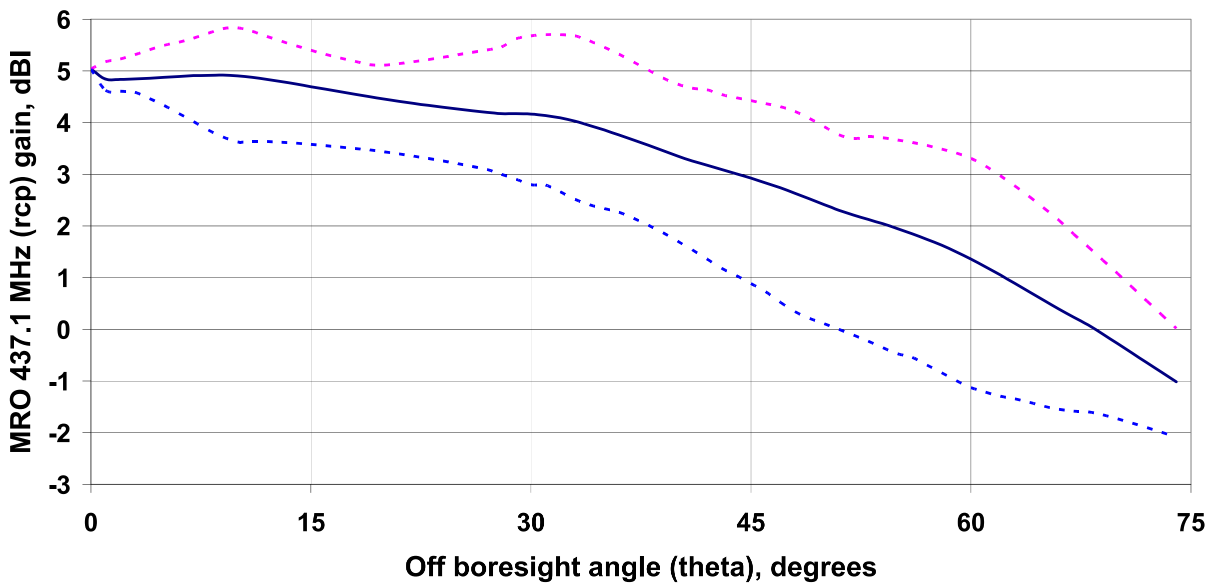

Figure 5.2-2 MRO 437.1 MHz (RCP) gain pattern

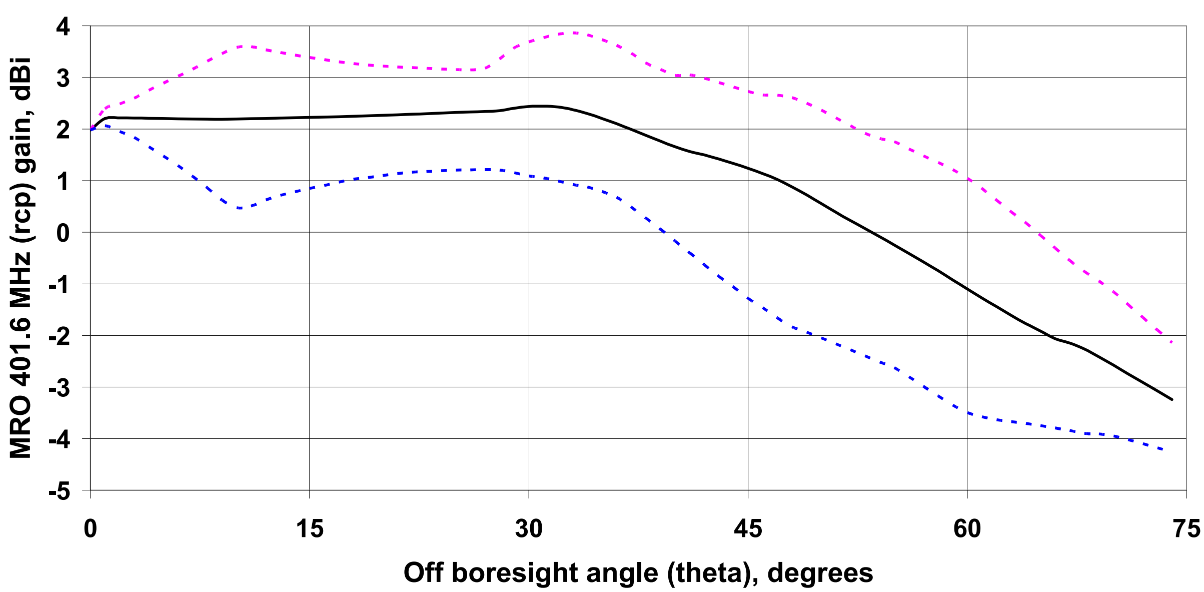

Figure 5.2-3 MRO 401.585625 MHz (RCP) gain pattern

operate at the optimal data rate. This feature is used routinely in MRO's relay 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 401.585625 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 HGA and a 100 W travelling wave tube amplifier (TWTA). 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, to the Opportunity rover through 2018, and to the InSight lander starting in 2018; all of which operated or 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 (ELT) that can select a return-link channel anywhere in the range 390 – 405 MHz. Prior to Curiosity's 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 (Channel 2 in the Proximity-1 specification), at which the EMI degradation is reduced to ~4 dB.[5]

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 relay service users still include 1 dB of EMI

[5] It should be noted that even though Curiosity operates on Channel 2, hailing still occurs on Channel 0, as per the Proximity-1 specification, with the radios reconfiguring to Channel 2 after a link is established between the orbiter and the lander.

degradation to account for possible low-level spurious signals generated by the spacecraft avionics.

MRO can only communicate with one surface asset at a time. For relay service user missions in close proximity on the surface of Mars, relay sessions must be coordinated across the network. This is further complicated by the implementation of the CCSDS Proximity-1 protocol, which specifies that hailing activities always occur on Channel 0, as previously discussed. Thus, even though MRO is capable of communicating with spacecraft on different channels, relay sessions by MRO and other orbiting assets must be coordinated to prevent frequency cross-talk during the relay sessions.

However, MRO does provide the ability to "split" relay services provided to two assets on the surface of Mars that are in close proximity to each other. For example, the Curiosity rover and InSight lander, which are at two different landing sites, are nevertheless usually visible by MRO at the same time during relay opportunities. Thus, the Curiosity and InSight projects must coordinate how they desire to "split" the available view periods (with an MRO-mandated, short cycle time between the sessions) to acquire relay services to both landers during a given relay session. See section 8 for a description of how relay services are coordinated across the network to avoid planning conflicts of this nature.

The MRO project provides relay services to landed assets with the spacecraft oriented such that its UHF antenna is pointed in a nadir or near-nadir direction.

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 incorporated an MEP-provided Electra payload and serves as an additional relay asset.

In November 2015, upon completion of its primary science mission phase, MAVEN entered an extended mission phase. Full relay services are available, with a capability of supporting up to 4 relay sessions per day. In practice, MAVEN supports one relay session per day and will continue to do so until the Mars 2020 rover lands in February 2021, where it will be expected to support 3-4 passes per day.

6.1 Orbit

To support its aeronomy science objectives, currently 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 about 4500 km to enable measurements of the solar wind upstream of the bow shock. The resulting orbit, with a ~3.6-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 characteristics (semi-major axis, eccentricity, and inclination) are accurate at the time of this writing, a small periapsis raise maneuver is planned for early 2020 that will raise the periapsis to ~180 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 2021.

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. Relay service 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, near-circular, sun-synchronous orbits of Odyssey and MRO. Near-equatorial relay service 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 sessions per sol, with a small region near the pole (well above +-75 deg latitude) where users can go for long periods with no available sessions when MAVEN's periapsis has precessed near that pole.

Table 6.1-1: MAVEN orbit elements

Orbit Element	**MAVEN**
Periapsis Radius (km)	3540
Apoapsis Radius (km)	7900
Semi-major Axis (km)	5722.4
Eccentricity	0.3851
Inclination (deg)	74.8
Ascending Node (deg)	273.4
Argument of Periapsis (deg)	242.5
Time from Periapsis (sec)	5528.5
Epoch	01-JUN-2019 00:00:00 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 session durations and the slant ranges over which the relay link operates are also highly variable based on MAVEN's orbit. Sessions supported from near MAVEN periapsis have short durations, low slant ranges, and can support high instantaneous data rates, similar to Odyssey, MRO, and TGO. However, sessions supported near MAVEN's apoapsis can have geometric view periods of almost 2 hrs, with slant ranges exceeding 5000 km. Such sessions require lower instantaneous data rates to account for the large slant range; the longer pass duration can partially compensate for this, particularly when coupled with the use of ADR.[6]

6.2 Relay Proximity Link Specifications

MAVEN carries a single-string version of the Electra Proximity Link Payload for provision of relay services. Detailed specifications are presented in Table 6.2-1. Highlighted here are the minor differences between the MAVEN and MRO Electra implementations.

The MAVEN EUT uses an internal temperature-controlled crystal oscillator (TCCO) for its frequency reference. The different reference oscillator on MAVEN results in slightly different open-loop sampling rates when compared to MRO, with support for powers of 2 up to ~128 kHz.

[6] Due to thermal considerations, MAVEN must limit the maximum duration of a relay session to 30 minutes.

The MAVEN EUT supports the 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 relay service user's transceiver also include an LDPC encoder.) Table 6.2-2 provides the detailed receiver thresholds for the MAVEN EUT 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 Rx; 435-450 MHz Tx
Full duplex carrier modes	Coherent, noncoherent
Transceiver RF output power	5.0 W full duplex, 7.0 W simplex
Transceiver to antenna circuit loss	0.6 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	–133.8 dB		
2 kbps	–131.2 dB		
4 kbps	–128.1 dB		
8 kbps	–125.1 dB		
16 kbps	–122.1 dB		
32 kbps	–119.0 dB	–121.0 dB	-122.75 dB
64 kbps	–116.0 dB	–118.0 dB	-119.7 dB
128 kbps	–113.0 dB	–115.0 dB	-116.7 dB
256 kbps	–110.0 dB	–112 dB	-113.7 dB
512 kbps	–106.5 dB	–108.5 dB	-110.7 dB
1024 kbps	–102.8 dB	–105.5 dB	-107.6 dB
2048 kbps	NA	–102.3 dB	-104.8 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.

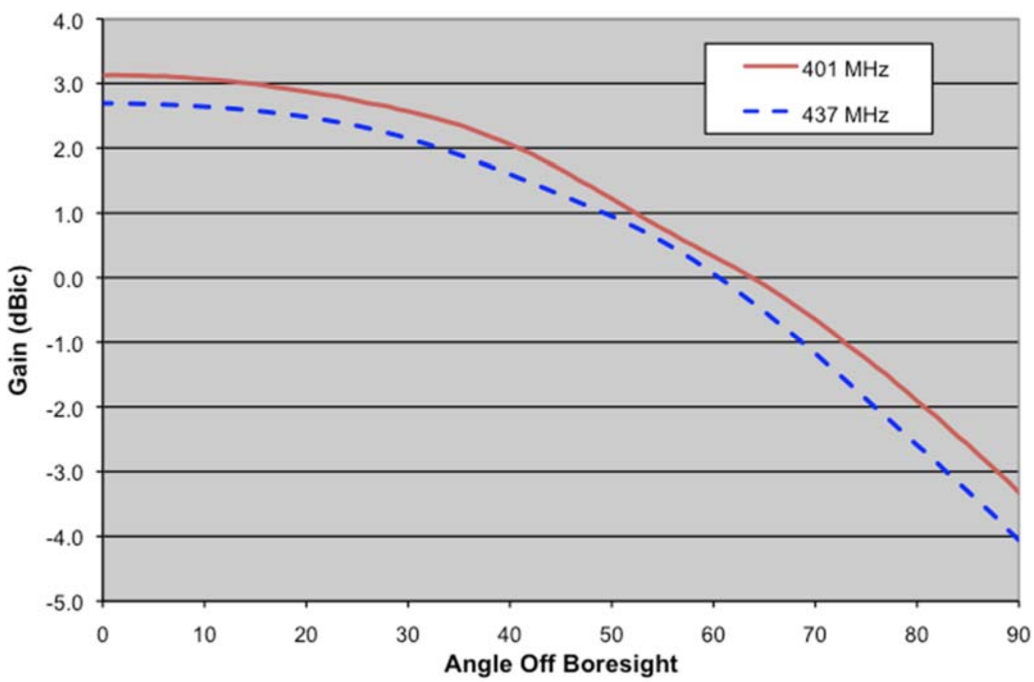

Fig. 6.2-1: MAVEN UHF Antenna Gain Pattern

MAVEN carries 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 HGA coupled with a 100 W TWTA 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 relay service user spacecraft.

For a supported relay session, MAVEN can optionally provide a deep space link opportunity 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 session allows uplink of lander command products from Earth to MAVEN for delivery on the forward-link during the relay session, while the deep space link session after the relay session supports downlink from MAVEN to Earth of all relay service user data transmitted on the return-link during the relay session, along with any Electra-collected phase and power data, time stamp data, engineering telemetry; or open-loop recordings, consistent with the data products generated similar to MRO as reported in Table 5.2-1.

During the relay service itself, the spacecraft attitude is adjusted to orient the UHF antenna boresight in or near the nadir direction for the duration of the relay session.

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. Thus, available relay services may be seasonally limited.

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 Roscosmos launch vehicle, carrying a suite of ESA- and Roscosmos-provided science instruments, including investigations of trace gas constituents of the Mars atmosphere. On approach to Mars, the primary spacecraft released an ESA-provided Entry, Descent, and Landing (EDL) Demonstrator Module (EDM), a short-lived lander that demonstrated EDL technologies applicable to future ExoMars landers. NASA provided a dual-string Electra UHF Transceiver (EUT), with the Electra design effectively identical to the EUT on MAVEN.

7.1 Orbit

ExoMars/TGO is in a ~400 km circular orbit with an inclination of 74 deg. As with MAVEN, this non-sun-synchronous orbit causes the local time of the orbit node to precess, moving earlier each day, and thus the contact times for relay service will drift. The orbit is summarized in Table 7.1-1.

Table 7.1-1: ExoMars/TGO orbit elements

Orbit Element	TGO
Semi-major Axis (km)	3785.7
Eccentricity	0.0071
Inclination (deg)	73.5
Ascending Node (deg)	243.6
Argument of Periapsis (deg)	266.8
True Anomaly (deg)	63.6
Epoch	11-APR-2019 08:34:34 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 has implemented a dual-string version of the Electra Proximity Link Payload for provision of relay services. The TGO Electra UHF Transceiver (EUT) is essentially identical to the MAVEN implementation; relay service specifications are listed in Table 7.2-1, and coded threshold performance in Table 7.2-2.

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 with adaptive data rate mode available.
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); and Low Density Parity Check (not presently implemented for use with ADR)
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

Each EUT on ExoMars/TGO is connected to a nadir-oriented helix UHF antenna with an on-boresight gain of 4.7 dBic. An 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	-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.

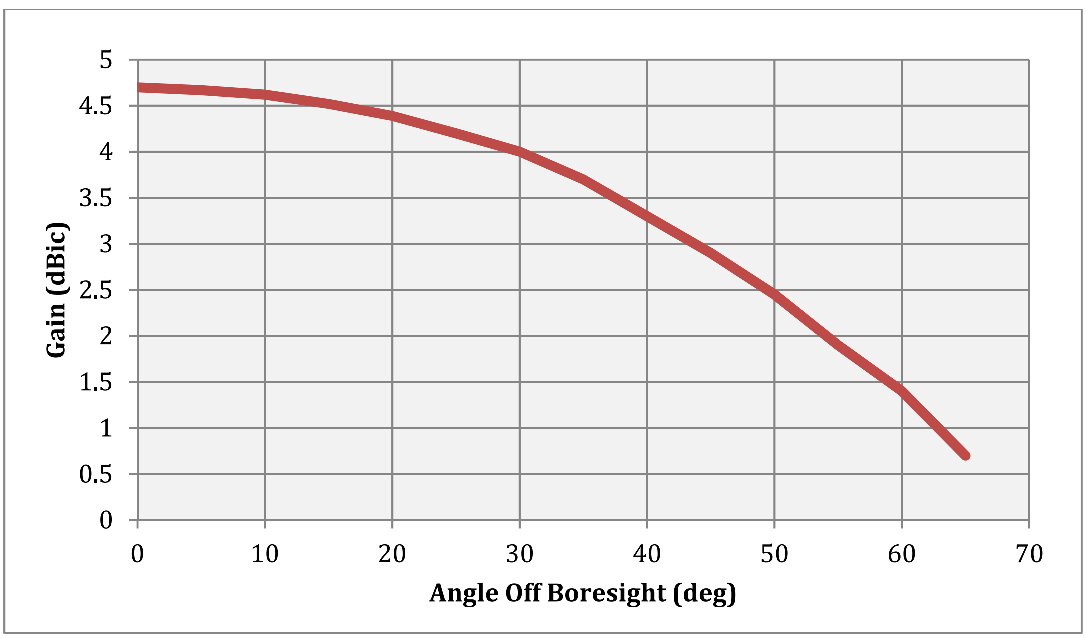

Figure 7.2-1: Preliminary ExoMars/TGO UHF Antenna Gain Pattern

7.3 Deep Space Link Characteristics

The ExoMars/TGI orbiter communicates with Earth via a 2.2 m HGA and a 65 W TWTA, enabling a downlink data rate of 150 kbps to a 34m DSN antenna at maximum Earth-Mars distance.

7.4 Operational Considerations

Similar to MRO, the ExoMars/TGO offers the ability to support “split pass” relay services for multiple assets near each other on the surface of Mars.

Also similar to MRO, the ExoMars/TGO provides relay services to landed assets with the spacecraft oriented such that its UHF antenna is pointed in a nadir or near-nadir direction.

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 Mars Relay Network Office 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 generated to document 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 sessions per sol).

Subsequently, a more detailed Interface Control Document is established between the relay service user mission and the orbiter acting as a relay 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. Additional documentation is generated as needed, often to detail planning cadences for long-term missions, policies for how “split passes” are to be implemented, test and training documentation, and other concerns not otherwise documented.

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. Relay coordination activities across the network occur on a bi-weekly basis, whereby relay service users request and secure relay services from the orbiter projects.

Supporting all aspects of relay operations, the Mars Relay Operations Service (MaROS) provides a centralized web-based toolset to support relay planning, user mission relay service requests, orbiter mission relay service commitments, standardized interfaces for the submission of relay service user forward-link products, and integrated service monitoring and assessment. This service is provided by MGSS on behalf of the Mars Exploration Program to all current participants in the Mars Relay Network, including those from ESA.

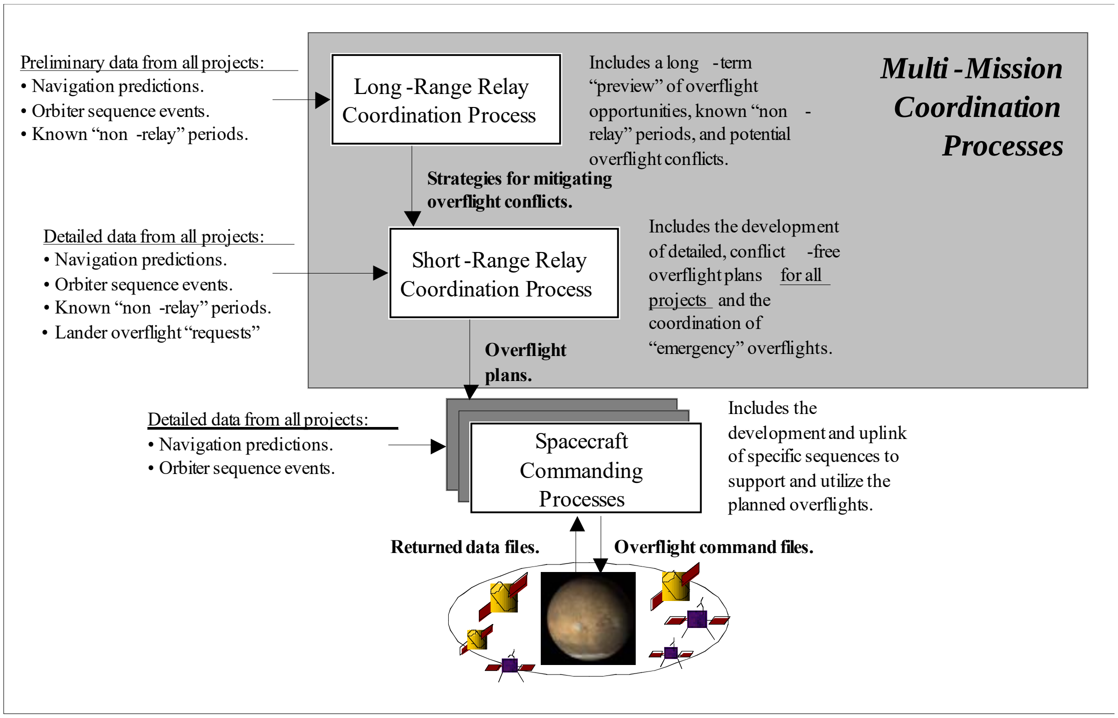

Figure 8-1 Multi mission Mars relay coordination process

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 session,
- relay session duration,
- time until deep space tracking 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, and
- 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 deep space tracking 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, and
- relay session duration.

When deep space tracking coverage is scheduled to overlap with relay sessions, end-to-end return-link latencies of less than 1 hour can typically be achieved.

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

8.3 EDL considerations

For critical events, such as a mission's Entry, Descent, and Landing (EDL); on-orbit relay assets can typically adjust their orbit phasing (that is, adjust the true anomaly of the orbit) to provide favorable viewing geometry for recording the asset's telemetry. Assuming that the desired orbit phasing is known several months in advance, the phasing can typically 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, relay service users should not assume that orbit plane adjustments can be accommodated. Any such orbit change would 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 Relay Service User Radios

Radio-to-radio compatibility testing and end-to-end information system testing between the relay service user mission testbed and the orbiter mission testbed are essential in order to ensure successful relay operations. This testing is typically done before the launch of a new user mission. 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.

Typically, this testing provides a means to verify the exact radio modes (data rates, encoding modes, inversion settings, etc.) to be used during on-surface operations. Connectivity between the two radios is demonstrated, as is the end-to-end exchange of data in both the forward- and return-link direction through the mission operations systems (which includes the ground systems) of both the relay service user mission and the relay service provider mission. This testing is considered critical to ensure that the radios will function together upon arrival at Mars.

9 Lessons Learned

Relay operations in support of the Mars Exploration Rovers, the Phoenix lander, the ExoMars/EDM, and the 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 transceivers of the relay service user and the relay service provider.
- 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 relay service user project and the relay service provider project.
- Operational Readiness Tests should be scheduled and performed to fully exercise the user and orbiter relay operations teams prior to flight relay operations.
- In-flight testing of expected modes of operation, when possible, are valuable to ensure readiness of the relay service provider mission.
- Limiting the number of distinct modes that a relay service 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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