Chapter 6
Mars Reconnaissance Orbiter

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6.1 Mission Overview

The Mars Reconnaissance Orbiter (MRO) [1, 2] has a suite of instruments making observations at Mars, and it provides data-relay services for Mars landers and rovers. MRO was launched on August 12, 2005. The orbiter successfully went into orbit around Mars on March 10, 2006 and began reducing its orbit altitude and circularizing the orbit in preparation for the science mission. The orbit changing was accomplished through a process called aerobraking, in preparation for the “science mission” starting in November 2006, followed by the “relay mission” starting in November 2008. MRO participated in the Mars Science Laboratory touchdown and surface mission that began in August 2012 (Chapter 7).

MRO communications has operated in three different frequency bands:

1) Most telecom in both directions has been with the Deep Space Network (DSN) at X-band (~8 GHz), and this band will continue to provide operational commanding, telemetry transmission, and radiometric tracking.
2) During cruise, the functional characteristics of a separate Ka-band (~32 GHz) downlink system were verified in preparation for an operational demonstration during orbit operations. After a Ka-band hardware anomaly in cruise, the project has elected not to initiate the originally planned operational demonstration (with yet-to-be-used redundant Ka-band hardware).

3) A new-generation ultra-high frequency (UHF) (~400 MHz) system was verified with the Mars Exploration Rovers in preparation for the successful relay communications with the Phoenix lander in 2008 and the later Mars Science Laboratory relay operations.

Lockheed Martin Space Systems, Denver, Colorado, is the prime contractor for MRO. They built the spacecraft and have provided flight operations support during the mission. The Jet Propulsion Laboratory (JPL), Pasadena, California, manages the project for the National Aeronautics and Space Administration (NASA), Washington, D.C. The Flight Team is located at both Lockheed and the Jet Propulsion Laboratory. Refer to the Mars Reconnaissance Orbiter home page [1, 2] for current MRO information.

6.2 Mission Phases and Orbit Summary

6.2.1 Mission Objectives

The Mars Reconnaissance Orbiter (MRO) mission has the primary objective of placing a science orbiter into a low and near-circular Sun-synchronous Mars orbit to perform remote sensing investigations to characterize the surface, subsurface, and atmosphere of the planet and to identify potential landing sites for future missions. The MRO payload conducts observations in many parts of the electromagnetic spectrum, including ultraviolet and visible imaging, visible to near-infrared imaging spectrometry, thermal infrared atmospheric profiling, and radar subsurface sounding, at spatial resolutions substantially better than any preceding Mars orbiter.

The driving theme of the Mars Exploration Program (MEP) is to understand the role of water on Mars and its implications for possible past or current biological activity. The MRO is studying the history of water on Mars. Another Mars mission, the Mars Exploration Rover (MER), has shown that water flowed across the surface in Mars' history. The MRO is searching for evidence for when the water was on the surface and where it is now, and any indicators of whether water persisted on the surface of Mars long enough to provide a habitat for life.

In terms of telecommunications (telecom), the MRO mission

- Provides X-band (~8 GHz) uplink (command), downlink (telemetry), and navigation (two-way Doppler, turnaround ranging, and differential one-way ranging) with the Deep Space Network (DSN). The direct-from-Earth (DTE) uplink can also carry data intended for relay to a surface vehicle, and the DTE downlink can also carry data relayed to MRO from a surface vehicle.

- Provides ultra-high-frequency (UHF) data relay and navigation support services to landing MEP missions during their entry, descent, and landing (EDL) phase, and subsequently provide UHF two-way relay and navigation services to landed surface vehicles or to other orbiting spacecraft, for example, a sample-return canister waiting for pickup and return to Earth.
- Perform an operational demonstration of high-data-rate Ka-band (~32 GHz) downlink telecommunications and navigation services (using the X-band uplink) with the DSN.

6.2.2 The MRO Spacecraft

The MRO uses a new spacecraft bus design provided by Lockheed Martin Space Systems Company, Space Exploration Systems Division, in Denver, Colorado.

The X-band antennas for communication with the DSN are at the top in Fig. 6-1. Of the two low-gain antennas (LGAs) that are fixed-mounted to the high-gain antenna (HGA), LGA1 is called forward-facing because it is pointed in the same general direction as the gimbaled HGA. The other LGA, LGA2, points generally in the opposite direction. The UHF antenna that is used for communicating with surface vehicles is aligned with the +z axis, which is also the science instrument boresight. Throughout the science and relay operations phase, this axis is usually oriented vertical toward Mars.

The orbiter payload consists of six science instruments and three new engineering payload elements listed as follows:

- Science instruments
  - HiRISE, High Resolution Imaging Science Experiment
  - CRISM, Compact Reconnaissance Imaging Spectrometer for Mars
  - MCS, Mars Climate Sounder
  - MARCI, Mars Color Imager
  - CTX, Context Camera
  - SHARAD, Shallow (Subsurface) Radar
- New engineering payloads
  - Electra UHF communications and navigation package
  - Optical Navigation Camera Experiment (ONC)
  - Ka-band Telecommunications Experiment

Figure 6-1 is a sketch showing the major externally visible parts of the spacecraft.

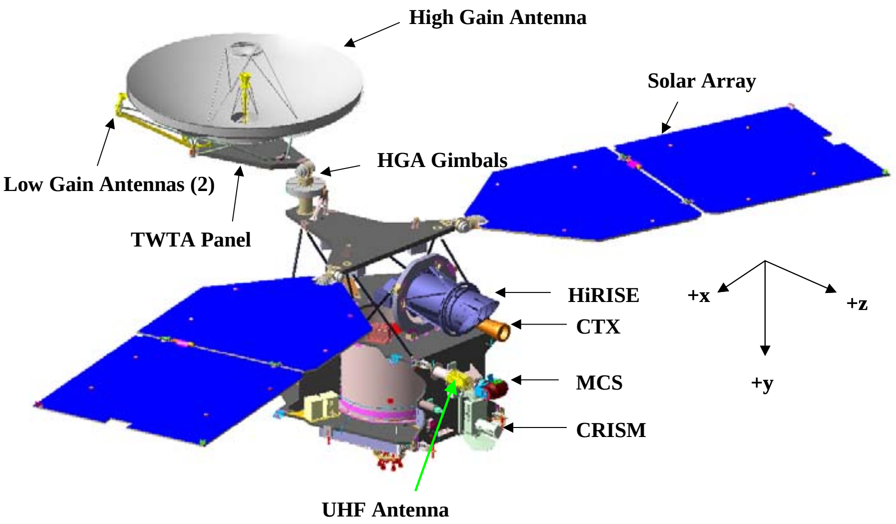

Fig. 6-1. Sketch of the MRO spacecraft with coordinate directions.

6.2.3 Mission Phases

In order of occurrence, the six phases of the MRO primary mission are: launch, cruise, approach and orbit insertion, aerobraking, primary science, and relay [3]. The following paragraphs provide overviews of the spacecraft activities in each phase. Specific telecom calibrations and activities are described in subsequent sections.

6.2.3.1 Launch. The spacecraft was launched on August 12, 2005. Approximately 58 minutes after launch, the spacecraft separated from the launch vehicle. About 4 minutes prior to separation, the X-band traveling-wave tube amplifier (TWTA) began warm-up, and the spacecraft began transmitting a downlink through the forward-facing low-gain antenna (LGA1) about 1 minute after separation. MRO remained in a single inertial attitude throughout the launch period. By 14 minutes after separation, the craft's solar panels finished unfolding. About 21 minutes after separation, in order to avoid interfering with solar array deployment, the HGA was deployed from the stow position.

The spacecraft established radio contact with Earth 61 minutes after launch and within 4 minutes of separation from the upper stage. Initial downlink-only contact came through an antenna at the Japan Aerospace Exploration Agency's Uchinoura Space Center in southern Japan.

When MRO came into view at the Goldstone, California, DSN site, a 34-m station established an X-band uplink with the MRO receiver. The uplink carrier provided a reference for two-way Doppler and turnaround ranging on the downlink, as well as establishing commandability.

The ultra-stable oscillator (USO) in the telecom subsystem was turned on within hours after launch so that the one-way downlink frequency would be stable prior to cruise phase activities. The USO has operated continuously except for a few hours during safe mode in January 2006.

6.2.3.2 Cruise. The cruise phase began about 3 days after launch and ended 60 days prior to Mars orbit insertion (MOI). The duration of the cruise phase was approximately 150 days.

Early cruise included an in-flight UHF antenna gain pattern measurement in conjunction with the 150-foot (46-m) diameter "Stanford Dish" radio telescope [23]. The receive and transmit gain measurements were made at the 400-MHz relay operations frequencies with the nadir deck (instrument and UHF boresight) pointed back toward the Earth.[1]

The Type-I interplanetary trajectories for MRO did not have transfer-angle constraints or other singularities, and so the trajectory correction maneuver (TCM) timing was based primarily on operational considerations and standard practice [22]. TCM-1 included firing the six main (170-newton, N) thrusters for 15 seconds on August 27, 2005. This engine burn followed a 30-second burn of six smaller (22 N) thrusters, which settled propellant in the craft's fuel tank for smoother flow. With communications on the LGA, MRO's orientation was adjusted prior to the burns to point the engines in the proper direction for the maneuver, and the spacecraft returned to cruise-phase attitude after the trajectory adjustment. Besides putting MRO on course for the Mars target point, TCM-1 checked out the engines that would be required for MOI.

Instrument payload calibrations began on August 30. The higher-resolution cameras were pointed at the Earth and the Moon as the spacecraft continued its flight to Mars.

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[1] Pre-launch measurements could not be nearly so accurate because the spacecraft was not in its final flight configuration and because of antenna interactions outside the spacecraft. At 400 MHz, any electromagnetic conducting surfaces on the spacecraft parasitically couple with the UHF LGA forming a composite antenna pattern. This parasitic coupling would also occur on the ground with any metallic test equipment surrounding the spacecraft. The Stanford Dish test was a "first" in terms of an in-flight measurement of this type.

TCM-2, on November 18, 2005, used only the smaller TCM thrusters in a 20-second burn. Two other TCMs built into the mission plan [3] were not required.

6.2.3.3 Approach and Mars Orbit Insertion. Following the interplanetary cruise and Mars approach phases of the mission, the MRO achieved MOI on March 10, 2006. The MOI burn fired the craft's main thrusters for about 27 minutes to reduce velocity by about 20 percent as the spacecraft swung around Mars at about 5 kilometers per second (km/s), or about 11,000 miles per hour (mph).

The initial post-MOI orbit started from the MOI aim point of 360 km above the Martian surface, approaching from the south. As an example of how flight dynamics in the form of trajectory design works, Mars actually caught up to the slower moving MRO spacecraft at this point. After launch, MRO spiraled out from Earth to Mars, and Mars caught MRO from behind as the MRO radial motion around the Sun was slower than the motion of Mars at time of MOI.

After MOI and before the aerobraking phase began, the orbiter flew about 426 km (265 miles) above Mars' surface at the nearest point (periapsis) of each orbit, then swung out more than 43,000 km (27,000 miles) to the most distant point (apoapsis) before heading in again. The initial orbit period was about 35 hours.

After MOI, while preparing for aerobraking, the flight team tested several instruments, obtaining the orbiter's first Mars pictures and demonstrating the ability of its Mars Climate Sounder instrument to track the atmosphere's dust, water vapor, and temperatures.

6.2.3.4 Aerobraking. In aerobraking, the trajectory design deliberately causes the spacecraft to pass through the upper reaches of the Mars atmosphere on each periapsis pass. The atmospheric friction acts as a velocity brake, and each such pass lowers the apoapsis altitude at the other end of the orbit. After the correct apoapsis altitude is attained, the aerobraking phase is ended with a periapsis raise maneuver performed to bring periapsis out of the atmosphere. Aerobraking is made more complicated because the Martian atmospheric density as a function of altitude and latitude also varies with time. Infrared-sensing instruments and cameras on two earlier Mars orbiters (Mars Global Surveyor through late 2006 and Odyssey continuing as of 2010) were the main sources of information to the advisory team of atmospheric scientists, providing day-to-day data about variations in Mars' atmosphere as the aerobraking campaign continued. In addition, the Mars Climate Sounder instrument on

MRO itself provided data to monitor changes in temperature that affected the atmosphere's thickness.

Aerobraking began on March 30, 2006 and ended August 30, 2006. An initial propulsive maneuver firing of the 22-newton (N) thrusters for 58 seconds at apoapsis put the MRO spacecraft into an active aerobraking orbit. That apoapsis maneuver lowered the periapsis altitude to 333 km (207 miles). The aerobraking phase required 445 orbits of carefully calculated dips into Mars' atmosphere. Aerobraking and a phasing maneuver on September 5 shrank its orbit from the post-MOI elongated ellipse to a more nearly circular orbit.

Aerobraking ended with MRO in a slightly elliptical low-altitude Sun-synchronous orbit, called the science orbit. After a successful final circularization, propulsive periapsis-raise, maneuver on September 11, 2006, the science orbit has a period of 1 hour and 52 minutes, with an apoapsis of 316 km over the North Pole and a periapsis of 250 km over the South Pole [1, 2].

Solar Conjunction: Between the end of aerobraking (with the primary science orbit established) and the start of the primary science mission phase was a solar conjunction. Defined as the time period when the Sun–Earth–Mars angle is 5 degrees (deg) or less, this first solar conjunction was from October 7 to November 8, 2006. The Ka-band communications demonstration was planned to conduct activities during conjunction to monitor and compare simultaneous X- and Ka-band telemetry downlinks. The DSN supported one 8-hr pass per day to a 34-m antenna during this period.

Solar conjunctions of Mars have a periodicity of about 26 months, and the Earth–Mars range is very nearly at maximum when the Sun–Earth–Mars angle is minimal at conjunction. The Sun–Earth–Mars geometry at conjunction causes several communications challenges. As the Sun–Earth–Mars angle decreases below about 5 deg, the communications signal passes through an increasing amount of solar plasma, which causes non-linear scintillation on the signal. In addition, the background noise from the Sun itself reduces the received signal-to-noise ratio (SNR) at the DSN. Finally, the Sun itself subtends 10.5 deg in the sky, as viewed from Earth, and can completely block the line-of-site signal path to the MRO spacecraft if the Sun–Earth–Mars angle falls below 0.25 deg. Because conjunction is established by Mars–Earth–Sun geometry, all orbiters and landers at Mars have the same conjunctions. Table 6-1 gives the dates of Mars solar conjunction for 2004 through 2021. Proximity communications with surface vehicles would not be directly affected.

Table 6-1. Mars solar conjunction dates and minimum SEP angles (2004–2021)*

Date of Minimum SEP Angle	SEP Angle (deg)	Date of Minimum SEP Angle	SEP Angle (deg)	Date of Minimum SEP Angle	SEP Angle (deg)
09/15/2004	0.96	02/04/2011	1.08	07/27/2017	1.10
10/23/2006	0.39	04/18/2013	0.40	09/02/2019	1.08
12/05/2008	0.46	06/14/2015	0.62	10/08/2021	0.65

*Data received from Ref. 4 and personal communication from David Morabito, 12/08/2010.

6.2.3.5 Primary Science Mission. During the science phase, MRO examined parts of the planet in detail and monitored the entire planet daily throughout a full cycle of Martian seasons, or 669 sols for one Mars year. The duration of this phase was about two Earth years (November 2006 to November 2008, starting with the end of aerobraking. The science experiments consisted of global mapping of Mars' surface, regional surveys for potential future Mars landing sites, targeted observations of areas of interest, and mapping of the Mars gravity field. The primary science mission ended with the onset of solar conjunction.[2] Figure 6-2 shows the Mars-to-Earth range in the primary science phase.

At the beginning of the science phase, Mars was about one-third of the way through a Northern Hemisphere summer. Throughout the phase, the orbiter generally kept its instruments pointed at Mars to collect data and its high-gain antenna pointed at Earth to send the data home. During this phase, conducting science observations was more complex than in previous Mars missions, because MRO had to coordinate three basic observation goals:

- Daily global mapping and profiling
- Regional surveys
- Globally distributed targeting of hundreds of specific sites.

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[2] While the primary science phase was planned to end in 2008 after one Martian year, NASA approved the continuation of science observations beyond the primary science phase until 2010, the end of the next major phase, the relay phase. NASA subsequently approved two additional mission extensions for science and relay operations. The latest extension is through October 2014. http://mars.jpl.nasa.gov/mro/mission/timeline/

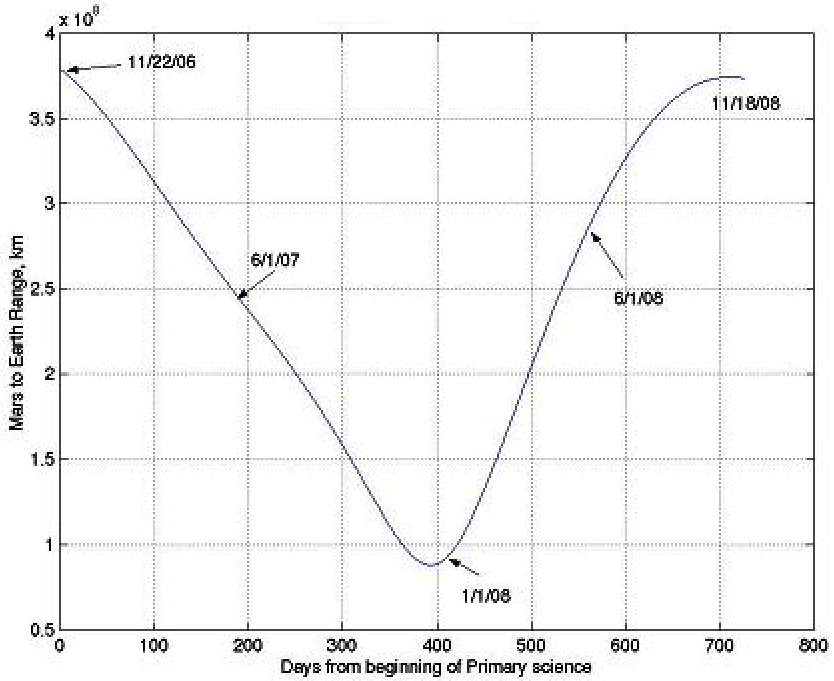

Fig. 6-2. Mars-to-Earth range during the primary science phase.

Many targeted observations also involved nearly simultaneous, coordinated observations by more than one instrument.

During this phase, primary communications was through the HGA to a 34-m DSN station. Precise Doppler measurements were taken to aid the gravity science experiments. Several times a day, the orbiter pointed to an off-nadir target for high-resolution imaging for about 15 minutes. During these slews, the HGA pointing error increased, but communications with Earth were still possible.

During the primary science mission, the DSN allocation to MRO was two 34-m passes at X-band per day, plus three 70-m passes per week.[3]

6.2.3.6 Relay Mission. Beginning 6 months before the end of the primary science mission in December 2008 and continuing until the end of the MRO

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[3] As of 2014, MRO has the highest rate Earth link telecom system for any planetary mission, going as high as 6 Mbps at closest distance Mars-Earth range. MRO has been collecting science data for nearly 8 years and so far has imaged about 2 percent of the planet surface with the high resolution camera.

primary mission in December 2010, the Electra payload provided relay support to various Mars assets. During this relay phase, the Jet Propulsion Laboratory (JPL) Mission Management Office (MMO) was chartered to coordinate relay services between Martian surface assets and MRO. The coordination plan was based on a 4-week planning cycle for relay coordination, with weekly updates for ad hoc relay opportunity assignment. The relay mission included support of two spacecraft arriving at Mars and descending to the surface:

Phoenix: Launched in August 2007, the Phoenix Mars Mission was the first in NASA's Scout Program. Phoenix studied the history of water and habitability potential in the Martian Arctic's ice-rich soil. The solar-powered Phoenix lander operated for 2 months longer than its planned 3-month mission in the Martian arctic in 2008. During the surface mission, the MRO mission plan stated that the Phoenix project would request two to three relay contacts daily with MRO's Electra at rates as great as 128 kilobits per second (kbps).

Mars Science Laboratory: The Mars Science Laboratory (MSL) is discussed in Chapter 8. MRO began has providing data for MSL site selection since 2009, and is scheduled to continue providing data through 2012. Since MSL landing in August 2012, MRO has received the bulk of MSL's science data via UHF relay and returned it to Earth by its X-band link.

At MSL arrival at Mars in 2012, MRO received one-way Doppler during entry, descent, and landing (EDL), and it received two-way Doppler for post-EDL reconstruction. After the MSL landing, MRO/Electra has been prime (with the Odyssey orbiter backup) for the surface-orbiter proximity communications relay, providing navigation and timing services, as well as forward- and return-link relay services.

For forward-link relay events, MRO has allocated space on the solid-state recorder (SSR) to store and forward up to 30 megabits per day (Mbits/day). For return-link events, the allocation is 5 gigabits per day (Gbits/day) for all landers. The MRO ground system has its own requirements for maximum data volume and data latency for data relayed from each lander during the primary science phase.

Figure 6-3 shows the activities planned to be performed during a typical relay session. Relay sessions between MRO and a surface asset are initiated by MRO. All information can be transferred via a reliable link—the Proximity-1 protocol (Prox-1). In outline, at the time of the overflight, MRO hails the surface asset. Once the surface asset has responded, the session begins. Once all the data has been transferred or the overflight is about to end, MRO terminates the link. If no scheduled termination time is forced, the link drops out due to geometric constraints, forcing a hard link termination.[4] The link session is later closed out by MRO Electra via the time out of a loss-of-lock event timer.

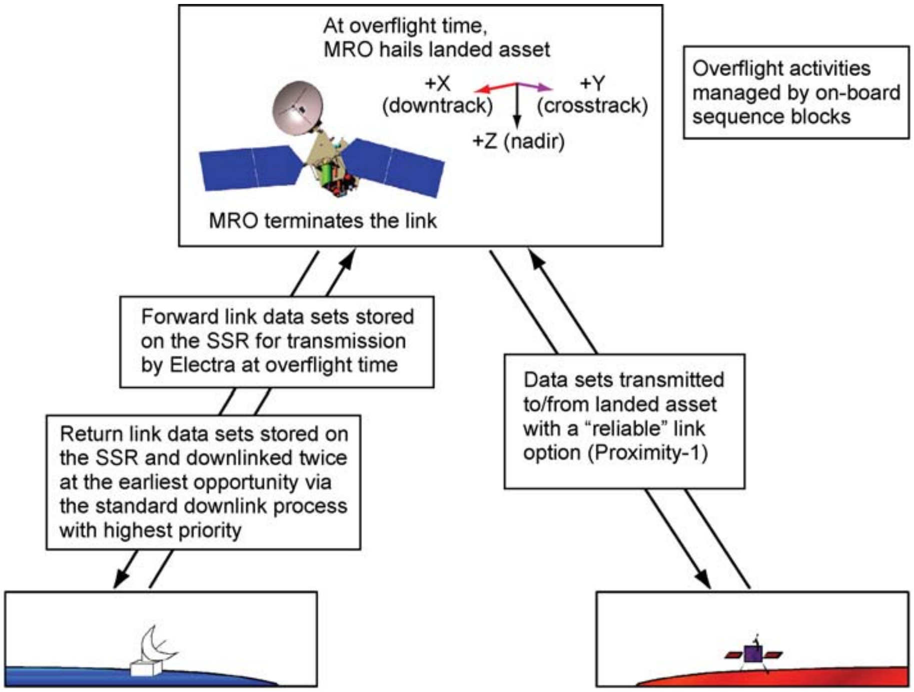

Fig. 6-3. A typical sequence of activities during a relay session.

Return-link data is downlinked at X-band from MRO to Earth at the earliest opportunity. The return-link data has the highest priority, and each frame will be sent twice.[5]

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[4] In actual MRO/MSL operations, the geometric impact of lower signal levels or complete line-of-sight blockage is always the factor that ends data transfer. When data transfer halts, the MRO Electra continues to hail the MSL Electra to try to restore communications and pick up any last bits of information. Loss of carrier lock actually initiates this rehail procedure. This continues until the larger relay session itself times out. At this point the relay session is closed out, and the final block of relay data is passed from the Electra radio to the MRO SSR. There is a maximum rehail counter, but the threshold is set so high, 120 rehails at about 12 seconds per rehail cycle, that the effect is to have the Electra rehail until the programmed relay session ends, which is past the time that MRO sets below the horizon.

[5] The MSL primary mission relay-data completeness requirements levied on MRO caused the project to respond by applying one retransmission of all relay data to Earth. The X-band downlink is not protected by a protocol like Proximity-1.

Transition from Primary Mission to Extended Mission: The nominal end of the MRO primary mission, which concludes with the extended science phase, was September, 2010. During the extended mission, currently planned through September 2012, MRO will continue both science and relay operations. The science goals include work on the nature and history of the Martian upper crust and on the polar caps and layered terrains and ice at all latitudes, as well as on atmospheric interannual variability. To support landing missions beyond MSL, in addition to providing UHF relay capability, MRO will provide data for landing site selection and for atmospheric characterization at the times of landing and surface operations [5].

6.2.3.7 Safe Mode. Safe mode provides a known, stable spacecraft configuration in case of a spacecraft anomaly. Safe mode may be entered via command (for example, for a flight software reboot) or from fault protection during any mission phase.

When MRO is configured in safe mode, LGA1 is boresighted at Earth, and the solar arrays are Sun-pointed. The spacecraft –y-axis tracks the Sun. Onboard Sun and Earth ephemerides that were loaded before launch are used to determine the Sun–probe–Earth (SPE) angle upon entry into safe mode and are used to point the HGA such that the forward-facing LGA1 boresight is pointed generally at Earth. The star trackers can be used to help with Sun acquisition if the spacecraft attitude knowledge is not good.

If the star trackers are not functioning and attitude knowledge is limited to that from Sun sensors, the spacecraft will rotate about its –y-axis (which in safe mode is pointed at the Sun) with a period of one hour for most mission phases. The rotation will cause the LGA1 boresight relative to the Earth to trace a cone of approximately half the SPE angle. As a result, the DSN station will observe a repeating power-level profile that depends on the SPE and LGA pattern.

In safe mode, the default USO is powered on. The X-band telecom transmit and receive paths are via LGA1. In safe mode, the command bit rate is set to 7.8125 bits per second (bps), and the X-band telemetry bit rate is set to 34.4 bps with (7,1/2) + Reed–Solomon (interleaving depth, $I = 1$) encoding. The short frame length reduces frame acquisition time at the station.

Further actions in safe mode ensure that the Ka-band TWTA is powered off and the small deep-space transponder (SDST) Ka-band exciter is turned off. The fault protection software also safes the Electra UHF transceiver (EUT).

6.2.4 The MRO Orbit and Its Relay Coverage for Surface Vehicles

MRO and Odyssey are the two NASA orbiters with Proximity-1 relay communications capability. Their orbits are Sun synchronous. Each time the orbiter crosses over the Martian Equator from south to north, the mean local solar time (LST) at the ground directly below is 3:00 p.m. (for MRO) or 5:00 a.m. (for Odyssey).

Table 6-2 [6] shows the orbit elements and related data for MRO and Odyssey. The MRO relay coverage defined in the three figures that follow is based on these values. Figures 6-4 through 6-6 define geometric coverage conditions between MRO and a surface vehicle as a function of the Martian latitude of the surface vehicle. The figures are based on composite statistics averaged over longitude and reflecting the maximum, average, or minimum over a 24-sol simulation using the Telecom Orbit Analysis and Simulation Tool (TOAST) [7].

Figure 6-4 shows the number of contacts (lasting at least 1 minute above 10 deg). Figure 6-5 shows potential average and maximum MRO pass durations in minutes as a function of landed latitude, assuming a 10-deg minimum elevation angle from the surface. Pass duration is the time the orbiter appears above the minimum elevation angle.[6] Figure 6-6 shows the maximum gap times between potential contacts with MRO. A gap is the duration of time between geometric contact opportunities. In polar locations, for the 1-hour 52-min MRO orbit, the gaps would be about 1-3/4 hours. At some near-equatorial latitudes, there is one contact per sol, resulting in a gap longer than 24 hours.

6.2.5 MRO Orbit Phasing to Support Landing Vehicle EDL

To cover a critical event such as an arriving spacecraft's EDL, MRO can perform an orbit trim maneuver to adjust the orbit phasing (that is, adjust the true anomaly of the orbit). However, MRO does not have the propellant budget necessary to make an orbit plane change (that is, significantly shift the local solar time that MRO crosses the Equator). 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 arrival. Communications during EDL would normally be one-way (return link to MRO only).

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[6] The minimum 10-deg elevation angle and assumed minimum 1-minute pass duration are for illustration. The figure omits minimum pass duration, which is generally not a useful statistic. For a near-circular Sun-synchronous orbit, there will always be a pass geometry that results in near-zero pass time except for surface locations near the poles.

The antenna placement on an arriving/descending vehicle and that vehicle's attitudes relative to the orbiter are critical to maintaining communication during EDL. It may be possible to coordinate roll steering of up to ±30 deg to point MRO's antenna to improve EDL coverage.

Plasma outages on the lander–MRO return link during atmospheric entry may occur depending on the entering spacecraft's approach angle and velocity.

Table 6-2. Mars solar conjunction dates and minimum SEP angles (2004–2021)

Orbit Element	MRO	Odyssey
Periapsis radius (km)	3624.4	3766.1
Apoapsis radius (km)	3691.1	3839.5
Semi-major axis (km)	3657.7	3802.8
Eccentricity	0.0091	0.0096
Inclination (deg)	92.6	93.1
Ascending node (deg)	–14.7	–159.8
Perigee argument (deg)	–78.8	–83.7
Time from perigee (s)	–1818.8	–1423.8
Epoch	2008-147T01:00:00	2008-147T01:00:00

Related data	MRO	Odyssey
Periapsis altitude/location	255 km/south pole	370 km/South Pole
Apoapsis altitude/location	320 km/north pole	444 km/North Pole
Mean LST, ascending node	3:00 p.m.	5:00 a.m.
Mean LST, descending node	3:00 a.m.	5:00 p.m.
Orbit period	1 hr 52 min	1 hr 58 min

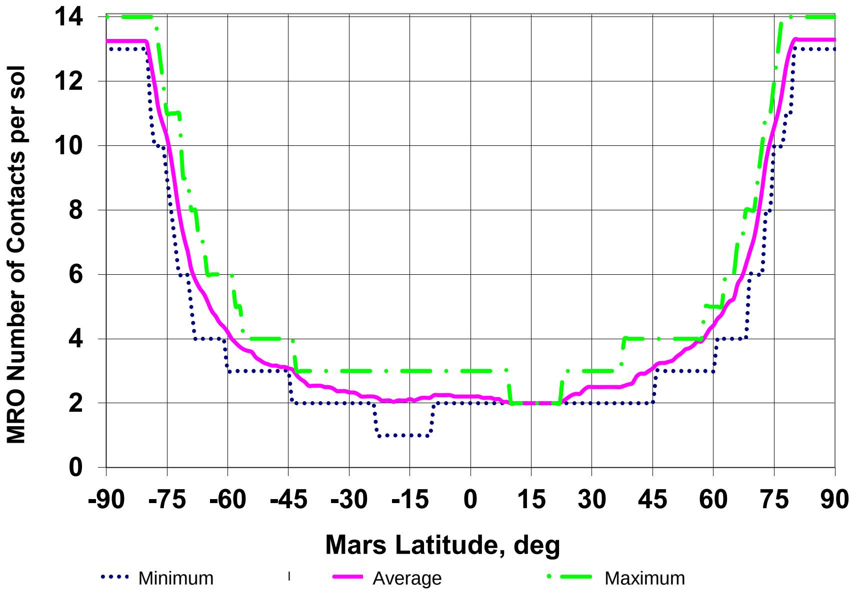

Fig. 6-4. Maximum, average, and minimum number of contacts per sol versus latitude of the lander for MRO orbit.

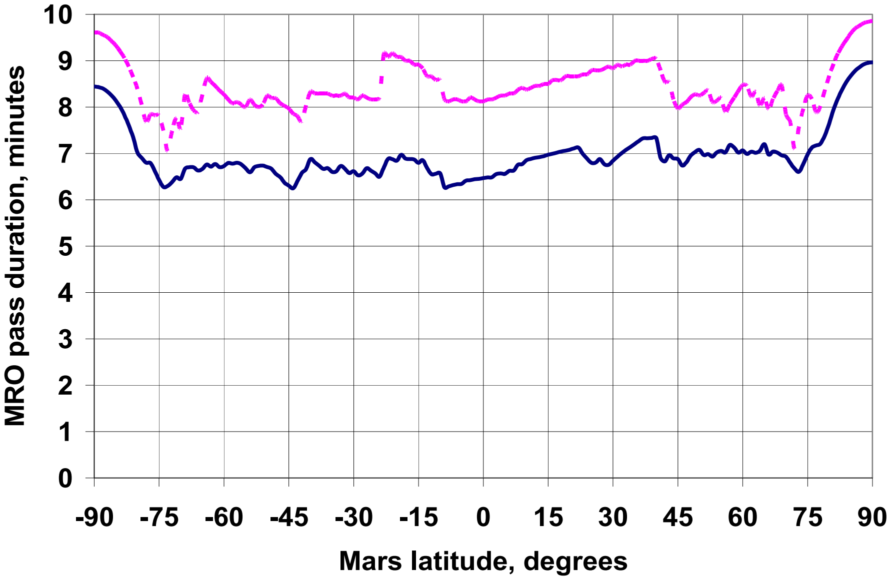

Fig. 6-5. Maximum (top) and average (bottom) pass duration versus Mars latitude for MRO orbit.

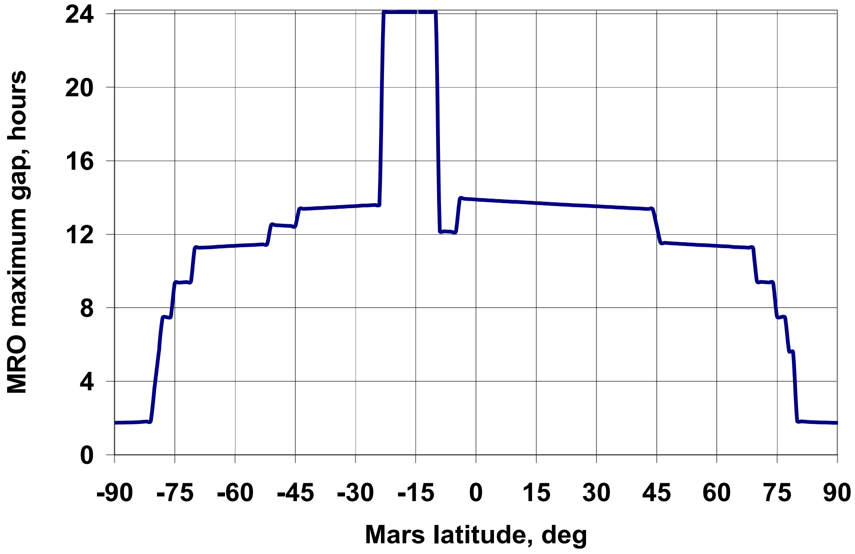

Fig. 6-6. Maximum gap between potential MRO contacts versus Mars latitude.

6.3 Telecommunications Subsystem Overview

6.3.1 X-Band: Cruise and Orbital Operations

Uplinks to MRO and downlinks from MRO at X-band are the primary means of communication between the MRO and the DSN antennas in California, Spain, and Australia.

The X-band communication system on the orbiter uses a 3-meter-diameter (10-foot) HGA and a 100-watt (W) X-band TWTA to transmit signals to Earth. Each of these devices is more than twice as capable as those used by previous Mars missions. As a result, MRO has been sending data back to Earth more than 10 times faster than previous missions.

At a maximum distance from Earth (400 million km [250 million miles]), the orbiter is designed to send data at a rate of at least 500 kbps. At closer ranges, the signal strength can be greater, so higher data rates are possible. When the orbiter is at its closest ranges (about 100 million km [60 million miles]), for several months the orbiter will be able to send data to Earth at 3 to 4 megabits per second (Mbps).

The MRO project scheduled two 34-m Deep Space Stations (DSSs) daily for an average of 16 hours per day during the science phase. Twice a week, the 70-m antennas were also requested.

With its large antenna, high-powered TWTA, and fast computer, the orbiter can transmit data to Earth at rates as high as 6 Mbps. This rate is quite high considering that MRO achieves it while 100 million kilometers from Earth. Over its 2-year primary science mission (2006–2008), the spacecraft transmitted more than 73 terabits of science data, about twice what was originally expected. This is about 20 times as much data as previous Mars missions and more data than all previous planetary missions combined. During the extended science mission (2008–2010), MRO sent down another 53 Tb of science data [5].

From the viewpoint of a DSN antenna on Earth, the orbiter spends about one-third of its time in every orbit behind Mars. During these times, the orbiter is occulted (has no line-of-sight communications path with the Earth) and cannot communicate with the DSN. Out of 16 hours daily that DSN tracking could potentially be scheduled during the orbital mission, MRO actually has sent data to Earth for 10 to 11 hours for more than 700 days. The data rate has averaged between 0.5 and 4 Mbps depending on Earth-Mars distance.

Figure 6-7 is a block diagram of the MRO telecom subsystem. Of the redundant active elements (EUTs, USOs, SDSTs, and X-band TWTAs), only one is powered on at a time.

The subsystem mass and spacecraft power input are summarized in Table 6-3.

The mass values are the totals for both redundant units for the SDSTs, X-band TWTAs, and UHF transceivers. The mass of microwave components, cabling, and waveguides (WGs) not individually called out is summed for the major telecom functional elements.

The project book keeps the HGA gimbals and their drive motors in a different subsystem. However, they are included in Table 6-3 as they would not be on the spacecraft except to direct the HGA to Earth.

The X-band system was designed to have no single point of failure (with the exception of the HGA, couplers, and diplexers), and to minimize circuit loss. The coupler (CP) and diplexer (DX) are waived because the probability of failure of these components is very low. Both are passive radio frequency (RF) components with no moving parts and no electronics.

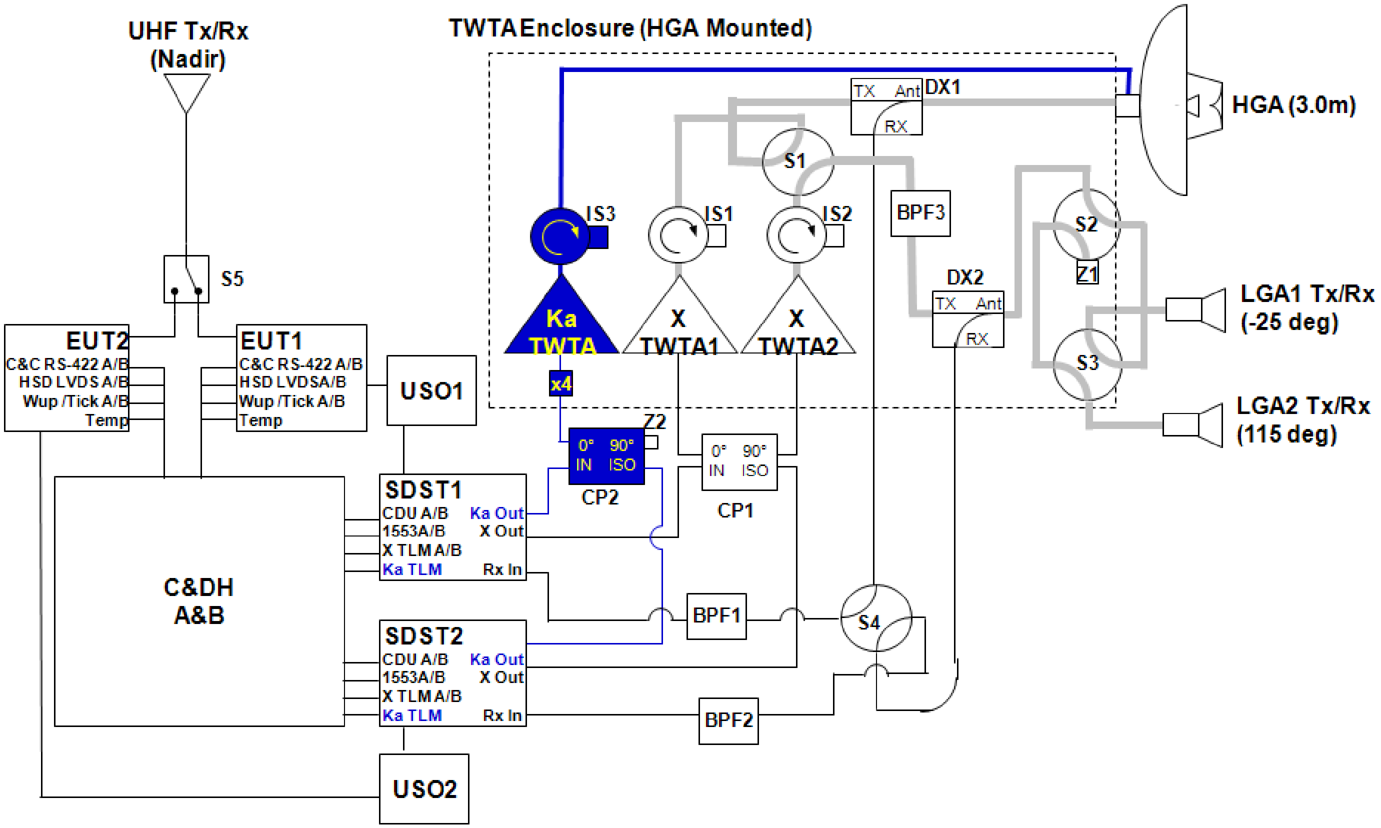

Fig. 6-7. MRO Telecom Subsystem block diagram.

Table 6-3. MRO telecom mass and power summary.

Assembly	Subtotal, kg	Total mass, kg	Spacecraft power input, W	RF power output, W	Note
X-band transponder		6.4	16		Orbit average power
SDSTs (2)	5.8				
×4 frequency multiplier bracket	0.1				
Other microwave components	0.5				
Traveling-wave tube amplifiers		12.1			
X-band TWTAs (2)	1.9		172	102	100 W nominal
Ka-band TWTA	0.8		81	34	35 W nominal
X-band electronic power converters	3.0				
Ka-band electronic power converter	1.5				
Diplexers and brackets	1.8				
Waveguide transfer switches	1.5				
Other microwave components	1.4				
Miscellaneous TWTA hardware	0.2				
X-band and Ka-band antennas		22.6			
HGA prime reflector	19.1				
Antenna feed assembly	1.6				
LGAs and polarizers	0.8				
Miscellaneous antenna hardware	1.1				
HGA gimbals and drive motors		45.0	14		Orbit average power

Table 6-3. MRO telecom mass and power summary (continued).

Assembly	Subtotal, kg	Total mass, kg	Spacecraft power input, W	RF power output, W	Note
Waveguides and coax		8.3			
USOs (2)		1.7	5		Orbit average power
UHF subsystem		11.5			
Electra transceivers (2) (each transceiver has an integral solid-state RF power amplifier)	10.1		71	5	On, full duplex (17.4 W standby)
UHF antenna and radome	1.4				
String switch (S)	0.1				
Telecom total		**107.7**	**359**		

X-Band Microwave Elements: In Fig. 6-7, S1, S2, and S3 are waveguide transfer switches. S1 allows for the output of either TWTA to be sent either to the HGA or to either LGA. S2 and S3 allow for the selection between LGA1 and LGA2. S4 is a coaxial (coax) transfer switch that routes the uplink to either SDST1 or SDST2.

The RF switches are designed such that the switches will fail in either of two switch positions. The probability that the switch will fail in between positions is remote.

The bandpass filters (BPFs) BPF1 and BPF2 are coaxial bandpass filters centered at the X-band receive frequency (7.183 GHz). They are used to filter out interference from the X-band TWTA output that could leak from the transmit port of the diplexer to the receiver port.

BPF3 is a waveguide bandpass filter that is centered at the transmit frequency (8.439 GHz) and is used to filter out the harmonics of the transmit frequency. This is needed to prevent interference to ground receivers operating in frequency bands that are the second, third, or fourth harmonics of the X-band output (that is, 16.9 GHz, 25.3 GHz, and 33.8 GHz), in particular during the first few days after launch when the power flux density of the downlink signal is high. BPF3 has no effect on transmissions through the HGA.

The isolators (ISs) IS1 and IS2 are X-band isolators to protect the X-band TWTA in case of a temporary short in the transmit path to the antenna. IS3 is the Ka-band isolator. The couplers in between the SDSTs and the TWTAs allow either SDST to drive either TWTA.

The USOs are cross-strapped (cross-strapping not shown) so that, if one fails, the other can be used by either SDST.

Ka-Band Elements: The Ka-band telemetry streams are cross-strapped. SDST1 gets its input data for Ka-band from command and data handling side A (C&DH-A) only, and SDST2 gets its input for Ka-band from command and data handling side B (C&DH-B) only. The Ka-band transmit chain is part of an operational demonstration experiment and therefore does not have to be single-fault tolerant.

6.3.1.1 High-Gain Antenna. The HGA consists of three main components—the feed, an ellipsoidal subreflector, and a 3-m offset parabolic main reflector. The HGA subreflector is 0.45 m in diameter and is located near the focal point of the main reflector. The X-band feed is a corrugated horn design, while the Ka-band feed is a disc-on-rod design. There is no uplink reception at Ka-band, only downlink transmission. The feeds contain polarizers at X-band and at Ka-band to generate right circularly polarized (RCP) microwaves.

Figure 6-8 shows the HGA pointing loss (the antenna gain relative to a reference 0 decibel (dB) value at boresight) at X-band transmit and receive frequencies.

Figure 6-9 shows the HGA pointing loss at the Ka-band transmit frequency.

The pre-launch HGA patterns are representative and are planned to be updated by in-flight calibrations.

The HGA, deployed shortly after launch, has since served as the primary means of communication to and from the orbiter.

The HGA must be pointed accurately and therefore is steered using the gimbal mechanism. The requirement for HGA pointing accuracy is 2.08 milliradians (mrad) at 99.7 percent circular error probability (CEP). This is a requirement on the mechanical system, in particular the gimbal motor that affects the link performance.

There are three gimbal mechanisms onboard Mars Reconnaissance Orbiter:

- One that allows the HGA to move in order to point at Earth
- Two that allow the solar arrays to move to point at the Sun.

Each of the gimbals can move about two axes. As the spacecraft travels around Mars each orbit, these gimbals allow both solar arrays always to be pointed toward the Sun, while the high-gain antenna can simultaneously always be pointed at Earth.

6.3.1.2 Low-Gain Antenna. Two LGAs are present for lower-rate communication during emergencies and special events, such as launch, MOI, or safe mode. The data-rate capability when using these antennas is lower because they focus the radio beam much more broadly than does the HGA. Figure 6-10 shows the pointing loss of the LGA at X-band transmit and receive frequencies. The LGA does not provide Ka-band capability.

The LGA is a horn design. It is essentially an open waveguide with RF choke rings at the end for pattern uniformity and side-lobe control. A septum polarizer placed before the waveguide horn provides RCP.

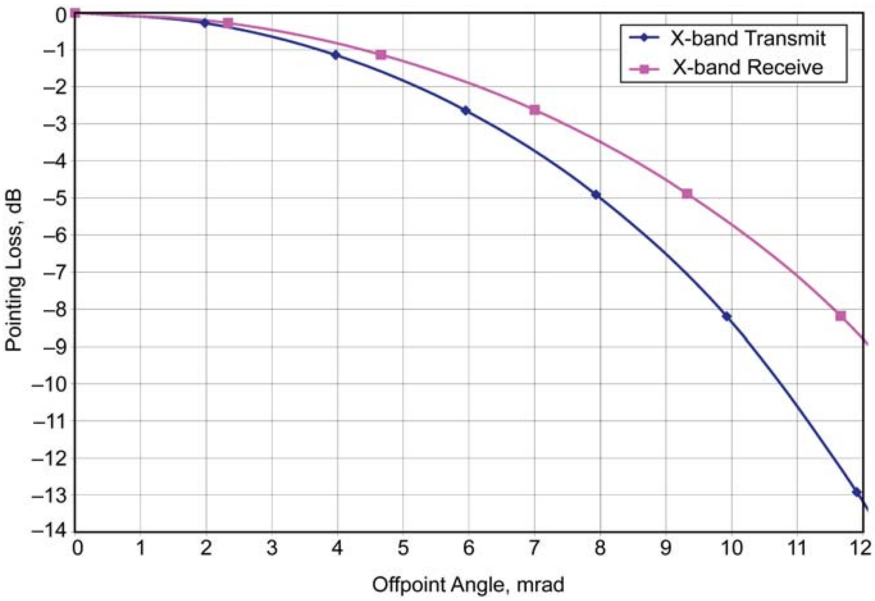

Fig. 6-8. HGA X-band transmit and receive pointing loss relative to boresight.

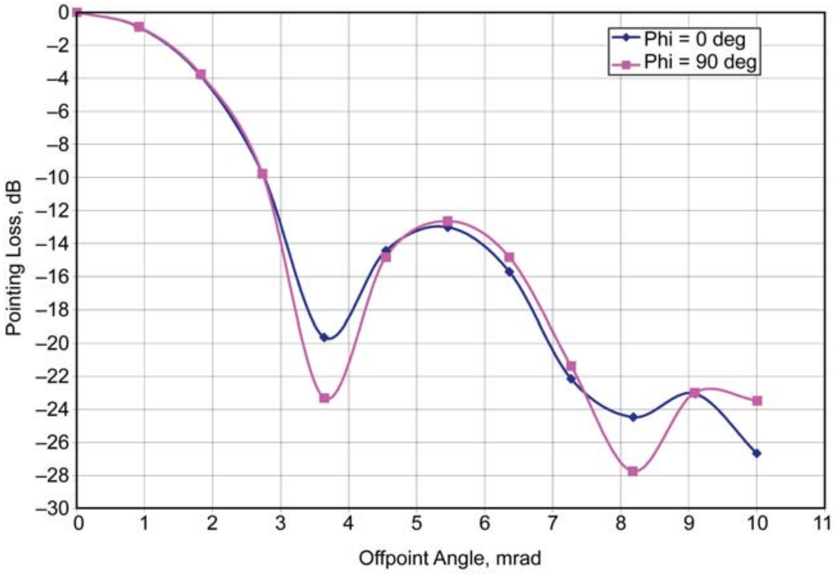

Fig. 6-9. HGA Ka-band transmit pointing loss relative to boresight.

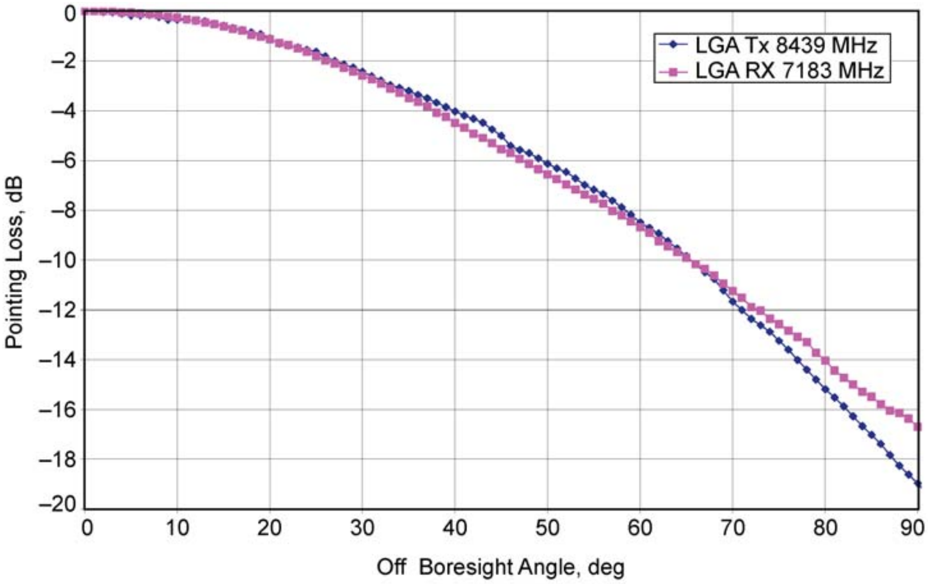

Fig. 6-10. LGA X-band transmit and receive pointing loss relative to boresight.

The two LGAs are mounted on the HGA dish—one on the front side and one on the back—and are moved with it. In that placement, the two LGAs make communication with the DSN possible at all times, no matter what the position of the spacecraft might be at a given time.

The forward-facing LGA1 is mounted near the rim of the HGA and is canted 25 deg from the HGA boresight. The cant angle was selected based on the off-point angle at critical spacecraft events, such as during TCMs and MOI, when the HGA is locked in position and not tracking Earth. The aft-facing LGA2 is mounted on the TWTA panel and is canted at –115 deg from the HGA boresight.

Table 6-4 summarizes key HGA and LGA link parameters as determined before launch.

Table 6-4. LGA and HGA antenna link parameters.

Parameter	LGA X-band transmit	LGA X-band receive	HGA X-band transmit	HGA X-band receive	HGA Ka-band transmit
Boresight gain	8.8 dBi	8.4 dBi	46.7 dBi	45.2 dBi	56.4 dBi
Gain tolerance	±0.5 dB	±0.5 dB	±0.5 dB	±0.5 dB	±1.0 dB
Axial ratio (max)	2 dB	2 dB	1.1 dB	2.2 dB	2.3 dB
Polarization	RCP	RCP	RCP	RCP	RCP
Antenna return loss (max)	–18 dB	–18 dB	–19 dB	–23 dB	–19 dB
Half-power beamwidth			0.69 deg		0.18 deg
Pointing error budget (3-sigma)			2.08 mrad	2.08 mrad	2.08 mrad

dBi = decibels with respect to isotropic gain

6.3.1.3 Transponders. MRO carries two small deep-space transponders (SDSTs). The SDSTs provide identical functions, and only one is powered on at a time. The SDST is a proven transponder with heritage from previous missions, such as Deep Space 1, Mars Odyssey, and MER A change from the MER (Group 1 buy) SDST to the MRO SDST was the addition of Ka-band [8].

The SDST is responsible for tracking the uplink carrier, demodulating commands from the carrier, generating the downlink carrier (coherent or non-coherent with the uplink frequency), performing convolutional coding, producing different subcarrier frequencies, modulating telemetry on the subcarrier or directly on the downlink carrier, demodulating and modulating turnaround ranging signals, and generating differential one-way ranging (DOR) tones.

The SDST is composed of four different modules: the digital processing module (DPM), the downconverter module, the power module, and the exciter module. The MRO SDST has several features differing from previous SDST designs:

- The MRO × 4 (times-four) multiplier that is used to generate the 32.2-GHz Ka-band signal from the 840f1 frequency output[7] (8052 MHz) is external to the SDST and placed on the TWTA panel (whereas the SDST is located middeck); this is done to minimize coaxial cable loss at Ka-band. In Deep Space 1 (DS1), the ×4 multiplier was internal to the SDST.
- The line receivers in the DPM are now low-voltage differential signaling (LVDS) receivers to support high-rate transmission over the compact peripheral component interconnect (cPCI) bus.
- A field programmable gate array (FPGA) with 72 thousand gates was added to the MRO SDST to support quadrature phase-shift keying (QPSK). The FPGA also performs (7,1/2) convolutional coding[8] for QPSK.
- Wideband DOR (8f1 DOR) capability was added at Ka-band.

The SDST has an internal, five-pole, 5.8-MHz low-pass filter (LPF) that filters input voltage to the phase modulator. Nominally, the MRO SDST will be configured to operate in the filtered mode. The filter reduces the amplitude of high-frequency components in the telemetry downlink to avoid interference to other missions. Use of the unfiltered mode is permitted only when the telemetry spectrum would not interfere with another mission.

Table 6-5 lists some of the parameter values that determine link configuration and performance for the MRO SDST.

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[7] In SDST nomenclature, f1 is the fundamental frequency from which the uplink and downlink frequencies are derived. For example, the X-band downlink is 880f1, and the X-band uplink is 749f1. The Ka-band downlink carrier is 3360f1, which is 4× the SDST's Ka-band output at 840f1. The MRO SDST operates on DSN channel 32. For this channel, f1 is approximately 9.59 MHz.

[8] Note that telemetry can be convolutionally coded in the SDST as on previous missions, but only with the (7,1/2) rate planned for use on MRO. For a turbo-coded telemetry downlink, the input to the SDST has been turbo coded in the C&DH upstream of the SDST. In this case, the stream of turbo symbols at the SDST telemetry input are treated by the SDST as bits, with the SDST's convolutional coder bypassed.

Table 6-5. SDST link configuration and performance parameters.

Parameter	Value
Receiver input levels, dBm	−156 dBm (threshold) to −70 dBm
Receiver 2-sided carrier loop bandwidth, Hz	20 (threshold)
Command data rates (bps, uncoded)	7.8125, 15.625, 31.25, 62.5, 125, 250, 500, 1000, 2000 bps
Command subcarrier modulation index	0.5 to 1.5 radians, peak
Minimum telemetry symbol rate	0 bps on subcarrier, 2000 symbols per second (sps) on carrier
Maximum symbol rate	Specified to 4.4 megasymbols per second (Msps) in normal (filtered) mode, tested to 6 Msps
Telemetry modulation index range	64 equal steps of modulation voltage from 0 to 135 deg
Turnaround ranging modulation index	4.375, 8.75, 17.5, 35, 70 deg peak (accuracy ±10%, stability ±20%)
DOR modulation index, peak	28 deg peak (accuracy ±10%, stability ±25%)
Ka-band output modulation bandwidth	Normal mode 5.5 ± 1.5 MHz, wideband mode 10 MHz minimum

6.3.1.4 RF Amplifiers. Located on the back side of the HGA is the enclosure for the TWTAs and associated microwave components. The enclosure is called the TWTA panel in the Fig. 6-1 sketch of external MRO components.

Figure 6-11 shows the layout of the bottom side of the TWTA panel, showing two of the TWTAs, the three power converters, and most microwave elements (diplexers, X-band bandpass filter, and isolator). The Ka-band TWTA and isolator are on the top side of the TWTA panel and are not visible in Fig. 6-11.

There are three amplifiers on board, two at X-band (only one powered at a time) and one at Ka-band. The nominal TWTA RF output power is 100 W at X-band (102 W measured pre-launch) and 35 W at Ka-band (34 W measured).

Each TWTA consists of two main components, the high-voltage power supply (HVPS), also called the electronic power converter (EPC), and the traveling-wave tube (TWT).

The diplexer is a passive device that allows for routing of X-band transmit and receive frequency signals that are present simultaneously at the antenna. The diplexer has three ports: the antenna port, the receive port, and the transmit port. The isolation between transmit and receive ports is essential to avoid selfinterference within the subsystem. The diplexer also provides significant attenuation of transmit frequency harmonics.

The passband at the receive port is centered at 7.183 GHz to allow for the uplink signal from the antenna port to pass through to the receive port. The passband at the transmit port is centered at 8.439 GHz to allow the output of the X-band TWTA to pass to the antenna port.

Additional attenuation of transmit frequency harmonics occurs in the waveguide bandpass filter in the LGA transmit path. Each isolator (one is called out in Fig. 6-11) protects its TWTA against RF power reflected back by a momentary short at the output.

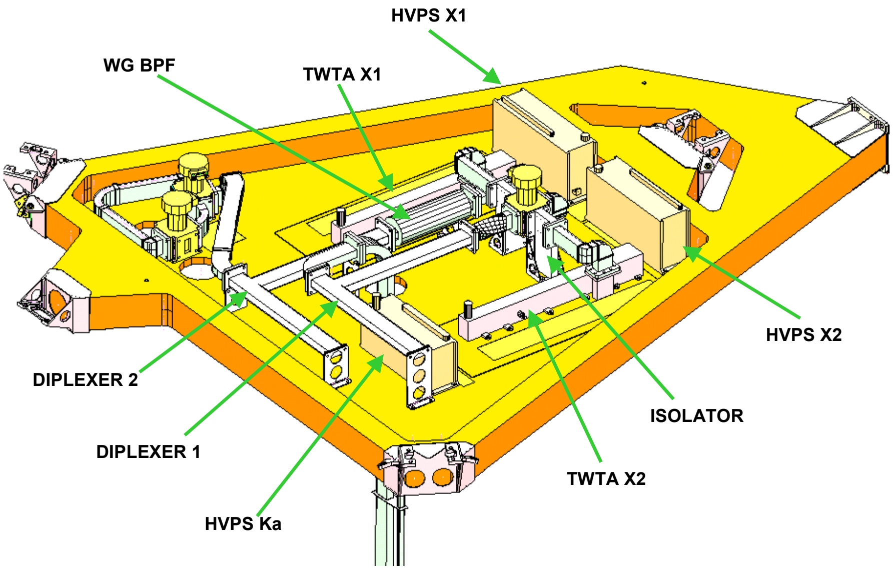


Fig. 6-11. Layout of microwave components in the TWTA panel.

Each TWTA provides three kinds of protection for itself and the spacecraft power supply:

- **Helix Overcurrent Trip.** If helix current exceeds 5 milliamps (mA), the power converter, responding within 2 ms, goes into an automatic restart mode involving removal and reapplication of the high voltage to the TWTA.
- **Power Converter Overcurrent Trip.** If the input current exceeds a maximum value, the switching transistor is protected by cycle peak

current limitation. Also, after about 2 ms, the converter goes into the automatic restart mode.

- **Bus Undervoltage Trip.** If the bus voltage at the converter input drops below 20.5 V, the high voltage switches off, and an undervoltage trip status flag is set. When the bus voltage rises above 21.5 V again, the TWTA startup sequence is initiated and preheating begins. The preheating lasts about 210 seconds. The nominal bus voltage is 28 V.

6.3.2 UHF: Proximity Relay Communications

As shown in Fig. 6-12, the Electra payload in MRO becomes a network node in the Mars network constellation that provides efficient relay of high-rate in-situ mission science and engineering data. The first landing vehicles that are planned to use MRO/Electra operationally are Phoenix and MSL.

Figure 6-13 is a block diagram of the MRO UHF system and its interfaces (I/Fs) with the command and data handling (C&DH) and SSR systems. The EUTs and the USOs (which also support the X-band and Ka-band systems) are redundant. The diagram shows the allowable combinations of redundant USOs and EUTs with the C&DH sides and the redundant SSRs.

Figure 6-14 is a sketch of the EUT.

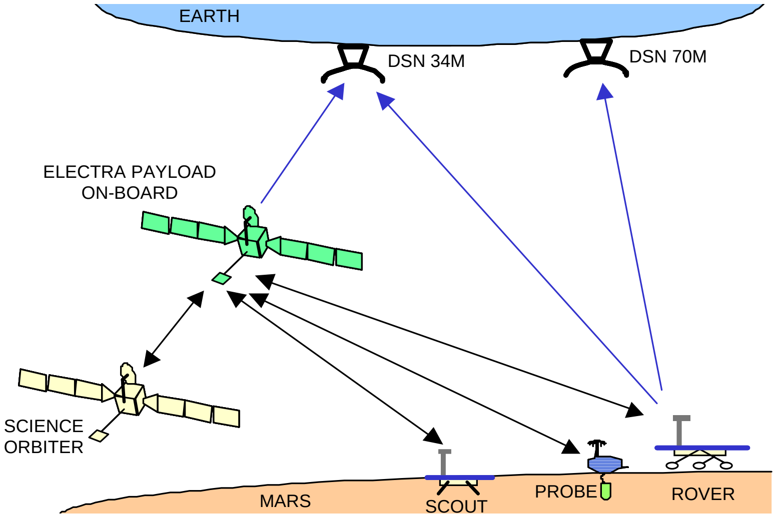


Fig. 6-12. MRO Electra payload operations concept.

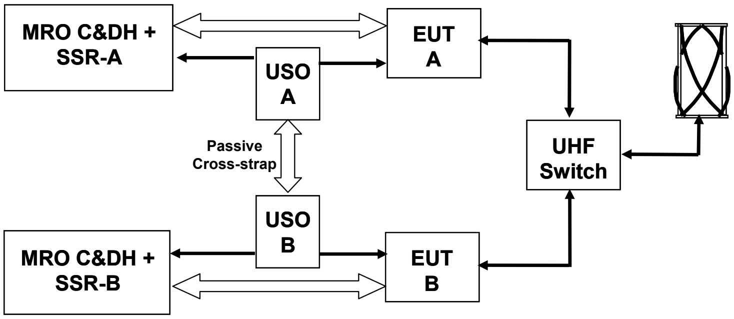


Fig. 6-13. MRO/Electra UHF block diagram and interfaces with C&DH and SSR.

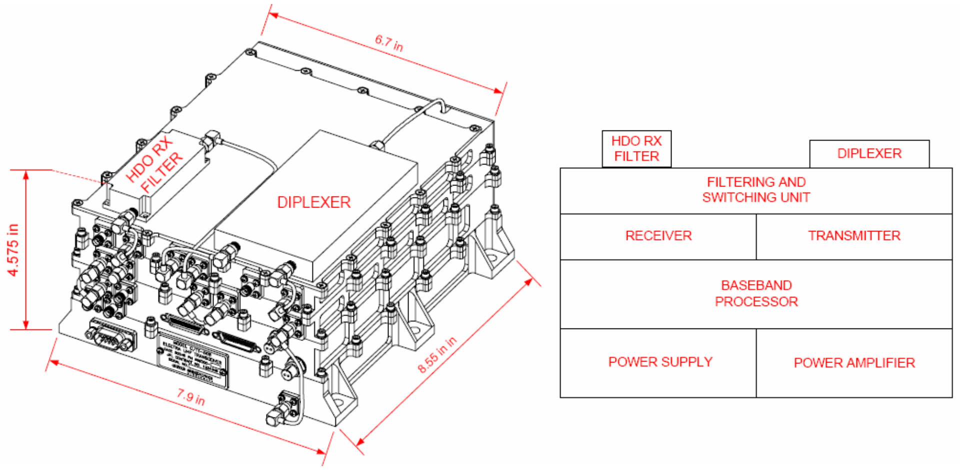


Fig. 6-14. Electra UHF transceiver (EUT) assembly.

The EUT assembly consists of five modular slices. From top to bottom, the slices are

- Half-duplex overlay (HDO) receiver filter and UHF diplexer
- Filtering and switch unit (FSU)
- UHF radio frequency module (RFM, the receiver and transmitter)
- Baseband processor module (BPM)
- Power supply module (PSM) with integral power amplifier module.

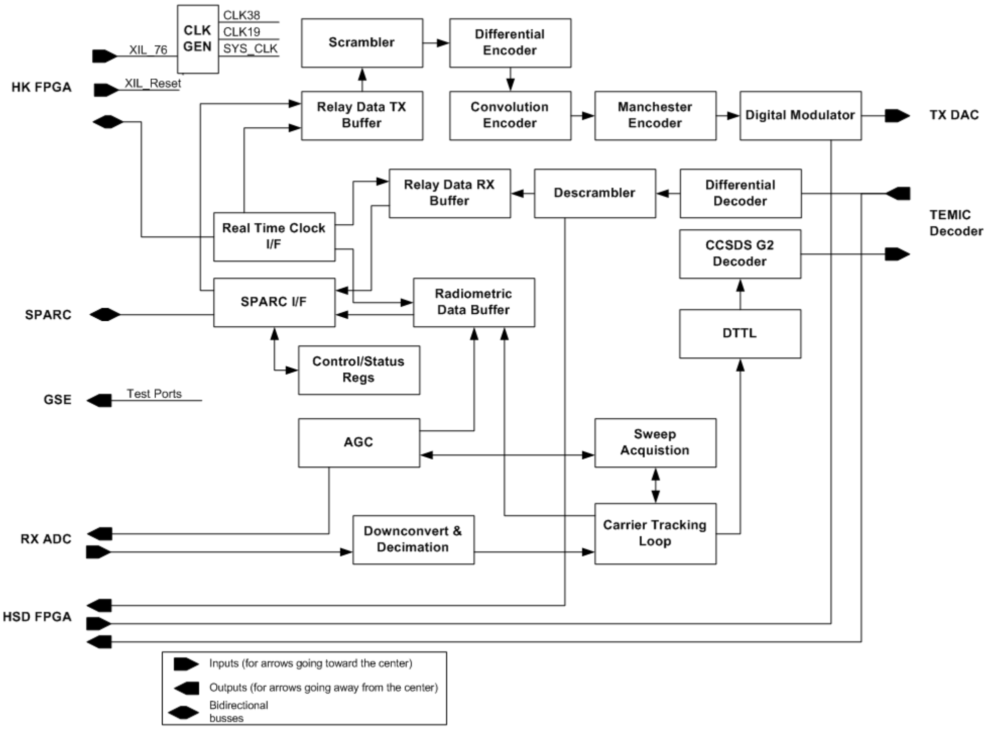
The FSU slice in the MRO EUT consists of a high-isolation diplexer, the HDO receive/transmit (R/T) switch, and the coaxial transfer switch. The BPM slice interfaces directly with MRO C&DH, the MRO SSR, the USO, and the modules that comprise the EUT.

The RFM slice consists of a single-channel UHF transmitter and receiver.

The PSM slice consists of the power supply and the driver/power amplifier. The PSM provides power to the BPM and, under BPM control, to the elements of the RFM. The PSM slice also includes a power amplifier that amplifies the modulated signal to the appropriate RF output level.

The BPM performs all signal processing, provides overall EUT control, and services the external spacecraft interfaces.

Figure 6-15 summarizes the functionality of the modem processor (MP) portion of the BPM in block diagram form, which was updated from Ref. [9].



ADC = analog-to-digital converter, AGC = automatic gain control,
CLK GEN = clock generator, DTTL = data transition tracking loop,
GSE = ground support equipment, SPARC = scalable processor architecture

Fig. 6-15. Electra transceiver block diagram.

The BPM consists of a 32-bit microprocessor, two radiation-hardened program-once field programmable gate arrays (FPGAs), and a large (~1 million gates (Mgate)) reprogrammable FPGA, along with a substantial amount of dynamic and static memory. The reprogrammable FPGA contains the modem functions and is reprogrammable post-launch. The 32-bit microprocessor manages the EUT and the relay Prox-1 protocol.[9]

In concept, one side of the BPM handles the spacecraft interfaces. A dedicated 1553 transceiver chip supports the command and telemetry interface to the host C&DH. An LVDS interface supports high-rate relay and radiometric data transfers through the high-speed data (HSD) FPGA. The other side of the BPM handles the EUT, with the housekeeper (HK) FPGA managing control and telemetry signals to and from the EUT front end, and the MP FPGA.

The main functions of the MP FPGA include

- Coding and decoding
- Modulation and demodulation
- Carrier, symbol, and decoder synchronization
- Prox-1 frame synchronization detection
- Prox-1 transmit (Tx) and receive (Rx) user data and control data buffering
- Receive signal level management, automatic gain control (AGC)
- Radiometric Doppler and open-loop record functions
- Clock (CLK) and timestamp functions
- Implementation of the physical layer of the communication link from baseband to an intermediate frequency (IF)

The MRO Electra does not have an internal clock. The clocks for the BPM FPGAs, including bit, symbol, and sample rate clocks, are derived from the external USO.

Table 6-6 [6] defines the major operating modes, functions, and constraints for the MRO EUT.

MRO Electra implements frequency agility and swappable transmit and receive bands. The EUT complies with the CCSDS Prox-1 channel definitions for eight frequency pairs. In all, Electra supports 16 preset frequency pairs, as defined in Table 6-7 [10].

In addition to the 16 preset pairs, the MRO Electra radio has the capability to tune its Tx and Rx frequencies across the entire 390-MHz-to-450-MHz band;

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[9] The EUT complies with the Proximity-1 protocol defined by the Consultative Committee for Space Data Standards (CCSDS) in Ref. 11. In this chapter, the protocol is abbreviated Prox-1.

thus, any frequency pair combination within this band is possible. For half-duplex operation, any pair of frequencies will work as an operational pair. For full-duplex operation, the Tx frequency must be chosen in the range of 435 MHz to 450 MHz, and the Rx frequency must be chosen in the range of 390 to 405 MHz.

Table 6-6. MRO/Electra modes, functions, and performance.

Capability	Values
Protocol	Prox-1 (reliable and expedited link layer protocols)
Frequencies	See next section (including Table 6-7)
Modes of operation	Half-duplex[10] Rx and Tx (no Prox-1 protocol in half duplex) Full-duplex transceiver
Full-duplex carrier modes	Coherent, noncoherent
Transceiver RF output power	5.0 W full duplex, 7.0 W half duplex
Circuit loss, EUT to antenna	–0.42 dB
Receiver thresholds, at antenna	–130.8 dBm (1 kbps) to –99.6 dBm (1024 kbps) coded –126.0 dBm (1 kbps) to –91.1 dBm (2048 kbps) uncoded
Carrier modulation modes	Suppressed carrier, residual carrier (60 deg mod index)
Modulation types	Residual carrier binary phase-shift keying (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 thousand symbols per second (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 phase locked loop (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/s

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

The MRO Electra payload provides a single nadir-looking (vertical down to Mars) UHF LGA. The antenna shares the nadir deck with science payloads. Some parts of these nearby payloads that are responsive at UHF frequencies couple with the antenna and distort its nominal gain pattern. To compensate for this, the MRO mission plan allows for spacecraft roll steering of up to 30 deg to point the better parts of the UHF antenna pattern toward the surface user. The orbiter sets up for this pass by roll steering to a fixed roll angle. The Electra payload performs the pass, and then the orbiter rolls back to the standard nadir pointing position.

Table 6-7. CCSDS Prox-1 "Blue Book" channel numbers and "preset" Electra frequencies.

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

Figures 6-16 (437.1 MHz) and 6-17 (401.6 MHz) show antenna gain in dBi versus angle from boresight. These angles from boresight are called cone or theta angles. In each figure, the solid curve is the average gain over cuts made in the axis orthogonal to cone. Angles in the orthogonal axis are called clock or phi angles. The dotted curves above and below the solid curve are the gains for the best-case and worst-case clock cut, respectively. The antenna is RCP for both the forward and return links.

The MRO Electra transceiver is compatible with the CCSDS Proximity-1 Space Link Protocol [10, 11]. Prox-1 transfer frames are sent on both the forward link (from the orbiter to the surface vehicle) and the return link (surface back to the orbiter) using the Prox-1 protocol link management in either reliable (retransmission) or expedited (no retransmission) mode. In retransmission mode, an automatic repeat queuing (ARQ) protocol is utilized to request retransmission of any proximity frames that are not received error-free. MRO also provides a relay service (called “raw data”) not utilizing the Prox-1 protocol. The orbiter also provides a form of Doppler data and a form of open-loop data. These data types or services are defined in the following.

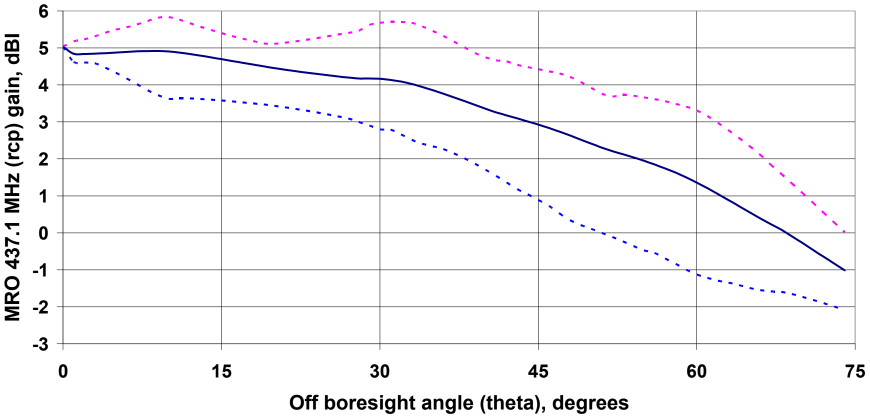


Fig. 6-16. MRO 437.1-MHz gain pattern.

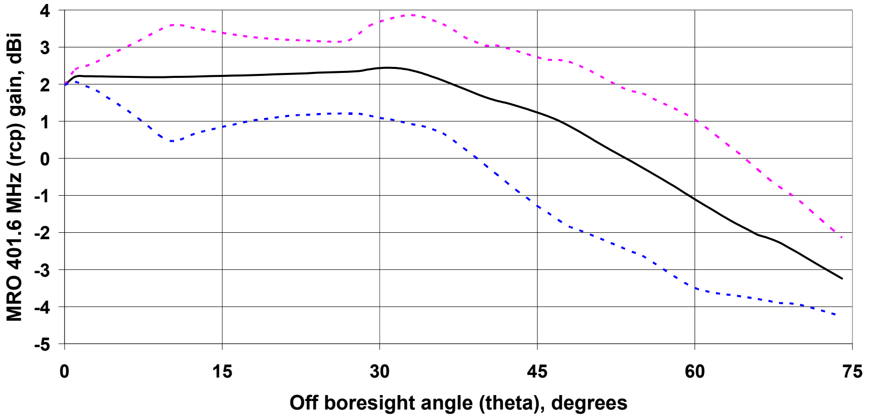


Fig. 6-17. MRO 401.6-MHz gain pattern.

6.3.2.1 Proximity-1 Data. Typically the MRO Electra will initiate a Prox-1 session by sending a string of “hail” data packets while looking for a response from the specific lander identified in the hail packet. This standard operating procedure can be reversed—that is, lander-initiated relay sessions are possible. The hail includes information describing the session operating mode for both the forward and return link directions. This includes, among other things, operating frequency, data rate, and channel-coding mode.

6.3.2.2 Time-Stamp Packets. Time-stamp data consist of snapshots of the local Electra clock corresponding to the ingress or egress times of Prox-1 frame-synchronization markers. Thus, time stamp data is only collected in conjunction with Prox-1 mode operations. The time stamps are paired with corresponding Prox-1 frame sequence numbers and noted as arriving or departing frames. If the other end of the relay link is also capable of collecting Prox-1 frame time stamps, the collection of these time stamps at both ends of the link can be used as a form of dual 1-way ranging and used to correlate clocks on the lander and orbiter.

6.3.2.3 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. 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.

6.3.2.4 Phase and Power Data. MRO’s Electra transceiver can sample and record the phase and power level of a phase-locked received carrier signal. This radiometric information is highly accurate (being based on the MRO USO signal and with successive samples tied directly to the USO-based local clock). Each sample contains phase, AGC power, in-phase (I) amplitude, quadrature (Q) amplitude, and a USO-based time. These data form the basis for a Doppler metric. The 160 bit data format is shown below.

Phase and Power sample format

Header	Phase	AGC	Iamp	Qamp	Spare	Time Code	Trailer
bit[159:156]	bit[155:107]	bit[106:101]	bit[100:88]	bit[87:75]	bit[74:60]	bit[59:4]	bit[3:0]

6.3.2.5 I/Q (Open Loop) Record Data. MRO’s Electra transceiver can capture complex in-phase/quadrature (I/Q) samples of the received signal, down-converted to baseband, at sample rates as fast as 150,000 samples/second. This mode is known as open-loop record and is primarily used in support of events like EDL where there is a concern that high signal dynamics or low signal levels will prevent real-time demodulation of the signal in the Electra transceiver. These open loop record samples are passed to the MRO solid state recorder (SSR) and later forwarded to Earth where a software receiver and spectrum analysis tools can be used to demodulate the signal and to decipher the signal dynamics. In addition to the complex I/Q samples, the AGC level is also captured for each sample. This allows open loop record to work over the full receive signal level range of the Electra radio and still allow for faithful reconstruction of the received signal later on Earth.

There are two data modes for open loop record. The first mode captures the USO clock as part of the sample data. This clock-stamped format is used for the first data sample and occasional later samples to establish a clock reference to the sample data. Most of the open loop record samples do not include a time stamp, and the time of each sample is inferred from the sample count and the sample frequency that is phase locked to the USO clock tick. The two data formats are shown below.

I/Q (open loop) sample time-coded format

Header	I	Q	Spare	AGC	Spare	Time Code	Trailer
bit[95:92]	bit[91:84]	bit[83:76]	bit[75:74]	bit[73:68]	bit[67:60]	bit[59:4]	bit[3:0]

I/Q (open loop) sample non-time-coded format

Header	I	Q	Spare	AGC	Trailer
bit[31:28]	bit[27:20]	bit[19:12]	bit[11:10]	bit[9:4]	bit[3:0]

6.3.3 Ka-Band: Operational Demonstration

The MRO spacecraft has a fully functioning Ka-band downlink equipment suite, comparable to that for the X-band downlink, including

- A one-way carrier (USO or auxiliary oscillator driven) or a two-way coherent carrier (using the X-band uplink carrier frequency reference)
- Modulation of telemetry with any of the available data rates, encoding types, and modulation index values
- Modulation of turnaround ranging from the X-band uplink, with a settable modulation index
- Modulation of differential one-way ranging tones, more widely spaced than at X band; Ka-band tones are 76 MHz from the carrier, as compared with X-band tones at 19 MHz.

The Ka-band components of the subsystem include a ×4 (times-four) multiplier, a Ka-band TWTA and its power converter, a Ka-band feed element in the HGA, and other microwave parts as defined in Section 5.3.1.

Deep Space Network 34-m antennas capable of receiving Ka-band are requested twice per week during the prime science mission as part of the demonstration.

6.4 Ground Data System

6.4.1 Deep Space Network

The three primary DSN ground complexes are located near Goldstone (California), Madrid (Spain), and Canberra (Australia). The DSN antennas are categorized according to their diameter and performance. During cruise and orbit operations, MRO was allocated use of the 70-m antenna subnet, the 34-m beam-waveguide (BWG) antenna subnet, and the 34-m high-efficiency (HEF) antenna subnet.

MRO used the 70-m antennas to support MOI and may require them for emergency mode communications (safe mode operations on the LGA).

MRO depends on the 34-m BWG antennas for the vast majority of the mission telemetry and commanding. The BWG antennas differ from the HEF antennas in that beam-waveguide optics (mainly consisting of a series of small mirrors) are used to direct microwave energy from the region above the main reflector to a location at the base of the antenna (typically the pedestal room). This allows for easier access to the microwave equipment, and the positional stability allows for use of state-of-the-art ultra-low noise amplifier and feed designs.

MRO may alternatively be allocated 34-m HEF stations (one at each complex) for passes that do not require Ka-band downlink capability. Because the low-noise amplifier (LNA) is located near the HEF antenna feed, the gain-to-noise temperature ratio, G/T, is about 1 dB better than in the BWG antennas.

With the new X-/X-/Ka-band (X-band up, X-band down, Ka-band down) feed and LNA upgrades to the 34-m BWG antennas, the upgraded 34-m BWG stations have a slightly higher gain over temperature (G/T).

The gain, noise temperature, and pointing characteristics of the antennas are listed in the *DSN Telecommunications Link Design Handbook* [12].

6.4.2 Ka-Band Demonstration Requirements

The Ka-band demonstration includes an assessment of the DSN's readiness to track Ka-band signals from deep-space missions. One operational station (DSS-25) tracked the "new technology" Ka-band downlink from Deep Space 1 in 1998–1999, and the DSN has tracked Ka-band sporadically for Cassini radio science activities. Several of the 34-m stations have Ka-band downlink capability to support the MRO Ka-band operational demonstration. These are DSS-25 and DSS-26 at Goldstone in California, DSS-34 near Canberra in Australia, and DSS-55 near Madrid in Spain.

The 34-m BWG Ka-band beam width is less than 18 millidegrees (mdeg). The basic antenna pointing capabilities required for the Ka-band demonstration include

- "Blind-pointing" of the antenna (computer driven, without input from the received downlink) must be better than 10 mdeg [13] so that the monopulse system (active pointing) will be able to operate.
- The monopulse must be operational (without it, pointing errors may cause link degradation of 4–5 dB).

Besides the normal functions of telemetry demodulation and decoding, and measurements of Doppler, two-way ranging, and delta-DOR, the Ka-band demonstration requires the following monitor data generation capabilities:

- Accurate measurement by the operational receiver of signal-to-noise ratio (SNR), particularly symbol SNR
- Accurate measurement by the operational receiver of system noise temperature (SNT)
- Sampling of receiver monitor data at the specified 5-second interval, with prompt delivery of the data to the MRO database.

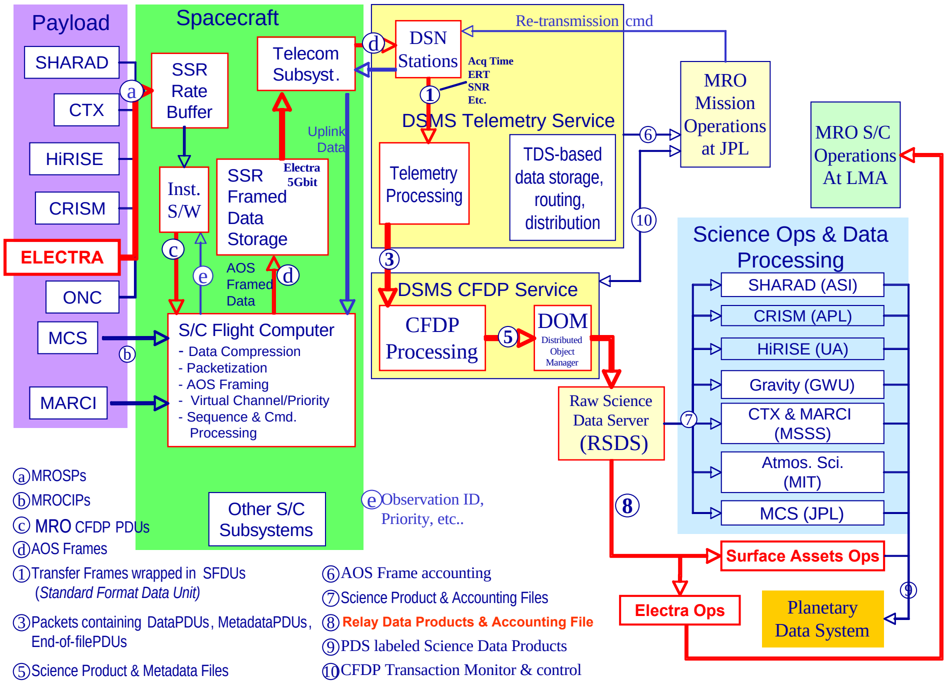
These additional requirements will enable the demonstration to identify data outages caused by weather events and to separate them from outages caused by other phenomena.

6.4.3 Ground Data Network Flow for Relay Data through Electra

Figure 6-18 shows the MRO science data flow, processing, and accountability mechanisms. In the context of the five Electra relay data types (Prox-1 data, raw data, time stamps, phase and power data, and open-loop data), all are "science data." The features highlighted in red identify the flow of Electra relay data to the ground.

Electra relay return-link data are routed over a shared LVDS interface to a dedicated SSR hard partition. When collecting data from Electra, the SSR's Electra interface software limits the amount of data to the space in the Electra partition minus the amount of not-yet-read data in the partition. The software will issue a telemetry event record with the difference between actual and planned sizes of the data collection.

In Fig. 6-18, telemetry processing extracts from the MRO telemetry stream the CCSDS advanced orbiting systems (AOS) frames containing MRO CCSDS source packets. AOS frames containing telemetry from Electra are processed to extract MRO science protocol packets.



APL = (Johns Hopkins University) Applied Physics Laboratory
CIP and SP = instrument output data
DOM = Distributed Object Manager
GWU = George Washington University
HiRISE = High Resolution Imaging Science Experiment
LMA = Lockheed Martin Aerospace
MSSS = Malin Space Science Systems
UA = University of Arizona

Fig. 6-18. MRO Electra science data flow.

These source packets are provided to the CCSDS File Delivery Protocol (CFDP) process running on the ground, which finds the MRO CFDP protocol data units (PDUs) and reconstructs the Electra pass product. Given that there may be gaps in the telemetry stream, retransmissions may be requested from the spacecraft on the AOS frame level. Associated with the Electra pass product will be a detached Planetary Data System (PDS) label, which will contain metadata that describe the circumstances of the collection, for example, MRO identifier, orbit, and so forth. There also will be a CFDP transaction report on the holes, if any, in the Electra pass product.

A second run of the CFDP process will take the Electra pass product and search for Electra CFDP PDUs to extract the PDUs for each Electra sub-product [relay (Prox-1 data), time stamp, raw data, phase and power, and open-loop I and Q data].

Each Electra relay telemetry product consists of a binary product file, which varies for each product type, as well as a CFDP transaction log file and a detached American Standard Code for Information Interchange (ASCII) label.

Figure 6-19 shows the relay pass product from the Ground Data System (GDS), and Fig. 6-20 shows the relay data product delivered. The pass product is a binary file with the CFDP PDUs, while the data product is a binary file with the Prox-1 transfer frames.

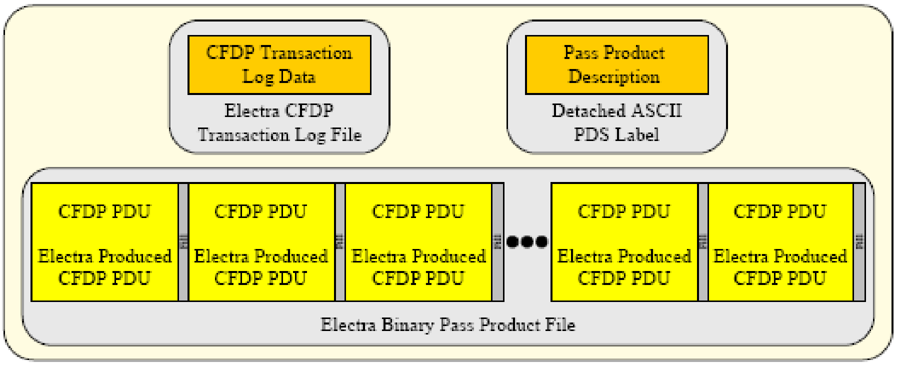


Fig. 6-19. Electra relay pass product output from GDS.

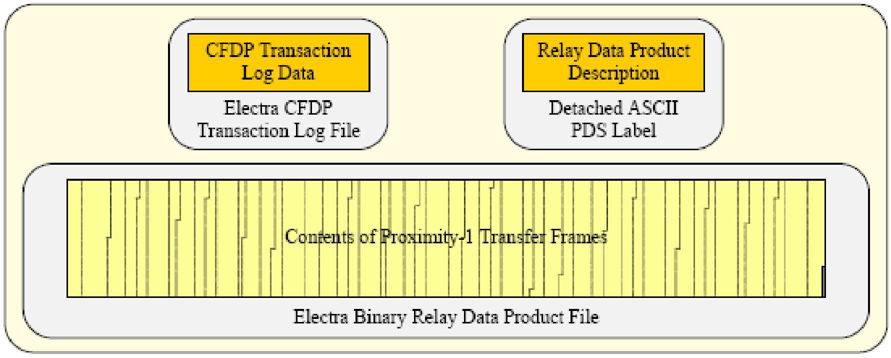


Fig. 6-20. Electra relay data product from GDS.

6.5 X-Band Telecom Operations

6.5.1 Cruise Calibrations

Planned telecom cruise calibrations are summarized in Table 6-8. During the X-band and Ka-band HGA calibration, the spacecraft articulates the HGA through a grid-like pattern (raster scan) about the pre-launch antenna boresight. By monitoring the received signal strength, the calibration determines if the HGA phase center has shifted during launch.

Table 6-8. Telecom cruise calibrations.

Calibration type	Date	Comments
X-band LGA performance	Launch + 9 days	Perform as part of normal LGA ops. Spacecraft slewing not required.
X-band HGA pattern calibration	Launch + 24 days	Raster scan; simultaneous with Ka-band HGA calibration
Ka-band HGA pattern calibration	Launch + 24 days	
Electra UHF pattern characterization	Launch + 40 days	Conical scan
Electra UHF performance	Launch + 40 days	
X-band Delta DOR checkout	Launch + 40 days	Done once per week, starting at L + 40 d
Ka-band wideband delta-DOR checkout	Launch + 40 days	Done once per week, starting at L + 40 d

6.5.2 MOI Telecom Configurations

The main engine burn for MOI began at 21:24 universal time coordinated (UTC) referenced to Earth received time (ERT), the time this event was seen on the Earth. Ninety minutes prior to this, the telecom path was switched to LGA1, which then was used throughout the orbit insertion process. Thirteen minutes prior to engine start, the spacecraft began a slew to MOI attitude. It ended the slew 5 minutes before engine start, and its inertial attitude remained fixed at this position throughout MOI. At the beginning of the burn, LGA1 was boresighted at Earth. By the time MRO entered solar eclipse (start + 21 minutes) and was occulted from Earth by Mars (2 minutes later), the off-boresight angle was around 20 to 25 deg. The burn ended at 21:51 ERT; the turn back to Earth ended at 22:13; and occultation ended (downlink reached the Earth) at 22:16 ERT.

During the MOI itself, the DSN supported downlink telemetry with two 70-m antenna stations simultaneously (DSS 14 and DSS 63 had overlapping coverage). Figure 6-21 shows the approximate elevation angles for the 70-m antennas on March 10, 2006.

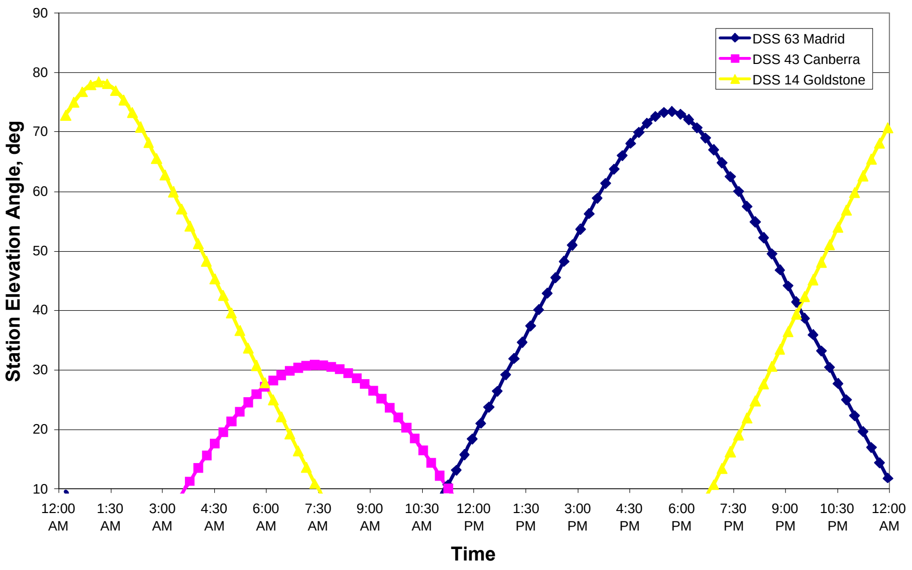


Fig. 6-21. Station elevation angles on day of Mars Orbit Insertion.

Following re-acquisition with LGA1, the X-band system was transitioned back to the HGA for spacecraft checkout. Navigation began to collect two-way radiometric data and to perform orbit determination of the capture orbit.

6.5.3 Aerobraking Telecom Configurations

During aerobraking, the two main activities are the drag passes and the aerobraking maneuvers (ABMs). The drag passes occur at the capture orbit perigee, and the spacecraft is oriented with the velocity vector in order to maximize the drag coefficient. The ABMs typically are conducted at the apogee of the capture orbit and are used to adjust the orbit after the drag pass if needed.

At 16 minutes prior to the start of each drag pass, an onboard sequence configures the telecom system to transmit a carrier-only downlink over LGA1. In addition, the uplink bit rate is switched to 7.8125 bps, the minimum available rate. After 1 minute for the DSN to lock up to the carrier, the HGA is locked into position and communications are through LGA1 throughout the duration of the drag pass. Ten minutes after the end of the drag pass, the sequence restores nominal downlink through the HGA.

Likewise, 16 minutes before the beginning of the ABM, the sequence configures the telecom system to transmit a carrier-only downlink through LGA1. This remains the telecom configuration until 15 minutes after the conclusion of the ABM, at which time the nominal downlink through the HGA is re-established.

6.5.4 Downlink Telemetry Modulation and Coding

The MRO project data volume goal for full mission success is to return more than 26 terabits of science data from Mars during its primary science phase, which exceeds any previous deep-space mission by more than an order of magnitude.

The following kinds of modulation are used on MRO [14]:

- BPSK on a subcarrier, with the subcarrier modulating the carrier
- BPSK directly on the carrier
- QPSK directly on the carrier

QPSK modulation capability by the SDST allows for twice the data rate to be transmitted through the same bandwidth as compared with the BPSK used in previous missions. Sequential tone ranging is not possible with QPSK because of the fully suppressed carrier.

Error-correcting codes as defined in Tables 6-9 through 6-14 are used on the downlink to the DSN. The table referenced in the title of each subsection summarizes the main MRO configuration items (bit rate and symbol rate, modulation type, modulation index, and station receiver loop type) and receiver thresholds.

In the following subsections, the symbol rate is defined as the output of the SDST (that is, channel symbols), and the information bit rate is defined as the frame bit rate coming into the C&DH (at point “d” in Fig. 6-18).

Table 6-9. Emergency mode (7,1/2) + RS (short frame) concatenated code.

							TLM only	TLM + RNG Lo	TLM + RNG Hi
Code Type	Framed Bit Rate, bps	Symbol Rate, sps	Modulation Type	Subcarr Freq (kHz)	Tlm Mod Index (deg)	Carrier Loop Type	Threshold Pt/No (dB-Hz)	Threshold Pt/No (dB-Hz)	Threshold Pt/No (dB-Hz)
(7,1/2)+RS (I=1)	34.4	80	Squarewave Subcar	25	58	Residual	21.4	21.7	22.5
(7,1/2)+RS (I=1)	137.5	320	Squarewave Subcar	25	71	Residual	26.2	26.5	27.3

Table 6-10. (7,1/2) + RS (long frame) concatenated code.

							TLM only	TLM + RNG Lo	TLM + RNG Hi
Code Type	Framed Bit Rate, bps	Symbol Rate, sps	Modulation Type	Subcarr Freq (kHz)	Tlm Mod Index (deg)	Carrier Loop Type	Threshold Pt/No (dB-Hz)	Threshold Pt/No (dB-Hz)	Threshold Pt/No (dB-Hz)
(7,1/2)+RS (I=5)	556.9	1280	Squarewave Subcar	25	72	Residual	31.2	31.5	32.3
(7,1/2)+RS (I=5)	1740.4	4000	Squarewave Subcar	25	72	Residual	36.0	36.3	37.1
(7,1/2)+RS (I=5)	27846.8	64000	Squarewave Subcar	375	72	Residual	47.9	48.2	49.0
(7,1/2)+RS (I=5)	87021.1	200000	Squarewave Subcar	375	72	Residual	52.8	53.1	53.9
(7,1/2)+RS (I=5)	139233.8	320000	BPSK Direct Mod	None	72	Residual	54.9	55.2	55.9
(7,1/2)+RS (I=5)	208850.7	480000	BPSK Direct Mod	None	72	Residual	56.6	56.9	57.7
(7,1/2)+RS (I=5)	348084.4	800000	BPSK Direct Mod	None	72	Residual	58.8	59.1	59.9
(7,1/2)+RS (I=5)	696168.9	1600000	BPSK Direct Mod	None	72	Residual	61.8	62.2	63.6
(7,1/2)+RS (I=5)	1044253.3	2400000	QPSK	None	82	Suppressed	63.4	-	-
(7,1/2)+RS (I=5)	1305316.7	3000000	QPSK	None	82	Suppressed	64.3	-	-
(7,1/2)+RS (I=5)	478616.1	1100000	BPSK Direct Mod	None	72	Residual	60.2	60.6	62.0
(7,1/2)+RS (I=5)	1740422.2	4000000	QPSK	None	82	Suppressed	65.6	-	-
(7,1/2)+RS (I=5)	2610633.3	6000000	QPSK	None	82	Suppressed	67.3	-	-

Table 6-11. Turbo code, rate 1/2.

							TLM only	TLM + RNG Lo	TLM + RNG Hi
Code Type	Framed Bit Rate, bps	Symbol Rate, sps	Modulation Type	Subcarr Freq (kHz)	Tlm Mod Index (deg)	Carrier Loop Type	Threshold Pt/No (dB-Hz)	Threshold Pt/No (dB-Hz)	Threshold Pt/No (dB-Hz)
Turbo 1/2	745645.4	1500000	BPSK Direct Mod	None	72	Residual	60.7	61.1	62.5
Turbo 1/2	1491290.8	3000000	QPSK	None	82	Suppressed	63.5	-	-

Table 6-12. Turbo code, rate 1/3.

							TLM only	TLM + RNG Lo	TLM + RNG Hi
Code Type	**Framed Bit Rate, bps**	**Symbol Rate, sps**	**Modulation Type**	**Subcarr Freq (kHz)**	**Tlm Mod Index (deg)**	**Carrier Loop Type**	**Threshold Pt/No (dB-Hz)**	**Threshold Pt/No (dB-Hz)**	**Threshold Pt/No (dB-Hz)**
Turbo 1/3	66279.6	200000	Squarewave Subcar	375	72	Residual	49.6	49.9	50.7
Turbo 1/3	132559.2	400000	BPSK Direct Mod	None	72	Residual	52.6	52.9	53.7
Turbo 1/3	198838.8	600000	BPSK Direct Mod	None	72	Residual	54.4	54.7	55.5
Turbo 1/3	497096.9	1500000	BPSK Direct Mod	None	72	Residual	58.3	58.7	60.1
Turbo 1/3	662795.9	2000000	BPSK Direct Mod	None	72	Residual	59.6	60.0	61.4
Turbo 1/3	795355.1	2400000	QPSK	None	82	Suppressed	60.1	-	-
Turbo 1/3	994193.8	3000000	QPSK	None	82	Suppressed	61.1	-	-
Turbo 1/3	1325591.8	4000000	QPSK	None	82	Suppressed	62.4	-	-

Table 6-13. Turbo code, rate 1/6.

							TLM only	TLM + RNG Lo	TLM + RNG Hi
Code Type	**Framed Bit Rate, bps**	**Symbol Rate, sps**	**Modulation Type**	**Subcarr Freq (kHz)**	**Tlm Mod Index (deg)**	**Carrier Loop Type**	**Threshold Pt/No (dB-Hz)**	**Threshold Pt/No (dB-Hz)**	**Threshold Pt/No (dB-Hz)**
Turbo 1/6	331397.9	2000000	BPSK Direct Mod	None	72	Residual	56.1	56.5	57.8
Turbo 1/6	497096.9	3000000	QPSK	None	82	Suppressed	57.6	-	-
Turbo 1/6	662795.9	4000000	QPSK	None	82	Suppressed	58.9	-	-
Turbo 1/6	994193.8	6000000	QPSK	None	82	Suppressed	60.6	-	-

Table 6-14. RS coding only (long frame).

							TLM only	TLM + RNG Lo	TLM + RNG Hi
Code Type	**Framed Bit Rate, bps**	**Symbol Rate, sps**	**Modulation Type**	**Subcarr Freq (kHz)**	**Tlm Mod Index (deg)**	**Carrier Loop Type**	**Threshold Pt/No (dB-Hz)**	**Threshold Pt/No (dB-Hz)**	**Threshold Pt/No (dB-Hz)**
RS only (I=5)	130531.7	150000	Squarewave Subcar	375	72	Residual	58.2	58.5	59.3
RS only (I=5)	1740422.2	2000000	BPSK Direct Mod	None	72	Residual	69.5	69.9	71.2
RS only (I=5)	2088506.6	2400000	QPSK	None	82	Suppressed	70.0	-	-
RS only (I=5)	2393080.5	2750000	QPSK	None	82	Suppressed	70.6	-	-
RS only (I=5)	2610633.3	3000000	QPSK	None	82	Suppressed	71.0	-	-
RS only (I=5)	2871696.6	3300000	QPSK	None	82	Suppressed	71.4	-	-
RS only (I=5)	3480844.4	4000000	QPSK	None	82	Suppressed	72.3	-	-
RS only (I=5)	5221266.6	6000000	QPSK	None	82	Suppressed	74.0	-	-

6.5.4.1 Short Frame Concatenated (Table 6-9). The [(7,1/2) convolutional + Reed–Solomon (RS) (short frame)] concatenated code will be used only for the emergency mode, 34.38 bps and a MOI data rate of 139 bps. The 34.38 bit rate is chosen for heritage reasons, with the coded bit rate out of the C&DH uplink–downlink (ULDL) card at 40 bps and the SDST output symbol rate at 80 symbols per second (sps).

6.5.4.2 Long-Frame Concatenated (Table 6-10). The [(7,1/2) convolutional + RS (long-frame)] concatenated code has been proven in many prior missions and is used to cover the largest span of bit rates. Because of bandwidth limitations, the maximum rate for the concatenated code downlink is a bit rate of 3.3 Mbps at the SDST input and a symbol rate of 6.6 megasymbols per second (Msps) at the SDST output. If interference with another project is an issue, maximum rates are 2 Mbps and 4 Msps.

6.5.4.3 Turbo Code (Tables 6-11 Through 6-13). Turbo codes are to be used for bit rates above 32 kbps. This capability, implemented in C&DH hardware, provides more link margin as compared with convolutional codes of the same code rate. Currently the maximum decode rate of the ground turbo decoder limits use of turbo codes to 1.6 Mbps and below. If interference to another project could occur, the limit is 4 Msps (SDST output channel rate).

6.5.4.4 RS-Only (Table 6-14). The RS-only coding is used primarily for very high data rates in situations where MRO is close enough to Earth that coding gain is less important (such as in early cruise and during Mars–Earth closest approach). The maximum rate for RS-only data is 6.6 Mbps (6.6 Msps). If interference to another project could occur, the limit is 4 Mbps (4 Msps).

6.5.5 Coordinating MRO and MER X-Band Operations

The MRO SDST operates on DSN channel 32. When it became apparent that MER-A (also on channel 32) and MER-B (on channel 29) were likely to still be active on Mars at MRO arrival, a coordination plan was agreed to between the projects. The original agreement, excerpted below, focused on the MRO MOI period. It has been extended to the MRO aerobraking phase and likely will require updates for the primary science phase.

According to the general agreement, as shown in Table 6-15, MER-A (“Spirit”) would forego use of the DSN during the MOI and aerobraking critical event periods. This agreement, to ensure MRO safety, documents the dates chosen for MER-A to use (and not use) DSN during this period.

Prior to the start of the critical aerobraking period (March–September, 2006), MRO and MER jointly developed a coordination plan to reduce the chances of an inadvertent MRO channel 32 uplink interfering with MER channel 32 commanding, or vice versa. The plan called for MER to define a one-hour period for each MER-A sol when the project would do any required X-band commanding for that sol. This period is outlined in Fig. 6-22. Times in the figure go from left to right on two rows. The top row is spacecraft event time at Mars. The bottom row is Earth transmit time at the station.

Table 6-15. MRO–MER agreement on channel 32 X-band uplink use.

Schedule	Agreement
Before February 28	MER-A operates normally, X-band downlink (direct to Earth) and uplink (direct from Earth) as needed
Starting February 28	2006-059T00:00 - 2006-060T00:00 No MER-A X-band operations on channel 32
March 1–5	MER-A X-band uplink allowed
March 6–12 (MOI was March 10)	2006-065T00:00 - 2006-072T00:00 No MER-A X-band operations on channel 32
March 13 through aerobraking exit (ABX) – 2 weeks	MER-A X-band uplink coordinated weekly with Mission Planning and Sequencing Team (MPST) to avoid overlaps with MRO uplink windows. MER-A will not use X-band uplinks if in conflict with MRO uplink windows
ABX – 2 weeks through ABX	No MER X-band operations (UHF with Odyssey)

Figure 6-22 and the acronym MUKOW (MRO uplink keep out window) define the goal of this coordination.[11] The term “keep out” refers to scheduling the DSN uplink to MRO to be turned off at an agreed-to time, to keep it out of the MER SDST receiver when MER uplinking is required, and to scheduling the uplink to MER to be turned off to keep it out of the MRO SDST receiver when MRO uplinking is required. The scheduling is required as part of the coordination agreement between the projects because the projects have individual planning processes, and the DSN stations allocated to different projects are operated separately.

Every two weeks, MER delivers a spreadsheet file with two entries in each row: (1) the time the DSN transmitter supporting MRO is to be turned off and (2) the time the DSN transmitter subsequently supporting MER-A is to be turned off.

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[11] The MUKOW coordination process has continued through the extended science phase (ending September 2010) and will continue into subsequent mission phases of the MRO and MER projects, as long as DSN support of MRO spacecraft and the Spirit Rover X-band activity continues.

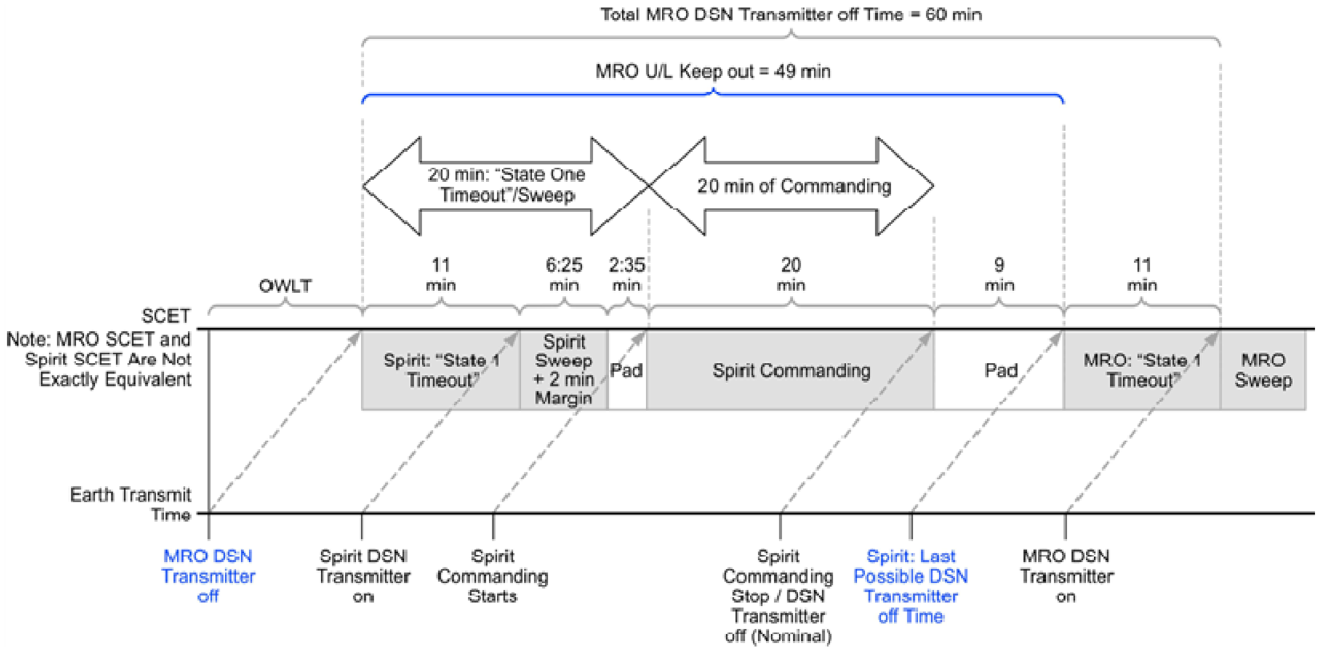

Fig. 6-22. MRO uplink keep out window (MUKOW) timing.

The MER and MRO SDSTs have a "State 1 timeout" duration of 10 minutes between when the SDST receiver goes one way (in response to the station transmitter turn off) and when it forces its phase-locked loop (PLL) to best-lock frequency. Each project uses a "sweep acquisition" uplink frequency profile by the station to ensure the station's uplink carrier goes through the actual (temperature-dependent) best-lock frequency.

The coordination process, as developed on a basic weekly schedule, allows for negotiated updates (including cancellations or additions) of keep-out times to meet significant needs of either project. These could include changes in MRO aerobraking times or anomalies that occur with either project.

Although the agreement primarily affects uplink operations, both MER spacecraft occasionally require a direct-to-Earth (DTE) X-band downlink for onboard spacecraft clock correlation with UTC. Also, both MER spacecraft rely on the detection by the DSN station of an unmodulated X-band downlink carrier ("beep") to verify the success of the "in the blind" direct-from-Earth (DFE) command session and the consequent hand off by flight software to the new sol's master sequence [15].[12]

Successful lock-up of MER DTE passes requires coordination with MRO because the MRO downlink signal level is much greater than the MER HGA DTE downlink. When MER-A needs to do a DTE, it needs to use a specific communications mode (504 bps or lower on a 25 kHz subcarrier, (7,1/2) convolutional code). During the time of the MER-A downlink, MRO needs to reduce its telemetry rate and be on the USO (achieved by the MUKOW ground transmitter coordination).

For a MER-B ("Opportunity") DFE uplink (three channels away), MRO can continue its normal uplink. During the time of a MER-B downlink (three channels away), it has been recommended that the coordination include the absence of uplink ranging modulation to MRO. This is achieved by defining the station configuration for the MRO pass to not include ranging.

Though the MUKOW process continues with the MER project, MRO aerobraking exit (ABX) was completed in September 2006, after which the

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[12] MER beep detection does not require any special MRO configuration or action. It does require (for both MER-A and MER-B) that the station tracking MER narrow the receiver's fast Fourier transform (FFT) in both bandwidth and signal level range to reduce the effects of MRO spectral components near the beep frequency. The beep frequency is precisely known because the beep is two-way coherent with the uplink.

instruments were given a check and configured for solar conjunction that began in October 2006.

6.6 Ka-Band Cruise Verification

6.6.1 Ka-Band Operations Overview

The MRO Ka-band mission activity was planned to have two components: an engineering verification of basic spacecraft and station Ka-band functionality during the MRO cruise to Mars, and a communications operational demonstration during the orbital mission. Before orbital operations began, an onboard Ka-band exciter anomaly occurred on May 26, 2006 [16], and an X-band waveguide transfer switch anomaly occurred on August 16, 2006 [17]. The project has elected not accept the risk of conducting the Ka-band operational demonstration during either the primary or extended orbital mission.

This section describes primarily the activities planned, executed and documented during cruise. At the end is a summary of the objectives of the operational demonstration relative to what had been started during the Deep Space 1 mission (Chapter 4).

6.6.2 Ka-Band Link Prediction and Performance during Cruise

MRO and four 34-m BWG stations participated in a total of 10 passes dedicated to Ka band during cruise. All three sites participated. DSS 25, DSS 34, and DSS 55 each had three passes, and DSS 26 had one.

The maximum Ka-band data rate achievable throughout the entire mission, with a 3-dB margin, is 331 kbps. In fact, a wide variety of data rates and modes was used during cruise. These were changed by the background sequence, with modulation index also changed by real-time command, as described in the next section. To simulate the occultation of MRO by Mars and to verify the ability of the stations to reacquire the Ka-band downlink, the Ka-band TWTA was turned off and back on.

During the dedicated pass on October 7, 2005, DSS-25 decoded turbo-coded data from the Ka-band downlink for the first time. During the pass on October 31, DSS-55 received a total of 133 Gbits from Ka-band, at rates as high as 6 Mbps; these represent the largest data volume and the highest data rate from deep space to date.

In the critical area of station antenna pointing, the best performance to date has been with DSS-34, which consistently achieved 4- to 5-mdeg blind-pointing error according to the monopulse system's correction offsets. It appears that DSS-34 has the best sky models for blind-pointing in the regions for MRO during cruise.

The MRO Ka-band team demonstrated functionality and characterized at both bands the performance of the radiometric data types used for navigation and radio science. Two-way Doppler and ranging performance (both downlink bands using the X-band uplink) were comparable at X-band and Ka-band and met or exceeded project requirements.

The two sets of shadow passes operated with both X-band and Ka-band set for 550 kbps RS and (7,1/2) convolutional concatenated coding. Table 6-10 shows the information rate was ~480 kbps in this mode, and the SDST output symbol rate was 1.1 Msps. Ranging was off for Ka-band in the first set of shadow passes and at 17.5-deg modulation index for the second set. The station monopulse system (not required for X-band) was not used in the first set of shadow passes, but was tried for some of the passes in the second set. Significant findings from the cruise tests included the following:

- Ka-band SNT measurements are sufficiently accurate, when the monopulse works, at signal levels corresponding to the shortest Earth–Mars distance.
- The MRO Ka-band system (35-W RF) can outperform the X-band system (100-W RF) in good weather, as shown in Fig. 6-23 [13].

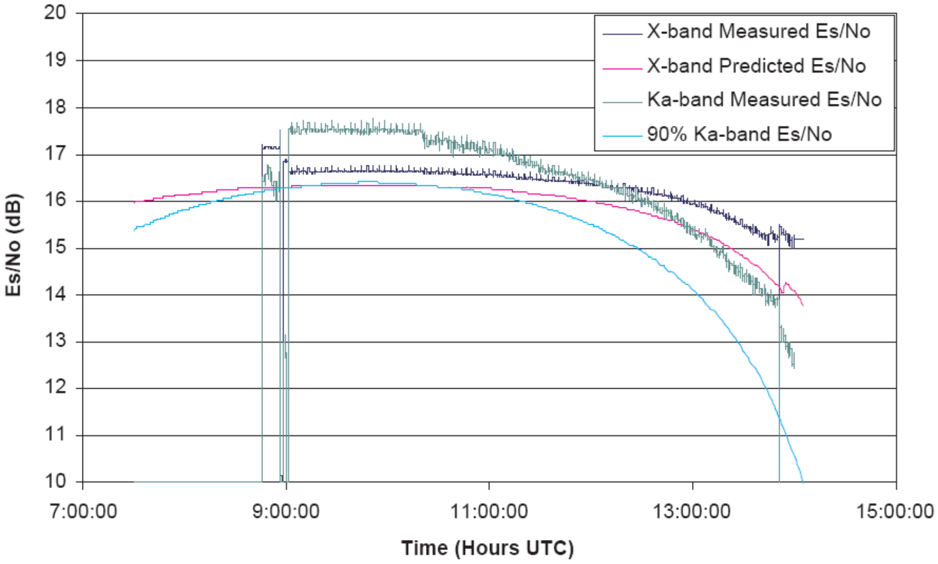

Fig. 6-23. Comparison of Ka-band and X-band telemetry (DSS 34, December 26, 2005).

The lessons learned section describes some of the other findings from the cruise tests [18].

6.6.3 Ka-Band Communications Demonstration Plans

The motivation for verifying the operational use of Ka-band was to build upon the results from Deep Space 1 and the MRO cruise experiment to achieve increased available bandwidth and, therefore, a higher available data rate. The deep-space allocation at X-band (8.4–8.45 GHz) is 50 MHz, and that at Ka-band (31.8–32.3 GHz) is 500 MHz. However, weather effects cause much larger fluctuations on Ka-band than on X-band. This characteristic makes the traditional link design for data return power inefficient for Ka-band. The traditional method involves a single downlink rate per pass and assigns a margin sufficient to provide a required data availability and to overcome a defined weather-effects severity. The margin is larger than required most of the time. By testing the operational use of Ka-band, MRO could have demonstrated the potential for greater average data rate using a concept of operations requiring significantly less power for the same total data volume. Several variations of this concept [19] use optimization techniques involving multiple data rates during a tracking pass. The rate-selection criteria account for the station elevation-angle profile as well as the distance of the spacecraft to Earth during each pass.

The MRO test was planned in the form of a telecommunications technology demonstration. The purpose of the demonstration was to develop operational procedures specific for Ka-band that account for the weather variations and are still compatible with the way the MRO flight team sequences the spacecraft. The demonstration would involve the use of data rate (and coding and modulation index) selection algorithms with input from time-variable weather models (and possibly forecasts). On the ground, the MRO cruise mission phase had already shown how the ability to point the station antenna accurately enough and to monitor signal-to-noise ratio and system noise temperature are factors to be resolved in order to determine the operational feasibility of using Ka-band for future missions.

The Ka-band experiment team planned to characterize and create or update models of Ka-band link performance. The operational demonstration planned to determine:

- The accuracy of existing Ka-band models
- Effects of weather forecasting/predicting on Ka-band telemetry
- Benefits of data-rate optimization during Ka-band passes
- Ka-band link performance during solar conjunction

- Differences in ranging and Doppler performance between X-band and Ka-band.

None of these plans were accomplished because the MRO Ka-band was not switched on during orbital operations.

6.6.4 Spacecraft X-Band and Ka-Band Constraints and Operational Factors

Considering one link (X-band or Ka-band) at a time, the codes available in the C&DH are

- Turbo codes with block length 8920 bits and rates 1/2, 1/3, and 1/6
- (255,223) RS block code.

The SDST has the capability to concatenate a (7,1/2) convolutional code on the RS, making a third coding type available.

The C&DH imposes the following limits on the coding and data rates available. The channel symbol rate is defined at the SDST output, so these limits refer to convolutional code symbols for the concatenated code.

- If the X-band and Ka-band downlinks have different data types (carry non-identical data streams), one has to use turbo coding and the other has to use RS coding.
- If X-band and Ka-band carry different data types, the combined channel symbol rate of the two bands should not exceed 6 Msps.
- If both bands carry identical data, the symbol rate on each band cannot exceed 6 Msps.

The ground turbo decoder limits the rate 1/2 code to a maximum bit rate of 1.5 Mbps.

At Mars, to minimize interference to missions in the same station antenna beamwidth and operating on nearby channels, X-band uses QPSK modulation for symbol rates higher than 2 Msps. For Ka-band, BPSK modulation is always used.

During the prime science mission, the MRO mission plan was to allocate the Ka-band demonstration two passes per week and one delta-DOR pass a month. The SDST allows for independently configurable telemetry subcarrier frequencies and modulation index values, independent control of DOR (on/off), turnaround ranging (on/off), and ranging modulation index.

The operations demonstration concept was based on maximizing the average data return subject to minimum availability. Three different scenarios were planned [19]:

1) Nominal link operations using link designs (predictions) based on long-term monthly or weekly statistics
2) Link operations using short-term forecasts
3) Link operations during superior solar conjunction.

The demonstration was planned to take advantage of the fact the spacecraft can be sequenced through two different procedures: background sequencing and mini-sequencing [13]. The approved sequence represents the onboard programming that controls subsystem configuration and operation. In addition, real-time commands can be used to change simple functions such as Ka-band modulation index. Use of real-time commands is very limited because of possible interaction with the planned sequences that must be validated before being uploaded.

The lead time for normal MRO sequencing meant that it would have been a challenge to incorporate very short term (1–2 days) weather forecasting into any Ka-band operational concept. Normal background sequencing programs the spacecraft for 28 days, and a background sequence goes through a 28-day cycle to design, test, and upload. During the cruise experiment, the Ka-band link's data rate and modulation index were changed according to the background sequence.

Mini-sequencing programs the spacecraft for specific events such as instrument calibrations or trajectory correction maneuvers. A second important use of the mini-sequence is to modify an already executing background sequence according to later information available to the project. The development cycle for mini-sequences typically takes a week. Using mini-sequencing, MRO Ka-band telecom parameters, such as data rate profile and modulation index, could be changed weekly – at best – rather than monthly [18].

6.6.5 Delta-DOR X-Band and Ka-Band Operations and Performance

Data at both X-band and Ka-band were acquired for seven delta-DOR passes during MRO cruise.

At X-band, the technique of delta differential one-way ranging (delta-DOR) has proved to be valuable for supporting deep-space cruise navigation, especially for missions with tight targeting requirements at Mars [13]. To make a delta-DOR measurement, a very long baseline interferometry (VLBI) system at each of two stations makes high rate recordings of signals from the spacecraft and angularly nearby radio sources. Driven by a sequence of events called the DSN Keywords File, the antennas at both stations point alternately, every few minutes, at the spacecraft and at the radio source in synchronism as the recordings are made. The radio source observations calibrate the system. For each source, the difference in signal arrival time between stations is determined and delivered to the navigation team, constituting the measurement. Operational X-band measurements are specified to provide an angular position accuracy of 2.5 nanoradians (nrad) [20].

The wider spectrum allocation at Ka-band can enable an advance in delta-DOR accuracy. To achieve a substantial improvement in accuracy at Ka-band, it was necessary to improve antenna-pointing performance at the ground stations, increase the frequency of the DOR tone at Ka-band, increase the sample rate for the VLBI data recordings, and continue work on surveying radio sources at Ka-band. These were accomplished as follows for the cruise experiment:

- Radio source flux surveys were made by the National Radio Astronomy Observatory (NRAO) at 24 GHz and 43 GHz.
- The VLBI receiver’s front-end bandwidth was widened to accommodate the ±76 MHz spanned by the MRO DOR tones.
- Initial models for station antenna “blind-pointing” were developed for pointing to the radio sources where monopulse could not be used.

Except for a few radio source observations that were degraded due to known ground station pointing problems, the measurement accuracy at Ka-band was comparable to the accuracy at X band and within expectations. The factor-of-four increase in the DOR tone frequency for MRO at Ka-band relative to X-band was just enough to offset the lower SNR for sources at Ka band relative to X-band.

6.6.6 Planned Solar Conjunction Experiments

Communications experiments were planned to compare X-band with Ka-band during the two solar conjunctions that bracketed the primary science mission. These conjunctions were in October–November 2006 and November–December 2008. The minimum Sun–Earth–probe (SEP) angles were 0.39 deg on October 23, 2006, and 0.46 deg on December 5, 2008. Because the Ka-band exciter anomaly and the waveguide transfer switch anomaly occurred prior to the first solar conjunction, no formal experiments were done. Similar to other projects, MRO invoked for each solar conjunction an uplink command moratorium and planned X-band data rate reductions based on the profile of SEP angles.

The solar conjunction communications experiment would have primarily been at DSS-25 at Goldstone, where Earth weather (tropospheric) effects are usually minimal. The experiment plan built upon data from previous missions by characterizing the solar charged-particle effects on the Ka-band and X-band carrier and telemetry links. At both frequency bands, the effect of the solar charged particles increases as the Sun-Earth-probe (SEP) angle decreases. The primary objectives were

- To evaluate Ka-band performance as a function of SEP angle against the concurrent X-band performance
- To measure any degradation to the link that occurred during solar coronal transient activity, such as coronal mass ejections.

Solar effects are smaller at Ka-band than at X-band, and this advantage of using Ka-band was known from previous in-flight experiments. One goal was to determine how low the SEP angle could possibly go (for each band) while maintaining carrier lock and achieving reasonably reliable telemetry (with care given to telemetry modulation index and station receiver loop bandwidth parameters). An X-band link using BPSK begins to degrade near a 2-deg SEP angle. Based on comparable solar effects, it is believed that a Ka-band link would begin to degrade somewhere near 1 deg.

To isolate the downlink effects from the uplink, the experiment planned to use the USO as the downlink frequency reference for passes when the SEP angle was 5 deg or less.

Below 1-deg SEP angle, the experiment plan included simulated frequency shift-keying (FSK) modulation using the carrier to demonstrate information flow at the equivalent of 1 bps.

6.7 Lessons Learned

The initial MRO X-band and Ka-band lessons learned were documented in the MRO Post-Launch Assessment Review (PLAR) [21], which was held in October 2005. Some of these problems have subsequently been resolved or worked around. As the project documents additional lessons, documentation updates will continue.

The major after-launch telecom hardware issues, discussed on previous pages, include

- The Ka-band exciter anomaly
- The X-band waveguide transfer switch anomaly

- The use of an SDST operating on the same X-band channel as the SDST on another active Mars mission and the consequent need for inter-project coordination between MRO and MER.

In addition to these, other issues have arisen during flight. Some issues have subsequently been resolved or worked around. The following paragraphs briefly summarize the MRO issues in terms of lessons-learned by frequency band: X-band, Ka-band, and UHF.

6.7.1 X-Band

Earth Network Bandwidth (from DSN stations to JPL): The term “bandwidth” refers both to the maximum bit rate a channel can carry and the longest time delays from one end of the channel to the other.

The MRO requirements are as follows:

- The Deep Space Mission System (DSMS) shall provide the capability to ensure that a version of a payload product set containing any data can be made available within 24 hours of receipt of the Earth-receive time of that data.
- For the aerobraking phase, the project requests a guarantee of real-time data at a rate of at least 220 kbps.

The MRO project documented their concerns and worked with the DSN to resolve them prior to the critical aerobraking mission activity. These concerns regarded the timely transfer of spacecraft data from the stations to the mission operations and the computational horsepower required to process the data for subsequent aerobraking sequences. Generalized to a lesson-learned as missions become more and more bandwidth intensive, these concerns are:

- The station-to-JPL link may at times have too much data transfer delay to support critical engineering and primary science rates. The data links are provided by the NASA Integrated Services Network (NISN).
- Computing power may not be sufficient to unwrap real-time engineering packets during planning activities with very short turnaround times.
- Reliable Network Service (RNS) may not be able to handle the full downlink rate from station to project, particularly when one site (for example Madrid) might be tracking several spacecraft, each with high rate downlinks.

6.7.2 Ka-Band

In-Flight HGA Calibration: The first HGA calibration was performed over DSS-55 on September 9, 2005. The calibration point spacing (1 deg by 1 deg) was too large to resolve the Ka-band antenna pattern. The calculated Ka-band boresight had an error of 0.1 deg. This is equivalent to an uncertainty (loss) in effective isotropic radiated power (EIRP) of 5 dB.

The received downlink Ka-band signal level was too high for a normally configured station to measure the antenna pattern accurately.

Station antenna pointing errors and atmospheric effects could significantly affect the calibration. Active measures to reduce or account for their impact are recommended.

6.7.3 UHF

Electromagnetic interference (EMI) to the Electra receiver: The EMI problem was documented as a result of pre-launch testing, it was subsequently confirmed in cruise phase testing, it was a continuing concern during the primary science phase, and it remains a concern in the relay phase.

Pre-flight EMI tests showed that almost all unwanted MRO payload and MRO spacecraft subsystem UHF output appeared as tones. Box level testing of various science payloads during MRO development revealed interferers that produced tones exceeding a specification threshold signal level of –140 dBm, with perhaps hundreds of tones in total. One tone from the CRISM instrument, inside the nominal Electra receive band, was measured at –70 dBm centered near 400 MHz. The power in this single EMI tone is higher than any signal level we expect to receive from any Mars lander. The tones have been identified as harmonic overtones of switching power supplies, data buses, or clock mechanisms.

For return-link communications at rates of less than 256 kbps, the Electra radio team reprogrammed the MRO FGPA modem post launch to include a digital filter that partially suppresses this large interference tone and allows relay support at the standard 401.6 MHz return-link frequency. For data rates greater than 256 kbps, the prescribed approach is to move the return-link center frequency more than 3 MHz away from the 400-MHz interference tone. Doing this allows the surface acoustic wave (SAW) filter in Electra to eliminate this tone completely. This approach is used for MSL support using a return link center frequency of 391 MHz.

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