Chapter 7
Mars Exploration Rover Telecommunications

Jim Taylor, Andre Makovsky, Andrea Barbieri, Ramona Tung, Polly Estabrook, and A. Gail Thomas

This chapter describes and assesses telecommunications of the two rovers launched in 2003 and named Spirit and Opportunity [1]. Throughout this chapter, the names MER-A and Spirit are used interchangeably, and likewise MER-B and Opportunity. Generally, the term "spacecraft" refers to the vehicle before landing, and the term "rover" refers to the vehicle after landing.

For each spacecraft (rover), there were three phases of the Mars Exploration Rover (MER) primary flight mission:

- As a cruise spacecraft, MER communicated with the tracking stations of the DSN via an X-band uplink and downlink.
- During entry, descent, and landing (EDL), the cruise stage had been jettisoned; the MER lander continued to communicate via an X-band downlink to the Deep Space Network (DSN), and it initiated an ultrahigh frequency (UHF) return link to the Mars Global Surveyor (MGS) orbiter.
- On the surface, the lander opened up to reveal the rover, which stood up and completed egress by driving off from the lander after several sols. The rover communicates with the DSN and with MGS as well as with the 2001 Mars Odyssey (ODY) orbiter and the European Space Agency's Mars Express (MEX) orbiter.

The primary surface missions for the Spirit and Opportunity rovers ended as planned in April 2004, after 90 sols, with extended missions continuing for both rovers. As of the end of 2010 each rover had accumulated more than 5 Earth years of surface operations. Opportunity remains healthy and continues to drive and collect and transmit science data back to Earth, primarily through its UHF links to both Odyssey and the Mars Reconnaissance Orbiter (MRO). Spirit remains silent at her location on the west side of the plateau area known as Home Plate. No communication has been received from Spirit since Sol 2210 (March 22, 2010), as the fourth Martian winter of surface operations was beginning [2].

This chapter provides, mainly in Section 7.3, a description of the MER X-band and UHF telecommunication subsystems, with emphasis on both their development and operational challenges and lessons learned.

The MER spacecraft were designed, built, and tested at the Jet Propulsion Laboratory (JPL) in Pasadena, California. The MER Flight Team is located at JPL.

Much of the telecommunication (telecom) subsystem design information in this chapter was obtained from original primary mission design documentation: the X-band Operations Handbook [3] and the UHF Operations Handbook [4]. "MER Reports" [5] is an on-line compilation of detailed sol-by-sol science and engineering reports in the form of downlink reports from each operational area, including the telecom flight team. Reference 6 is a DocuShare library containing project reports and operational documents. (References 5 and 6 are only accessible from within JPL,)

7.1 Mission and Spacecraft Summary

7.1.1 Mission Objectives

The MER project had an initial primary objective of placing two mobile science laboratories on the surface of Mars to remotely conduct geologic investigations, including characterization of a diversity of rocks and soils that might hold clues to past water activity. The project intended to conduct fundamentally new observations of Mars geology, including the first microscale studies of rock samples, and a detailed study of surface environments for the purpose of calibrating and validating orbital spectroscopic remote sensing. The project aimed to achieve these objectives in a manner that would offer the excitement and wonder of space exploration to the public.

The Mission Plan [7] quantifies the objectives of a 90-sol surface mission in terms of minimum and full mission success. The project required that minimum mission success be achievable through use of X-band only or UHF only.

The rovers achieved more than full mission success. One example of the success criteria relates to the requirement to drive and use the instruments:

Full success: Drive the rovers to a total of at least eight separate locations and use the instrument suite to investigate the context and diversity of the Mars geologic environment. Every reasonable effort shall be made to maximize the separation between investigation locations to increase site diversity, without compromising overall mission safety or probability of success.

Minimum success: Drive the rovers to at least four separate locations and use the instrument suite to investigate the context and diversity of the Mars geologic environment.

With drives of nearly 8 km for Spirit and more than 25 km for Opportunity, and a total surface campaign lasting nearly 6 years through 2010, each rover has completed the "full success" objectives multiple times. In fact, there have been spirited debates in science planning about where stops can be made, and for how long, balancing the science that can be done at any given stop against achieving the long term driving objectives.

7.1.2 Mission Description

MER-A and MER-B are identical. Each had a launch mass of 1,063 kilograms (kg). MER-A was launched using a Delta II 7925 launch vehicle from Space Launch Complex 17A (SLC-17A) at the Cape Canaveral Air Force Station (CCAFS) in Florida. MER-B was launched using a Delta II 7925H launch vehicle from SLC-17B at the Cape Canaveral facility. The launch period and arrival dates were as follows:

Mission	Open Window	Close Window	Actual Date	Arrival
MER-A	May 30, 2003	June 16, 2003	June 10, 2003	January 4, 2004
MER-B	June 25, 2003	July 12, 2003	July 7, 2003	January 25, 2004

The two 18-day launch periods were separated by a minimum of 8 days. The launch vehicle provider required 10 days to turn around launch operations, and if MER-A had not launched until the last day or two of its launch period, MER-B would have been delayed so that 10 days would have separated the launches. Each launch day had two instantaneous daily launch opportunities, providing a high probability of liftoff within the back-to-back MER launch periods. A fixed arrival date was used to make the planning for each of the MER-A and MER-B missions tractable.

Most of Table 7-1, from the Mission Plan, summarizes the planned phases of the primary mission. The last two rows (italicized) define the first two extensions of the mission. The initial extended mission was approved to the end of FY2004 (September 28, 2004). A 6-month extended-extended mission began the next day and concluded March 27, 2005. Since then, NASA has extended the mission several times, and it is currently into 2014 for the still active Opportunity rover. The extensions have been granted (funded) based on detailed project proposals for the kinds and value of the science that each extension would make possible.

7.1.3 The Spacecraft

The MER Flight System [7],[1] which is based on the Mars Pathfinder (MPF) cruise and EDL systems, delivered a large (185-kg) rover to the surface of Mars. The rover design is based on the Athena rover (carrying the Athena science payload), which began development under the Mars 2001 and Mars Sample Return (MSR) projects. An exploded view of the MER Flight System is shown in Fig. 7-1.

The Flight System consists of four major assemblies: 1) cruise stage, 2) aeroshell (heat shield and backshell), 3) lander, and 4) rover. The following description, table, and diagrams are from Ref. [7]. Table 7-2 summarizes the assembly masses.

7.1.3.1 Cruise Stage

The spacecraft in its cruise configuration is shown in Fig. 7-2.

The cruise stage is very similar to the MPF design and is approximately 2.65 m in diameter and 1.6 m tall (attached to aeroshell) with a launch mass of 1063 kg. During flight, MER is a spin-stabilized spacecraft with a nominal spin rate of 2 revolutions per minute (rpm). Six trajectory correction maneuvers (TCMs) were planned during the flight to Mars, as well as payload and engineering health checks.

[1] See Fig. 7-11 for a block diagram of the telecom subsystem elements discussed in the following paragraphs.

Table 7-1. Mission phases and planned dates for MER-A and MER-B (detailed to 2005).

Phase	Definition	MER-A Open Phase Start	MER-B Open Phase Start
Launch	Launch to thermally stable, positive energy balance state, launch telemetry played back	May 30, 2003	June 25, 2003
Cruise	End of Launch phase to Entry -45 days	May 31, 2003	June 26, 2003
Approach	Entry -45 days to Entry	November 20, 2003	December 11, 2003
EDL	Entry to end of critical deployments on sol 1	January 4, 2004	January 25, 2004
Postlanding through Egress*	End of EDL to receipt of DTE following successful placement of rover wheels on the Martian surface	January 4, 2004***	January 25, 2004***
Surface Operations**	End of Egress to end of Primary Mission	January 8, 2004	January 28,2004
Primary Mission End	Successful receipt of last scheduled UHF data return the night of sol 91	April 6, 2004	April 27, 2004
Extended mission		*May 2004*	*May 2004*
First Continuations of extended mission		*October 2004 (start FY 2005)*	*October 2004 (start FY 2005)*

* Sometimes referred to as "egress" for short, or as "impact through egress" (ITE).

** Sometimes referred to as "surface" for short.

*** The planned minimum duration of ITE (for Spirit) was 4 sols, establishing the planned start date of surface operations.

"Extended missions" refers to surface operations in the period May 2004 through October 2014.

Table 7-2. Flight System mass breakdown.

Component	Allocated Mass (kg)	Cumulative Mass (kg)
Rover	185	185
Lander	348	533
Backshell / Parachute	209	742
Heat Shield	78	820
Cruise Stage	193	1013
Propellant	50	1063

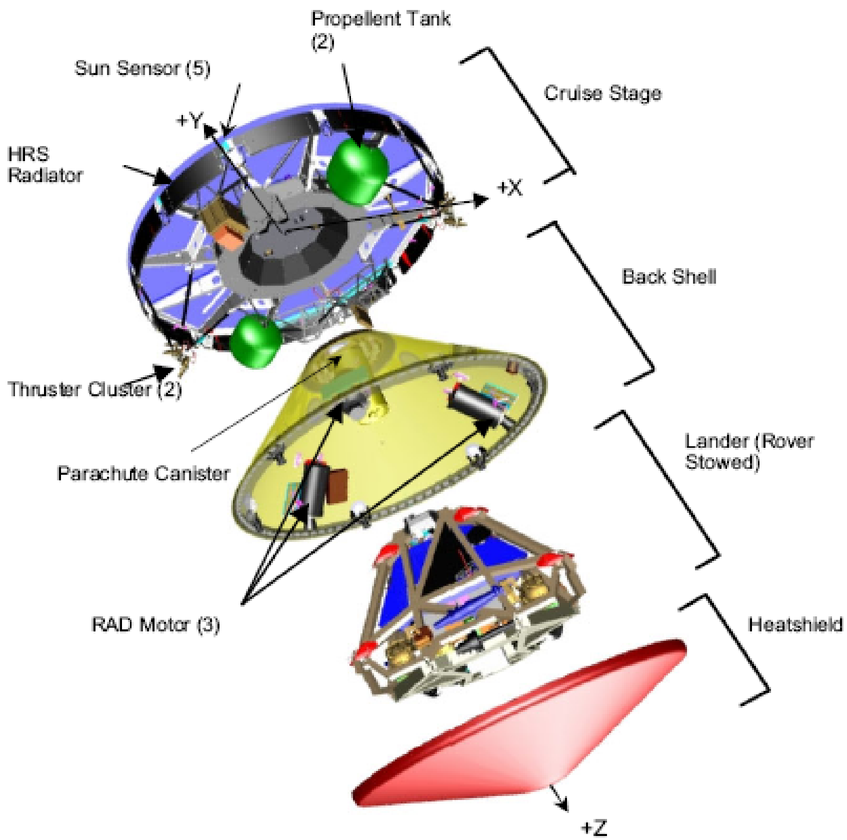

Fig. 7-1. MER Flight System, "Exploded" View.

7.1.3.2 Entry, Descent, and Landing Systems (Aeroshell and Lander)

Approximately 15 minutes (min) prior to entering the Martian atmosphere, the cruise stage was separated from the aeroshell containing the lander and rover. The aeroshell, shown in Fig. 7-3, is based on the MPF design, utilizing a Viking-heritage heat shield and thermal protection system. Stowed at the top of the backshell was an MPF/Viking-heritage parachute that was scaled up to approximately 15 meters (m) in diameter to accommodate MER's heavier entry mass of 825 kg.

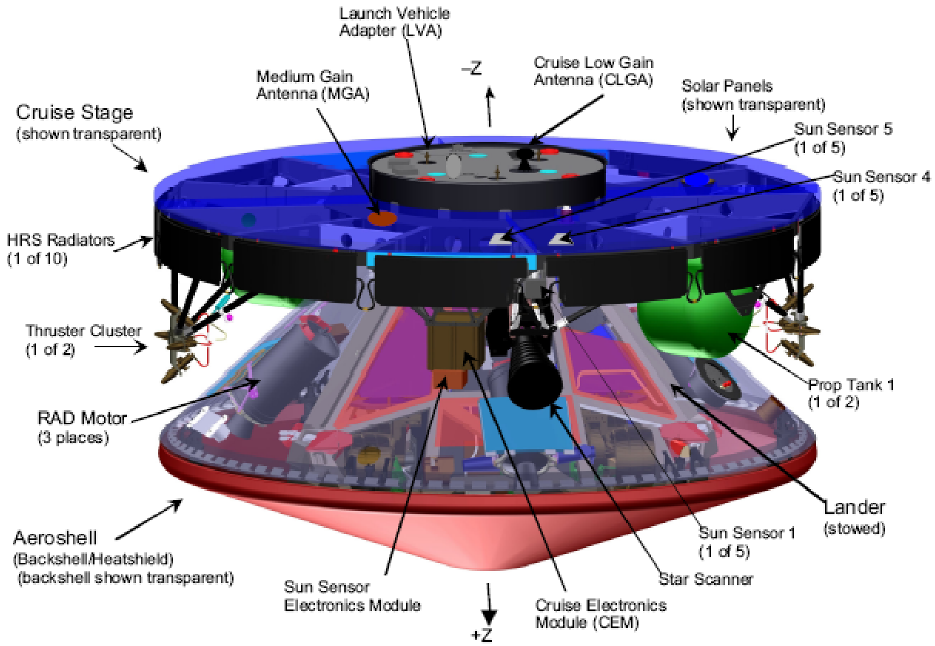

Fig. 7-2. MER Spacecraft in cruise configuration.

Several other components used during EDL were mounted on the backshell. These included the backshell pyrotechnic device (pyro) switch assembly with relays controlling EDL pyro events, as well as redundant thermal batteries to power the pyros. A Litton model LN-200 Inertial Measurement Unit (IMU) mounted on the backshell propagated spacecraft attitude during entry and was also used to determine parachute deploy time based on deceleration in the atmosphere. Three small solid rockets mounted radially around the backshell constituted the Transverse Impulse Rocket System (TIRS); they provided horizontal impulse. The three large solid rockets of the Rocket-Assisted Deceleration (RAD) system nulled vertical velocity just before landing.

After ~4 min of atmospheric deceleration, at an altitude of ~10 kilometers (km) and an atmospheric relative velocity of ~450 meters per second (m/s), the parachute was deployed. The heat shield was released using six separation nuts and push-off springs. The lander was lowered from the backshell on a Zylon[2]

[2] Zylon is a trademarked name for a range of thermoset polyurethane materials manufactured by the Zylon Corporation. These materials are members of the synthetic polymer family. Somewhat related to Kevlar and nylon, Zylon is used in applications that require very high strength with excellent thermal stability (from Wikipedia).

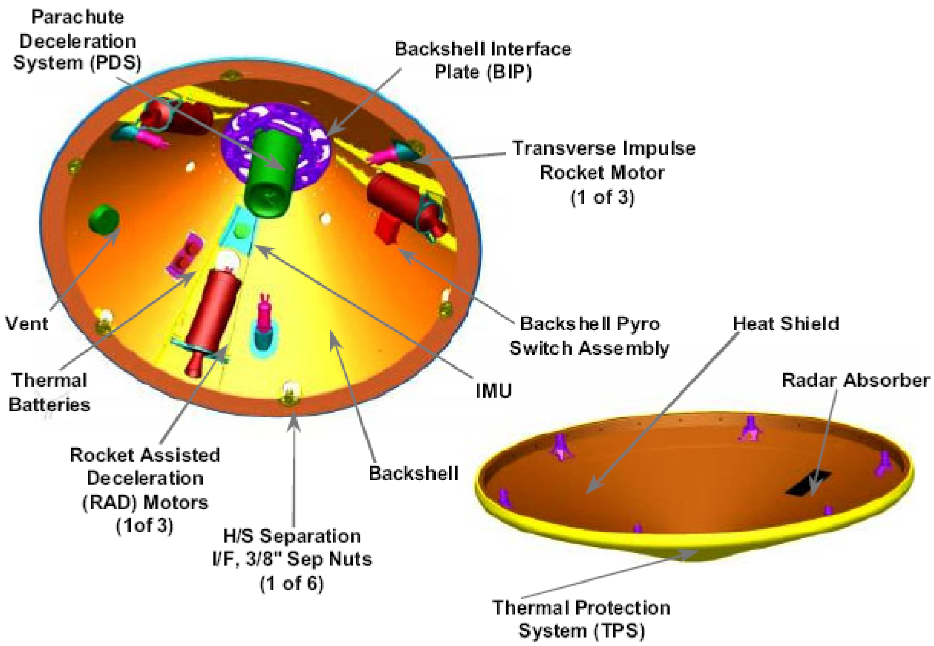

Fig. 7-3. Aeroshell configuration.

bridle, ~20-m-long, which was stowed in one of the lander side petals. The separation rate was controlled by a descent-rate limiter, which consisted of a friction brake and steel tape and was deployed with the bridle. The bridle incorporated an electrical harness that allowed the firing of the solid rockets from the lander/rover as well as providing data from the backshell IMU to the flight computer in the rover.

Figure 7-4 shows the lander in its stowed configuration and Fig. 7-5 in the extended position, ready for rover egress.

A radar altimeter unit, whose antenna is mounted at one of the lower corners of the lander tetrahedron, was used to determine distance to the Martian surface. Radar acquisition occurred within 2.4 km (~7900 ft) of the surface, ~5 min after entry, with the descent system traveling ~75 m/s. The radar data was used to determine a firing solution for the RAD solid rockets on the backshell.

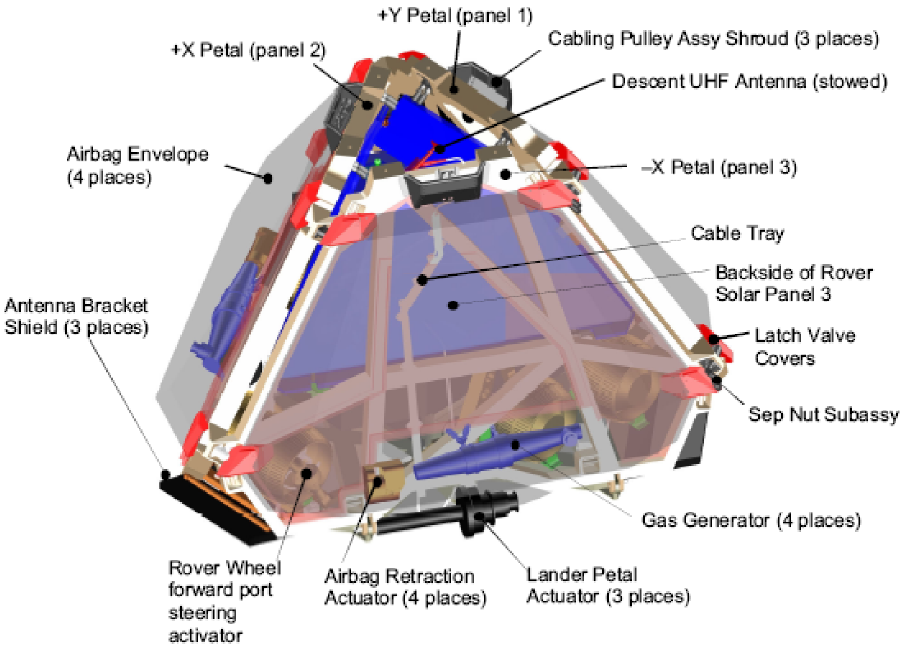

Fig. 7-4. Lander in stowed configuration.

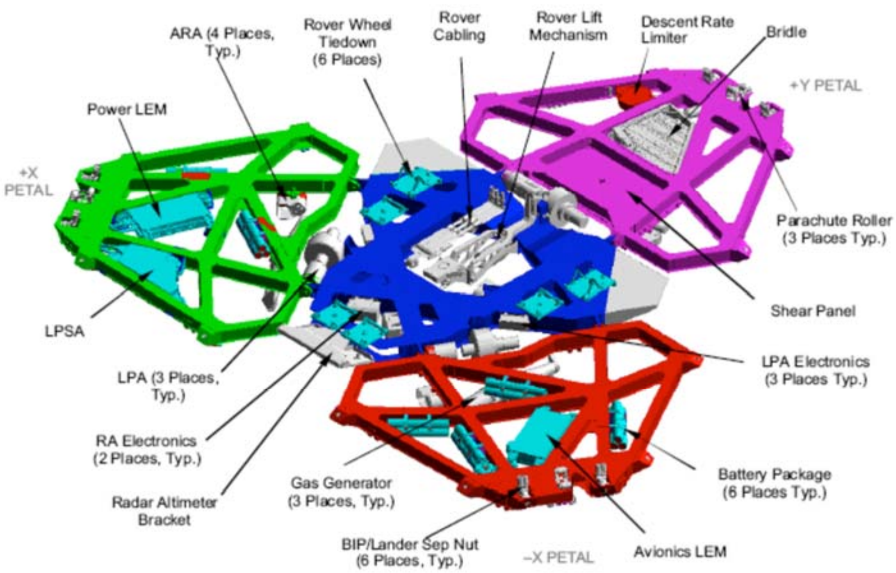

Fig. 7-5. Lander in deployed configuration (for clarity, egress aids are not shown).

A soft landing was achieved by using the RAD to slow the lander to zero vertical velocity 10–15 m from the surface. A major concern during RAD firing was any backshell tilt that might have been introduced by winds in the lower atmosphere. The TIRS, an addition over MPF, could be fired in any combination to reduce a tilt effect.

The Pathfinder-heritage airbag system was used to cushion the impact of the lander on the surface. The radar provided data to determine (on-board) the RAD firing solution. Then, before RAD ignition or TIRS firing, the airbags were inflated to ~1.0 psig (as for MPF) via three pyro-initiated gas generators. The system was (correctly) expected to bounce many times and roll before coming to rest on the surface several minutes after initial contact.

The lander's primary structure was four composite petals with titanium fittings. The base petal connected to the three side petals through the high-torque lander petal actuators (LPAs), which could independently adjust the petals from the stowed position. The Flight Team could then command adjustment of the petals up or down to potentially improve the conditions for egress of the rover. Egress aids, or "ramplets," were connected between the side petals and were passively deployed when the petals opened.

7.1.3.3 Rover

At the heart of the MER spacecraft is the rover, shown in Fig. 7-6 in its stowed configuration, as it looked just after the lander had opened its petals.

Figure 7-7 shows the rover deployed. At its wheelbase, the rover is approximately 1.4 m long and 1.2 m wide. At its solar panel, the rover is 1.8 m wide and 1.7 m long. In its deployed configuration, with the Pancam Mast Assembly (PMA) deployed, the rover is just over 1.5 m tall and has ground clearance of at least 0.3 m. The rover body and primary structure, called the Warm Electronics Box (WEB), is an exoskeleton of composite honeycomb lined with aerogel[3] for insulation. The top face of the box, a triangular panel called the Rover Equipment Deck (RED) completes the WEB enclosure.

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[3] Aerogel is a highly porous solid formed from a gel, such as silica gel, in which the liquid is replaced with a gas. Often called frozen smoke or blue smoke, it is composed of 99.8 percent air and is a stiff foam with a density of 3 milligrams per cubic centimeter (mg per cm^3), which makes it the world's lowest-density solid. The substance has extremely low thermal conductivity, which gives it its insulative properties. (from Wikipedia)

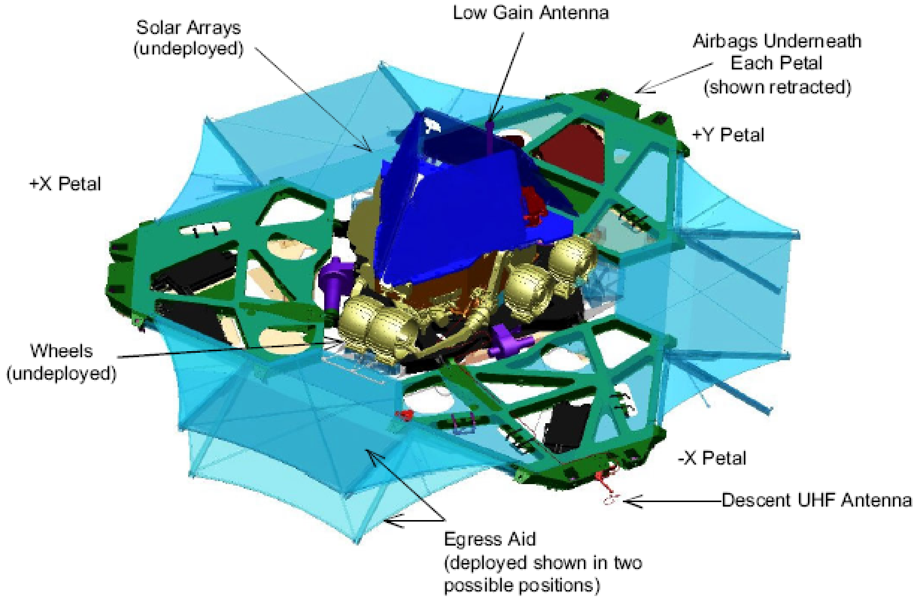

Fig. 7-6. Rover stowed on lander after petal opening.

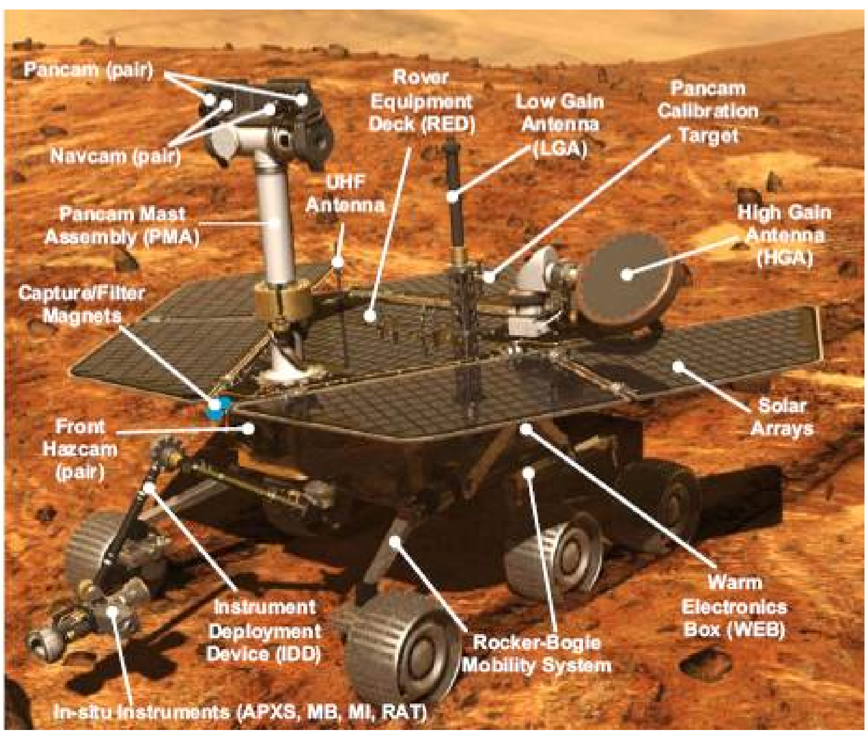

Fig. 7-7. Rover in deployed configuration.

7.2 Telecommunications Subsystem Overview

7.2.1 X-Band: Cruise, EDL, Surface

Communication functions on the rover are provided by an X-band transponder (the Small Deep-Space Transponder [SDST]), a solid-state power amplifier (SSPA), and a UHF transceiver located in the rover WEB. The SDST and SSPA operate in all mission phases. During cruise, the SDST received and transmitted via the Cruise LGA (CLGA) or the Medium-Gain Antenna (MGA). The CLGA served for the first few weeks after launch and for some TCMs. The MGA provided added capability as the Earth-to-Mars distance increased.

Communication during EDL was required to provide information to help reconstruct a fault should one occur. The LGAs available during EDL accommodated wide variations in orientation. During EDL, the X-band system transmitted multiple-frequency shift-keying (M-FSK) tones or semaphores, indicating the spacecraft state and completion of major EDL phases; the tones could be received at the expected orientations. (A similar, but simpler concept was used for MPF.) The Backshell LGA (BLGA) was used to radiate out from the backshell interface plate (see Fig. 7-3) from cruise stage separation until lander deployment.

Once the lander was separated from the backshell, the Rover LGA (RLGA) was then used to radiate from the top of the lander. In addition, a small patch antenna, mounted on the base petal (petal LGA [PLGA]), was used once the lander reached the surface. The rover cycled between the RLGA and PLGA once per minute to increase the probability that the signal would be received on Earth independent of which petal the lander came to rest on.

During the primary and extended surface missions, the X-band transponder has been supported by either an HGA or the RLGA mounted on the RED (Fig. 7-7). The RLGA has provided near omnidirectional coverage for both command and low rate telemetry data. Throughout the surface missions, the rover has been able to receive commands at a minimum rate of 7.8125 bps and transmit telemetry at a minimum rate of 10 bps on the RLGA. The HGA is a steerable, flat-panel, phased array, providing high-rate reception of command and transmission of telemetry data. During the surface missions, the uplink and downlink rate-capability via the HGA has depended on the Mars-Earth distance. At smaller ranges, command rates up to the 2-kilobits per second (kbps) maximum and telemetry up to the 28.8-kbps maximum have been used.

7.2.2 UHF: EDL, Surface

In addition to the X-band system, the UHF system was also used for the portion of EDL where the lander was suspended on the bridle. Following lander separation, a Descent UHF Antenna (DUHF, a small monopole antenna mounted at the top of the petals) was deployed to communicate with Mars Global Surveyor (MGS) at 8 kbps, providing engineering telemetry that was later relayed to Earth.

On the surface, the UHF system operated in a relay mode using both the Odyssey orbiter and the MGS orbiter's Mars balloon relay system. A relay/command demonstration with the MEX orbiter was also conducted. The rover's UHF system is implemented using a Cincinnati Electronics transceiver (Model CE-505) and was designed to be especially compatible with a like transceiver on Odyssey. The system uses a rover UHF antenna (RUHF, a 19-cm monopole antenna) mounted on the RED. This radio is capable of rates of 8, 32, 128, or 256 kbps for either transmission (rover to orbiter) or reception (orbiter to rover). The rover Flight System design limited the forward link to a single rate, 8 kbps. After some checkouts in the primary mission, the MER project coordinated with Odyssey to use either 128 kbps or 256 kbps on the return link for each pass, depending on which rate would give the greater data return. See Section 7.5.2.4.

7.2.3 Direct-to-Earth Downlink Capability

Figure 7-8, from Ref. [7], shows the prelaunch predicted direct-to-Earth (DTE) data-rate capability from MER-A landing to MER-B end-of-primary-mission. Each capability is a series of decreasing rates caused by the increasing Earth–Mars range over the time span. The least capability is RLGA to the 34-m stations (bottom curve), with the RLGA to the 70-m stations the second least. The greatest capability is the Earth-pointed HGA to 70-m stations, with the HGA to 34-m stations the second greatest. For a given combination of rover antenna and station type, on average the (15,1/6) code provides slightly greater capability than the (7,1/2) code.

7.2.4 UHF Relay Capability

UHF downlink data relays were planned through both the Odyssey and MGS orbiters. As defined for the primary mission, this link is used for the return of noncritical science and engineering telemetry.

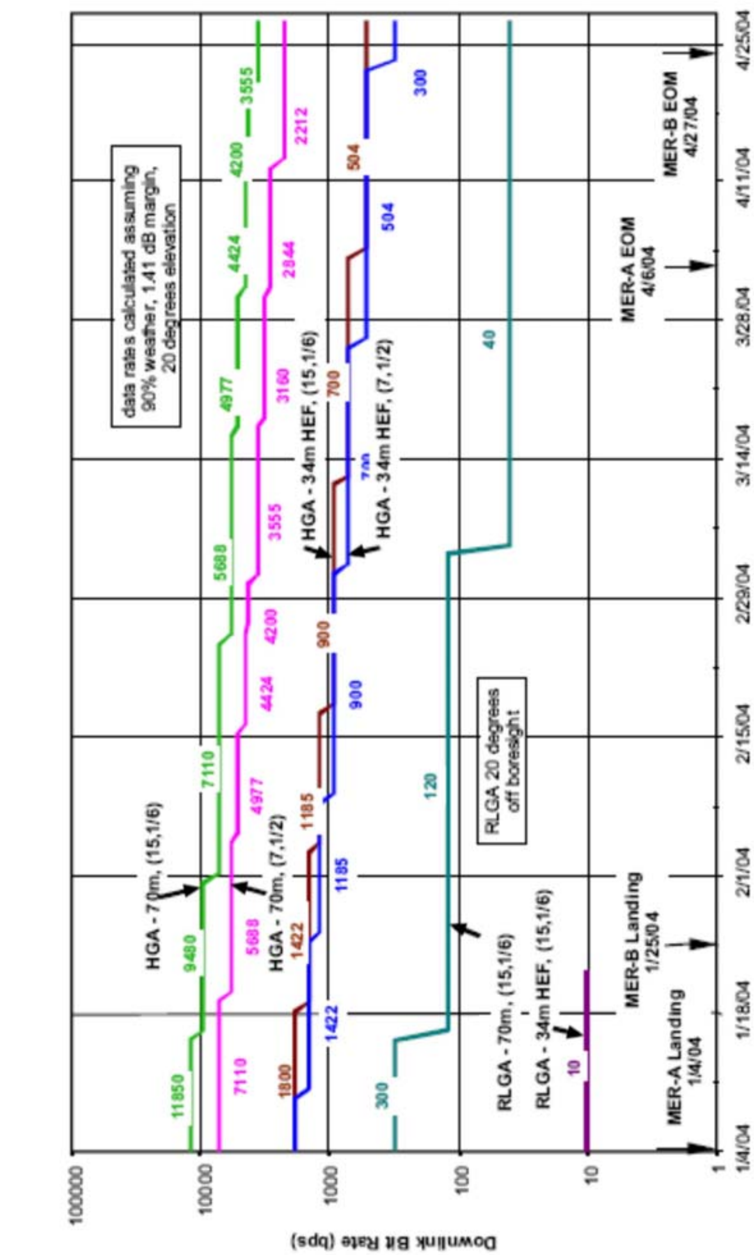

Fig. 7-8. X-band predicted downlink capability for mission planning.

More than 60 percent of the total mission data return[4] was planned to come through the UHF relay channel. An average of 1.8 potential communications passes above 20 deg elevation (with respect to the landing site) per sol per orbiter are available with a minimum of three passes every two sols and a maximum of four passes. These passes range in duration from 2 to 8 minutes, and the return-link data rate from the rover to both orbiters was planned to be as great as 128 kbps.[5] Maximization of the data downlink volume necessitates the use of as many of these UHF passes as possible.

Each rover had the potential for UHF relay passes with each of the two orbiters in the local morning and the local afternoon, providing as many as four UHF passes per rover per day. The orbiter morning passes are distributed between midnight and sunrise (local solar time), and the afternoon passes from midday to late afternoon. Figure 7-9 shows a typical distribution of passes for the Spirit rover with both Odyssey and MGS in local solar time units and the corresponding maximum elevation of each pass. The figure shows Spirit could be planned to communicate with MGS at about 01:30 and 13:30 local solar time, and with Odyssey at about 04:30 and 16:30. As the MER missions continued, the MGS orbiter mission ended, to be replaced for UHF relay by the MRO mission.

Rover tilt was expected to be a minor factor in link performance, as rover-orbiter distance dominates the tilt as a factor in link performance.[6] Rover azimuth, however, strongly affects link performance due to the asymmetry in the antenna-gain pattern. In addition, the same pass that returns 50 megabits (Mb) in a favorable azimuth, could see that return cut in half if the HGA

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[4] Data-return statistics for the Spirit and Opportunity primary missions through September 2005 are in Section 7.5.2. In summary, about 92 percent of the total data return was to Odyssey, 5 percent to MGS, and 3 percent over the X-band DTE link.

[5] The specific plan was to return data from the first few post-landing passes at the lowest rate, 8 kbps, then to jump to 128 bps if the link performed as expected and could support that rate. This plan was achieved. In fact, the 256-kbps rate was used in the extended missions for many Spirit and Opportunity relay passes.

[6] The first postlanding relay planning predicts were based on the average of those made for every 10 deg in azimuth since data-return volume was not initially a factor in planning rover orientation. Before too long in the primary mission, the rovers were sometimes deliberately oriented in azimuth after a sol's science activity to increase the data return. Still later, the relay link-prediction program was augmented with a capability to predict for tilt as well as azimuth. In one case, on sol 278 (November 4, 2004), Opportunity was driving through steep and rocky terrain and was tilted as much as 31.04° during the Odyssey afternoon pass. The difference between no-tilt and 31-deg tilt predicts was 57.4 Mb versus 41.5 Mbs.

assembly blocks the view. The average data-return volume is estimated to be about 56 Mb/sol per rover for Odyssey and about 49 Mb/sol per rover for MGS.

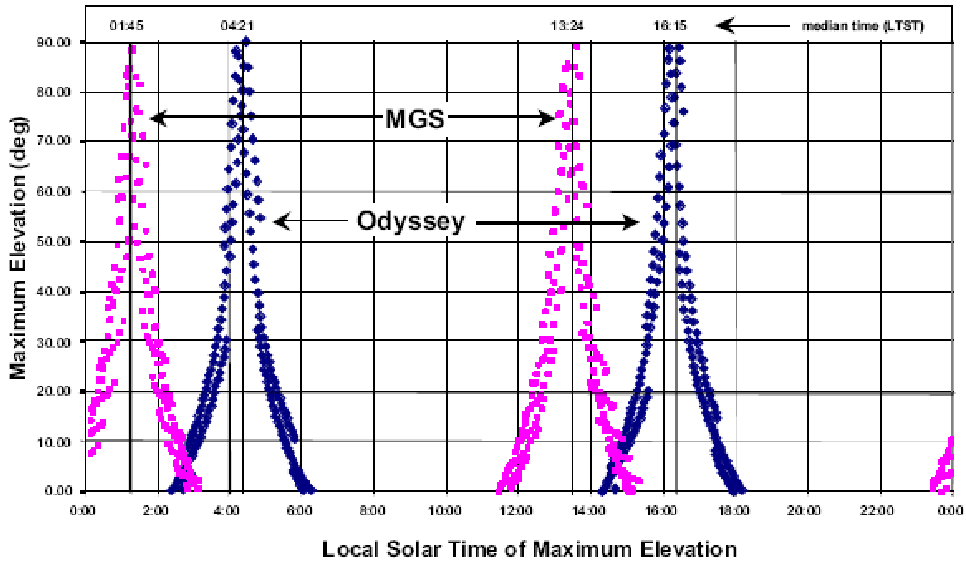

Fig. 7-9. Distribution of Odyssey and MGS overflight times and maximum elevations (MER-A site).

It must be noted, however, that the actual volume of data that can be returned via the UHF link varies from pass to pass, and depends on both the highly variable maximum elevation angle and rover orientation. Higher maximum elevation angle results in both a longer pass time and more time at a shorter slant range. The project chooses higher elevation passes that can support a higher data rate and thus usually a larger total data volume for the pass. Figure 7-10 provides an example of the sol-to-sol variability of the data volume returned via Odyssey showing both the effects of variable pass durations and various rover azimuths. Similar results have been obtained for the MGS relay.

The potential data-return volume was further constrained by the availability of Odyssey onboard memory. The Odyssey UHF Relay Operations Plan made prior to MER surface operations allocated a total of 100 megabits 12.5 megabytes) of Odyssey onboard memory to both MER rovers (and to Beagle II, which did not operate). The allocation was later increased to 120 Mb per rover for the primary mission. Thus, the volume of data that may be relayed through Odyssey is constrained by data that may remain in the Odyssey buffer from the previous relay pass. How quickly the buffer can be emptied is a function of the DSN coverage allocated to Odyssey for downlinking this data.

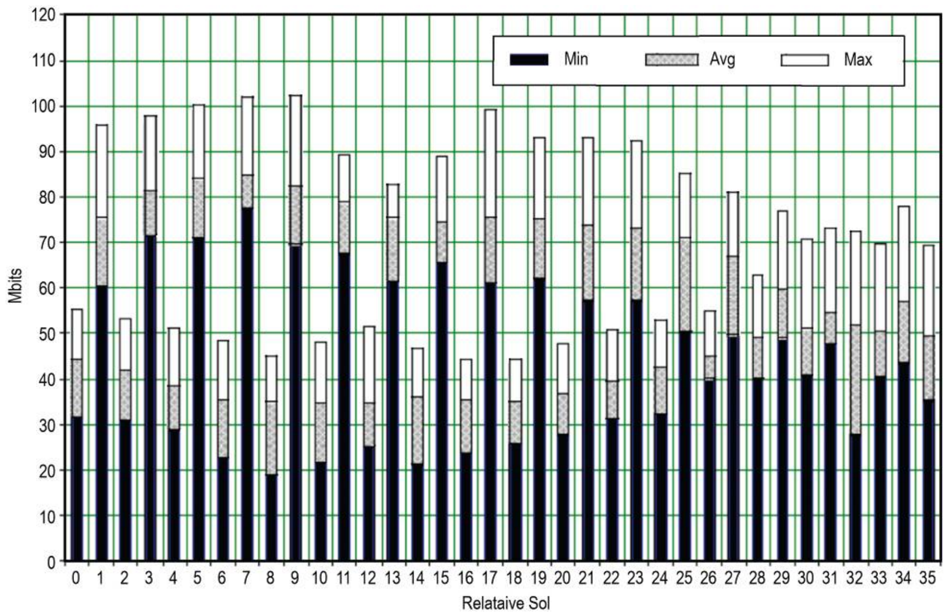

Fig. 7-10. Odyssey 128-kbps data volume from MER per sol from a 0°-latitude landing site (averaged over all azimuths, no tilt).

7.3 Telecom Subsystem Hardware and Software

7.3.1 X-Band Flight Subsystem Description

7.3.1.1 X-Band Functions

The telecommunications subsystem was designed to perform the following functions:

- Receive an X-band uplink carrier from the DSN.[7] This carrier may be unmodulated or modulated by command data or by a ranging signal or both.
- Demodulate the command data and the ranging signal.

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[7] The DSN is a global network of antennas and related support facilities, managed by JPL for NASA. The DSN provides both command uplink and navigation to deep-space probes and downlink telemetry to the Space Flight Operations Facility and the end-users it serves.

- Generate an X-band downlink carrier either by coherently multiplying the frequency of the uplink carrier by the turn-around ratio 880/749, or by utilizing an auxiliary crystal oscillator (aux osc).
- Phase-modulate the downlink carrier with either of two signals (or both):
  - A composite telemetry signal, which consists of a square-wave subcarrier (25 kilohertz [kHz] or 375 kHz) that is binary-phase-shift-keying (BPSK)–modulated by telemetry data provided by the avionics subsystem.
- As modulation for navigation, either
  - A ranging signal that was demodulated from the uplink during cruise (this is referred to as two-way or turn-around ranging), or
  - A set of unmodulated tones, used for delta differential one-way ranging (delta-DOR) during cruise. The SDST DOR module generated these tones.
- Permit control of the subsystem through commands to select signal routing (for example, which antenna should be used) and the operational mode of the subsystem (that is, the configuration of the elements of the subsystem). Examples are command data rate, telemetry subcarrier, convolutional code, downlink ranging modulation index). This commanding can be done either directly from the ground (with real-time commands) or through sequences of commands that were previously loaded on the spacecraft.
- Provide status telemetry for monitoring the operating conditions of the subsystem. Examples are aux osc temperature, SDST current, subcarrier frequency, ranging channel state (on or off) coherent/noncoherent operation, and receiver lock state (uplink carrier in or out of lock).
- For the radio frequency (RF) transmitter, provide on/off power control to permit the conservation of power.
- Upon a power-on-reset (POR), the system is placed into a single, well-defined operating mode. This provides a known subsystem state from which the ground can command the telecom subsystem during safe-mode (emergency) operations.

In addition, as planned for the EDL phase, the SDST could generate and transmit the so-called M-FSK tone described in Section 7.2.1 above. In this alternative to telemetry, a unique subcarrier frequency is used to signal (as a semaphore) that a particular spacecraft event has occurred. The M-FSK tones were used during the EDL portion of the mission, where the expected signal level was too low and the Doppler environment too dynamic to provide telemetry via a conventional phase-coherent receiver.

7.3.1.2 Functional Block Diagram

Figure 7-11 is a block diagram of the X-band telecom subsystem, with the functional elements as described in the four major assemblies of Fig. 7-1.

7.3.1.3 Interfaces with Other Subsystems

The telecom subsystem interfaces with the spacecraft are illustrated in Fig. 7-12.

The interfaces with the avionics subsystem and the power subsystems are as follows:

Avionics includes hardware and the flight software. The telecom subsystem relies on avionics to control its operating mode. This control can be done via

- A real-time command from the ground, demodulated from the X-band uplink carrier and provided to avionics, or
- A sequence of commands stored on board and issued by the sequence engine, or
- Communications behavior, where the change of state occurs as the result of opening of a communications window[8] or the closing of the window (that is, return to the current default or background state), or
- Fault protection, where the change of state occurs as the result of a response algorithm that activates when the fault-protection software detects a defined fault.

[8] A communications window (comm window) delivers a set of communications parameters to the rover using a single command. The parameters include start time, duration, choice of rover antenna (which determines whether the window is X-band or UHF), durations for real-time and recorded data-priority tables (DPTs), uplink (or forward) and downlink (or return) data rate, hardware configuration table to invoke, and an optional sequence for the window to initiate at its start time. Comm windows operate within a “communications behavior” portion of the flight software. A comm window does not rely on the rover’s sequence engine.

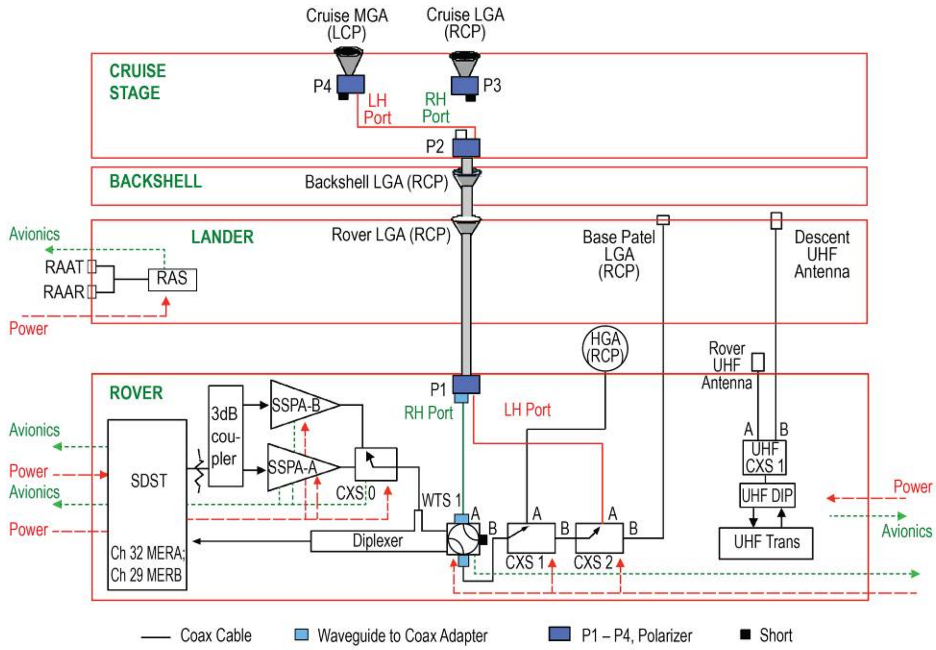

Fig. 7-11. X-band Telecom Subsystem block diagram. (RAAT and RAAR are Relay Antenna Assembly Transmit and Relay Antenna Assembly Receive.)

In each case, it is the avionics subsystem that issues the commands that control how the telecom subsystem is configured. The only exception is the POR state. If a POR is triggered, the SDST will enter its POR state.

The avionics subsystem provides the telecom subsystem with the telemetry data to be downlinked, as well as a data clock to drive the convolutional encoding done by telecom. The clock is to be either data clock × 2 for (7,1/2) encoding or data clock × 6 for (15,1/6) encoding. Avionics does the frame and packet formatting and the Reed-Solomon (RS) encoding of the telemetry data that is to be transmitted by telecom.

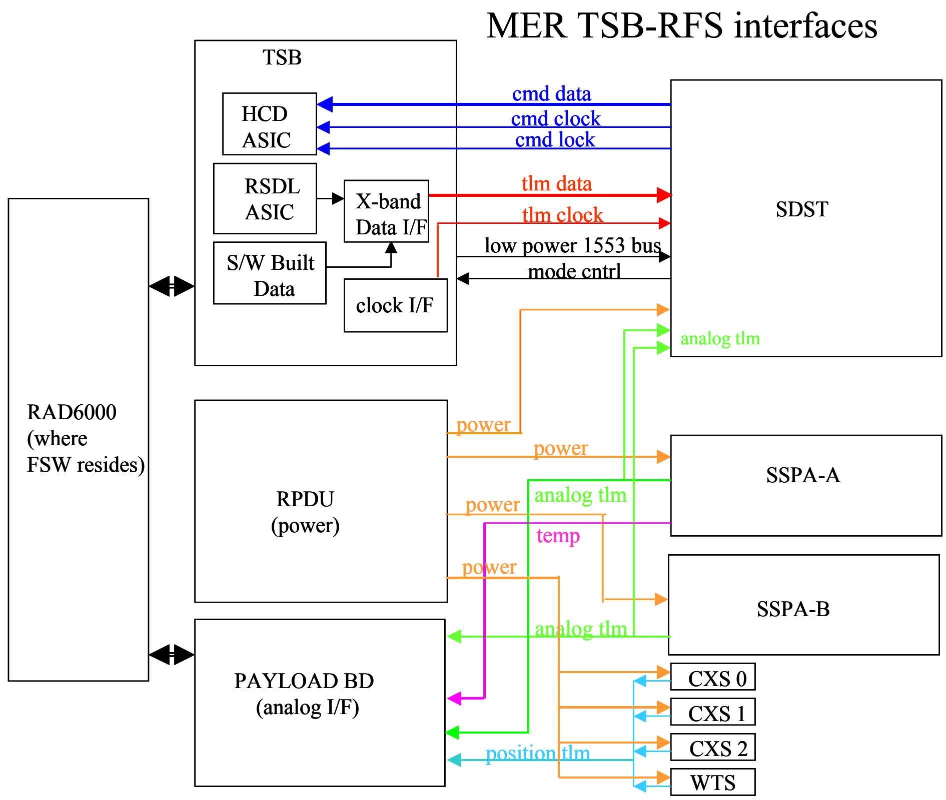

Fig. 7-12. Telecom Subsystem interfaces.

Avionics selects the frame size (either long or short) and whether the data sent to telecom is RS-encoded or check-sum- (CS)–encoded. The CS mode was not used for X-band during mission operations. Data to be RS-encoded is produced by the RS downlink (RSDL) application-specific integrated circuit (ASIC) on the telecom support board (TSB).

For the uplink, telecom provides avionics, specifically, the hardware command decoder (HCD), with

- The detected command bits it has demodulated from the uplink signal sent by the DSN station,
- The bit clock, and
- The command detection in-lock status.

Telecom relies on avionics to do error-control of the uplink data stream. That is, avionics determines what is a valid command and what is not a valid command.[9]

SDST mode control commands (such as: telemetry mod index, ranging on/off, coding, coherency) are done via the 1553 bus; they are issued by avionics.

RS422 interfaces exist between the SDST and the avionics TSB card, for (a) telemetry data and clock and (b) command data, clock and lock status (to the HCD.)

Telecom relies on the power subsystem to drive the waveguide transfer switch (WTS) and coaxial switches (CXSs), which select the X-band SSPA and the X-band and UHF antenna.

7.3.1.4 Description of X-Band Components

7.3.1.4.1 Antennas. As described in Section 7.3 and shown in the block diagram Fig. 7-11, each MER had several antennas, used during different phases of the mission:

- **Cruise** communications were through the MGA and the CLGA, both located on top of the cruise stage;
- During **EDL**, as the cruise stage and then the backshell were jettisoned, the spacecraft used the BLGA; and for the **first day** of deployment on the surface, the PLGA.
- For **surface operations**, the X-band antennas were the RLGA and the HGA.

Table 7-3 summarizes the major RF characteristics of the antennas and, at the bottom, their size and mass. The rover X-band antennas (RLGA and HGA) and the rover UHF antenna are mounted on the RED as shown in Fig. 7-13.

The CLGA, the BLGA, and the RLGA are RF horns mounted on the same circular waveguide "stack" that is designed to break off in sections as described in Section 7.3. The RLGA is the shortest section of waveguide; hence, the RLGA circuit losses are the smallest while those of the CLGA are largest.

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[9] We discovered one instance in the MER extended mission where the HCD and the flight software failed to handle gracefully a command containing multiple-bit errors. The error-filled "command" that went to flight software wrote to an incorrect location and caused rover entry to safemode. ISA Z84599 [8].

Table 7-3. MER X-band antenna characteristics.

Mission Phase	Cruise		EDL		Surface	
Antenna	CLGA	MGA	BLGA	PLGA	RLGA	HGA
Receive frequency, MHz	7183.118057 MER-A 7179.650464 channel 29 (MER-B) 7183.118057 channel 32 (MER-A)	Same	Same	N/A	Same	same
Transmit frequency, MHz	8435.370372 MHz channel 29 (MER-B) 8439.444446 MHz channel 32 (MER-A)	Same	Same	Same	Same	same
Gain, boresight, RX, dB	7.68	18.1	N/A	N/A	5.73	20.5
Gain, boresight, TX, dB	7.18	19.2	7.71	6.0	6.89	24.8
Polarization*	RHCP	LHCP	RHCP		RHCP	RHCP
Beamwidth, deg	±40 RX ±42 TX	±10.3 RX ±9.3 TX	N/A RX ±35 TX	N/A RX ±52 TX	±46 RX ±37 TX	±5.0 RX ±4.2 TX
Axial ratio, on b/s, dB	0.49 RX 0.85 TX	1.01 RX 0.27 TX				6.34 RX 4.47 TX
Axial ratio, off b/s, dB	85° off boresight: 7.70 dB RX 6.00 dB TX	20° off boresight: 6.29 dB RX 7.53 dB TX				
Design	Open-ended waveguide with choke	RF conical horn	Open-ended wave-guide with choke	Microstrip array 1.5 × 1.5 in. (3.8 × 3.8 cm)		0.28–m-dia. Printed dipole array
Mass, kg	0.431	0.499	0.235	0.020	0.775	1.1

* The polarization of the RLGA (and BLGA) is normally right-hand circular polarization (RHCP or RCP). It could be set to left-hand circular polarization (LHCP or LCP) to counteract a “stuck WTS” failure.

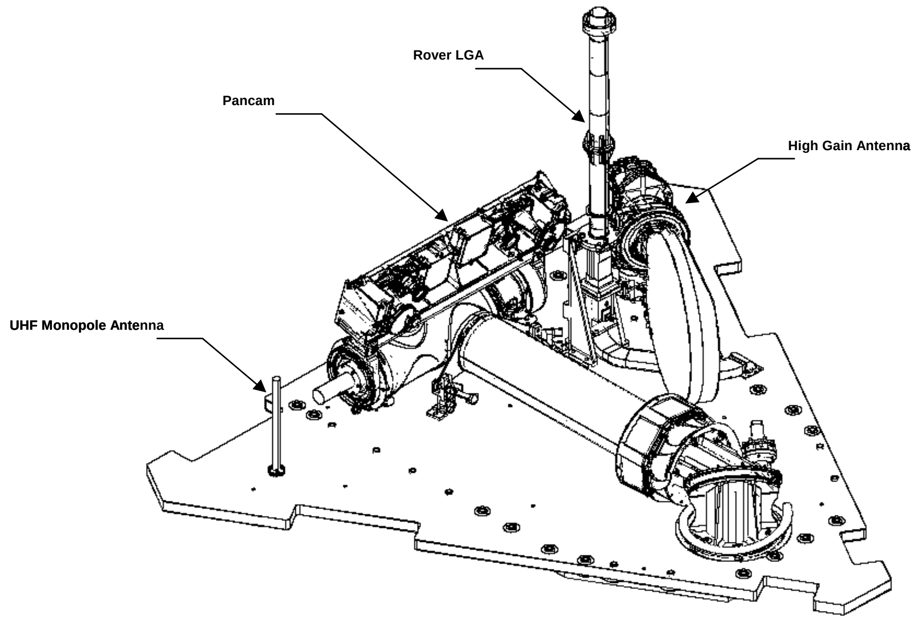

Fig. 7-13. X-band and UHF antennas on the RED.

The HGA is mounted on a two-axis gimbal located on top of the RED, so it became available only after deployment of the rover.

7.3.1.4.2 Radio Frequency Subsystem. The Radio Frequency Subsystem (RFS) is a general name for the three active X-band elements of the telecom subsystem and the passive elements that connect them[10]. The active elements are the SDST and the two SSPAs. The other active telecom subsystem element is the UHF transceiver, along with its diplexer. Figure 7-14 shows the locations of the SDST and SSPAs on one side of the rover electronics module (REM) along with the X band switches and diplexer. The UHF transceiver is on the other side of the REM. The REM is inside the WEB, as Fig. 7-15 shows.

[10] Spacecraft power into the RFS and the UHF transceiver that is not radiated as RF is converted to heat that must be managed. During cruise when the RFS was powered on continuously, MER thermal control was accomplished by the Heat-Rejection Subsystem (HRS). Figure 7-14 shows a heat pipe, part of the HRS, between the SDST and the SSPAs.

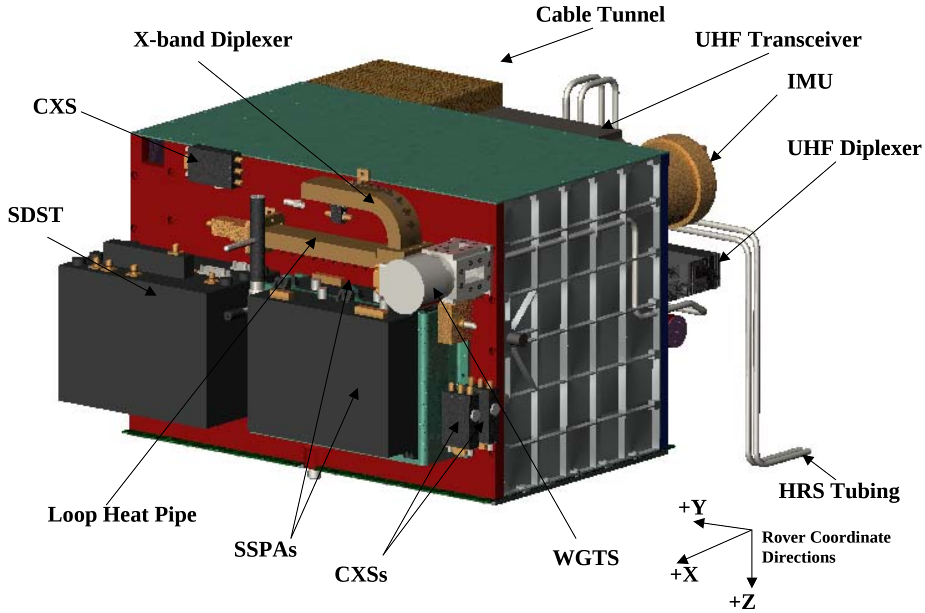

Fig. 7-14. RFS mounted on the sides of the REM.

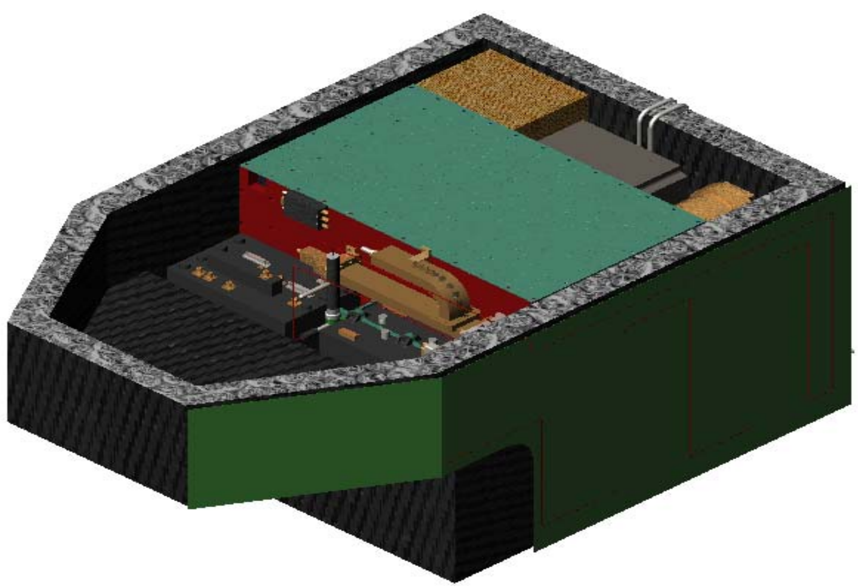

Fig. 7-15. MER warm electronics box.

During cruise, the cruise stage's HRS evacuated unwanted heat generated by the SSPA. Upon arrival at Mars, the HRS tubing was severed, as designed, at the interface with the aeroshell. Subsequently, excess heat was evacuated from the rover by passive thermal control.

On the surface, the WEB kept the rover warm at night, when no heaters could be left on. During the day, when X-band and UHF transmitters operated successively three or four times, the rover temperature would rise toward the hot temperature limits[11] because X-band and UHF heat-generating elements were so near each other on the REM. The amount of heat generated by operating X-band and UHF elements limited the durations and intervals between successive X-band and UHF transmitter operations.

7.3.1.4.3 X-Band Diplexer. The diplexer is a device that allows signals to be simultaneously transmitted at one frequency and received at another frequency. It provides sufficient receive side rejection of the SSPA generated transmitter signal preventing damage of the SDST receiver front end or interference with the uplink signal from Earth. It allows simultaneous transmit and receive signals to use the same antenna. X-band diplexer functional parameters are shown in Table 7-4.

7.3.1.4.4 Transfer Switches (WTS and CXS). Refer to the block diagram in Fig. 7-11. There are two types of transfer switches, coaxial and waveguide (CXS and WTS). The subsystem has three CXSs and one WTS. Transfer switch functional parameters are shown in Table 7-5.

- CXS 0 allows us to select either SSPA-A or SSPA-B for the downlink. Since launch, CXS 0 has been set to SSPA-A.
- CXS 1 selects between the HGA and the input to CXS 2.
- CXS 2 selects between the LCP port of polarizer P1 and the base petal LGA (PLGA) with left-hand circular polarization (LHCP or LCP).

The WTS (also known as a "baseball switch") is mounted on the output of the diplexer port 2. The WTS is commanded to select between the LGA stack, and the input to CXS 1.

[11] The upper (hot) temperature limits were 50°C allowable flight temperature (AFT) and 60°C protoflight qualification limit for SDST; 50°C AFT and 70°C protoflight qualification limit for SSPA; and 55°C AFT and 70°C protoflight qualification limit for UHF transceiver.

Table 7-4. X-band diplexer functional parameters.

Parameter	Diplexer Port	Parameter Value
Passband	TX	8.29–8.545 GHz
	RX	7.1–7.23 GHz
Insertion Loss	TX	26 dB max
	RX	9 dB max
Isolation	TX/RX	95 dB min
		100 dB nominal

Table 7-5. Transfer switch functional parameters.

Parameter	WTS Value	CXS Value
Frequency, GHz	7.1–8.5	7.1–8.5
Insertion Loss, dB	0.05	0.15
Return Loss, dB	23	20
Power Handling Capability, watts (W)	1000	70
Isolation, dB	>60	>60
Switching Time, ms	50	5

A WTS is heavier than a CXS. Because it has lower insertion loss, the WTS is used for the most important low-gain transmit path. A CXS is used on other paths where a higher insertion loss can be tolerated. These include the paths leading to the MGA, the HGA, and the PLGA. Though an LGA, the PLGA was used only on the first day of Mars surface operations.

To select a particular antenna for X-band receive and transmit may require commanding the WTS, CX1, and CX2. The connections between switches also enable use of the HGA and RLGA in surface operations even if the WTS should get stuck in the CXS1 position.

7.3.1.4.5 Solid-State Power Amplifier. Each of the two redundant SSPAs receives its RF input from SDST exciter via a 3-dB coupler, as shown in Fig. 7-11. Table 7-6 defines the major functional parameters of the 3-dB coupler.

The active SSPA provides about 16.8 W (42.25 decibels referenced to milliwatts [dBm]) of RF output power, as shown by Fig. 7-16, a graph taken from test data. The first point (mean and tolerances) is the prediction program model, and the four points to the right of the model point represent prelaunch measurements of the four MER SSPAs.

The direct current (DC) power input for each SSPA is about 58 W. The DC input varies a little with temperature.

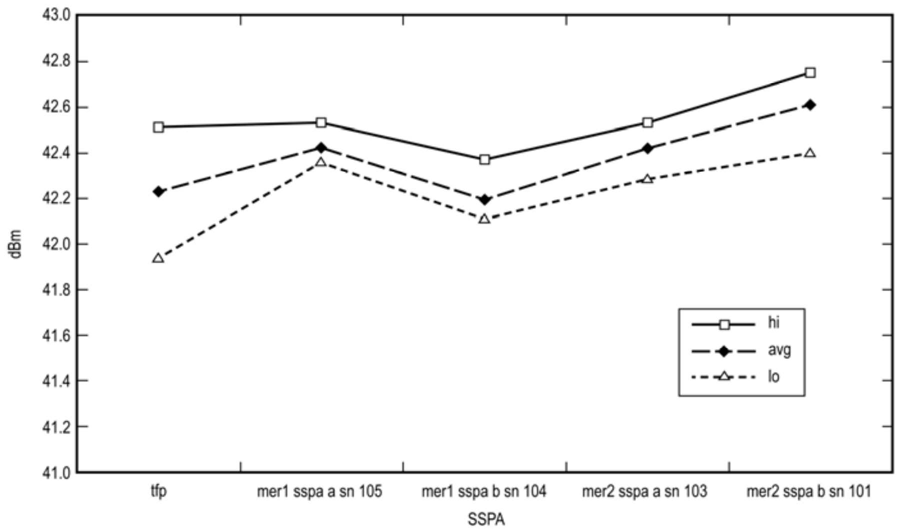

Fig. 7-16. RF output of the two MER-B (MER-1) and two MER-A (MER-2) SSPAs.

Table 7-6. 3-dB coupler functional parameters.

Frequency Range	7.1–8.5 GHz
Insertion Loss	0.5 dB
Isolation	20 dB
Coupling	3 dB
Power Handling	5 W

7.3.1.4.6 Small Deep-Space Transponder. The MER SDST is based on the proven design first flown on Deep Space 1 (DS1) in 1998, but its phase modulator was improved so as to be more linear (it is now a dual-stage modulator). Figure 7-17 is a photograph of the SDST. The SDST consists of four slices (boards): the power-converter module, the digital-processor module (where the signal processing is done), the down-converter module (where the analog part of the receiver phase-locked loop is) and the exciter module (where the telemetry and or ranging or DOR is modulated onto the downlink RF carrier). Receiver carrier-loop parameters are shown in Table 7-7.

Fig. 7-17. MER SDST

Having a POR state is very desirable. It ensures that the SDST comes up in a known state, for example every morning at rover wake-up. The flight software then has only to enter a limited set of well-defined commands to place the SDST into its desired operating state. Table 7-8 shows the POR state for the SDST.

Ranging Performance: Ranging is a means to determine the position of the spacecraft by measuring how long radio signals (ranging codes) take to travel from Earth, to the spacecraft, and back to Earth. Accuracy of the measurement depends on knowing how much of the total delay is produced in the transponder, the spacecraft antenna cabling, and the station ranging equipment.

Table 7-9 shows the delay the ranging signal experiences as it goes through the SDST. See Table 7-10 for total delay through the spacecraft.

In Table 7-9, one range unit (ru) = 1478/221 * 1/Ftx = 0.931 nanoseconds (ns) for MER-A and B.

Table 7-7. Receiver carrier loop.

Parameter	Parameter Value			
Noise Figure, dB	Temp	60°C	25°C	-40°C
	Channel 29 SDST (S/N 203)	2.59	2.15	1.27
	Channel 32 SDST (S/N 201)	2.58	2.12	1.91
Tracking Threshold	–155 dBm			
Tracking Rates	200 Hz/s for uplink $P_t \leq -120$ dBm			
Capture Range	±1.3 kHz			
Tracking Range	Greater than ±30 kHz at 200 Hz/s for uplink P_t down to –140 dBm			
Loop Noise Bandwidth at Threshold ($2Bl_0$)	20 Hz			
Loop Noise Bandwidth for Strong Signals	231.3 Hz two-sided, at P_c/N_0 = 100 dB-Hz			

Table 7-8. Power-on-reset state table.

Controlled Parameter or Mode	Value at POR
Auto Coherent/Noncoherent Transfer	Enabled
VCXO*/aux osc Transfer	Enabled
Command Data Rate	7.8125 bps
Normal TLM Encoding Mode	(7,1/2)
Normal TLM Mod. Index	50°
Normal TLM Mode	Subcarrier
Ranging Mod. Index (Gain)	17.5°
Ranging Mode	Baseband
Ranging	Off
Remote Terminal Time-out	Disabled
Remote Terminal (RT) Event Counter	0
SDST Event Counter	0
State 1 Time-out	Enabled
Subcarrier Frequency	25,000 Hz
Transponder Mode	Normal Operation
Wideband TLM	Off
X-band DOR	Off
X-band Exciter	On

* VCXO = voltage-controlled crystal oscillator

Table 7-9. SDST range delay (in range units).

Parameter	S/N 203—Channel 29	S/N 201—Channel 32
Range delay, average	1388.66 ru	1386.75 ru
Range delay variation at one temperature	±2.5 ru	±2.5 ru
Carrier suppression, dB	0.3 (17.5° nom) 1.2 (35° nom)	0.3 (17.5° nom) 1.2 (35° nom)
Ranging channel noise equivalent bandwidth	1.96 MHz	2.24 MHz

Table 7-10. SDST range delay after spacecraft integration (in nanoseconds).

Antenna Path	SDST (S/N203)—Channel 29	SDST (S/N201)—Channel 32
CLGA up/CLGA down	1383.9 ns	1384.0 ns
MGA up/MGA down	1393.5 ns	1394.5 ns

7.3.1.4.7 Range Delay after Integration on Spacecraft. The total range delay through the spacecraft (Table 7-10) will vary depending on which antenna path is used. This is because the cable lengths are significantly different. The table does not include values for the RLGA or HGA because ranging was not used for surface operations.

7.3.2 UHF

The MER UHF subsystem, a block diagram of which appears in Fig. 7-18, consists of the following components:

- Transceiver, which performs transmission and reception of UHF communications. It is also the interface with the avionics subsystem.
- Two UHF antennas: the DUHF (on the lander), used to transmit to MGS during EDL, and the RUHF, used to transmit and receive with orbiters during surface operations.
- Diplexer and coaxial switch to connect the transceiver to one of the two antennas.

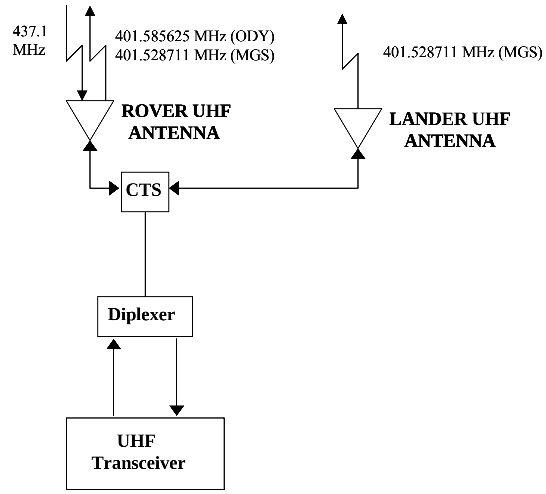

Fig. 7-18. UHF subsystem block diagram.

7.3.2.1 UHF Antennas

The descent and rover UHF antennas are quarter-wavelength monopoles. Figure 7-19 shows photographs of the rover UHF antenna.

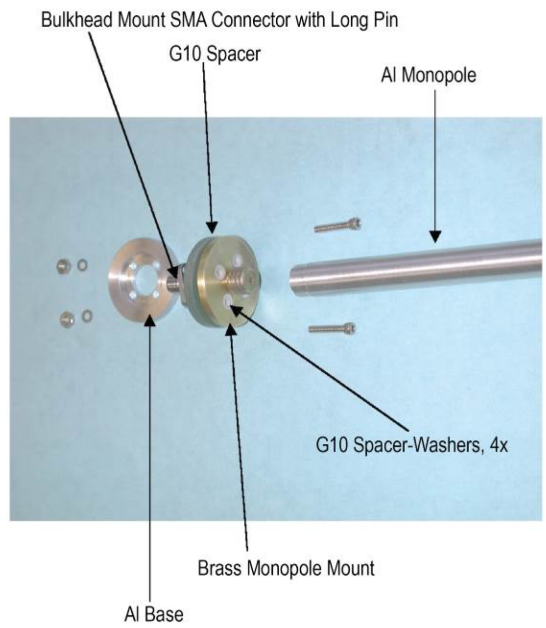

Fig. 7-19. Rover UHF antenna.

The DUHF has an additional mechanism that deploys the antenna parallel to the bridle after backshell separation. While the monopoles are nominally linearly polarized with a toroidally shaped gain pattern, parasitic coupling of the UHF transmit and receive signals with structures on the spacecraft create significant distortions to both gain and polarization. This is especially true for the RUHF, due to vertically oriented structures (mainly the LGA and PMA) on the deck that act like passive parasitic antenna elements.

A right-hand polarization pattern, as measured on a rover mock-up in the JPL antenna range, is shown in Fig. 7-20. The figure shows the RUHF antenna pattern in polar coordinates, with the concentric grid markers (0 to 120 deg) representing the cone angle (angle from the boresight) and the radial grid lines (0 to 360 deg) representing the clock angle. The RUHF pattern is not symmetrical with respect to the clock angle. The asymmetry causes significant variations in returned data volume from pass (orbiter overflight) to pass. The data-volume variations result mainly from

- The elevation profile of the orbiter and thus the pass duration,
- The azimuth profile of the orbiter during the overflight, and
- The rover orientation (tilt from horizontal) on the surface.

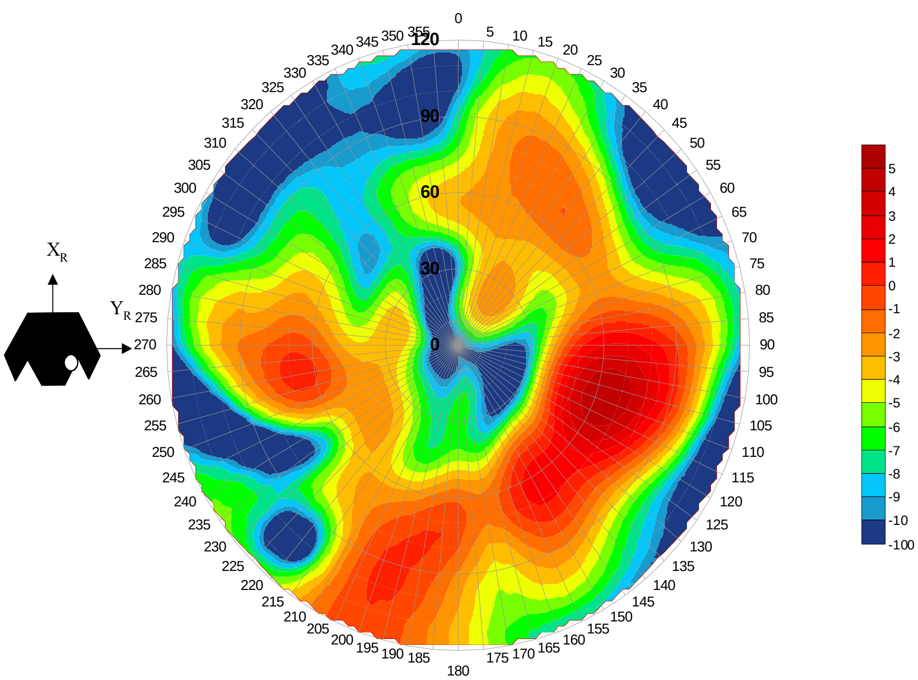

Fig. 7-20. Rover UHF antenna pattern as measured on a mock-up at 402 MHz.

7.3.2.2 UHF Transceiver and Diplexer

The UHF transceiver is the core of the UHF subsystem. It is manufactured by CMC Cincinnati Electronics. With few exceptions, the MER units are identical to the two UHF radios flying on Mars Odyssey (Fig. 7-21). The MER transceiver has the receive frequency and transmit frequency swapped relative to Odyssey's, and the MER receiver is compatible with MGS as well as with Odyssey.

CMC also manufactured the MER UHF diplexer used to isolate transmit and receive frequencies for simultaneous operation. The transceiver and diplexer were thoroughly tested as a single subsystem.

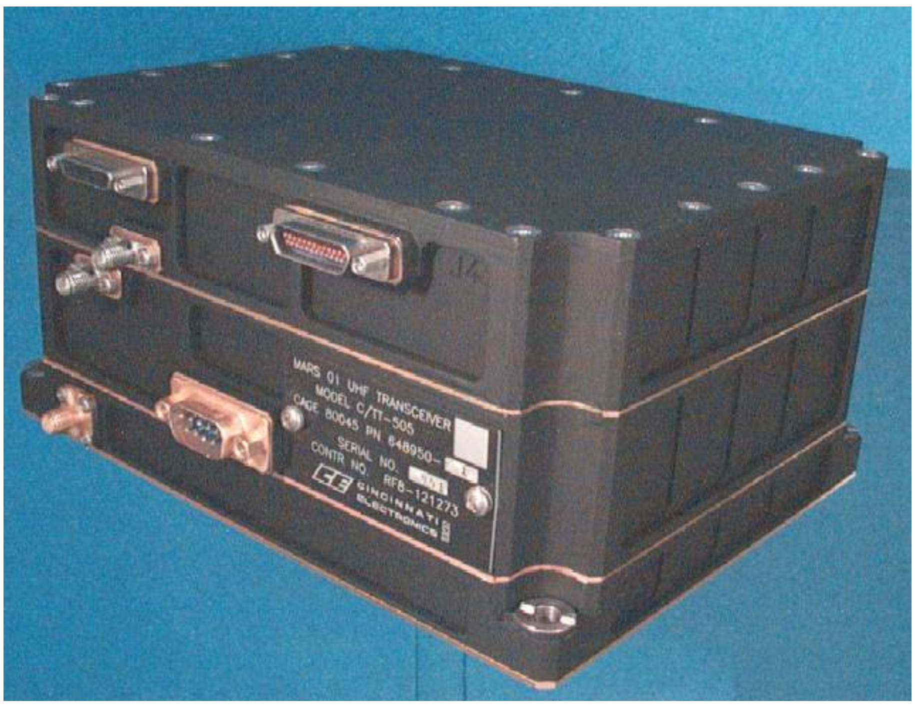

Fig. 7-21. Odyssey UHF transceiver.

7.3.2.3 UHF System Operation

7.3.2.3.1 Physical Layer. At the physical layer [23], the following are the main characteristics of the MER UHF system:

- Power (measured)
  - Power consumption 6 W (receiving only), 43 W (transmitting/receiving)
  - RF output 12 W (typical, transmitting)
- Frequency
  - One forward frequency (orbiter to rover) of 437.1 MHz
  - Two return frequencies (rover to orbiter):
    - 401.585625 MHz (Odyssey and MEX)
    - 401.528711 MHz (MGS)
- Modulation
  - PCM/Bi-Phase-L/PM modulation with residual carrier, with a modulation index of 1.05 radians (60 deg)
- Data Rates
  - Forward link: 8, 32, 128, 256 kbps[12]
  - Return link: 8, 32, 128, 256 kbps[13]
- Encoding
  - Forward link: none
  - Return link: convolutional with rate 1/2 and constraint length 7
- Carrier Acquisition at ±8 kHz off center frequency (forward link)
- Receiver threshold, typical, forward link, for bit error rate of 1×10^{-6}
  - 8 kbps phase-shift-keyed, uncoded: –117 dBm

7.3.2.3.2 Data Frame Layer (Odyssey and Mars Express). At the data frame layer, MER implements the Consultative Committee for Space Data Systems (CCSDS) Proximity-1 Space Link protocol (UHF1) [8], which is the standard used for relay communications by all the missions currently at Mars, except MGS, launched in 1996.

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[12] The UHF radio was implemented to support these four rates. However, MER required, tested, and operated the forward link with only the 8-kbps rate. The command path to the rover has a low data-volume requirement.

[13] Operationally, the highest return rate to MGS is 128 kbps. Initially, the highest rate to Odyssey was also 128 kbps. Later in the primary mission, the 256-kbps rate was also used. See Section 7.4 of this chapter.

The data layer of the Proximity-1 protocol provides the structure (frame sequence number and forward error coding) that allows the establishment of a compatible link and the exchange of error-free information between the orbiter and a surface vehicle such as the rover. It also allows verification that the orbiter is communicating with the intended surface vehicle.

The link with a surface vehicle is always initiated by the orbiter at 8 kbps, sending a Proximity-1 transfer frame (17 bytes long) with Set Transmit and Set Receive directives in order to configure the transceivers at both ends in a compatible mode. Information about communications mode, data rates, coding, and modulation to be used are all contained in this frame.

The nominal mode of communications with a surface vehicle is the sequence-controlled service defined in the Proximity-1 protocol. This mode ensures the error-free transmission of the input bit-stream to the receiving end. The serial data from the transceiver transmit buffer is formatted in the data field of the Proximity-1 transfer frame.

The following are the most important fields of the transfer frame header:

- Attached Synchronization Marker to allow identification of the start of the frame
- Spacecraft ID of the surface vehicle
- Frame Sequence Number to allow the receiving end to verify that data is being received in the proper order
- 32-bit cyclic redundancy check (CRC) appended after the frame to allow the receiving end to detect if any bit of the packet suffered an error during transmission.

In the sequence-controlled mode, MER implements a Go-Back-2 [frames] Automatic Repeat Request (ARQ) protocol. This protocol permits transmission of the next sequenced frame while waiting for the acknowledgment (ACK) for the one previously sent. In this way, the throughput is increased relative to a Stop-and-Wait protocol. In the case where an ACK is not received before the end of the transmission of the second frame, the orbiter will continue sending the same two transfer frames still to be acknowledged. MER can receive and send Proximity-1 frames up to 1024 bytes long.

To transfer data, the sequence-controlled service needs both a forward link and a return link to be active. If an anomaly (such as a failure of a transmitter) has occurred in one of the two links, data can still be sent on the remaining functional link by operating in the so-called unreliable bit-stream mode. In this mode, the Proximity-1 protocol is bypassed, and delivery is not guaranteed to be error-free or in order.

All forward- and return-link equipment are operational on the Odyssey and MRO orbiters and on Opportunity (though Spirit's condition has been unknown since March 2010). The unreliable bit-stream mode has not been known to be required since EDL. However, the unreliable mode was verified on Opportunity/orbiter return link tests, and has been routine in post March 2010 Spirit return link planning for both Odyssey and MRO.

7.3.2.3.3 MGS Operations. The MER UHF transceiver is also backward-compatible with the Mars Balloon Relay protocol (MBR, also called UHF2) implemented on MGS (originally designed in support of Russian and U.S. missions consisting of small landers, balloons, and penetrators).

The UHF2 protocol has no data-layer protocol. During a 16-s cycle, the forward link is used to send two types of tones:

- One of three request commands (RCs) that allow MGS to address any one of three surface vehicles at the same time.[14] After detection of the RC tone, the surface vehicle will send a pseudonoise (PN) code while waiting for the transmit command (TC).
- The TC is sent by MGS when its receiver achieves bit-sync-lock on the initial return link. After detection of the TC tone, the surface vehicle starts sending its science and engineering data.

If the return power-to-noise ratio drops below threshold, MGS begins transmitting a carrier only. Upon receiving the carrier, the surface vehicle radio will stop transmitting. Due to timing issues and the fact that no data layer is present, the quality of the UHF link to MGS is less than what is possible in the link to Odyssey or MEX.

7.3.3 MER Telecom Hardware Mass and Power Summary

The mass and input power of the elements of the telecom subsystem are summarized in Table 7-11.

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[14] Both Spirit and Opportunity respond to the same tone RC1, since it was required that the two UHF radios be swappable between rovers during ATLO. Because Spirit and Opportunity landed on opposite sides of Mars, there is no possibility of overlap during an overflight.

Table 7-11. MER X-band and UHF mass and input power summary.

Assembly	Input Power, W	RF Power out, W	Mass, kg	Quantity	Mass Total, kg	Dimensions, cm
X-Band						
SDST each			2.682	1	2.682	18.1 × 11.4 × 16.6
Receiver (R) only	11.0					
R+exciter, two-way (coherent)	13.3					
R+exciter, one-way (aux osc)	13.8					
SSPA	58	16.8	1.300	2	2.600	4.4 × 17.2 × 13.4
Hybrid			0.017	1	0.017	2.5 × 1.0
WTS			0.378	1	0.378	4.1 × 9.65 × 10.9
CTS			0.062	3	0.187	5.3 × 3.0 × 4.0
Coax			0.057	4	0.228	
Diplexer			0.483	1	0.483	27.7 × 5.6 × 7.9
Attenuator			0.004	1	0.004	0.79 × 2.18
HGA			1.100	1	1.100	28.0 dia.
CLGA			0.431	1	0.431	10.0 × 2.3
BLGA			0.235	1	0.431	10.3 × 3.5
RLGA			0.775	1	0.431	60.2 × 3.1
PLGA			0.020	1	0.020	1.5 × 1.5
MGA			0.499	1	0.499	23.4 × 13.4 at rim
Terminations, dummy loads, etc.			0.006	4	0.026	
X-band totals	71.8 max	16.8	5.367		6.835	
UHF						
UHF transceiver	6 rx only 43 rx/tx	12 *	1.900	1	1.900	5.1 × 6.8 × 3.7
Diplexer			0.400	1	0.400	2.9 × 3.7 × 1.3
CTS			0.083	1	0.083	5.3 × 3.0 × 4.0
RUHF			0.100	1	0.100	16.9 × 1.9 × 1.9
DUHF			0.100	1	0.100	16.9 × 1.9 × 1.9
Coax			0.300	1	0.300	

* UHF RF power out is measured at diplexer output.

CTS = coaxial transfer switch, WTS = waveguide transfer switch

7.4 Ground Systems

7.4.1 Deep Space Network

7.4.1.1 Background

Communication between the MER spacecraft and the DSN has been at X-band for all mission phases (cruise, EDL, and surface operations, and continuing into the extended missions). Furthermore, even though the MGS and Odyssey orbiters have received surface data from rovers via a UHF link, the data from the orbiters was transmitted to the DSN via X-band. Specific station operating modes and configurations to support MER are in the Network Operations Plan [9].

Cruise passes were conventional, most of them 6–10 hours long with both uplink and downlink. Ranging or delta-DOR navigation signals shared the carriers with command-and-telemetry modulation. Cruise commanding could be initiated any time after MER's mission controller (call sign ACE, the real-time interface with the DSN) verified that the uplink sweep was successful by seeing the downlink frequency transition from one-way noncoherent to two-way coherent. This transition confirmed that the spacecraft receiver was in lock with the uplink carrier and ready to receive commands. During cruise and again beginning in May 2005, the one-way light time (OWLT) was less than 10 min, and the tracking passes were long, so it was feasible to wait for confirmation of sweep success before commanding.

Surface operations during the first portion of the primary mission used two-way DTE passes 30–60 min in duration, with both uplink and downlink. Later surface operations relied on uplink receive-only passes called direct-from-Earth (DFE). These were 20–30 min in duration and had no downlink. DFE passes were used to reduce spacecraft power use. Neither delta-DOR nor ranging was used during surface operations, since other means of determining rover position were accurate enough.

The OWLT began to exceed 15 min shortly before the end of the primary mission and did not again fall below 15 min for nearly a year. Fifteen minutes is significant compared to the duration of the communications pass. To avoid tying up rover operations for an extra round-trip light time (RTLT), extended-mission commands were radiated prior to receipt of confirmation of uplink sweep success. The normal downlink mode was coherency-enabled, not only to obtain two-way Doppler data, but also because SDST temperature varied continually during a sol. Temperature changes caused frequency variations in the SDST aux osc output that made one-way downlink difficult or impossible to acquire and track.

7.4.1.2 Stations Used by MER (34-m and 70-m, All Complexes)

For cruise and surface operations phases, all three 70-m stations, all three 34-m high-efficiency (HEF) stations, and all of the operational 34-m beam waveguide (BWG) stations tracked MER. During launch, a 26-m station's X-band acquisition aid antenna was used to initially detect the downlink and to help with station pointing correction in case of deviations from the nominal trajectory. During cruise, a DSN array of stations successfully tracked MER as a demonstration.

7.4.1.3 DSN Changes Instituted during the MER Mission

7.4.1.3.1 34-m BWG 20-kW Transmitter and X/X/Ka-Feed Upgrades. Station transmitter power has generally been less of a concern to MER than is using a standard uplink (command) bit rate consistently to avoid confusion and errors over the rate. However, MER mission planning became simpler when all of the 34-m BWG transmitters were upgraded from 4 kW to 20 kW. This meant that the X-band uplink performance of all DSN 34-m antennas could be treated as essentially the same, and a single uplink rate could be used for long periods of time. Two of the 34-m BWG stations (DSS-26 and DSS-55) also received new feeds that allowed them to transmit at X-band and receive at both X-band and Ka-band, with a lower X-band system noise temperature than with the previous feed. Though MER transmits and receives X-band only, the X/X/Ka feeds improved X-band downlink performance for these stations, making them comparable to (or slightly better than) 34-m HEF antennas.

The nominal cruise uplink rate was 125 bps. Because of the shorter communications periods (comm windows, defined in Section 7.3.1.3) during surface operations, the uplink rate via the HGA was initially 1000 bps until increasing Earth–Mars distance reduced this to 500 bps. Similarly, the uplink rate via the RLGA was initially 31.25 bps, and later was made 15.625 bps.

On launch day, the first three passes were with 34-m stations operating at a reduced uplink power (200 W). If the received power at the spacecraft had been too high, risks would have included digital-to-analog converter (DAC) rollover glitches[15] or even damage to the SDST hardware.[16]

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[15] The SDST's receiver has a DAC. The DAC rollover glitch is a known idiosyncrasy. When the receiver static phase error (SPE) crosses binary rollover points (for example, 8, 16, and 32 DN) as the frequency to the in-lock SDST receiver is increasing, the DAC generates a current spike that can knock the receiver out of lock. The SDST is most susceptible to this glitch at strong signal levels and cold temperatures.

For the cruise and surface flight software loads involving large uplink file loads, the 20-kW transmitters supported 2000 bps (highest uplink rate available) on the cruise MGA and the rover HGA during the primary mission. In the extended mission, the flight software update was uplinked at 1000 bps over many passes (~30 min each). A flight software patch was uploaded at 2000 bps in February 2005.

7.4.1.3.2 Network Simplification Project Changes. The Network Simplification Project (NSP) changes were largely transparent to MER.

The project had to change station monitor channels to reference newly defined Monitor-0158 channels in the data monitor and display (DMD) and query processes. However, MER incorporated a set of multimission monitor DMD pages that were already developed and tested by the Lockheed Martin Aerospace (LMA) Mars operations team. Not having to develop these from scratch saved MER flight operations considerable time.

Twice during cruise, as documented in Incident, Surprise, Anomaly report (ISA) Z82482 [10], the new ability of a DSN station to transmit and receive on different polarizations was accidentally invoked, despite the fact that the spacecraft antenna in use always transmitted and received with the same polarization at any given time. Because of less-than-perfect isolation in the spacecraft polarizers, imperfect termination of an unused port on the WTS, and coalignment of the boresights of the MGA (connected to the left-hand [LH] port) and the CLGA (connected to the right-hand [RH] port), there were leakage paths that allowed uplinks sent with the wrong polarization to get into the SDST.

One occurrence was during a critical spacecraft cold-reboot activity when the CLGA was selected, but a left-hand-circular-polarized (LCHP, or LCP) uplink (and commands) got in through the MGA via a leakage path. The opposite situation occurred later in cruise when the MGA was selected, but a right-hand-circular-polarized (RHCP, or RCP) uplink sweep got in through the CLGA (no commands were sent). In the first case, the off-boresight angle from the MGA to the Earth was only about 2.5 deg; in the second, the angle from the CLGA to Earth was about 8 deg.

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[16] Use of 200-W uplink power ensured that the maximum uplink power would not exceed –60 dBm on the first pass after launch, taking into account station-to-spacecraft range, and angle to the spacecraft LGA. The specified SDST damage threshold is +10 dBm.

The polarizers (septum design) have inherent port-to-port isolation of better than -20 dB. However, in the stack configuration, there are significant mismatches at several interfaces that contribute to degrading the isolation. The use of a dead short on the unused port of the WTS (to save spacecraft mass) allows oppositely polarized signals to leak into the other port of the polarizer. A secondary leakage path results from the imperfect polarization generation of the polarizers.

Since surface operations began, only the RH port has been used (for either the HGA or RLGA), so it is unlikely that any LHCP uplink from the DSN would affect the spacecraft.

7.4.1.3.3 Multiple Spacecraft per Aperture. In late cruise, MER began regularly participating in Multiple Spacecraft per Aperture (MSPA) sessions with the Odyssey and MGS orbiters once the MER spacecraft came close enough to Mars to be in the same station antenna beamwidth as these orbiters. For surface operations, MSPA has in fact become a valuable capability for MER, in addition to the inherent ground-system efficiency improvement of being able to track two or three simultaneous downlinks.

Because MER surface operations at X-band used 20- to 60-min communications sessions of the same order of magnitude as the OWLT (10–20 min), or without a downlink at all, stations could not Conscan[17] on the MER downlink signal in time for it to improve uplink pointing. Furthermore, when MER was downlinking via the RLGA, Conscan was generally not used. Ripples in the RLGA pattern (several decibels from peak to peak) would be misinterpreted by Conscan as pointing errors, causing the DSN antenna to change its pointing (adversely) in an attempt to compensate. Enabling Conscan on an orbiter X-band downlink (via the HGA) improved 70-m pointing for the MER uplink by 3 to 5 dB for many uplink passes, as later determined from recorded spacecraft telemetry sent back over the UHF relay link. MSPA was also useful for troubleshooting anomalous signal characteristics in the MER

[17] Conscan (from "conical scanning") is an antenna-pointing technique that relies on the antenna system using its received signal to minimize the angle between the antenna's boresight and the direction of the received signal. To begin, the boresight is intentionally moved a small angle away from the predicted pointing direction, then continuously scanned in a cone around the predicted position at that small angle. The Conscan algorithm estimates the position around the cone where signal strength is the highest and moves the boresight in that direction. In contrast with the predict-driven pointing that sometimes caused significant (3- to 5-dB) pointing errors with MER surface downlinks, Conscan is not dependent on modeled Earth atmospheric refraction.

uplink and downlink. Comparing the signatures with those of the orbiter uplink and/or downlink (when available) helped determine whether the cause was the DSN, weather, or the spacecraft.

7.4.2 Entry, Descent, and Landing Communications

Figure 7-22, from the Mission Plan [7], summarizes the events and representative relative times for MER-A and MER-B during the EDL mission phase.

EDL was divided somewhat arbitrarily into the segments listed below. Together they took about 6 min, hence the nickname for this period, “six minutes of terror.”

- Cruise (prior to atmospheric entry [E])
- Entry (from E to E + 230 s)
- Parachute deployment (from E + 230 s through E + 270 s)
- Bridle deployment (E + 270 s through E + 360 s)
- Landed (beyond E + 360 s)

The most challenging period of the MER-to-ground communications was during EDL. As each vehicle entered the Martian atmosphere, it slowed dramatically. The extreme acceleration and jerk caused extreme Doppler dynamics on the 8.4-GHz (X-band) signal received on Earth. After the vehicle slowed sufficiently, the parachute was deployed, causing almost a step in deceleration. After parachute deployment, the lander was lowered beneath the parachute on a bridle. The swinging motion of the lander imparted high Doppler dynamics on the signal and caused the received signal strength to vary widely due to changing antenna pointing angles. All during this time, the vehicle was transmitting important health and status information that would have been especially critical for future missions if the landing had not been successful.

Even using the largest station antennas, the weak signal and high dynamics rendered it impossible to conduct reliable phase-coherent communications. Therefore, a specialized form of M-FSK was used. The signal processing that was required to demodulate the X-band DTE data tones used, as a point of departure, the methods of the Mars Pathfinder mission. However, the process for MER extended these to allow carrier tracking in conjunction with tone demodulation. The M-FSK scheme used 256 different signal frequencies, each a semaphore to indicate the completion of a particular EDL event or the status of the flight software and fault protection at a particular time.

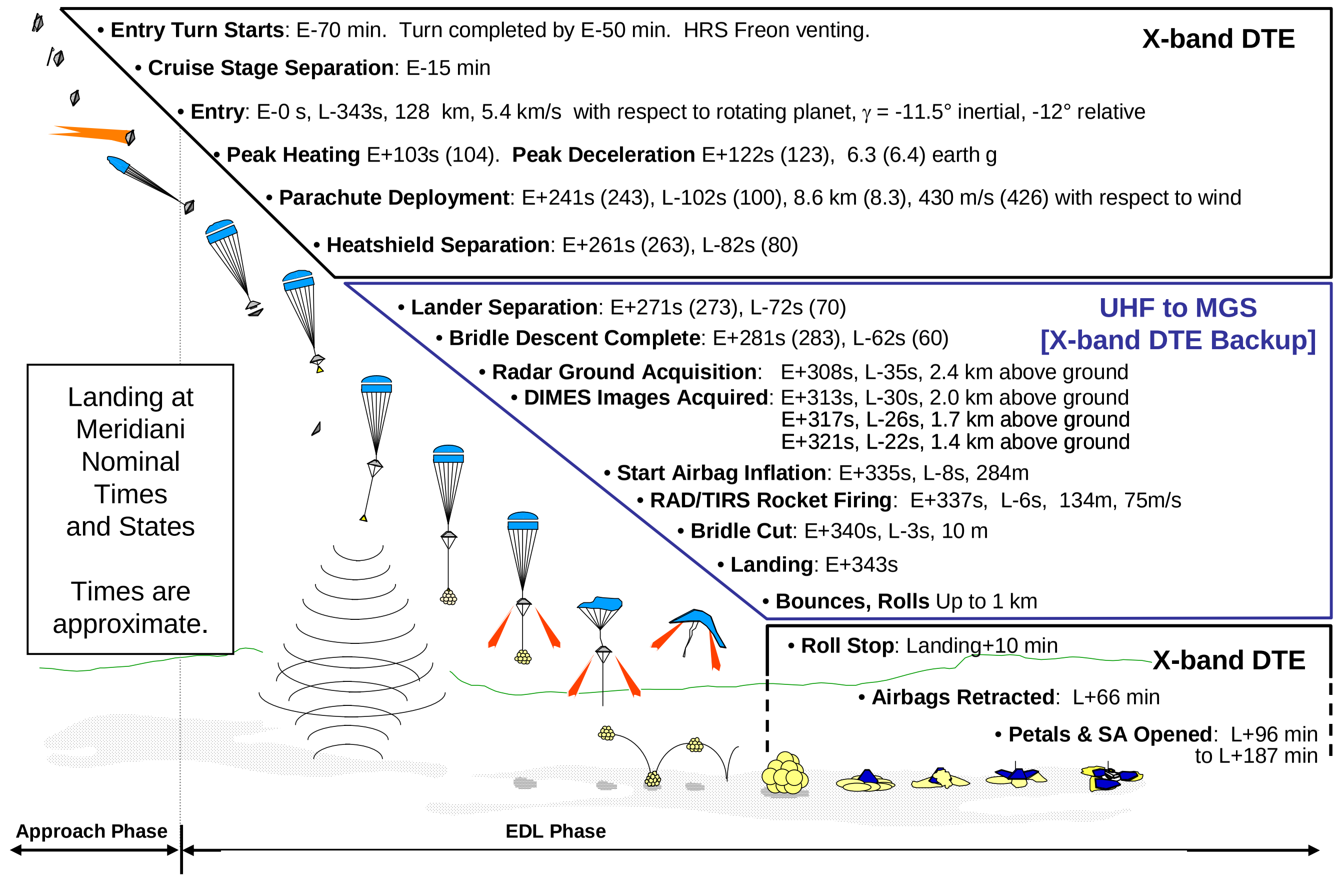

Fig. 7-22. MER-A EDL representative timeline (MER-B times in parentheses).

The following summary of carrier-frequency and signal-level variations that occurred during EDL has been adapted from the plans and expected variations described in [11]. The signal frequencies were modulated on the carrier, one at a time, as a subcarrier, using the SDST's capability to produce many distinct subcarrier frequencies. During hypersonic entry, the signal frequency could be switched every 10 s, resulting in the communication of 8 bits of information each 10 s. When the lander was suspended from the bridle, and the UHF link was prime, the duration of the modulation frequencies was extended to 20 s to better facilitate detection during this period of highly varying signal-to-noise ratio (SNR). This would result in fewer messages, but each would be of higher reliability than would be possible with the use of a 10-s duration.

The expected MER-B dynamics profile, magnitude, and uncertainty are illustrated in Fig. 7-23. The profiles are shown for one of the candidate landing sites. Three different profiles are shown—the nominal entry path angle (centered) and two other path angles (to the left and right) that correspond to the estimated maximum deviations from the nominal profile. For each entry angle, the spacecraft-to-Earth Doppler shift at the X-band frequency is shown in Fig. 7-23 (a). The range of Doppler shift is approximately 90 kHz, and the (two-sided) range of Doppler uncertainty is approximately 50 kHz. Figure 7-23 (b) shows the expected Doppler rate, or first derivative of Doppler frequency, due to acceleration.

The first maximum occurred due to atmospheric drag during hypersonic entry, at 150 s to 220 s past entry. The maximum varied from 700 Hz/s to 1200 Hz/s, depending on entry angle. The second maximum was a spike in Doppler rate due to parachute deployment. During the hypersonic entry, the range of uncertainty in Doppler rate was roughly the same as the maximum possible Doppler rate. For example, at approximately 150 s past entry, the acceleration could be anywhere from approximately 0 Hz/s to 1200 Hz/s. The same is more obviously true for the parachute release. Figure 7-23 (c) shows the second derivative of Doppler frequency due to jerk. During hypersonic entry, the value ranged from approximately -25 Hz/s^2 to 40 Hz/s^2. The exact values shown at parachute deployment are not precise due to the inaccuracy in the numerical differentiation used to obtain them.

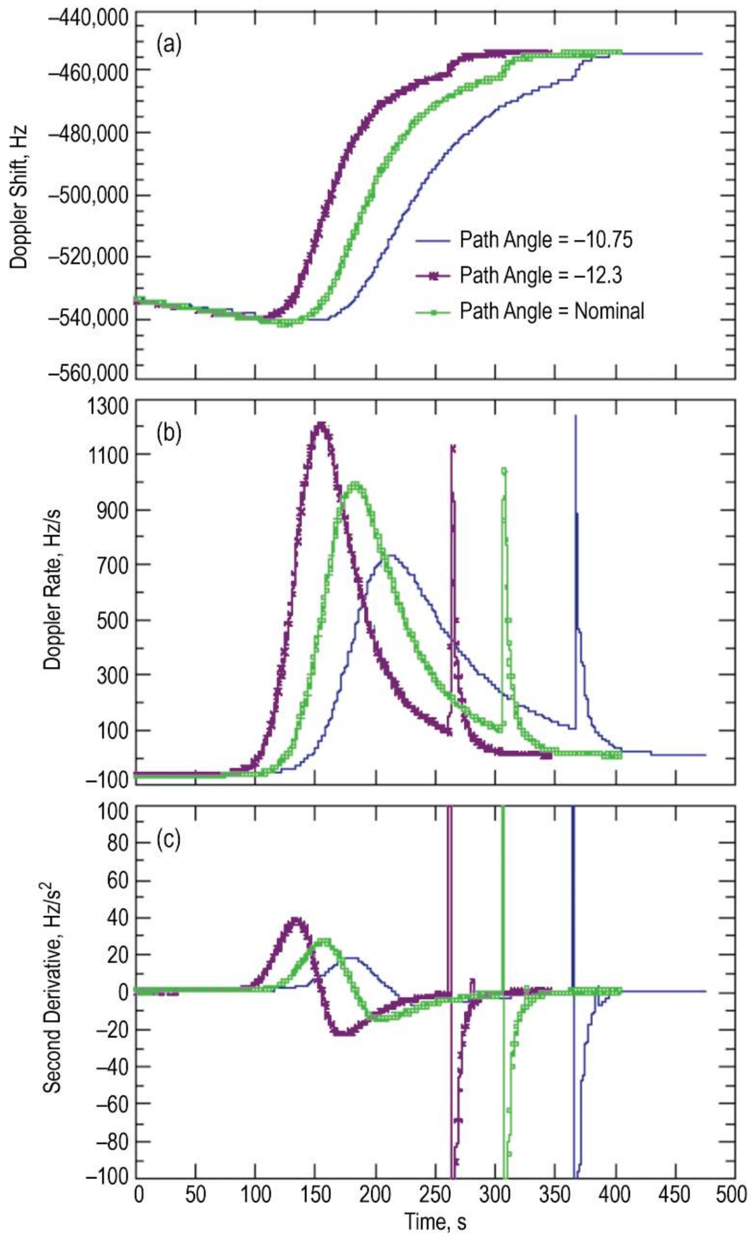

Fig. 7-23. MER-B EDL dynamic properties of (a) Doppler, (b) Doppler rate, and (c) Doppler acceleration. (The nominal path is at the center and the other two path angles to the left and right are the estimated maximum deviations from nominal.)

The predicted SNR for the MER-B downlink signal during EDL is shown in Fig. 7-24. It is the ratio of total power-to-noise spectral density of the X-band signal received at a 70-m DSN antenna. The total power received at Earth from the spacecraft depends on the angle of the spacecraft with respect to the Earth and on the antenna-gain pattern. The antenna gain depends both on the angle off the axis of rotation of the spacecraft and on the rotation angle. The center curve in Fig. 7-24 is the nominal expected total power SNR versus time. This nominal SNR is based on the spacecraft axis orientation being the nominal angle, and on the nominal antenna gain with respect to rotation angle. The upper curve is the maximum SNR that might be achieved and is based on the most favorable orientation angle, and the lower curve is the minimum expected SNR. The three vertical dashed lines indicate the nominal times of the key events of parachute deployment at 246 s past entry, lander separation from the backshell at 276 s past entry, and full extension of the bridle with the lander at its end at 286 s past entry.

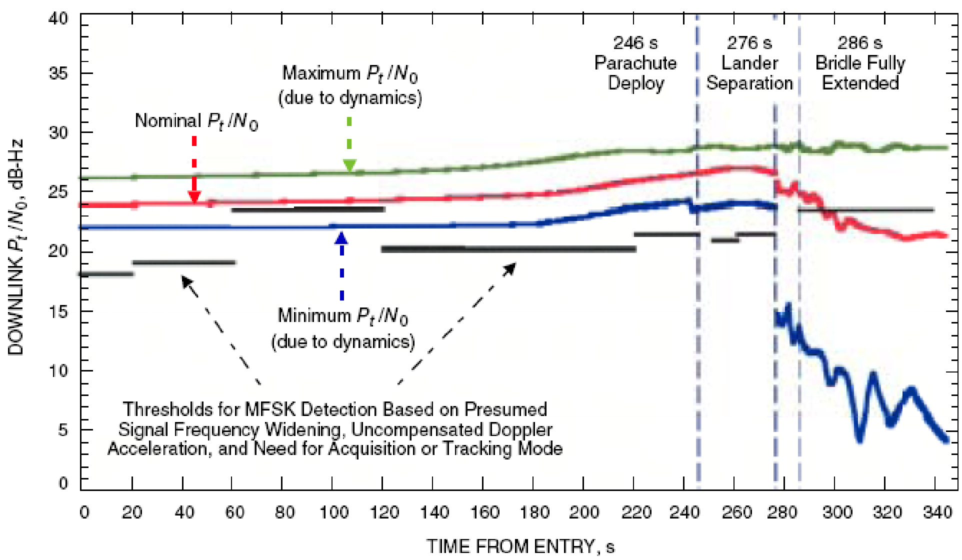

Fig. 7-24. Predicted X-band downlink signal levels during MER-B EDL.

Figure 7-25 (a) shows the block diagram of the EDL data analysis (EDA) processor[18] and Fig. 7-25 (b) the EDL tracking process.

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[18] A NASA Tech Brief [12] documents the EDA, described as a system of signal-processing software and computer hardware for acquiring status data conveyed by M-FSK tone signals transmitted by a spacecraft during descent to the surface of a remote planet. The design of the EDA meets the challenge of processing weak,

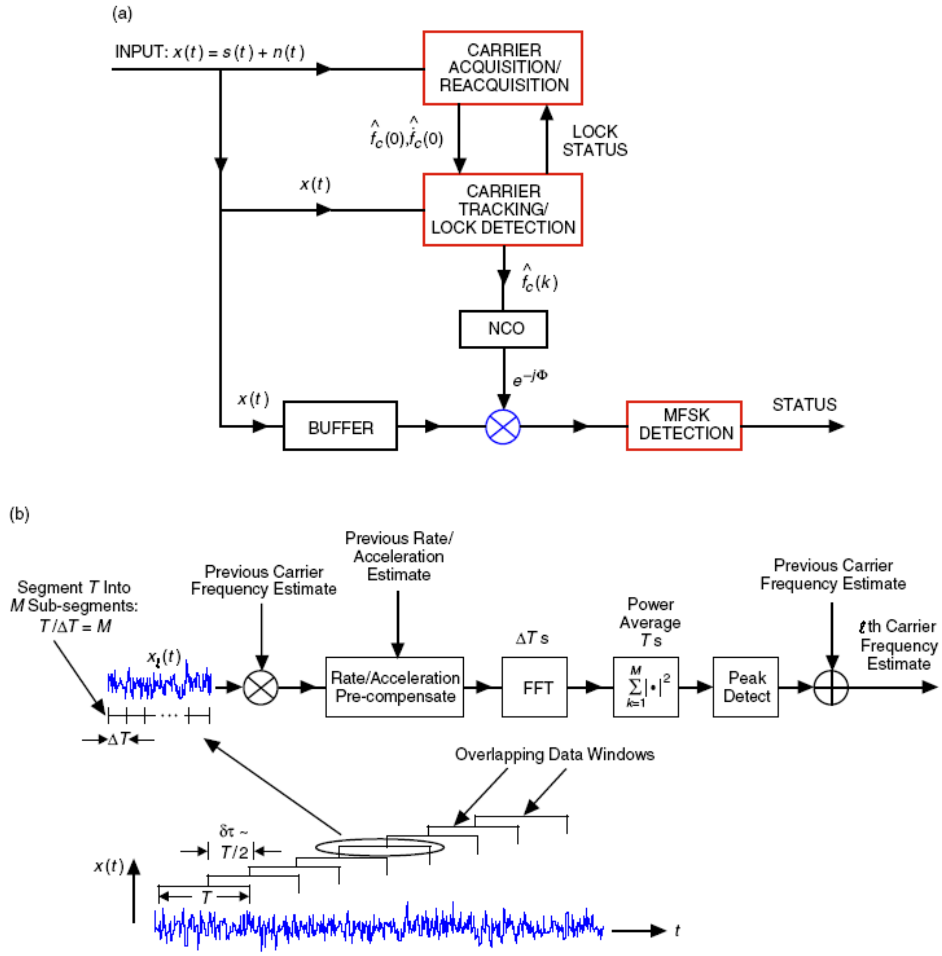

Fig. 7-25. Entry, descent, and landing (EDL) (a) signal processor and (b) tracking process.

fluctuating signals that are Doppler-shifted by amounts that are only partly predictable. The software supports both real-time processing and post processing. The software performs fast-Fourier-transform integration, parallel frequency tracking with prediction, and mapping of detected tones to specific events. The use of backtrack and refinement parallel-processing threads helps to minimize data gaps. The design affords flexibility to enable division of a descent track into segments, within each of which the EDA is configured optimally for processing in the face of signal conditions and uncertainties. A dynamic-lock-state feature enables the detection of signals using minimum required computing power—less when signals are steadily detected, more when signals fluctuate. At present, the hardware comprises eight dual-processor personal-computer modules and a server. The hardware is modular, making it possible to increase computing power by adding computers.

During the higher-dynamics portions of EDL (pre-entry cruise, entry, parachute deployment, and bridle deployment), the detection interval, T, used for carrier tracking and acquisition was made 1 s (2 s in the lower-dynamics cruise portion). However, in the final phase of EDL, once the lander came to rest, the dynamics remained very low. A much longer interval (T ~15 s) could be used and in fact was desirable due to the lower SNR conditions. On the other hand, the tone-detection interval throughout was matched to the symbol duration (10 s) since the effects of carrier dynamics had been removed to a large extent by the carrier tracker.

7.4.3 Relay Data Flow

Active orbiters (Odyssey and MGS in the early days of MER and Odyssey and MRO in the latter part of the surface mission) have a relay package on board that allows the reception of data from vehicles (landers, rovers, etc.) on or near the surface of Mars. This surface-to-orbiter link can be referred to as the return link or, by analogy to DTE, downlink.

7.4.3.1 Odyssey

The total allocation in the Odyssey memory for surface vehicle data is approximately 260 Mb.

At the beginning of the primary mission, each of the two rovers was allocated 120 Mb.[19] Data received in the relay was divided into fixed length packets with a distinct application process identifier (APID) for each rover. These packets have fairly high priority on the Odyssey downlink with data rates to the DSN of up to 110 kbps at the beginning of the mission. As the Mars-Earth distance increased, Odyssey rates dropped to approximately 40 kbps into a 70-m DSN station, 14 kbps into a 34-m antenna. Odyssey can also operate in bent-pipe mode, that is, downlink to Earth while at the same time receiving data from landers at UHF (for the passes where Odyssey does not need to transmit data to the rover at UHF).

Like any other data source on board Odyssey, MER relay data can overflow its buffer allocation; if this occurs, the oldest data in the buffer is deleted by the new data.

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[19] This allocation provided ability to store on board up to 15 min of data received at 128 kbps. Maximum Odyssey overflight time—horizon to horizon—can be as long as 17 min, but due to antenna pattern and other link considerations, the best UHF pass at 128 kbps was on the order of 110 megabits. The remainder of the memory was allocated to the Beagle 2 lander, but unfortunately no Beagle data was ever received.

When the RUHF return rate was increased to 256 kbps for some Odyssey passes, it was recognized that the MER buffer allocation might be exceeded. Since Odyssey downlink rates were also decreasing due to increasing Mars–Earth distance, it was decided to combine the allocation of the two rovers into a single buffer. This arrangement worked well initially because it is practically impossible for a single overflight to overflow the allocation at 256 kbps (the best pass recorded returned 170 Mb); the likelihood of having two consecutive passes with very high data volume is also very small.

Later in the extended mission, at near maximum Earth range, not overwriting relay data became more problematic. Two consecutive rover passes to Odyssey might be only 2 hr apart. With a minimum Odyssey X-band downlink rate of 14 kbps to the DSN, Odyssey could downlink approximately 50 Mb per hour, including Odyssey data with higher priority than the stored MER relay data.

MER has automatic tools to query the Odyssey ground system after each pass for the packets with the APIDs assigned to MER. The packet header is then stripped off, and the data is sent to the MER ground data system for frame synchronization; at that point the data looks as if it came directly via the MER X-band downlink.

7.4.3.2 Mars Global Surveyor (operated until November 2006)

On the MGS spacecraft, the interface with the UHF radio was the Mars Orbiter Camera (MOC). Relay data from the rovers and the MOC images shared the same buffer allocation. The total data volume available for MER relay during the primary surface mission was approximately 77 Mb.[20] This allocation was routinely overflowed during MER operations at 128 kbps. In contrast to Odyssey relay storage, if the MGS MOC buffer had no additional space available, any new MER data is not recorded, and the old data is preserved.

The relay data in MOC packets reached the principal investigator for the instrument (at Malin Space Science Systems in San Diego), where the relay data was extracted from the MGS-to-Earth downlink and sent at JPL for frame synchronization.

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[20] The MGS project defined storage volume in the MOC buffer in terms of “frags” of 240 kilobytes (kB) (1.92 megabits) each. The maximum data volume allocation was 40 frags or 76.8 megabits. However, by mutual agreement between the MER and MGS projects, the relay allocation was nominally between 30 and 37 frags (51 to 71 megabits). Occasional passes were allocated only 15 to 20 frags (29 to 38 Mb) if MGS was performing compensated Pitch-and-Roll Targeted Observation (cPROTO) imaging activities or if MGS DSN coverage was limited.

7.4.3.3 Commanding the Rover via UHF

The UHF link from an orbiter to the rover is called the forward link. A forward link is comparable in function to an X-band DFE link and in general can provide commanding of the rover. However, MGS could not send data at UHF to a lander. The Odyssey and MRO forward links can provide a UHF backup to the X-band that is normally used to command the rovers.

Commands destined for the Odyssey–rover UHF link are sent from the MER ground system to the Odyssey ground system, where they are bundled in files. Each of these files is uniquely identified by a number, the spacecraft identifier (SCID) of the destination (Spirit or Opportunity), the pass number, and the day of the year. These files are then wrapped into Odyssey telecommand frames and uploaded to Odyssey memory. At the time of the specified overflight, these files are pushed into the Odyssey UHF transceiver buffer for transmission. While the Odyssey forward link is being used for commanding, return-link data cannot be simultaneously transmitted to Earth via X-band. That is, bent-pipe rover-to-Odyssey-to-DSN immediate relay is not possible. Odyssey stores the rover data on board and waits until the forward pass to the rover is finished before relaying the stored data back to the ground.

7.5 Telecom Subsystem and Link Performance

7.5.1 X-Band: Cruise, EDL, and Surface

In cruise, the MER spacecraft received an X-band uplink from the DSN and transmitted an X-band downlink back to the DSN. On the Mars surface, the X-band uplink is often referred to as a DFE link, to distinguish it from a UHF link received by the rover via relay from the Odyssey or MGS orbiter. The X-band downlink is often referred to as a DTE link.

Refer to Chapter 2 (Voyager) for standard uplink and downlink spacecraft–DSN design control tables (DCTs). MER has uplink and downlink DCTS (not shown) that are similar to these tables, though modeled with MER parameters (transmitter power, receiver system noise temperature, circuit loss, antenna gain, antenna pattern).

This section begins with the performance of the on-board telecom subsystem and the Deep Space Network at the other end of the links during two critical mission phases: initial acquisition after launch, and EDL.

7.5.1.1 X-Band Performance during Initial Acquisition

Link performance during the first pass after launch was different for MER-A and MER-B. The MER-B trajectory produced higher required tracking antenna angular rates. The station antenna pointing on MER-B was also hampered because the launch vehicle performance (and hence its trajectory) were slightly different from predicted values. Consequently, station antenna pointing was off, resulting in lower than expected signal strengths. The suspicion that the MER-B trajectory was off-predict was substantiated when the DSN tried adding various time offsets (as great as ±50 s) to the pointing predicts on the backup station's antenna, and got a significant increase in signal strength using one of the nonzero time offsets. Link performance improved substantially when MER Navigation delivered their first post-launch trajectory update less than 24 hours later.

The downlink signal, especially for MER-A, was so strong as to produce unexpected signatures in the station receiver monitor data, as shown in Figs. 7-26 and 7-27. The symbol SNR (SSNR) estimator and Maximum Likelihood Convolutional Decoder (MCD) bit SNR estimator saturate at approximately 40 dB bit SNR. The actual received values were much higher (about 70 dB), but the Block V Receiver (BVR) and the MCD would read values higher than 40 dB as still only 40 dB. Fortunately, the uplink received power level (the SDST wideband automatic gain control [AGC]) was telemetered with reasonable accuracy. By tying together the saturated downlink measurement (reading an expected 30 dB too low) and the more accurate uplink measurement that matched predicts, the telecom analyst on the MER Flight Team was able to assert that the MER telecom subsystem and the DSN were both performing normally. The cause of the discrepancy has been documented for use on launch day by future missions that will face similarly strong uplinks and downlinks.

Similarly, the carrier SNR (ratio of carrier power to noise spectral density, P_c/N_0) estimator saturates as P_c/N_0 increases from below 80 to above 90 dB-Hz. Also, P_c/N_0 decreases due to bleed-through of (strong) P_d harmonics into carrier noise estimation bandwidth, raising the noise floor. This bleed-through effect persists until range increases to the point that P_d harmonics are below the equipment floor noise. The amount of this P_d bleed-through differs for the 375 kHz subcarrier used for the 11850 bps playback telemetry rate and the 25 kHz subcarrier used for the 1185 kbps real time telemetry rates, causing the jumps at the transition to and back from 11850 bps.

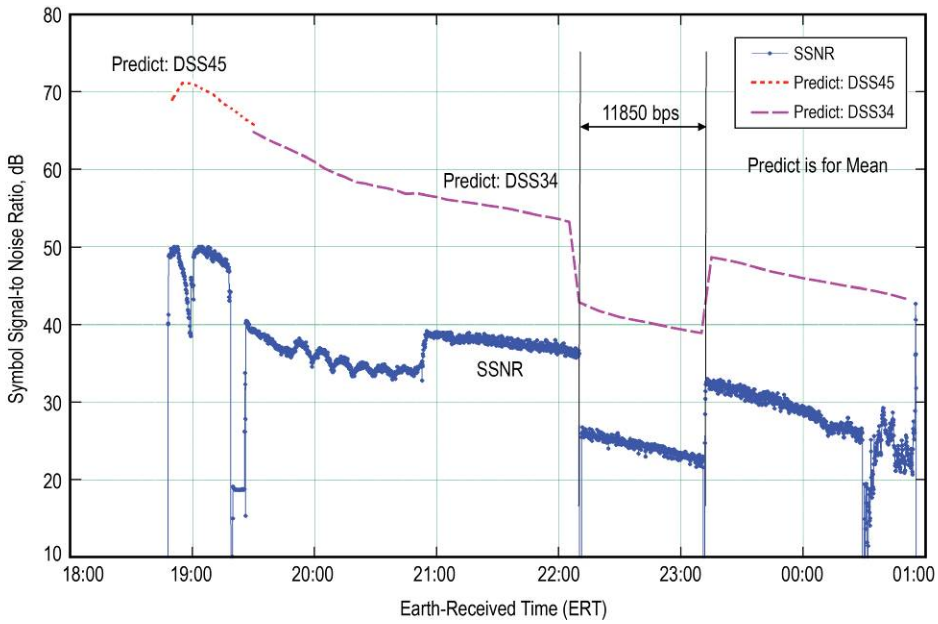

Fig. 7-26. MER-A initial acquisition symbol signal-to-noise ratio.

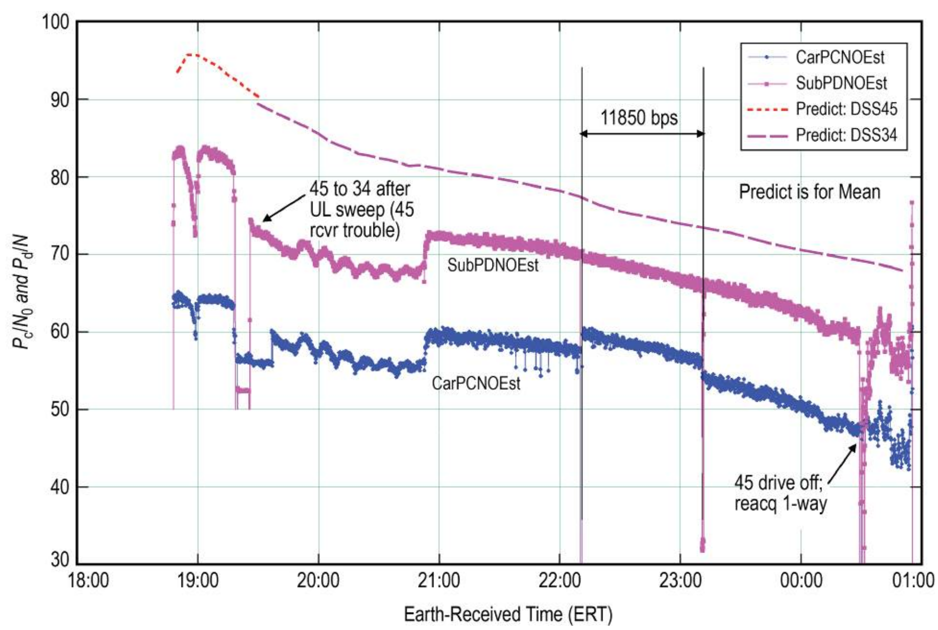

Fig. 7-27. MER-A initial acquisition, P_c/N_0, and P_d/N_0.

However, another effect was noticed by the operations analysts: when the telemetry subcarrier frequency was 25 kHz (for the initial acquisition data rate of 1,185 bps), the BVR estimate of P_c/N_0 was less than later in the same pass when the subcarrier frequency was switched to 375 kHz (for the launch data playback data rate of 11,850 bps), even though the telemetry modulation index for both rates was set to the same value. The reason for this phenomenon is that the telemetry data is modulated onto the subcarrier. With the strong downlink signal levels, harmonics from the data spectrum contributed significant “noise” power into the BVR carrier-loop bandwidth. In fact, this noise source dominated over thermal noise in the channel, increasing the apparent noise spectral density, P_c/N_0. Increasing the subcarrier frequency moved the data spectrum further away from the carrier-loop bandwidth, decreasing the noise power, and thereby resulting in a larger P_c/N_0.

For both MER-A and MER-B, the saturated SNR and P_c/N_0 estimator idiosyncrasies were effectively gone within 48 hours after launch.

Another effect commonly seen on missions shortly after launch is the ranging “pedestal effect” (where turned-around uplink noise is the dominant downlink noise source, and raises the effective noise floor), but this was not noticeable on MER due to weaker downlink-signal levels.

7.5.1.2 X-Band Performance during EDL

Section 7.4.1 describes the special ground-system elements required to process the downlink modulation during EDL, and Fig. 7-22 describes the spacecraft configurations and the on-board telecom hardware and communications link transitions through the EDL sequence. The following summary of X-band carrier frequency changes is taken from Ref. 13; it applies to both Spirit and Opportunity EDL, except as noted.

Before the onboard EDL sequence started, the spacecraft was in the nominal cruise configuration, transmitting a two-way coherent signal from the MGA. The first telecom subsystem and link configuration change from the onboard sequence occurred one hour and forty-five minutes before Mars atmospheric entry interface (henceforth entry), when the spacecraft transitioned from using the MGA to the CLGA and to a telemetry rate of 10 bps. The standard DSN closed-loop receivers were reconfigured to look for the one-way signal using RH polarization.

When the aux osc came on, the downlink carrier underwent a warm-up frequency transient that was observed in the Radio Science Receiver (RSR). In-flight measurements confirmed preflight testing, showing a frequency increase of approximately 300 Hz over the first 15 s of aux osc operation, then a slow decay to steady state. The temperature of the aux osc was stabilized by the HRS, which was used during the interplanetary cruise to keep the temperature of the spacecraft environment stable. The cyclic behavior of the HRS caused the aux osc frequency to oscillate. HRS cycles tended to last approximately 6 min. Figure 7-28 (a) shows a 2-rpm spin rate of the cruise stage superimposed as ripples on the aux osc drift and HRS cycling signatures.

The CLGA is not on the spin axis, so the spin signature in Doppler frequency became more prominent at the turn to entry attitude. The first effect of the aux osc drift was movement of the mean frequency from 170 Hz at 03:20 to a peak of 185 Hz at 03:36, then back down to 180 Hz by 03:45. The second effect was the cycling of the HRS, evidenced by the 6-min, 12-Hz peak-to-peak oscillations. The third effect was the spacecraft spin Doppler. After the turn to entry, the peak-to-peak one-way frequency variation was 3.3 Hz at 2 rpm.

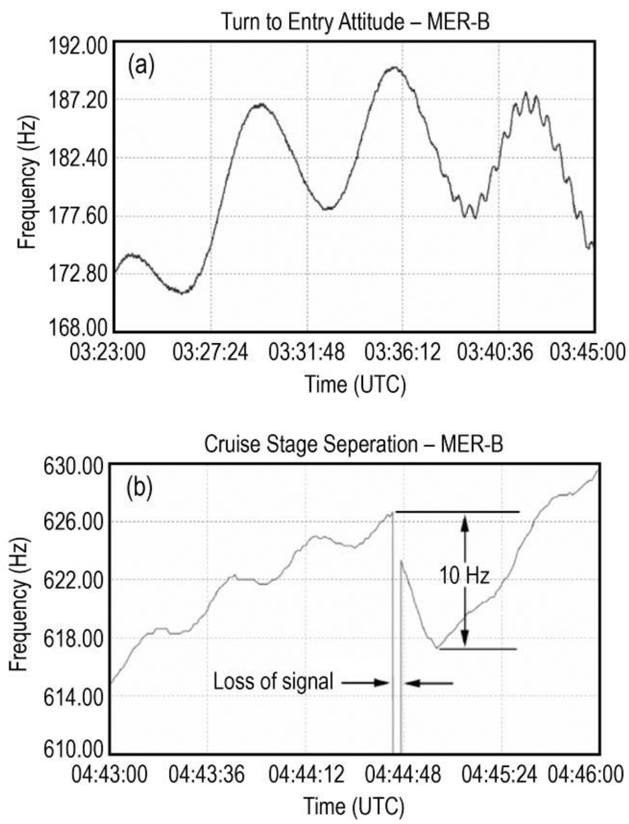

Fig. 7-28. MER-B signature of (a) CLGA spin and HRS cycling and (b) cruise stage separation.

Before the lander entered the Martian atmosphere, the HRS was disabled. Without the temperature control provided by the HRS, the temperature of the aux osc increased from the cruise temperature of approximately 0°C. A 2-kHz rise was expected from 0°C up to 8°C, followed by a 7-kHz drop before landing as the temperature reached 25°C.

The cruise stage was jettisoned from the landing package 15 min before entry. The firing of the pyros imparted a force on the lander. Seen in Fig. 7-28(b), a 10-Hz Doppler shift occurred in the received signal. The discarded cruise stage blocked the downlink signal path on its way to burning up in the Mars atmosphere, causing the 2-s signal outage.

The beginning of the entry segment of EDL, the lander hitting the top of the Martian atmosphere, was rather benign so far as Doppler frequency effects were concerned. Soon, however, the friction caused the velocity to drop dramatically, and the spacecraft transitioned from speeding up towards Mars to slowing down, as seen in Fig. 7-29 for MER-A. Then, the deployment of the parachute caused an almost instantaneous 7-kHz jump in the received signal. This event caused the closed-loop DSN tracking receivers to go out of lock. Good closed-loop lock was not regained until the landers were stationary on the surface. The RSR and EDA were able to identify the signal.

All of the Doppler shifts came from changes in the acceleration of the craft. When the frequencies and the accelerometer data recorded on board MER-A are overlaid on one another, as in Figs. 7-29 and 7-30, the correspondence between the two can be seen. RAD firing is –4 s in Fig. 7-30. The data in that figure, collected during the bouncing, shows that the downlink signal was maintained until the beginning of the seventh bounce, at which time the signal was lost for a period. Review of the accelerometer data in non-real-time shows that the magnitude of the impacts decreased at precisely this time. A portion of the energy had been converted into rotational energy, and the higher spin rate caused a larger Doppler shift that was not tracked. When the lander's spin began to slow again on about the 23rd impact, the signal was identified once again.

The following summary of signal-level changes and the operation of the EDA is synthesized from Refs. 13, 14, and 15. Transmission of the M-FSK signal (described in Section 7.4.2) directly to Earth via X-band continued until RAD firing. For Spirit, ~4 s prior to landing, the RAD system on the backshell decelerated the lander from 240 to 0 km/h. Three seconds later, the lander cut its bridle and fell freely to the surface. It hit the soil at an expected speed of over 80 km/h with a force of 40 g. The X-band carrier-only signal and a UHF

8-kbps signal were transmitted through bridle-cut, touchdown, and the subsequent bouncing on the surface of Mars.

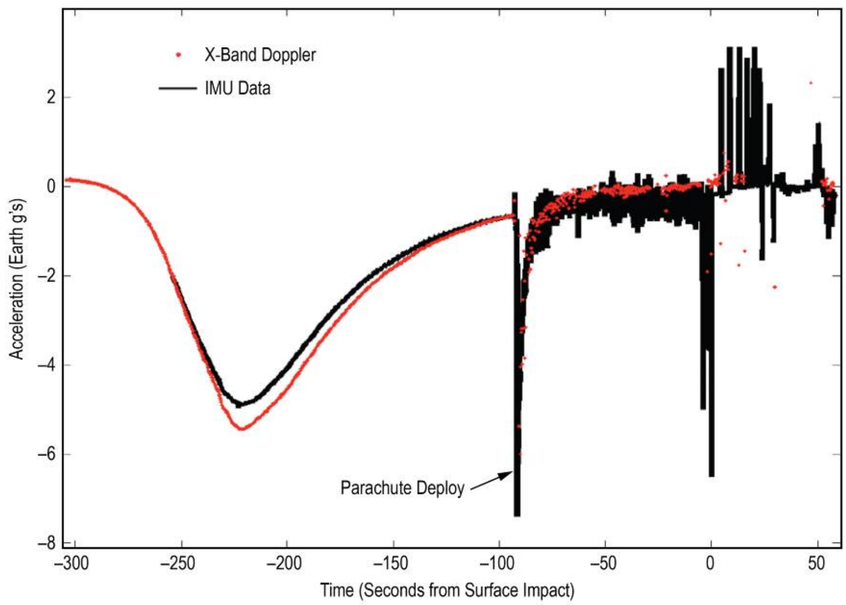

Fig. 7-29. Spirit EDL Doppler frequency and accelerometer data: entry compared to landing.

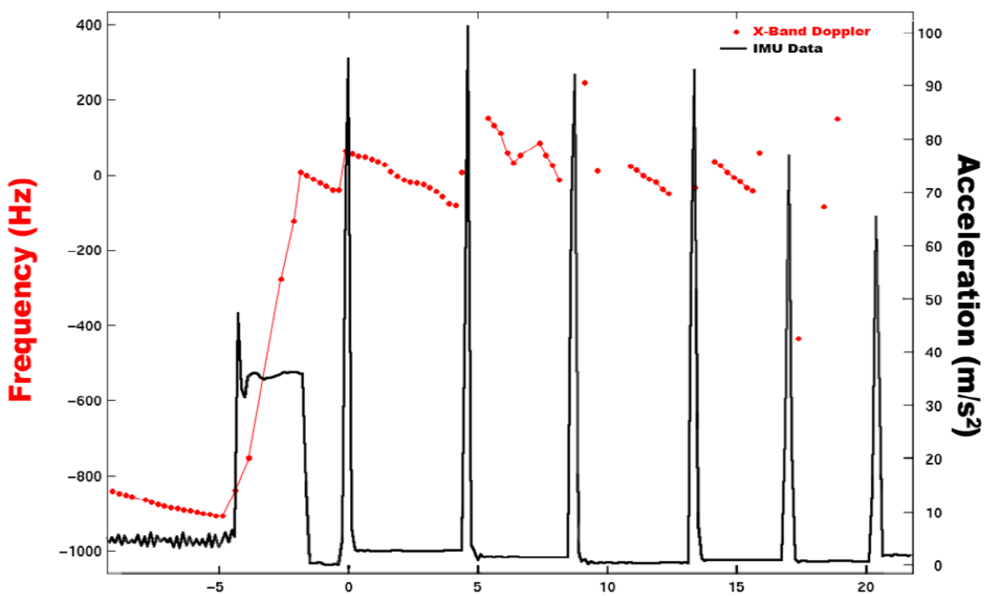

Fig. 7-30. Spirit Doppler frequency and acceleration due to RAD firing and bounces.

The ability of the DSN or the MGS spacecraft to receive these signals could not be guaranteed as it depended primarily on lander orientation. Spirit and Opportunity each bounced for about 90 s after touchdown until they came to rest on Mars. When the lander flight software transitioned into the critical deploy state, the UHF transmitter was sequenced off and the lander was sequenced to transmit a set of five subcarriers—each 30 s long—via the RLGA, then to switch to the PLGA for transmission of the carrier-only signal for 3 min prior to repeating the original five subcarriers. These subcarriers signaled the lander state prior to the critical mechanical deployments.

Figure 7-31 shows the received carrier SNR per Hz (P_c/N_0) and the data SNR per Hz (P_d/N_0) in dB-Hz for the Opportunity EDL.

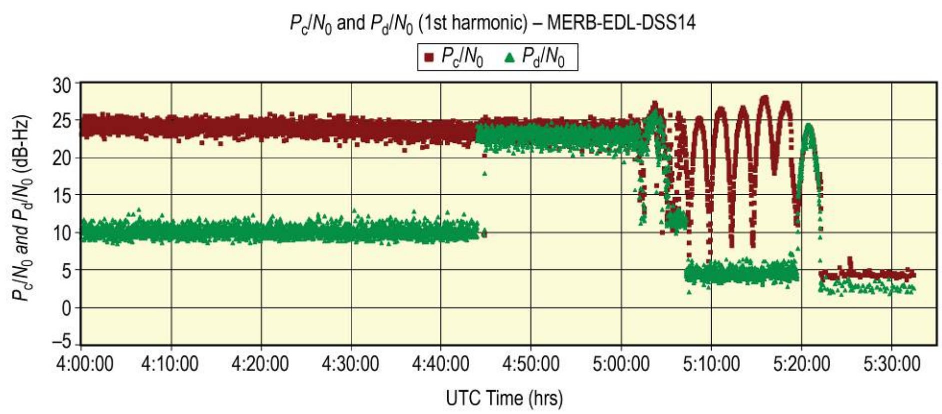

Fig. 7-31. X-band received P_c/N_0 during Opportunity EDL

This Opportunity plot spans from about 44 min before cruise stage separation until after the second set of landed tones were transmitted. Each division in the plot represents 10 min. The entry point occurred at 4:59:46 Universal Time, Coordinated (UTC). Landing occurred at 5:05:28 UTC. The Opportunity lander bounced until 5:07:15 UTC. From that time until 05:22, six peaks separated by deep nulls can be seen in the received X-band carrier (orange points in Fig. 7-31). These variations were caused by multipath between the direct and reflected-from-Mars X-band signals as the Earth set at the landing site.[21] The

[21] Multipath means the receiver sees two (or more) radio waves, one of them coming directly from the transmitter and the other reflected from something (such as the surface of Mars) and so arriving via a different path. Because the reflected path is longer than the direct path, the two waves may arrive in phase (constructive interference, stronger signal) or out of phase (destructive interference, weaker signal). As the Earth sets and the path lengths change, the signal level versus time shows a characteristic variation called fading.

carrier and all of the entry and descent tones were received in real time for both Spirit and Opportunity. For Spirit, there was a loss of signal for more than 15 min after landing. Most of the data from this outage was recovered in post-EDL signal processing.

Figures 7-32 and 7-33 and the following description from [15] summarize the results from the EDA real-time and non-real-time processing during Spirit's EDL in terms of the X-band carrier and tone SNR levels through EDL.

For Spirit's EDL, Fig. 7-32 (tone power to noise spectral density ratio) and Fig. 7-33 (carrier power to noise spectral density ratio) and the following description come from Ref. 15. Figure 7-32 provides P_d/N_0 values from the DSS-14 EDA in real-time. Figure 7-33 shows (a) real-time P_c/N_0 values and (b) post-processed P_c/N_0 values from DSS-43. Note the start/stop times in Figs. 7-32 and 7-33 are not the same. Blue in Fig. 7-32 indicates low-quality data (mostly prior to cruise stage separation) that was not analyzed. Green in both figures indicates periods of analyzed valid data, and violet shows periods of analyzed invalid data. Figure 7-32 (b) highlights an interval of improved post-detection data (now green).

In Fig. 7-32, the tones do not begin until after cruise stage separation, at about the time marked 2700 s on the time scale. In this figure, the signal level indicated prior to 2700 s is for a subcarrier modulated with telemetry. After separation, the output tone power is constant, so the different levels shown come from spacecraft antenna selection and antenna orientation relative to the Earth.

Overall, the results from the actual EDLs were better than originally anticipated. All tones marking critical events (such as cruise stage separation, parachute deployment, and PLGA deployment) were detected during real-time operation.

Early in mission operations planning, there was a concern about the ability to maintain contact with the spacecraft during the parachute-deployment and bridle-descent segments. This concern was prompted by the known possibility that the RLGA would point away from the Earth during the swinging motion. Also of concern was a potential communications blackout upon entry due to plasma induced by hyperdeceleration. In the 1997 landing of Mars Pathfinder, a 30-s outage was attributed to this factor.

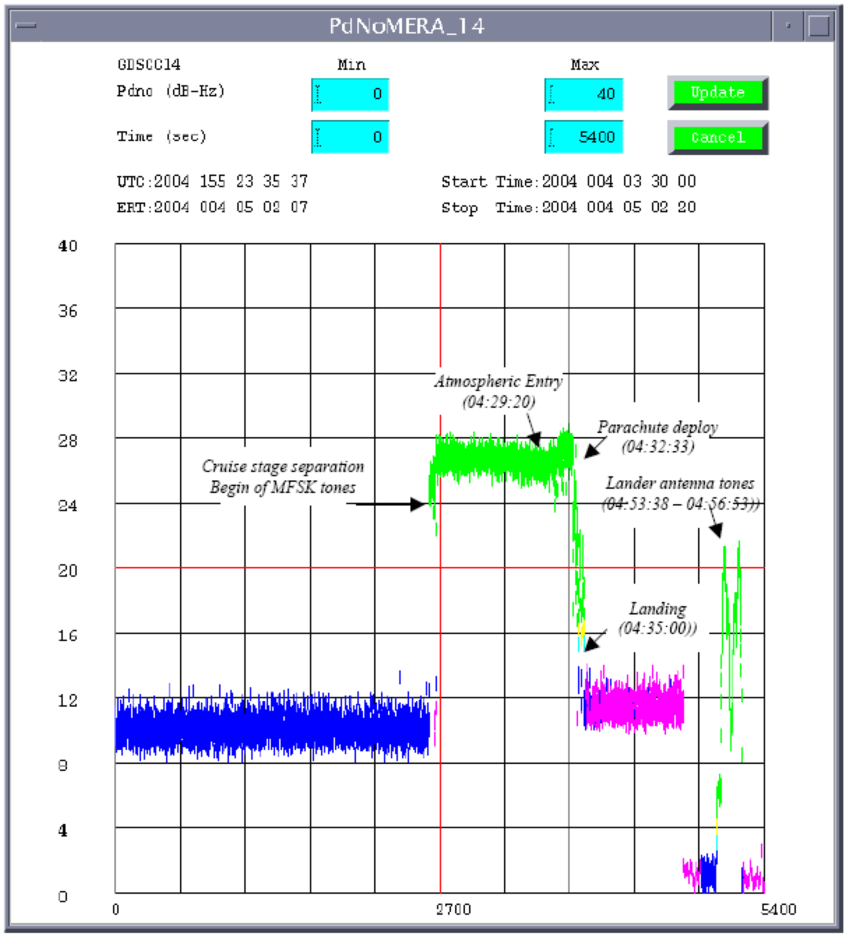

Fig. 7-32. M-FSK tone power during Spirit's EDL.

In the case of Spirit's EDL, constant contact was maintained during this whole period, all the way until touchdown. The suspense came between touchdown and the first received post-landing signal. The project expected a few minutes of communications outage during this period. However, the actual outage lasted more than 15 min. Later reprocessing with longer integration time and wider frequency-rate search recovered 11 min of this gap. Figure 7-33 shows the comparative results of real-time and post-pass processing, with data in the top half of the figure from DSS-43 and data from DSS-14 in the bottom half. Green indicates valid data processed in real time, and violet shows periods of receiver noise (lost data). At DSS-14 (Fig. 7-33(b)), the green segment over the period 5000 s to 5800 s after start includes the post-pass recovered data. At DSS-43 (Fig. 7-33(a)), the corresponding period shows violet unrecovered data.

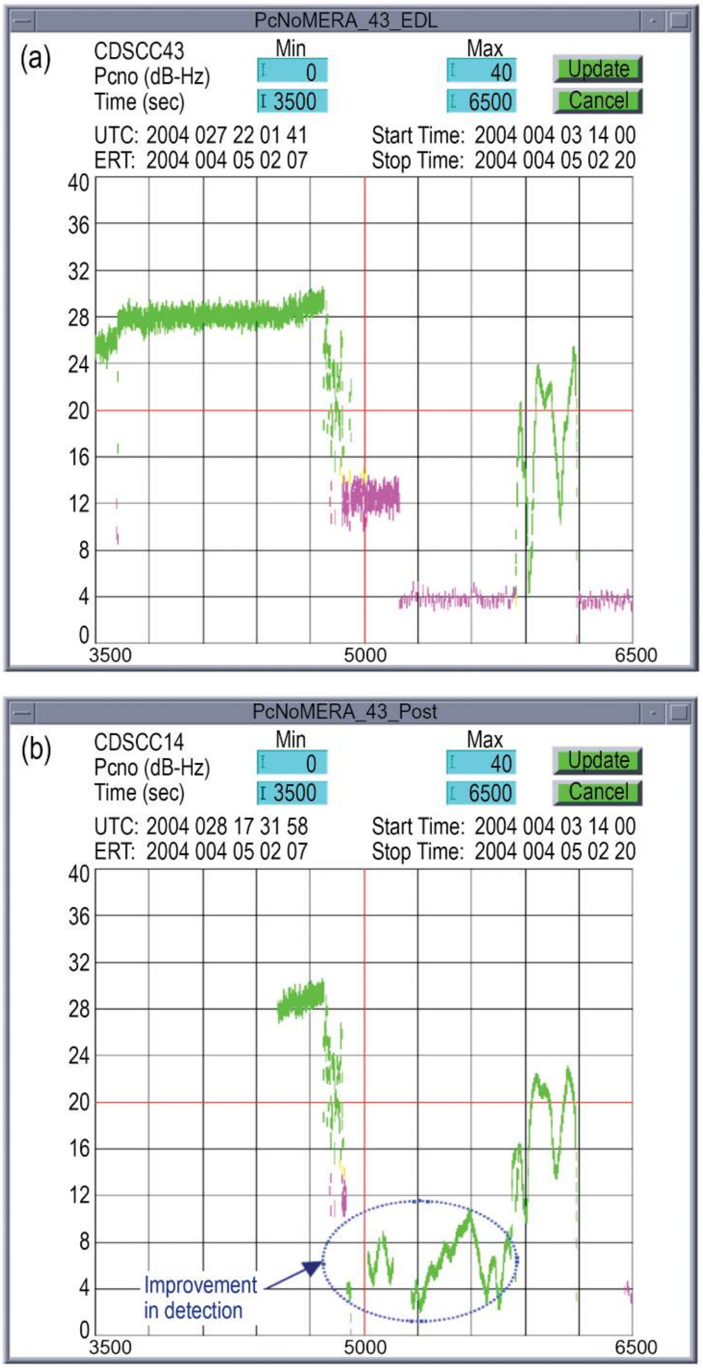

Fig. 7-33. Comparison between (a) real-time and (b) postpass carrier detection for Spirit EDL.

During the 15-min outage, the Radio Science Team reported unexpected detection of LH-polarized signal. Post-landing analysis by the MER project confirmed the possibility of LH reception. It was attributed to the orientation of the lander relative to the Earth as it came to a full stop, and to the antenna polarization ellipticity in the direction away from the main beam axis.

Because of this experience with Spirit, additional EDA equipment was deployed to process any LH signal during the landing of Opportunity. Figure 7-34 shows the EDA carrier detection of Opportunity from DSS-14 in oppositely polarized (RH and LH) channels. As in Figs. 7-32 and 7-33, blue indicates low-quality data, green indicates valid data in real time, and violet is lost data. LH signal power was 4–8 dB lower than its RH counterpart, as expected; however, at 4930 s after start, the LH channel remained detected for an additional 1.5 min while the RH channel experienced outage.

Detection of Opportunity's landing was even better than that of Spirit's. Again, all critical tones were detected. The post-touchdown outage was only ~1 min, compared to 15 min for Spirit. That outage occurred 3950 s after start, as shown in Fig. 7-34.

7.5.1.3 Performance versus Predicts: Cruise

As with other recent JPL deep-space missions, MER predictions for the X-band links are made using the Telecom Forecaster Predictor (TFP) ground software. TFP details are included in the user's guide [16]. Project-specific models (antenna gains and patterns, SDST receiver and transmitter parameters, etc.) in TFP are initially based on pre-launch subsystem tests that then are updated as required during flight.

During cruise, with stable performance day after day, the standard downlink criterion of (mean minus 2-sigma) worked well for both the CLGA during the early days and the MGA later. Telecom analysts became familiar with the usual link signatures. The time between sequence approval/command uplink and sequence execution was at least several days, allowing for an orderly process between link evaluation and data-rate planning.

X-band performance compared well with the TFP models. Because of an excellent prelaunch telecom test program, no spacecraft-specific models needed to be updated during the mission.

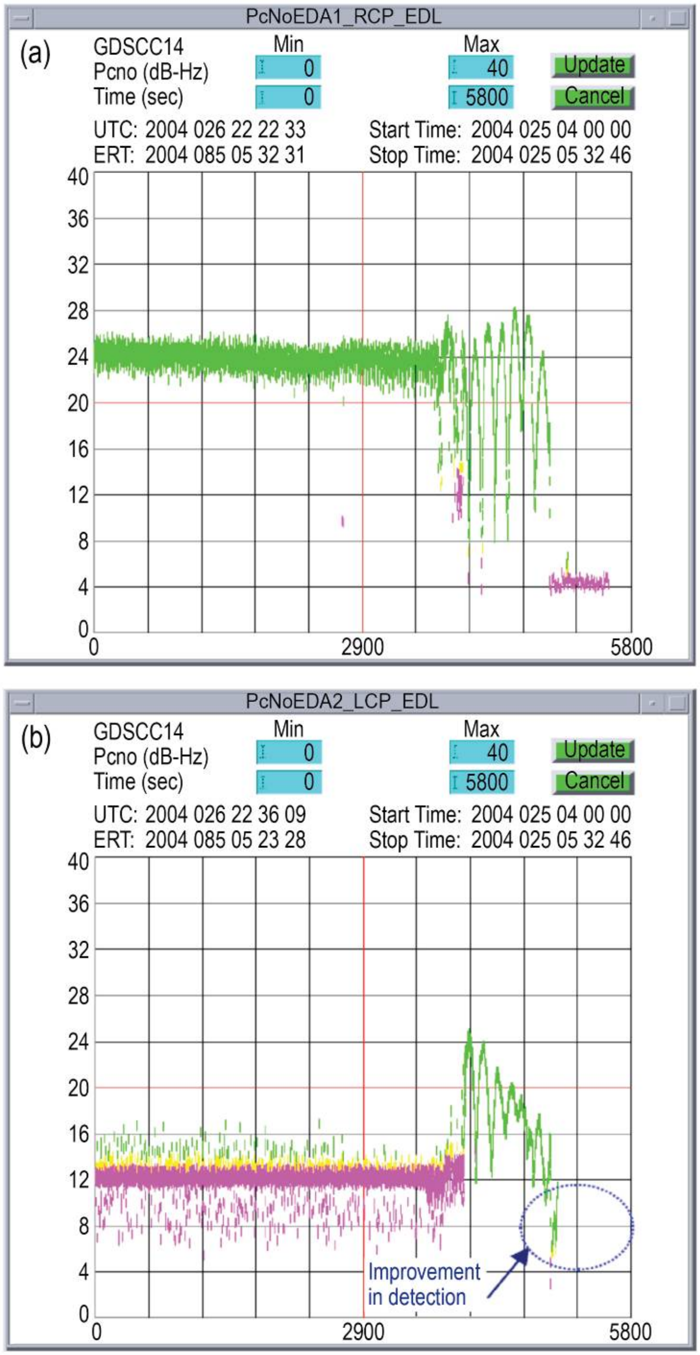

Fig. 7-34. Comparison of RCP and LCP carrier detection during Opportunity EDL.

Despite the excellent telecom performance, midway through cruise it became apparent that generating the number of Attitude Control Subsystem (ACS) turns originally planned to maintain fairly good MGA pointing toward Earth was creating excessive workload for the systems and ACS members of the Flight Team. As part of a cruise "workload simplification" strategy, the project cut this number approximately in half, trading off larger off-Earth angle (thus a lower data rate) for a smaller off-Sun angle. In retrospect, it did not really simplify the overall workload because telecom, thermal, and power flight team analysts had to rerun studies to see if the changes in the plan were okay (even though we were deleting turns). The rerun studies had to be run yet again if the planned turn dates had to be changed to accommodate other constraints. Nonetheless, creative use of TFP and Excel tools alleviated the telecom analyst workload somewhat.

The 10-bps telemetry rate was not used during cruise because there were alternatives to accepting its long lockup time and slow transfer of data: (a) request a 70-m station in case of a spacecraft emergency that would otherwise require 10 bps, or (b) wait until the elevation angle at the 34-m station was high enough (about 30 deg) to support the planned data rate of 40 bps.[22]

7.5.1.4 Performance vs. Predicts: Surface

On the surface of Mars, the mean-minus-2-sigma downlink criterion proved to be too optimistic because there was a shorter time between link evaluation and planning and because little or no data loss could be tolerated. A 2-sigma criterion meant there was only about a 1- to 1.2-dB margin to absorb performance variation. Any weather- or pointing-related problems larger than that would cause data loss. In retrospect, allowing more margin (3 sigma) would have been preferable. Instead, the work-around often was scrambling to reduce the data rate to the next available lower one (by building a real-time command and radiating it to the spacecraft just prior to a communications session) when weather threatened to make the downlink unsupportable.

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[22]Besides 10 bps, 20 bps was available with short coding. The short RS code, while allowing for faster acquisition time, had a high coding-overhead penalty. Because of this, the MER fault-protection engineer wanted to avoid using the short code in cruise, which made 20 bps also unattractive. The P_t/N_0 thresholds for the low data rates are more closely spaced than 3 dB (due to higher station-receiver-system losses for operating at low SNRs), so it does not cost as many decibels (about 3 dB from 10 bps to 40 bps, instead of the 6 dB expected for a 4:1 ratio) to increase the data rate. Conversely, you do not get as much "bang for the buck" by lowering the data rate.

If DTE telemetry had been required over the RLGA at the larger Earth–Mars distances during the extended mission, 10 bps would have been the only RLGA-supportable downlink rate, even with a 70-m station.

Later-than-planned lockup by the DSN of the MER telemetry was a continuing challenge. The time of lockup is when the station has locked the carrier, subcarrier, and symbols so that after lockup the telemetry data will be valid. The project had always planned for transmission of only lower value "real-time" data until planned lockup. Lockup time varies with bit rate, and it is typically about 1 min for HGA data rates. Because the time to lock up varies somewhat from one pass to the next, the project had to decide how long a lockup time to plan for before starting the higher-value playback data. Plan too short, and some valuable data that has been sent will be lost. Plan too long, and the amount of valuable data that can be sent is reduced. The consequence of specifying a too-short lockup time becomes even greater because data organization on board places the highest-priority playback data (such as fault and warning event reports [EVRs] and the reports of spacecraft health) earliest in the DTE pass. Considering these factors, and using experience from previous DTEs, the project changed the comm window parameter for lockup time from 1 min to 3 min (for downlink rates of 3160 bps and higher). Three minutes use up 10% of the data-return capacity of a 30-min comm window. The parameter has been set to 2 min for some windows in the later extended missions.

During diagnosis of and initial recovery from an anomaly in the Sprit flash memory file on sol 18, the RLGA supported a 40-bps or 300-bps downlink rate, as controlled by a high-priority comm window that overrode the 10-bps default mode. This downlink rate provided the repeating EVRs that led us to suspect the flash memory as the source of the problem in the first place.

7.5.1.5 Pancam Mast Assembly Occlusion

In addition to the general performance issues just described, a specific surface DTE and DFE problem that was difficult to characterize was "PMA occlusion." The problem so named comes about when the Pancam Mast Assembly (PMA) is directly or nearly in the field of view of the HGA. For use during surface operations, the ACS engineer modeled in the Tball attitude geometry visualization tool[23] the expected timing of possible PMA occlusions, but the model did not adequately account for the variability in effect of the PMA shape and size for different camera bar positions; and therefore, it was not adequate to capture the magnitude of the problem.

During prelaunch development, both telecom and ACS analysts recommended characterizing and modeling for PMA occlusion, knowing that it would occur

[23] Tball is a JPL-developed 3D visualization program that depicts the celestial sphere with the spacecraft at the center. It permits computation of Sun-to-spacecraft position/velocity vectors at the desired epoch using the latest ground-based spacecraft ephemeris.

during surface operations. Analyzing and modeling occlusion was not made a priority by the project. As a result, ACS is able to predict probable occlusion in DTE passes, but there are no models to predict accurately the severity or duration of an occlusion. Unfortunately, during the Spirit flash-memory-file anomaly, the rover happened to be parked such that PMA occlusion degraded most of the HGA sessions from 12:00 local solar time (LST) and later (usually as great as –8 dB; once up to –14 dB), resulting in substantially compromised downlink-rate capability.[24] Because the rover's instrument deployment device (IDD) was deployed, the attitude could not be changed to move the PMA out of the HGA field of view. PMA occlusion effects on the next sol had to be estimated based on the empirical data from the current sol. In retrospect, good prelaunch characterization would have helped resolve the problem more quickly, by removing the PMA occlusion factor in link-performance variability.

7.5.1.6 X-Band Carrier-Only Beeps

For the surface mission to date, the sequences for most sols have included 5-min carrier-only downlinks called "beeps" (when transmitted with the rover stationary) or "honks" (when transmitted while driving) to convey information when scheduling a DTE is not practical (due to power, thermal, or activity constraints). The beeps or honks are most often used to indicate successful upload and execution of the new sol's master sequence. The new master sequence is uploaded each morning "in the blind" (without downlink confirmation of uplink sweep and command success). The beeps are first detected by the station operator visually by using the open-loop carrier fast Fourier transform (FFT). After the carrier has been detected in the FFT, the station will try to lock up the signal using the closed-loop receiver, and this is nearly always successful. The timing of the received beep conveys whether the upload and initiation of the new master were successful or not. In the absence of onboard faults, the beep will occur at one of two deterministic times: a nominal beep time or an off-nominal beep time. Each sol's master has two beeps sequenced: one at the nominal beep time for the new sol, and one at the off-nominal beep time for the following sol (new sol + 1). If the upload succeeds, the new master terminates the old master sequence (before the time the old off-nominal beep would be sent), and sends its beep at the nominal time. If the morning load fails, the old master remains alive and performs two actions. It executes a "run out" (canned science sequence), and it sends its beep at the off-nominal time.

[24] During the extended-extended mission, Spirit suffered another period of PMA occlusion to the LGA during sols 557 through 570 (July 27–August 10, 2005).

From very shortly after EDL on both rovers, beeps have been sequenced, with SDST coherency enabled. The certainty of beep detection and lockup is increased when coherency is enabled and the SDST receiver is in lock on an uplink. At weak SNR levels, the stable two-way downlink frequency is far easier to detect than is a noncoherent one-way downlink, which may drift by several kHz in a few minutes. For about the first 20 sols for each rover, the project requested Radio Science to provide beep detection using the RSR, in parallel with the station using the FFT and the closed-loop receiver. The stations soon became proficient in detecting, locking up, and reporting the times of beeps, so RSR support is no longer routinely used.

In the primary mission, nearly 100 percent of the beeps sent were detected by the DSN. In the first extended mission, the DSN missed all but one of the inadvertent one-way beeps (no uplink in lock) and one coherent two-way beep. Not unexpectedly, several two-way beeps were missed during solar conjunction due to solar scintillation effects and the weakness of the beeps. Carrier-only beeps are reliably detectable in the standard receiver down to a P_t/N_0 of 12 dB-Hz. Occasionally the DSN has been able to detect and lock up on slightly weaker beeps. Figure 7-35 shows the predicted P_t/N_0 of the 11 a.m. (local solar time) beeps for MER-A through the end of 2004. The colors indicate the DSN sites: gold for Goldstone, red for Canberra, and green for Madrid. The lower the station elevation angle at beep time, the lower the predicted P_t/N_0.

7.5.1.7 Antenna Pointing

7.5.1.7.1 Station. An occasional problem with DFE passes has been a specific type of excessive uplink pointing error by the 70-m stations. The resulting degradation in SDST received power was as high as 8 dB for some passes in July 2004 and worsened with increasing Earth-Mars distance. All three 70-m stations have had this problem to some degree, and it occurred with both rovers. The cause of this uplink pointing loss is a combination of the angular motion of the spacecraft during a round-trip light time (RTLT)[25] and the DSN predict-driven (blind-pointing) error. With nonzero values of RTLT and angular motion, a station antenna cannot point perfectly for an uplink and perfectly for a downlink at the same time.

[25] This loss is currently not modeled in the MER adaptation of the multimission Telecom prediction tool but will be incorporated in the future.

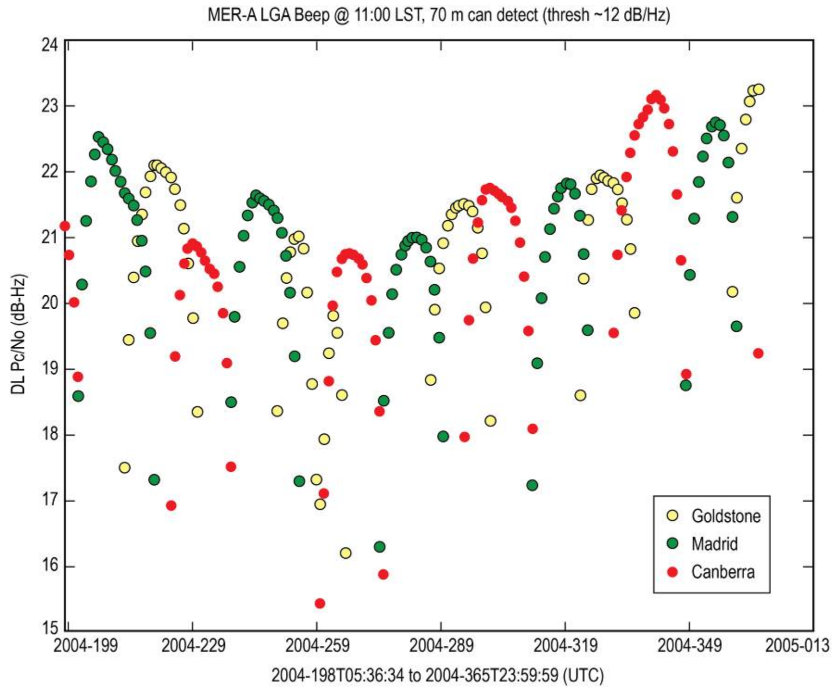

Fig. 7-35. Predicted MER-A 11 a.m. beep received P_t/N_0 at 34-m stations.

Because the downlink is at a higher frequency than the uplink, the station antenna beam is narrower for the downlink. Also, downlinks usually have a significantly lower signal margin than do uplinks. For these reasons, the pointing algorithm favors the downlink and points the antenna toward the current spacecraft location for receiving the downlink as nearly perfectly as possible. But this pointing causes a problem for the uplink. This problem is called aberration. Think of a station antenna pointed to receive a rover downlink now. By the time an uplink that is transmitted now reaches the rover at Mars, the rover is no longer in the direction the antenna was pointing when it sent the uplink. The current radiated uplink does not arrive at the spacecraft until an OWLT later, and in the meantime, the spacecraft has moved with respect to the station antenna's pointing.

Figure 7-36 shows the uplink pointing error (between pointing positions for rover-transmitted downlink and rover-received uplink signals) caused by the angular motion of Mars during the signal travel time. Figure 7-37 compares the uplink pointing loss for 70-m and 34-m antennas that results from the pointing errors in Fig. 7-36.

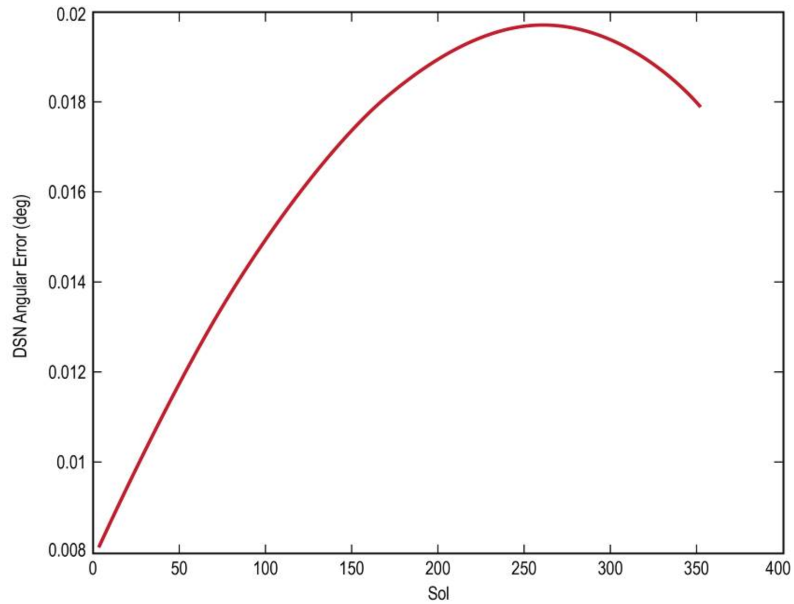

Fig. 7-36. MER-A angular motion with respect to DSN during a RTLT.

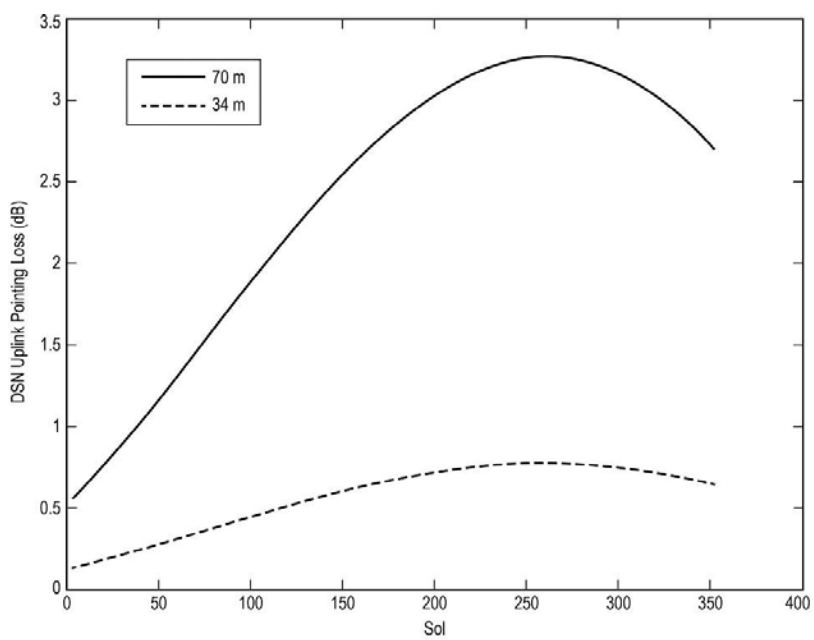

Fig. 7-37. MER-A uplink pointing loss due to angular motion in RTLT.

The performance loss in dB is greater for 70-m than for 34-m antennas because the former use narrower beamwidth than do the latter. The pointing error worsens with increasing Mars-Earth range (longer RTLT). It reached a maximum of about 3.25 dB near solar conjunction in September 2004, when Mars motion was perpendicular to the line-of-sight of the Earth. Because the uplink operates nominally with an inherent pointing error up to 0.019 deg, any incremental DSN pointing changes/errors (including those of Conscan) have a magnified effect on the uplink when compared to the downlink, which operates nominally with a pointing error of 0 deg. On the occasions when an uplink pointing loss as great as 8 dB was observed from 70-m stations, analysis of signal strength telemetry suggests an overall pointing error of 0.03 deg, with 0.02 deg due to spacecraft motion and 0.01 due to 70-m blind-pointing error. The effect of a 0.01 deg blind-pointing error on the downlink is only 1 dB, which is why not much improvement is observable by the station when Conscan is enabled.

To reduce the effects of station pointing issues during the first extended mission, the project decided to uplink to the HGA rather than to the RLGA and to limit the command rate to 500 bps from all stations. The lower command rate increased the link margin and thus the pointing errors that could be tolerated. The 70-m stations were also requested to Conscan on MGS or Odyssey downlinks during MSPA tracks.[26] Conscan improves downlink pointing somewhat, but of course it does not eliminate the uplink aberration problem mentioned above. Fortunately, the excess margin at the 500-bps command rate at the 70-m stations has accommodated the amount of uplink pointing loss that has occurred so far, whether or not Conscan is enabled.

7.5.1.7.2 Rover. The control of HGA pointing toward Earth is subject to ACS subsystem errors caused by such factors as temperature and bus voltage variations. The ACS analyst on the flight team periodically recommends the correction of HGA pointing through an activity called the fine-attitude update. These updates are infrequent because science activity dominates the rover resources. The telecom analyst tries to separate out rover HGA pointing errors and station errors by comparing HGA performance with RLGA performance during the same sol and by comparing HGA performance at the same station before and after an update. HGA pointing accuracy was determined to be generally within 2 deg in the primary mission, and downlink data-rate capability planning has been based on a 2-deg error assumption.

[26] Conscan is not requested for MEX MSPA tracks. MEX has a highly elliptical orbit, and MER did not seek an agreement with MEX to allow MER to affect that mission's uplink and downlink by requesting Conscan.

Figures 7-38, 7-39, and 7-40 show typical uplink received carrier power (from the SDST telemetry channel called carrier-lock accumulator [CLA], cla_snr, expressed as a signal-to-noise ratio) at a 34-m station and a 70-m station (with and without Conscan), respectively. Each figure includes both HGA and RLGA periods, and the TFP predicts together with the telemetry data. All the curves in each plot are labeled. A quick key to these figures: the HGA predict is the generally horizontal line near the top, and the RLGA predict is the somewhat decreasing line about 13 dB lower. In each figure, the data curve in the shape of an ascending staircase is the telemetered temperature of the SDST voltage-controlled oscillator (VCO), with the temperature scale in degrees Celsius on the right axis.

The cla_snr from the HGA begins at about 20:30 UTC in Fig. 7-38, 03:20 in Fig. 7-39, and 01:35 in Fig. 7-40. It ends 20 min later, corresponding to a 20-min comm window. The cla_snr from the RLGA is the short interval preceding the HGA, and the longer period following it. During the HGA interval, command transmissions (with 5.8-dB carrier suppression) cause the deep, short-duration dips in each figure. The predictions are run without command modulation, so they are compared against the noncommand values of cla_snr. Comparing Fig. 7-39 with Fig. 7-40 shows the effect of Conscan. Conscan improves the overall 70-m uplink level by optimizing pointing on the (orbiter) downlink, thereby moving the average uplink level to 3 dB below the level for perfect uplink pointing. However, the signal level becomes more variable due to the periodic conical scanning performed by the DSN antenna, which introduces additional pointing errors on the order of the size of the scan radius.

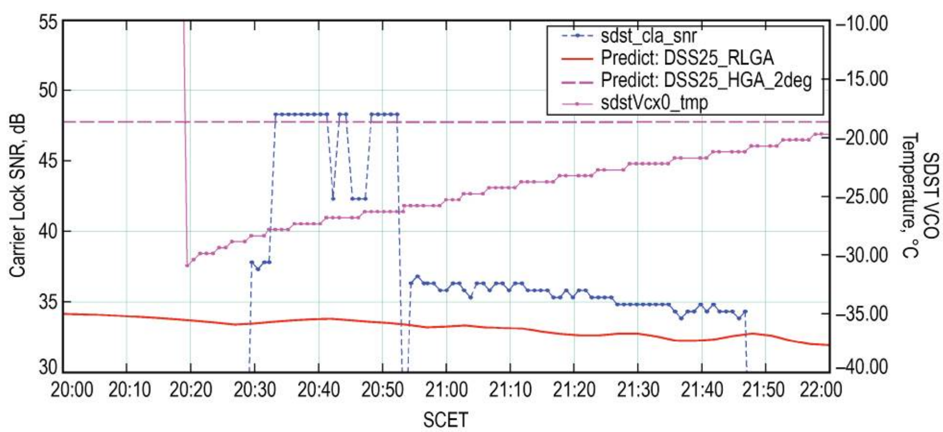

Fig. 7-38. MER-A surface uplink performance from a 34-m station (without Conscan).

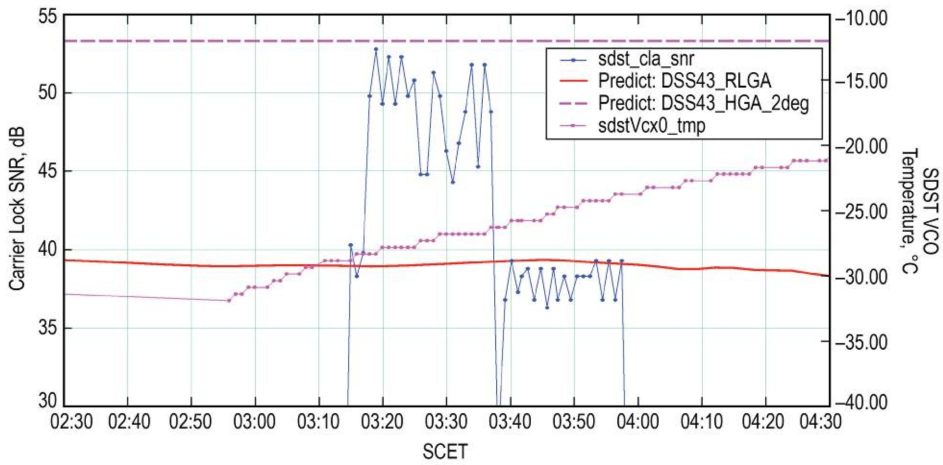

Fig. 7-39. MER-A surface uplink performance from a 70-m station (with Conscan).

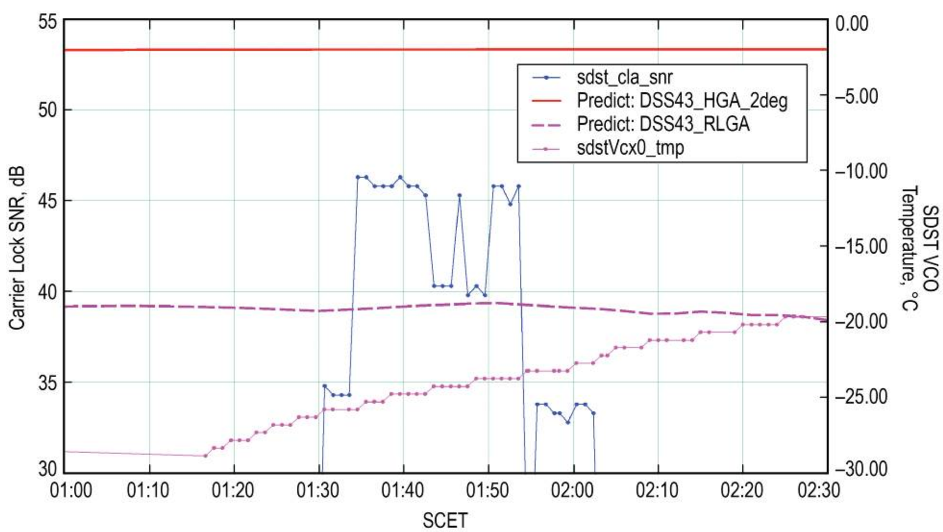

Fig. 7-40. MER-A surface uplink performance from a 70-m station (without Conscan).

7.5.1.8 Uplink Acquisition Problems Caused by Rover Temperature Variations

The SDST best-lock frequency (BLF) is the uplink frequency that results in zero static phase error (SPE); hence it places no stress on the tracking loop. BLF varies with the temperature of the VCO in the tracking loop. In cruise, the VCO temperature changed very slowly (unless there was an attitude-changing TCM), generally much less than 1°C from day to day. Because of that stability, the project needed to provide BLF updates to the DSN only a few times for each MER during cruise. The DSN uses BLF as a scaling input to the uplink and downlink frequency predicts that are sent to the station for each tracking pass. Each pass requires a new set of predicts since each pass has a unique Doppler profile.

Using the uplink predicts, the station acquires the uplink using the Magellan acquisition (MAQ) tuning template, with ramped uplinks for all passes. The MAQ is a template to –130 dBm or less. To accommodate the –130-dBm constraint, the 70-m stations were requested to operate at 10-kW transmitter power during sweeps until the Earth–Mars distance increased to the point that full power (20 kW) could again be used. MER-B did not spend as much time in the coldest temperature regime as did MER-A. MER-B used a different day/night power profile called "deep sleep" that was started in July 2004 and was used during the periods of lowest power available in the Martian winters.

Characterization of the BLF during surface operations, as compared with prelaunch testing data, yielded the plots in Figs. 7-41 and 7-42.

The frequency of the VCO on MER-A can change by as much as 15 kHz over a period of 10 min due to temperature-dependent coherent leakage, as discussed in Section 7.5.1.9.1. To account for VCO temperatures down to –20°C, the MER-A BLF and sweep range (SR) about that center were both changed on some sols. Eventually as rover wake-up temperatures decreased toward –30°C and most recently to lower than –40°C, it became necessary to use an uplink frequency reference offset (FRO) for the morning acquisitions.[27] Uplink FRO values as large as –13 kHz have been requested for MER-A in 2010.

To accommodate even colder temperatures, the SR for MER-A was increased to 8 kHz. For initial surface operations, SR for MER-A was made 3 kHz (the cruise value), then increased to 5 kHz, then 8 kHz, with even wider values being tested. To keep the sweep duration the same, some in-flight tests were made with an SR twice as large (16 kHz), and a sweep rate twice as fast

[27] An uplink FRO is a constant frequency adjustment added at the time of the pass to the pregenerated BLF-based uplink (ramped) frequency from the DSN Predicts Group. Use of an FRO allows for morning and midday passes and simplifies operations, allowing a single TSF despite greatly different VCO temperatures at the two times. The Telecom analyst can verify that the proper FRO has been used by verifying the presence of a constant bias in the downlink Doppler residual. The bias is the FRO multiplied by the SDST X-band "turn-around" ratio (880/749). This offset occurs because downlink frequency predicts are not adjusted for the FRO. The downlink receiver can still acquire the biased carrier frequency, provided the carrier frequency remains within the acquisition FFT range.

(200 Hz/s).[28] For the MER-B SDST, which does not have coherent leakage or minimum temperatures as low as those of MER-A, FROs have been limited to –5 KHz. The MER-B BLF has stayed within the nominal ±5-kHz SR for all VCO temperatures so far.

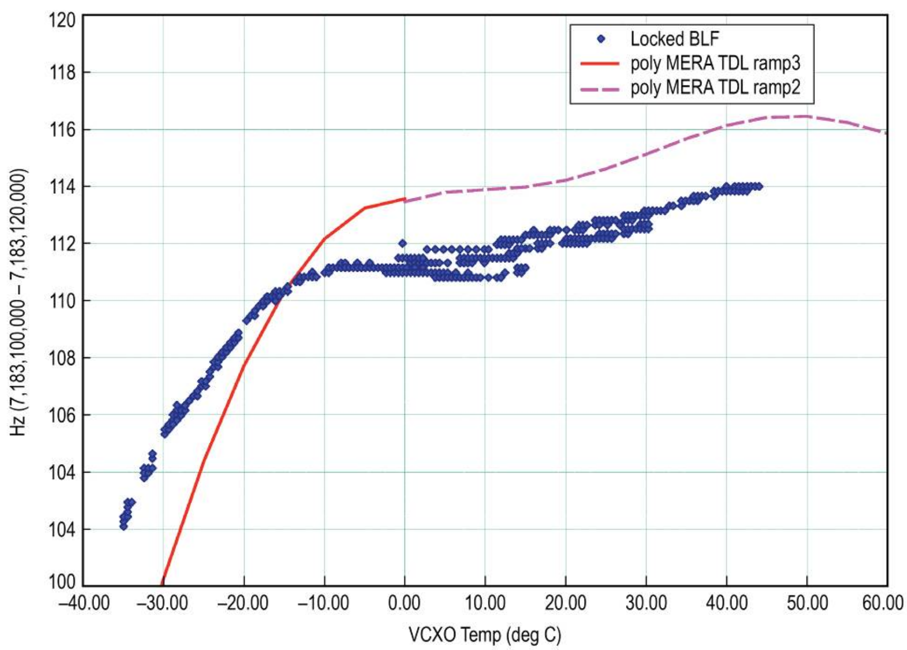

Fig. 7-41. MER-A surface best-lock frequency (in flight vs. prelaunch test).

[28] To conserve power and maximize the time available for science, the project minimized the period between wake-up and start of the DFE comm window and also the duration of the comm window. These intervals have been designed to work with a sweep-duration of about 4 min maximum, whether the sweep is to the RLGA in the morning prior to the window or to the HGA at midday within the window.

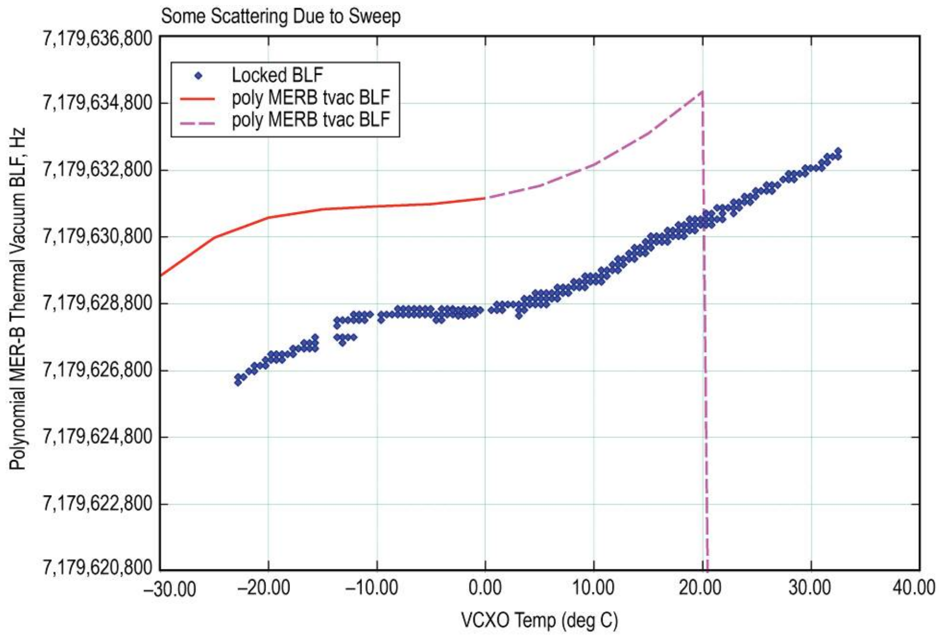

Fig. 7-42. MER-B surface best-lock frequency (in flight vs. prelaunch test).

7.5.1.9 Other Key X-Band Technical Issues

7.5.1.9.1 Coherent Leakage in MER-A SDST. This leakage, present only in the MER-A SDST, causes buildups in the receiver static phase error of as large as 15 kHz during periods between the SDST's state 1 (S1) time-outs. The S1 time-out resets the carrier loop to its BLF (SPE = 0). After an S1 time-out, the receiver will lock to an uplink sweep centered at BLF. Depending on the SPE drift rate, during some portion of the 10 min between time-outs, when the SPE becomes large enough, the receiver will not lock to an uplink centered at BLF.

The effect of the leakage is most severe at cold temperatures, the maximum drift magnitude increasing sharply below –25°C. The direction of the drift between time-outs may be positive or negative depending on the specific temperature. The operational mitigations include

- Increasing the SR to 8 kHz,
- Using an FRO to center the actual sweep around the predicted BLF, and
- Trying to time the acquisition to get an S1 time-out in the middle of the sweep. The S1 time-outs can be predicted from the rover wake-up time.

Figure 7-43 is a plot of MER-A static phase error in the SDST receiver loop. The relatively smooth variation between 14:50 and 16:10 occurred with the receiver in two-way lock with a station, and the 10-minute cycling between 0 and several kHz after that occurred with the receiver out of lock.

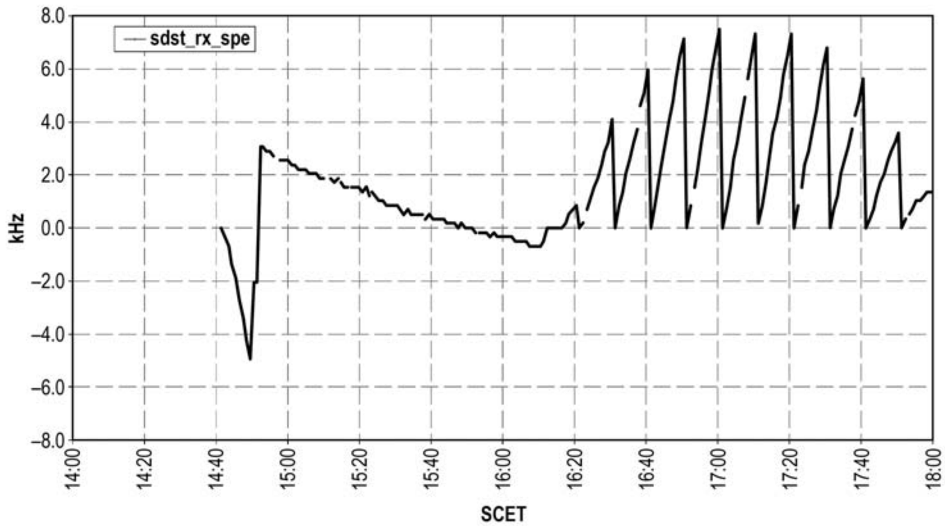

Fig. 7-43. MER-A SDST receiver static phase error showing effect of coherent leakage.

The sawtooths before and after this time are one-way, with the S1 time-outs at 10-min intervals resetting the SPE to 0. An SPE of 0 indicates the SDST will acquire carrier lock at BLF.

7.5.1.9.2 SDST Receiver DAC Rollover Glitch. A DAC in the receiver induces a voltage spike in the VCO when the digital value of the SPE rolls over from all ones to mostly zeroes. The voltage spike could cause a loss of already-achieved uplink lock. The receiver is most susceptible to this problem for positive-going sweeps, at temperatures lower than –15°C, and for strong uplinks, greater than –130 dBm. This is a problem seen during prelaunch testing and during rover operations in the extended missions.

The operational mitigations that have been used to avoid DAC rollover include

- Sweeping into the RLGA rather than the HGA to reduce received power,
- Using the MAQ template, to sweep downward from above to below BLF, sweeping positive only while returning to BLF,

- Reducing 70-m transmitter power to 10 kW to limit the received power to –130 dBm for HGA acquisitions at smaller Mars–Earth distances, and
- Keeping the SR narrow to avoid most rollovers.

7.5.2 UHF: EDL and Primary Mission Surface Operations

In this chapter, the UHF link from the orbiter to the rover is called the forward link, analogous to the X-band uplink from the DSN to the rover. The UHF link from the rover to the orbiter is called the return link, analogous to the rover X-band downlink to the DSN.

7.5.2.1 EDL UHF Link Predictions and Performance

After parachute deployment, the MER lander transmitted a UHF return link at 8 kbps to MGS, whose orbit had been phased so that the orbiter would be in view of the descending MER. Both the X-band DTE carrier-only signal and the UHF 8-kbps signal were transmitted throughout bridle-cut, touchdown, and subsequent bouncing on the surface of Mars. During the EDLs for both Spirit and Opportunity, the UHF 8-kbps signal was received by MGS from the time when the lander separated from the backshell until the time when MGS set at the landing site. During this interval, the UHF link returned about 3.5 Mb.

For mission design purposes, a link margin of 10 dB was kept for the UHF EDL phase. Such a high margin was justified by the challenges of getting a good antenna measurement on the lander mock-up at UHF; in addition, there were great uncertainties in the geometry for this mission phase (for example, MGS position, and angles between the antenna and MGS due to swinging on the bridle). Due to the possibility of the antenna's breaking off during airbag deployment and the challenges of guaranteeing a good signal while the lander was bouncing on the surface, no requirement was specified in UHF performance after RAD rocket firing.

Figure 7-44 shows the received UHF power at MGS and the lock status of the carrier, bit synchronizer, and Viterbi decoder during the MER-B EDL. In this timeline, bridle-cut was at 04:54:21 UTC, roll-stop at 04:56:08 UTC, and MGS-set at 05:02:38 UTC (0-deg horizon for the planned rover landing site).

For both MERs, UHF performance during EDL exceeded predictions. The lander UHF antenna was not damaged during the inflation of the airbags, and the MGS receiver was able to stay in lock even while the lander was bouncing.

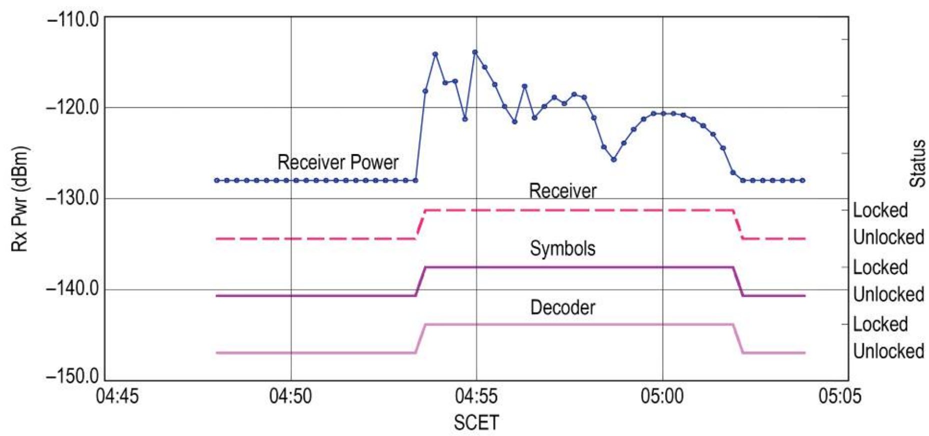

Fig. 7-44. MER-B EDL (January 25, 2004), UHF received power and lock status.

7.5.2.2 Primary-Mission Surface UHF Link Predictions

At X-band, predictions are often generated in the form of data-rate capability, and the results are used to set the downlink rate to the DSN from among more than a dozen possibilities, depending on Earth–spacecraft range, spacecraft antenna pointing angle, and station-elevation angle. For MER UHF, data-volume predictions have proved to be especially useful because of the limited variation in range between the rover and the orbiter, the lack of modeled elevation-angle effects, and the small number of data rates from which to choose.

The Generalized Telecom Predictor (GTP) tool, together with a series of scripts, generates a data-volume capability file (DVCF) for all overflights for the specified rover-orbiter pair in a given time period. The output is in the form of tabular summaries displaying volume (in megabits) for each view period (potential relay pass) and for all rover yaw angles in steps of 10 deg. The DVCF predictions assume that the rover is not tilted. Not tilted means that at the landing site, the RED is horizontal and the RUHF is vertical.[29] The output

[29] For much of the primary and early extended mission, “no tilt” was a good approximation, with the actual tilt generally less than 4 deg. As the extended missions have continued, with the rovers climbing hills or descending slopes into craters, Odyssey-MER communications have occurred with the relevant rover at a tilt as great as 31 deg. Though DVCFs are still run with “no tilt,” the exactness of predictions has now increased with scripted use of GTP, taking into account telemetered rover roll, pitch, and yaw angles. These predictions have also sometimes accounted for line-of-

can be displayed in several forms. Figure 7-45 shows an example of tactical use of Generalized Telecom Predictor/data-volume capability file (GTP/DVCF) volume predictions. Part (a), top, shows the predicted volume in megabits at every 10 deg in azimuth on a polar plot, for each of two potential low-elevation passes. Part (b), bottom, shows the geometry of each of these passes superimposed on the rover UHF antenna pattern (oranges and reds indicate higher gains) for the actual yaw of 297 deg. Based on the yaw and the predictions, the pass shown to the right was selected, and it returned 75 Mb.

Based on these kinds of predictions, and after verification of normal UHF link performance on the surface, the return-link rate was raised to 128 kbps for all MGS and Odyssey passes shortly after landing.

DVCF predicts showed that the return link to Odyssey could often support a rate of 256 kbps, but this rate had very limited testing before launch, and was initially restricted from use. However, in February 2004, a test of 256 kbps was successful except for dropouts caused by a transceiver idiosyncrasy referred to as “extra byte at 256 kbps.” This problem was corrected by MER ground software in March 2004. Afterwards, Odyssey comm windows were planned for either 128 kbps or 256 kbps, depending on Odyssey constraints and whichever rate showed a greater predicted data-volume return.[30]

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sight blockage from the local terrain rather than using a simple, fixed, minimum elevation angle.

[30] Once normal surface operations began, UHF window planning was always more fully automated than was X-band window planning. However, plans for a week’s worth of UHF windows could not fully account for the changing yaw angle that could result from sol-to-sol driving plans. As the extended mission went on, UHF windows were changed in the sol-to-sol “tactical” process to optimize for 256 kbps or 128 kbps, and some planned windows were cancelled if their data volumes were predicted to be significantly lower than other possible windows 2 hr before or after. Eventually, some changes also took into account the rover tilt and horizon obstructions. As described in the next section, MER developed a process for notifying the Odyssey and MGS ACEs via e-mail of cancelled windows or ones with changed data rates.

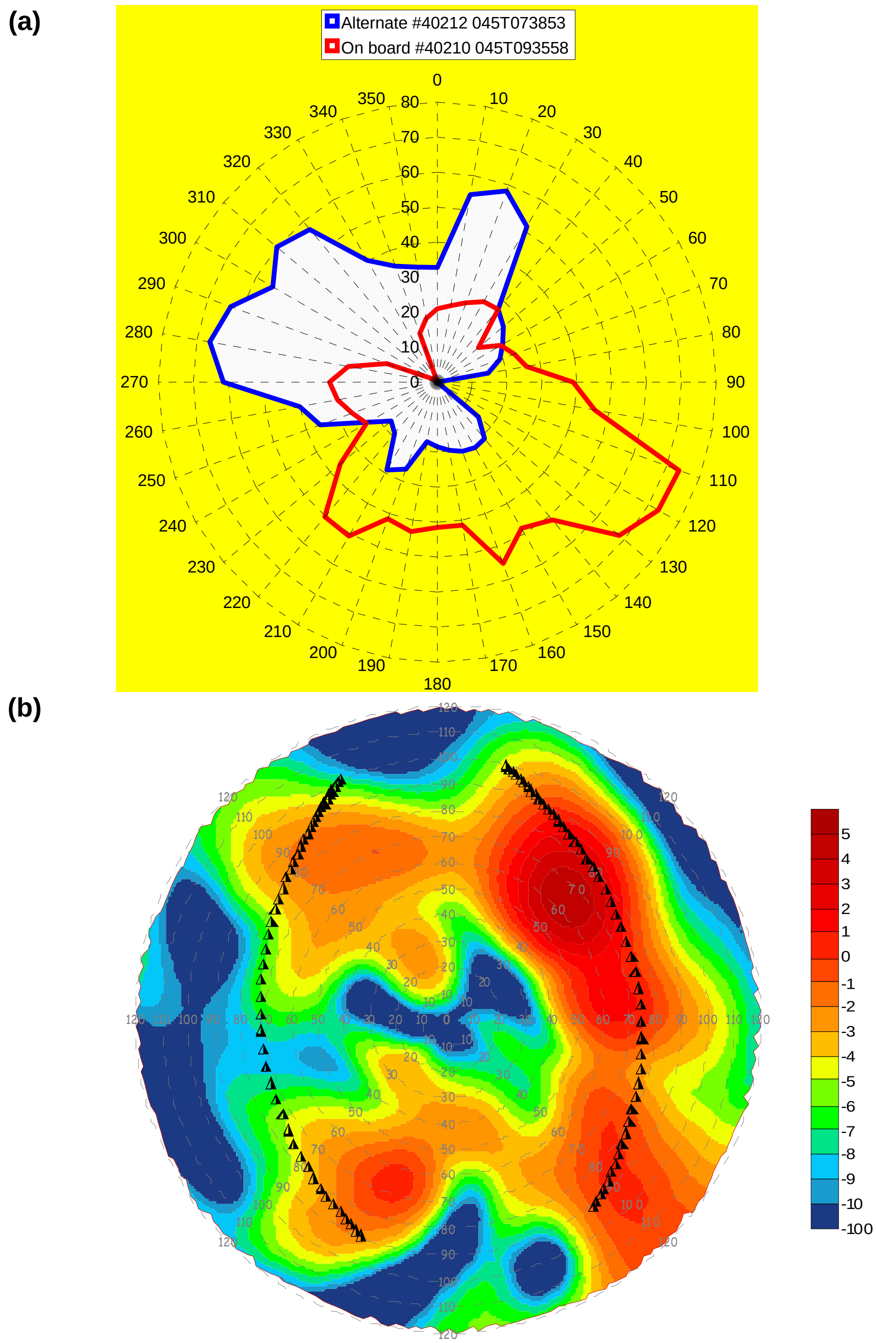

Fig. 7-45. Example of tactical use of GTP/DVCF volume predictions with (a) showing predicted volume and (b) showing the geometry of each of these passes superimposed on the rover UHF antenna pattern.

7.5.2.3 Primary-Mission Surface UHF Performance

As soon as the return-link data rate was increased to 128 kbps, the UHF link began returning the majority of the data. By the end of the primary mission in April 2004, UHF data totaled 89 percent of the total. Figure 7-46 (for Spirit) and Fig. 7-47 (for Opportunity) show how much data has been returned from the rover in each of three possible ways: by DTE, via MGS, and via Odyssey. The top half of each figure shows the data return individually for each sol during the primary mission, with the amount from the DTE in yellow at the bottom of the bar, the amount from MGS in blue in the middle, and the amount from Odyssey in violet at the top. The bottom half of the figure shows the accumulated data return at any point in the primary mission. The colors in the bottom half correspond to those in the top half for DTE, MGS, and Odyssey data return.

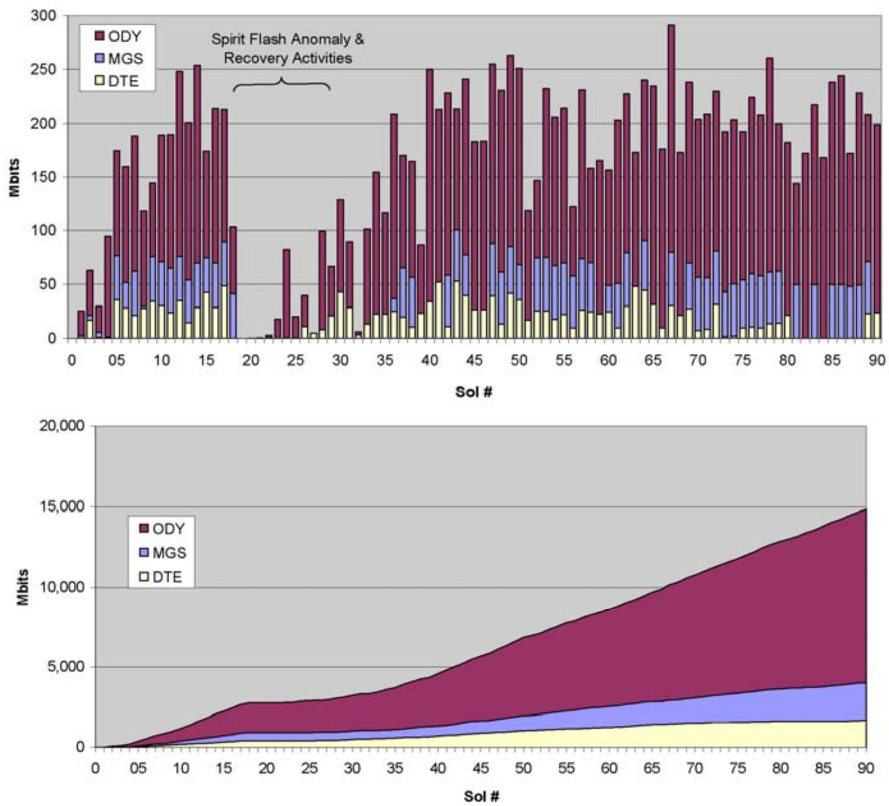

Fig. 7-46. MER-A primary-mission data sources: volumes per sol (top) and accumulated (bottom).

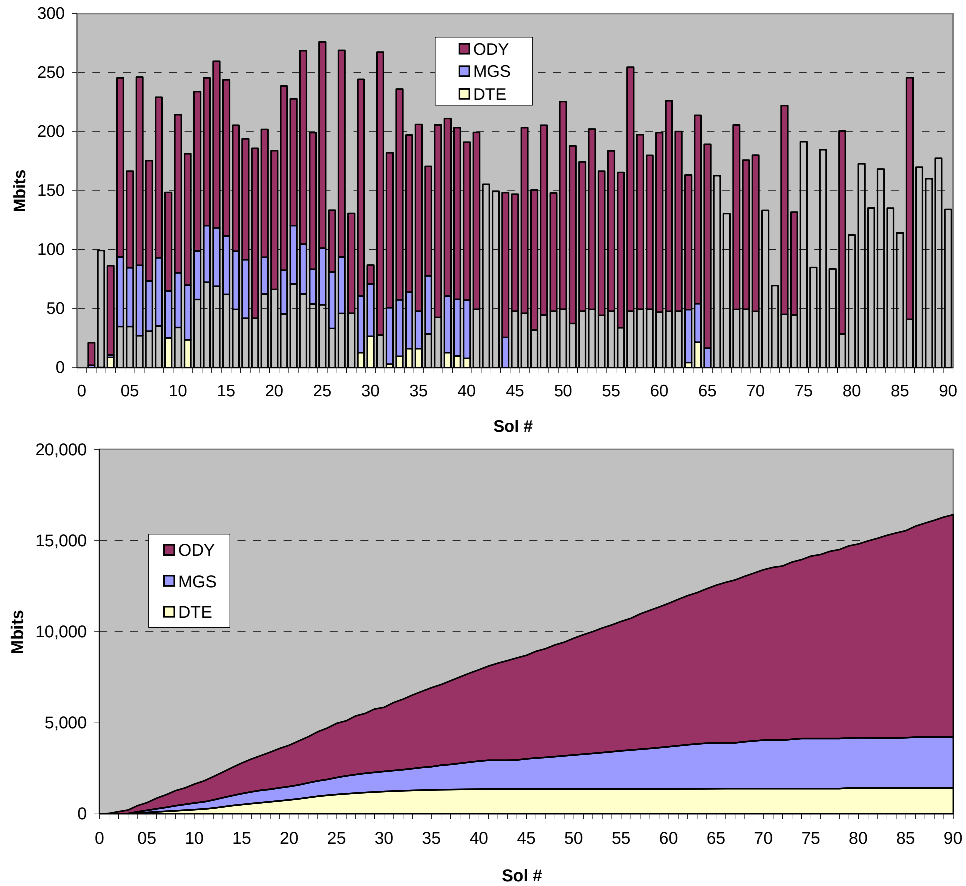

Fig. 7-47. MER-B primary-mission data sources: volumes per sol (top) and accumulated (bottom).

During the first extended mission, the portion of total data returned via UHF increased to 95 percent and by October 2005 to 97 percent. Additionally, relay communications compatibility was demonstrated with the MEX orbiter during a few coordinated passes at 32 and 128 kbps.

The UHF links were generally compared in detail with predictions only when the actual performance was significantly lower than expected or showed an unusual signature. To get high-resolution forward-link telemetry data on received UHF power, a "UHF report" would have to be included in that sol's rover sequence. This report provides telemetry with a sampling resolution as small as 1 s, compared to the standard engineering health (or housekeeping) and accountability (EH&A) rate of 30 to 60 s.[31] In the primary mission there were as many as four passes per rover per sol, most often one by MGS and the rest by Odyssey.

7.5.2.4 UHF Pass Planning and Optimization

Primary mission UHF pass selection was a coordinated effort involving both long-term (strategic) and short-term (tactical) planning.

Strategic planning was conducted several weeks in advance by a multi-mission team of representatives from MER, Odyssey, and MGS.[32] Geometrically, there are four overflights per sol per orbiter. The LST of the passes is typically 2–3 a.m. and 2–3 p.m. for MGS, and 4–5 a.m. and 4–5 p.m. for Odyssey. The orbiters' view periods (time above the horizon) are short; as a result, a typical UHF comm window is about 15 min long. During the primary mission, all passes with geometric view periods greater than 5 min were sequenced. MER Mission Planning designated a subset of these overflights as "requested" passes, and chose the return-link rates based on DVCF results (128 kbps for MGS; 128 or 256 kbps for Odyssey). The remaining "unrequested" passes were sequenced on the orbiters with a default link configuration. Among the criteria considered for pass selection were geometry, data volume, and the potential to minimize orbiter buffer overflow. Sequences were built to generate comm windows to support the requested passes. Depending on how many passes were planned per sol, the sequences were uplinked every one or two weeks.

Tactical planning was conducted on a sol-by-sol basis, and it considered passes occurring in the next sol or two. Attention was focused on optimizing UHF data return, subject to various constraints, such as rover attitude, available energy, and expected time of data receipt on the ground. DVCFs identified desirable yaw angles for parking the rover. If the rover was significantly tilted

[31] In the primary mission, the UHF telecom analyst requested UHF reports in order to analyze specific relay passes and to characterize relay operations for planning. During the extended mission, UHF reports, initially assigned a low priority, were routinely generated for all Odyssey passes by attaching a "generate UHF report" sequence that began when the UHF comm window started preparation. To mark a selected UHF report for transmission, MER data management would generate a command to raise its priority. Data management routinely reprioritized the UHF reports generated for all passes every seventh sol so that Telecom could spot-check UHF performance. Telecom could also request reprioritization of UHF reports that were of "interesting" passes. Data management marked for automatic deletion any UHF reports older than 7 sols.

[32] Coordination for the Mars Express interoperability demonstration (experiment) was done separately.

(particularly in the east-west direction), data volume could vary significantly from zero-tilt DVCF predicts, especially for low-elevation passes or 256-kbps passes. Sometimes the tilt was so large (~20°) that the orbiter was occluded by the rover deck for most or all of a pass. In these cases, GTP was run using the estimated rover attitude for more accurate link assessment. Results from tactical planning included identification of passes to keep, modify, or delete, yaw(s) to park the rover for maximum data return (for mobility planning), and predicted data volume for those passes (for science planning). Maximizing UHF data return was so important that on some occasions the rover was commanded to turn (change its yaw direction) in the time between two afternoon overflights. This was to maximize the total data return. In the example of Fig. 7-37, it can be seen that if the rover were turned by 180 deg, the east pass would be on the high-gain region of the antenna pattern.

Odyssey uses the CCSDS Proximity-1 Space Link protocol (UHF1) [8], which is designed to ensure error-free delivery of data by using a Go-Back-N (frames) protocol. Idiosyncrasies in the design of the radio do cause the Odyssey return link to have a few (0 to 15) data gaps per pass, each starting with loss of lock and ending with reestablishment of the link. Despite the gaps, the Odyssey link can achieve a throughput of 97 percent when the SNR in the link is high.

MGS, which was launched several years before Odyssey, implements the Mars Balloon Relay protocol (MBR or UHF2) [17], which is less robust than Proximity-1. At 128 kbps, typically two rover transfer frames every 16 s were lost while the MGS radio changed modes (and meanwhile stopped accepting data), and the MER radio, not detecting the change, continued to send data. Because of the large number of gaps, only lower-priority data was sent during MGS passes. (By the end of 2010, UHF passes were via Odyssey or MRO.) The MBR protocol is less efficient than Proximity-1. Even when the bit error rate at MGS is low (indicating a solid link), data is transmitted for only 13.3–13.8 s out of every 16 s.

In addition to data protocol issues, MGS passes were data-volume limited, and they ran a high risk of buffer overflow, as described in Section 7.4.3. Because UHF data was recorded in the MOC buffer, MGS limited the amount of UHF data it would collect per pass (typically 30 to 60 Mb). Once the buffer allocation was reached, MGS stopped collecting data even though the UHF link might still be active. As a result, any rover data sent after the MOC buffer was full was lost and had to be retransmitted by MER during another pass. On some sols, MGS passes were used in place of afternoon HGA passes to get higher data volume (especially when the rover was energy-limited).

MER UHF tactical plans are communicated to Odyssey and MGS via the "uhf-tactical" e-mail list. Receipt of messages and actions taken by the orbiters are also confirmed via this list. Normally after confirmation of successful receipt of the daily command load, the MER ACE sends an e-mail identifying the passes to be kept and deleted by MER. Notification of pass deletions are a courtesy that allows MER to avoid unnecessary troubleshooting for missing data. In addition, the MER tactical team uses the e-mail mechanism to document orbiter data collection from previously unrequested passes.[33]

Changes to UHF link parameters are handled via an orbiter relay state-change (ORSC) request since the orbiter (which does the hailing) has to be commanded to change the link configuration. The most common request by far has been to change the return-link rate (from 128 kbps to 256 kbps or vice versa). The ORSC request to change return-link rates involves sending commands to Odyssey twice: one command before the overflight changes a global variable to override all sequenced return-link rates and use the specified one, and one command after the overflight changes the global variable back to honor the previously sequenced return rates. ORSC requests must be e-mailed and received by the orbiter ACE before the drop-dead uplink time (DDUT) to allow time for the state-change command(s) to be radiated from the tracking station to Odyssey.

7.5.2.5 Commanding the Rover via Odyssey UHF Link

Forward-link verification activities were run for the first few days on the surface. These activities explored a UHF frame-duplication idiosyncrasy that can cause problems with the forward link from Odyssey to a rover. This problem can result in loss of parts of commands or repeated execution of immediate, virtual channel 1 (VC-1) commands. In order to maximize the chances for success, recommendations were developed based on the results of the UHF forward-link verification activities. Recommendations included

- Duplicating the commands within a single uplink session (in case of partial command loss),
- Padding the desired VC-1 immediate command uplink transfer frames front and back with "no operations" (no_op) commands (so that the only immediate command that can be executed twice is a no_op),
- Delaying the Odyssey forward-link start time until several minutes into the overflight, when the geometry is better, and

[33] During the strategic planning process, unrequested passes are sequenced on the orbiters, but not on MER.

- Lowering the return-link rate (to reduce link dropouts, which can induce the frame-duplication problem).

Routine commanding of each rover during surface operations through September 2005 was via the DSN DFE link. Prior to the extended missions, commanding via the UHF link (which is possible only with Odyssey) was generally limited to verification tests. A significant exception occurred in June 2004, when the next available HGA DFE window was still hours away, and commanding via the LGA at 15.625 bps was either too slow or not possible. To correct a rover onboard power profile, MER-A was commanded via Odyssey during a 256-kbps UHF comm window to change the power modes. The MER project transmitted a command file (in which each of the short commands was repeated several times) to the Odyssey control center, and the Odyssey operations team sent the file to their spacecraft for relay to the rover. The rover responded properly, and later telemetry showed that all commands got in.[34]

A practical reason for the limited use of UHF commanding of the rovers during the extended missions was the LST of the morning Odyssey pass, typically between 4 and 5 a.m. This time is more than 5 hr before the typical 10 a.m. LST of the X-band command window. When working on Mars time, the science and sequencing teams would have had 5 hr less to plan and prepare activities for the next sol after the afternoon receipt of data if they commanded at UHF instead of at X-band. The commands would have had to be ready before the DDUT, and the Odyssey ACE (who was generally not living on Mars time after the MER primary mission) would have had to be available to send them to the orbiter.

UHF commanding of the rover, based on the rover team operating on Earth time and with a revision of the sequencing activities timeline, was re-evaluated for the March 2006 MRO Mars orbit insertion. This was to avoid X-band uplink interference with the MRO with MRO and the Spirit Rover (both operating on DSN channel 32) were within the station antenna beamwidth. The co-channel operation had not been thought likely with the planned 90-Sol MER mission starting in January 2004. Aside from using UHF for MER, a more common technique called MUKOW (MRO uplink keep out window) in which station X-band transmitter operation is carefully timed between MER and MRO when both vehicles are in view of the station (not occulted by Mars).

[34] MER also conducted UHF forward-link tests in September and October 2005 in preparation for a one-week UHF-only operational demonstration in late October 2005.

7.5.2.6 UHF Link Analysis

UHF link analysis was conducted during the primary mission using several data sources. Typically, they included a combination of queried MER telemetry, queried Odyssey telemetry (e-mailed by the Odyssey team), and GTP predictions. Higher visibility was obtained by including UHF report data products (which had to be requested by the telecom analyst). The data was plotted using various Excel tools developed by MER telecom. Generally, link volume predictions have compared well with actual data return (usually within 10–20 percent). Occasional outliers are due to excessive tilt (not considered ahead of time), obstruction or occlusion by surroundings or rover deck, and operation near threshold for a significant portion of the pass.

As an example of the UHF link analysis achieved, Figs. 7-48 through 7-53 compare the performance of a high-volume and a low-volume UHF pass. In each case (high volume and low volume), there are two figures that show mean and adverse prediction curves, offset vertically from each other, as well as a plot of the forward-link received power from rover telemetry or return-link received power from Odyssey telemetry. Both forward- and return-link margins (Figs. 7-48 and 7-49) are also shown as dotted lines for reference since the Proximity-1 protocol dictates that both links must be above threshold for the link to be established. Figure 7-50 shows the link geometry superimposed on the MER UHF return-link pattern. The predictions account for the orientation of the rover (azimuth and tilt from horizontal). Azimuth angle is referred to as “rot” (rotation) in the two performance and prediction figures of each set and as “yaw” in the pattern figure. See figure numbers for high-volume and for low-volume links in the following two paragraphs.

In the high-volume examples (Figs. 7-48, 7-49, and 7-50), the actual received power curves generally follow the shape of the predicted total power curves, with the return link modeled much better than the forward link.[35] The large dip in the return link just before 03:45 corresponds to the orbiter passing over the null in the pattern shown in Fig. 7-50. (Figures 7-50 and 7-53 are polar antenna plots showing the angles 0 to 120 deg from boresight radially.) This 256-kbps pass was predicted to return 83 Mb, but the actual return was 125.5 Mb. The reason for the higher data volume is that the link was predicted to drop out at about 03:49, but the link performed closer to average than to marginal (a few decibels better), allowing the return link to remain above threshold for a few extra minutes. This is shown in Fig. 7-49.

[35] The return link has been closer to predict than the forward link for the entire surface mission. However, since performance is usually limited by the higher return-link rates, this has not caused a problem in MER planning.

There is room for improvement in our UHF prediction capability; however, it has been difficult to use the accumulated UHF reports to measure rover polarization and gain antenna patterns. We also suspect the source of some of the difference between predicted and actual performance may lie in the orbiter antenna patterns. It has proven difficult to decouple rover and orbiter quantities. Antenna measurement on good-quality spacecraft mock-ups should be made a priority for future missions.

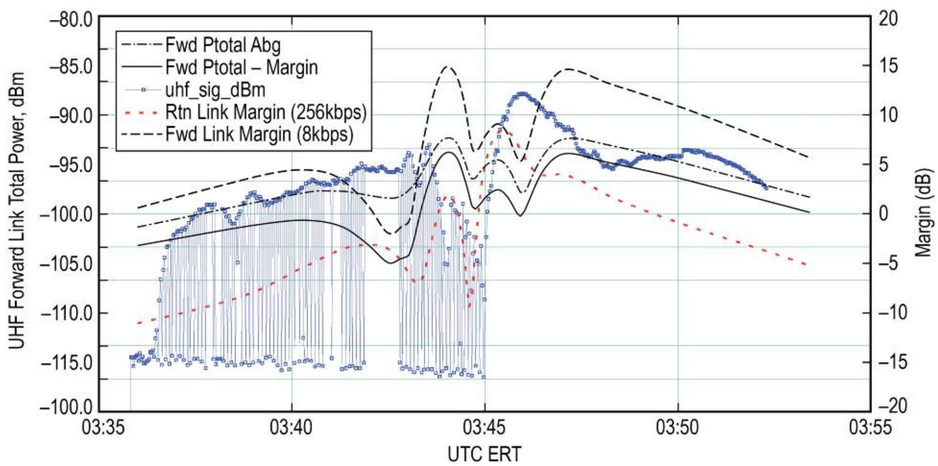

Fig. 7-48. High-volume forward link—Odyssey to MER-B, sol 104 p.m. (5/10/2004).

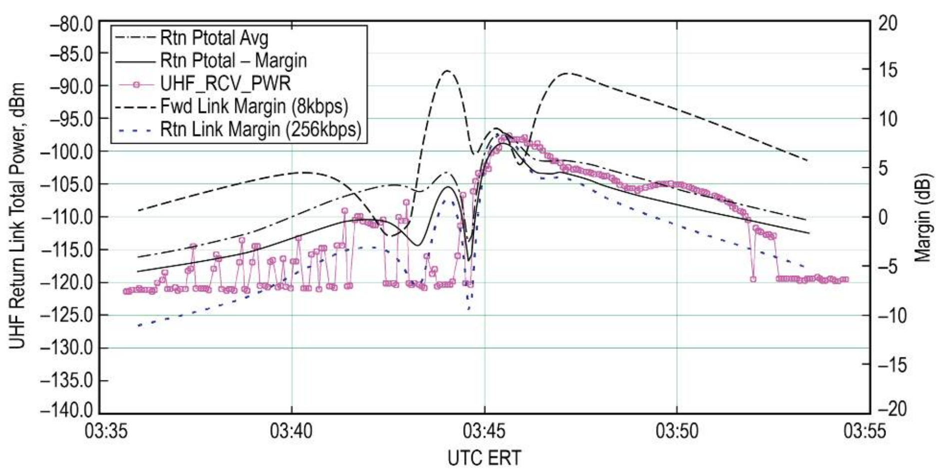

Fig. 7-49. High-volume return link—Odyssey to MER-B, sol 104 p.m. (5/10/2004).

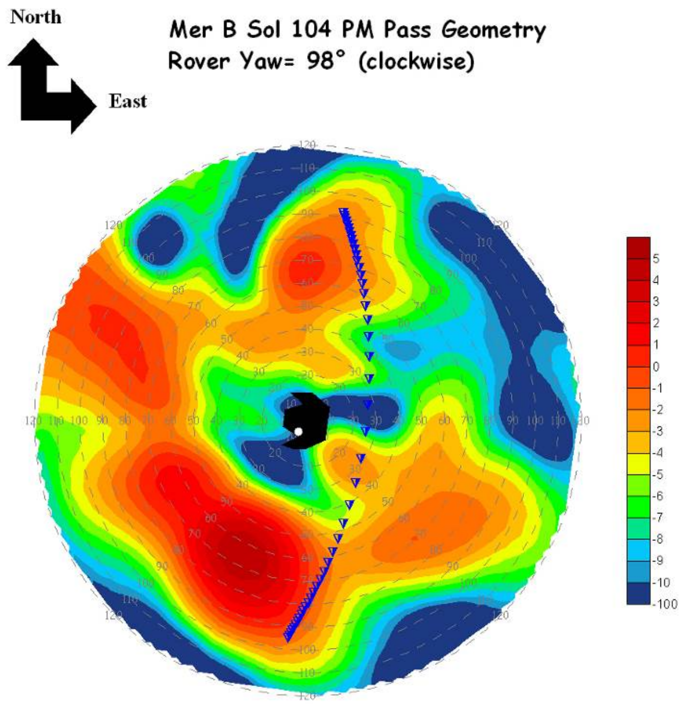

Fig. 7-50. High-volume return-link polar geometry—Odyssey to MER-B, sol 104 p.m. 5/10/2004).

In the low-volume example (Figs. 7-51, 7-52, and 7-53), the actual received-power curves again generally follow the shape of the predicted total power curves. However, during the period highlighted between the two vertical black lines in Fig. 7-52, the link was expected to close and it did not. The predicted data volume for this 256-kbps pass was 80 Mb, but the actual data return was 4.4 Mb. When the link is analyzed, the performance is not too surprising despite the large discrepancy between predicted and actual data volume. Figure 7-53 shows the overflight geometry, with the predicted above-margin period highlighted. The geometry plot in Fig. 7-53 shows that during the part of the pass highlighted in Fig. 7-52, the overflight was in a steeper portion of the antenna-gain pattern. Because it is not possible to separate the antenna gain and polarization loss to model each accurately, errors in the modeling or small differences between predicted and actual pointing angle could have pushed the link below threshold.

During the latter portion of the above-margin period, the predicted link margin was only slightly above zero for 2 min. A predicted 30 Mb was not relayed during that period. This highlights another weakness in the current method of UHF data-volume estimation. When the link margin is above zero, the link is predicted to close, and when it is below zero, it is predicted not to close. It is a hard-decision algorithm, that is, there is no consideration (or weight) given to how far above threshold the link is operating. This means that links predicted to operate near threshold (either above or below) for significant portions of the pass will have much higher variability in their actual data return than those links in which the above-threshold and below-threshold portions are more distinct. This is especially true for 256-kbps passes like this one.

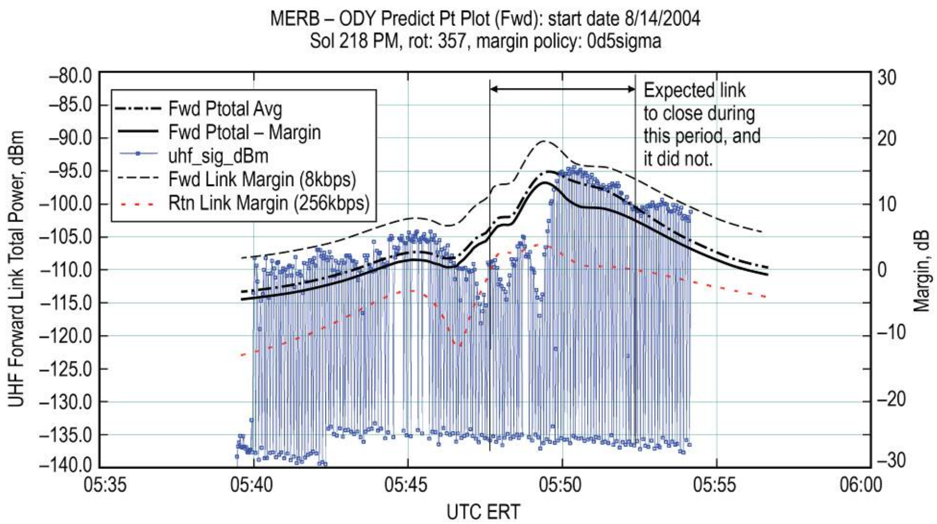

Fig. 7-51. Low-volume forward link—Odyssey to MER-A, sol 218 p.m. (08/14/2004).

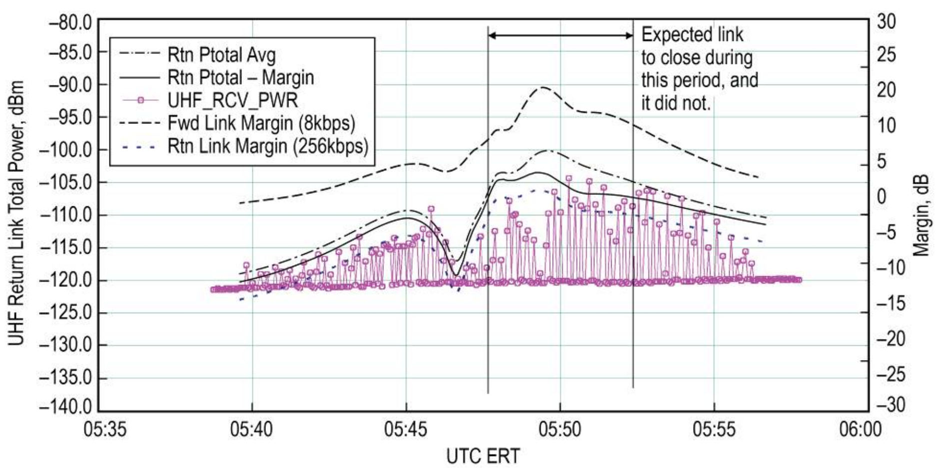

Fig. 7-52. Low-volume return link—Odyssey to MER-A, sol 218 p.m. (08/14/2004).

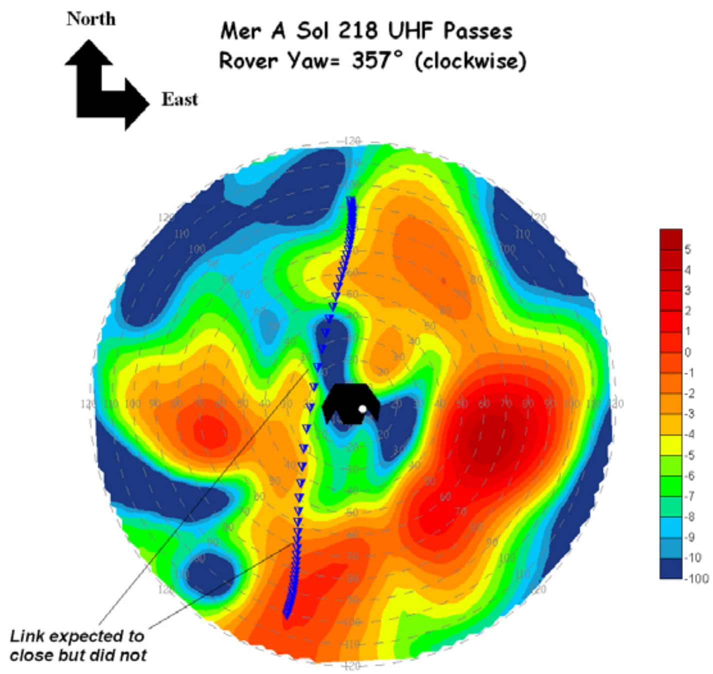

Fig. 7-53. Low-volume return link polar geometry—Odyssey to MER-A, sol 218 p.m. (08/14/2004).

7.6 Lessons Learned

MER has been a fantastically successful mission, with both rovers reaching Mars' surface and embarking on explorations lasting far longer than the full mission-success criterion of 90 sols each. Both the X-band and UHF parts of the telecom subsystem were well conceived, designed, tested, and operated. We would want to use these processes as models for the future. Even so, there were some problems that made it difficult to build, test, and operate the hardware. Other problems made it difficult to predict the UHF data volume and to assess why the predictions were in error, required peaks in telecom staffing, made telecom planning time-consuming, or resulted in lost data. Lessons drawn from both the good and bad experiences could smooth the operation of telecom subsystems for future Mars surface projects.

These lessons learned are grouped by major mission phases: development; assembly, test, and launch operations (ATLO); and the cruise, EDL, and surface portions of the mission operations phase. Because the DSN is an integral part of any project's telecom operations, and two Mars orbiters played a major part in rover surface operations, this section includes MER, DSN, and orbiter operations lessons learned.

In some cases, a lesson may look overly obvious in hindsight. However, the experience documented here did occur, and can be used to make future deep space telecom endeavors better.

7.6.1 What Could Serve as a Model for the Future

7.6.1.1 X-Band Development

Schedule. The biggest challenge to MER telecom subsystem implementation was the very short development schedule (about 2 years). This meant that subsystems could not wait for all the higher-level requirements to be documented; they had to order parts right away.

Tight quarters. A second challenge was the physical space allocated to telecom components. Having to fit so many hardware elements inside a tight space (the WEB) meant that the placement of some of these elements (such as cables and connectors) had to be redone several times, which meant that certain cables had to be ordered three or more times. This MER problem was not unique to telecom hardware.

Lesson: MER is widely recognized as having had an "impossible" development cycle, a low probability of both rovers successfully landing and meeting even minimum mission-success criteria, and an exhausted development team. One institutional and project lesson learned is that even development difficulties such as these do not necessarily preclude mission success. The MER project should articulate reasons (even in hindsight) why the mission could be so successful in the face of factors like an overly ambitious schedule and almost too-constrained space allocations. Future projects can use the MER information to weigh more accurately than before the risks and benefits of their own development approaches.

Communications behavior. Communications behavior was embodied in comm windows for the first time on MER. The concept differed enough from traditional sequencing of the onboard telecom hardware to make the learning curve steep.

Lesson: Test new flight software (FSW) concepts early and often. Do software-intensive tests, such as with the rover Communications Behavior Manager (CBM), as early as possible in the ATLO process, to catch and perhaps correct problems between comm windows and other parts of the FSW. The effective use of the new comm window concept on MER was significantly advanced through on-the-job training during the flight mission.

Receiver ops. One of the design principles JPL has adhered to for many years is not to turn its receiver off after launch. For this project, however, power limitations (MER runs on solar power, with batteries to get through the night) forced the project to turn the SDST off every night.

Thermal cycles. Until MER, no SDST had undergone as many temperature cycles (at least three a day) and power cycles (about two to three a day). It is a tribute to the resilience of the SDST and SSPA design that their performance has not degraded in this extreme temperature environment. A good parts program, together with assembly and subsystem testing under expected mission conditions, helps to ensure dependable operation.

Lesson: Qualify hardware for intended modes. Link the parts qualification and screening program and test program to the specific intended operating modes, especially new ones.

SDST frequencies. The Mars environment has an effect on the SDST BLF versus temperature. We found that trends in this frequency during surface operations were similar to prelaunch trends, but with some differences in terms of offset and slope. Wide temperature excursions occurred within every sol, but generally were similar from sol to sol over periods of weeks. It proved difficult for the thermal analysts to model temperature profiles in new surface modes (such as deep sleep).

Lesson: Calibration campaigns, such as the calibration of the MER X-band telemetry channels, should be continued on future projects. Calibrations include uplink received signal level, receiver frequency variation (static phase error), and power amplifier RF output, with as much data as possible collected at expected and extreme temperatures. Quantities (such as oscillator frequencies affected by pressure (should be calibrated for each distinct environment (such as vacuum of space as opposed to Mars surface atmospheric pressure).

Seeing trends. Direct measurement of link performance revealed large changes that could be attributed for the most part to certain known factors (such as DSN antenna pointing, RLGA pattern variations, and HGA occlusion or RLGA signal scattering by the PMA). Direct measurement of performance shed little light, however, on smaller trends that may have occurred (none have been observed) in other quantities (like SDST receiver sensitivity, SDST exciter RF output, or SSPA RF output changes due to aging).

Lesson: Well-calibrated and stable telemetered measurements of critical parameters like receiver sensitivity and RF output power can be more applicable to discerning slowly changing or small differences in performance than is direct measurement of link performance.

7.6.1.2 X-Band Cruise Operations

Daily operations. The telecom analysts monitored two spacecraft during cruise, each one supported by one or several DSN tracking passes per day. Planning data rates that would work with the scheduled 70-m or 34-m stations, reviewing the comm windows that implemented these data rates, and monitoring and reporting spacecraft telemetry and station monitor data for each pass became increasingly easy with repetition, but the workload was always challenging. Fortunately, there were no significant performance changes within the telecom subsystem itself during cruise. Even so, characterizing the interaction of the telecom hardware with other onboard or ground subsystems required looking at many instances of the same configuration to see if any unusual performance was repetitive and perhaps due to a particular configuration.

Lesson: Automate repetitive ground software activities. For MER, certain macros for these activities were developed during cruise and perfected during surface operations: data-query scripts were developed in UNIX and trending macros in Excel for X-band hardware (SDST and SSPA) and station monitor (MON) data. Not requiring much user input, these macros provide comprehensive display of telemetry data as "digitals" (tabulations of data numbers or state values as a function of time) or plots (graphical displays of the data numbers [DNs] or engineering units [EUs] of one or more quantities versus time) and comparison of selected quantities such as SDST signal level with predicts. The tabulations and plots were then converted to Portable Document Format (PDF) and e-mailed to all telecom team members for review.

Automating the generation of link predictions. Telecom predicts for use by the ACE for each pass were partially automated in the "dkf2pred" scripts during cruise and by the "genmer" and "pred2pdf" scripts during operations. Even so, generating predicts for every pass during the final weeks before EDL was time-consuming. Each pass had to be set up individually by the analyst for start and end times, station, and downlink rate. Automation might be to create a script that calls TFP to have the ability to read in a previously generated project file and extract from the file the information that an analyst would otherwise type in to the TFP or GTP graphical user interface (GUI). Work on scripts to do this for MER began in July 2004.and is now in routine use on many projects.

Lesson: Fully automate telecom predicts. Besides being faster and easier to generate, than predicts that come from manual inputs, automated predicts produce consistent output formats (the same tabulated or plotted quantities always output, in the same order). Analysts become familiar with the format and therefore make fewer errors in using the automated predicts.

7.6.1.3 X-Band Entry, Descent, and Landing

EDL planning. From eight hours before EDL until two hours after, the MER project scheduled both of the 70-m stations and many of the 34-m stations with MER in view at Goldstone and Canberra. Rehearsals with EDA and RSR components at the stations and at JPL verified configurations and procedures to route downlink signal inputs from each station antenna (front-end assembly) to the EDA and the RSR for processing. Because the EDA was equipment developed especially for MER, and the RSR configurations for EDL were unique, the rehearsals included participation by EDA and RSR experts on site and at JPL to operate and monitor the equipment to process the signal inputs.

Lesson: Rehearse complex activities. A full-up in-flight EDL rehearsal during late cruise—involving the spacecraft, elements of the Flight Team, all participating stations, and the EDA and RSR—proved invaluable in wringing out procedural and interface issues. As a result, the EDL and telecom teams found the lander performance in both real EDLs easy to assess as compared to the simulated performance during the rehearsal.

7.6.1.4 X-Band Surface Operations

Comm window changes. Similar to the bit-rate optimization of late cruise operations, comm window optimization occurred in surface operations during the “tactical” (just-in-time, sol-by-sol) sequence development process. This optimization was essential for the complex and rapid-turnaround activities on the surface. Comm windows developed by Mission Planning during the “strategic” (multisol) process used the data-rate capability file (DRCF). During MER surface operations, the telecom analyst checked the 17 parameters in each comm window. Changes to X-band comm windows, particularly to the start time or duration parameters, had to be carefully—and manually—checked against station allocations and uplink timing. Manual checking of changes in individual windows is time-consuming and error-prone.

Lesson: If only manual checking is available, minimize changes to existing comm windows and to subsystem configuration changes during windows.

Global window changes. Constraint-checking processes more automated than those of MER would facilitate changes in the timing or data rate of existing comm windows. Fortunately, an automated process allowed tactical leads to change certain parameters (downlink bit rate, duration, or start time as a function of a reference time on Mars such as 8:00 a.m.) in whole groups of windows at once. These "global" changes worked well and did not require a separate check beyond the original DRCF validation.

- The "add_seq_to_window" parameter is handy and has been used. It allows the comm window to kick off another (possibly unrelated) activity. Very often these kicked-off sequences are used to generate UHF reports (Section 7.5.2.3).
- The ability to modify comm configuration within a window's execution time using individual secondary commands to the SDST, such as downlink rate change, was used sparingly but proved useful.

Window-checking scripts. During the extended missions, the telecom team began to find the time to develop scripts to check applicable flight rules, many of which involve the interrelated modulation telemetry parameters of comm windows. Others dealt with the interaction of window start time (in spacecraft event time [SCET]) and duration with station ground times (as transmit time or receive time). These time relationships are particularly onerous to check manually because there are many of them in a sequence, and they involve both OWLT and conversions between Earth time and Mars time.

Lesson: Automate window-checks that can be defined by rules. Give particular emphasis to comparing start times and durations of windows with activity times in the station-allocation files that define MER station passes. These include beginning of track, uplink acquisition (including duration of the uplink sweep), uplink handover, and end of track. For MER, such checks have helped to ensure that commanding is not attempted before the SDST receiver is in lock, and likewise that a nominal or off-nominal beep is not scheduled with the uplink out of lock (and thus the downlink in one-way mode).

RLGA operations. Considering boresight gain alone, one would observe that the RLGA is some 13 dB less capable than the HGA. However, when planned signal levels permit, using the RLGA, with its separate location on the RED and its wide gain pattern, is sometimes a means to avoid two factors that compromise the capabilities of the HGA: signal-scattering caused by PMA occlusion (described in Section 7.5.1.5 above) and the timing constraints imposed by HGA "flop" (described in Section 7.6.2.1, below).

Lesson: Consider telecom hardware characteristics and system factors, not just gain, when planning communications. At cold temperatures, when the uplink received power at the spacecraft should be limited to avoid DAC rollover glitches, sweeps can be performed into the RLGA rather than the HGA. Carrier-only "beeps" via the RLGA instead of the HGA may result in fewer interactions and constraints. Using the RLGA for a beep does not require HGA actuator heating or interruption of science activities. The RLGA can be used for a honk while the rover is driving, whereas the HGA would require a stationary rover for pointing.

Coherent downlinks. Usually one-way noncoherent downlinks are thought to be easier to manage than are two-way coherent links because they do not rely on an uplink being in lock. However, temperature swings on the Mars surface caused very large variations on the one-way downlink carrier frequency from the aux osc. The station receiver could not lock to the rapidly changing carrier frequency at the available downlink level. Very quickly it became standard that all DTE and beep downlinks be made two-way coherent. Doing so required planning for the SDST receiver to be in lock when the rover transmitted planned DTEs and beeps. Providing for coherent downlinks eventually included configuring coherent mode for the onboard fault responses, except for the final step in the response algorithm.

Lesson: The simplest mode may not be the best. Take advantage of the greater frequency stability in the ground station to combat temperature changes in spacecraft oscillator frequencies.

Blind commanding. Usually, having telemetry in lock is considered necessary to monitor the progress of commanding a spacecraft. Commanding without immediate command confirmation is called “blind commanding.” On most deep-space missions, blind commanding is done only in an emergency. MER surface operations have required it routinely, whenever the command period (uplink windows) and the light time are comparable and the next downlink pass or UHF relay is hours away. In the primary surface mission, blind commanding caused only one command error and one failed command load (both involving the same station) to the RLGA.

Lesson: MER surface operations prove that blind commanding can be very reliable. However, successfully establishing and maintaining the uplink for such commanding requires repeatable behavior of the receiver, precise use of the tuning template and its parameters, well-trained command operators (ACEs), and good command system monitoring capability.

Beeps. The beep has become an enduring marker for success (or not) of the command upload and initial operation of each new master sequence. The beep (a 5-minute X-band carrier-only downlink) is a simplified form of the semaphores (M-FSK tones) used in EDL. The timing of the detected beep designates it as either “nominal” (all okay) or “off nominal.”

However, the failure to detect a beep has not invariably meant that there is a problem on the rover. Most often the telemetry sent back during a subsequent UHF pass has shown that the SDST and SSPA sent a beep at the planned time. During the extended missions, this experience sometimes gave the project confidence to press on with planned activities (such as sending the command–loss-timer command) even after a station failed to detect the planned nominal beep.

Lesson: Use of a beep (or semaphore or other simple go/no-go signal) may make it possible to proceed with planned activities in cases where standard telemetry is unavailable to support such a decision.

RSR Operations. When the beep-detection process was new in the primary mission, the project requested beep detection by the RSR as a backup to the DSN's beep detection. As a result, after staffing for a few beeps, the JPL Radio Science group made available a prototype Web page for requesting RSR support for beep detection over specified time periods without the need for intervention by station personnel or staffing by Radio Science. Given Mars-time beep scheduling, this proved a useful automation. It worked at some stations, some of the time.

Lesson: To reduce overall project staffing costs, consider cross-training nonspecialists to run the RSR remotely and evaluate the output in a simple preset mode, such as to detect a beep. As an example, improve the operability of the remote (Web-based) access to the RSR setup.

Multipath. The telecom analyst could reliably predict uplink and downlink performance and operate 80 deg from the RLGA boresight (10 deg from the horizon with the rover level), and with the HGA Earth-pointed with the direct signal path close to the rover deck. Signal variations with the characteristic fading that may have been caused by multipath occurred on a few passes, but this variation never degraded planned DTEs.

Lesson: Multipath may not be a problem. The MER experience should be applied to the analysis of potential multipath in predicting the telecom link performance for other missions where it may occur.

7.6.1.5 UHF Development

The keys to success in the UHF test program (two rovers, three kinds of orbiters, a short development schedule) included

- The full-time availability of Odyssey and MGS test sets, and MER's own UHF system test equipment (STE)

- For surface operations, choosing a few out of the many available transceiver modes and a single forward-link rate
- Insisting on testing only in the most key areas, such as measuring the extent of electromagnetic compatibility (EMC) with surface subsystems and instruments
- Knowing which equipment can be operated during UHF passes (that is, which equipment is least likely to cause interference with the UHF receiver or be interfered with by the UHF transmitter), knowledge that has proved valuable in the time- and power-constrained Martian winter
- The Proximity-1 protocol, which ensures that if data comes down at all, it is error-free data.

Lesson: Ensure that similar trades are made a part of future mission implementation.

7.6.1.6 UHF Surface Operations

Communications behavior works well for UHF windows.

UHF windows. UHF comm windows are significantly less work to create and review than are X-band windows because the UHF radio has fewer “adjustment knobs” (such as modulation index and subcarrier frequency) than does the SDST.

Few window changes. Parameters of strategically delivered comm windows are not modified. Because they are of fixed duration and span all or most of the geometric overflight view period, they cannot be moved in time. This means the tactical team does not spend its limited time reviewing UHF comm windows.

Window deletions and rates. In the primary and extended missions, tactical changes have been limited to

- Deletion of some strategically planned UHF comm windows because others (also strategically planned and in the sequence) provided greater expected data volume or because of rover power constraints
- Changes between 128-kbps and 256-kbps return-link rate (or between coherency and noncoherency) on Odyssey, using the ORSC process.

Lesson: Simplify a “utility” like communications when it makes sense to do so. Relay link planning between Mars’ surface and orbiters involves fewer comm issues—such as HGA pointing, station weather, or station antenna pointing—than does planning for links that originate or end on the Earth’s surface.

Relay protocol. The Proximity-1 protocol means that if relay data comes down at all, it is error-free data. Analysis of performance is much less labor-intensive for UHF than for X-band.

Lesson: Consider the appropriate use of modern communications protocols in deep-space missions.

7.6.2 What Could Be Improved

7.6.2.1 X-Band Development

FSW simulator. Because there was no avionics simulator before the start of ATLO, the debugging of problems related to onboard hardware performance was rather time-intensive and required the interaction of many teams. One specific example was that resolution of a bit-timing problem at 10 bps led to using a DSN test facility (DTF-21) twice, and tied up DSN test operators and Ground Data System (GDS) personnel as well as ATLO test personnel.

Lesson: Provide for stand-alone project facilities (in this case a flight software [FSW] simulator) to test new capabilities without requiring the early and repeated involvement of multimission facilities.

Downlink rates. Uplink rates are in factors of two. A finer resolution between adjacent downlink rates between 40 bps and 120 bps possibly would have reduced the time to resolve the MER-A sol 18 flash-memory-file anomaly (see Section 7.5.1.4). The 3:1 ratio between 120 and 40 bps means it takes nearly 5 dB more link performance to support 120 bps.

Providing low downlink rates is a challenge because they take the longest to test and are affected in performance by factors that do not vary linearly with data rate.

Lesson: Thoughtfully trade the complexity of implementing, testing, and using numerous bit rates against the utility of specific rates, including in contingencies.

Surface environment. The time available to characterize the SDST in Mars-like conditions, especially cold temperature and partial vacuum, was limited because of the need to debug several serious FSW problems involving rover instruments.

In retrospect, the telecom hardware areas to focus on should have been the SDST BLF and acquisition and tracking characteristics at cold temperatures and partial vacuum (to approximate the thin atmosphere in which the rover operates on Mars). This was particularly so for MER-A, where SDST coherent leakage (see Section 7.5.1.9.1) made cold-temperature uplink acquisitions operationally demanding.

Frequency calibration. In addition to the unlocked static-phase-error (SPE) drift (coherent leakage) in the SDST on MER-A (but not on MER-B), surface operations were made more difficult by the relatively coarse calibrations of the uplink signal level (cla_snr) as a function of temperature. The SPE drift makes blind uplink acquisitions problematical at some temperatures, and the coarse calibration makes separating out the effects of rover's antenna pointing and station pointing difficult.

Lesson: Consider the environmental factors, the intended equipment use, and any specific deficiencies in particular units when designing the test and characterization program.

RF leakage. The implemented onboard X-band system had some opposite-polarization leakage paths that became apparent twice during cruise when a station inadvertently transmitted with the wrong uplink polarization to MER-B [10]. The incorrectly polarized uplink signal still made it into the SDST. The SDST telemetry data led to a quick correction of the configuration.

Refer to Fig. 7-11, which shows that when the MGA is selected (for both uplink and downlink), the CLGA is not selected, and vice versa. In the first occurrence, a cold-reboot activity, the selected antenna path was the CLGA (RH polarization). The tracking station had been wrongly configured to transmit LH polarization, though it was correctly configured to receive RH. Because of an RF leakage path through the MGA antenna (LH), the SDST received from the MGA a lower-than-predicted (for the CLGA) uplink level, but the SDST still properly decoded commands sent with the wrong polarization. This "success" caused a great deal of confusion until the alternate uplink path was identified. In the second incident, the station was incorrectly transmitting RH, and the selected antenna path was the MGA (LH polarization). The SDST acquired carrier lock via a CLGA (RH) leakage path. However, ranging modulation was below threshold. Ranging data was lost until the uplink polarization could be corrected.

Lesson: Controlling (and measuring the magnitude of) leakage paths is a necessary consideration in spacecraft microwave-component selection and configuration.

Lesson: The ability to absolutely verify uplink and downlink polarization settings has not kept pace with the ability to separately control these settings at a station.

PMA occlusion. Obstruction of the X-band downlink via the HGA by the PMA was a significant problem during communication attempts to resolve the MER-A sol-18 flash-memory-file anomaly. Also, obstruction of the X-band uplink via the RLGA has occurred in some rover orientations during the extended missions.

HGA flops. An HGA "flop" will occur when the required HGA pointing nears a singularity in a gimbal axis. Testing of surface operations in a testbed uncovered an FSW flaw that would cause a fatal software error during an HGA flop. The problem was traced to improper CBM and HGA interaction during flops. As a result of the testing, comm windows during the primary mission that were predicted to be interrupted by the ACS software autonomously performing an HGA flop were cancelled or moved. Rover attitudes were carefully chosen to avoid flops until the FSW could be patched. No planned or autonomous flops have occurred on either rover.

Lesson: Fully characterize antenna pointing and antenna interaction problems (PMA occlusion, risk of HGA flops), and develop operational workarounds before flight.

Antenna characterization. MER is not the first project that has been operated with relatively poorly characterized antenna-gain and polarization patterns.

Lesson: Spend the necessary time and resources to characterize antenna performance with a high-fidelity spacecraft model before launch. This applies to both UHF and X-band antennas, both uplink and downlink. A project that fully characterizes spacecraft antennas (including the obstructive and scattering effects of nearby portions of the spacecraft) can make solid plans to use higher downlink rates to return more downlink bits per pass, and higher uplink rates to complete commanding and get on to science activities more quickly than would otherwise be possible. If the project did not need higher downlink or uplink rates, with antenna characterization, it could elect to conduct operations with smaller and less costly ground stations.

7.6.2.2 X-Band Cruise Operations

Comm window types. Communications behavior (default states and comm windows) proved reliable during cruise with standard configurations (telemetry and ranging, or delta-DOR). Telecom subsystem configurations during cruise were controlled, for the most part, using normal comm windows, with each window having its start time defined as a parameter.

High-priority comm windows (HPCWs) could be made that would execute immediately upon receipt because the start time was in the past. However, an HPCW always reinforces amplifier and antenna switch states. This is undesirable in principle when it involves pulsing (reactuating) an existing switch position and cycling the SDST exciter and SSPA off then on to enforce SSPA selection. Cycling these units off also interrupts the downlink.

Lesson: A normal window that does not reinforce switch states but that starts as soon as it is received combines two good usable features of HPCW and regular comm window types.

Comm window usage. During cruise, there was a great deal of debate about whether to use HPCWs or regular comm windows for data-playback events. Regular comm windows won out because HPCWs cycle hardware (notably the SSPA and SDST exciter) to reinforce telecom hardware states.

With increasing range to Earth, telemetry rates could no longer support all the real-time and playback data that the team had come to expect. It proved to be a large burden on systems and telecom analysts to optimize downlink rate with individualized comm windows for each pass, because window parameter and timing checking was manual during cruise. In the extended missions, a window-checking script eased the manual workload.

Lesson: MER was the first deep-space project to use comm windows. The experience MER gained in generating and reviewing comm windows, then modifying or deleting them when necessary, points to ways that another project may wish to improve on MER's first-generation communications behavior and comm windows. Besides the immediate-upon-receipt versus defined-start-time trade, a project may wish to consider how to simplify the generation and review process when changing a single parameter such as bit rate while still working within the full power of communications behavior. Another trade may be combining comm windows with a simplification of the X-band communications modes (as has been done with MER UHF).

Downlink reports. During cruise, each subsystem used the same facility, software on the MER server named Quill, to complete a daily downlink report. Like a word processor, the software allowed the user to input a character string; then the software would search for all previous instances of that character string. This provided the analyst a quick means of finding and referring to earlier instances of recurring problems or activities.

Initially in surface operations, with different downlink report software, Quill did not have the string-search capability. Late in 2004, a new version of Quill was implemented. Its response in moving from one downlink report to another is much faster than that of the version in use during the primary and first extended surface mission; and it has restored the string-search capability.

Lesson: Consider the typical repetitive uses that a person will make of required software in an intense operations environment, and implement capability to enable or improve those uses.

7.6.2.3 X-Band Surface Operations

Link margin criteria. Standard criteria were developed and used to set telecom subsystem configurations and data rates for the cruise and surface mission phases. These criteria were intended to account for the inherent variability from one instance to the next of a comm link. These criteria included

- A margin policy: predicting was based on adverse margins defined as mean minus 3-sigma for commanding and mean minus 2-sigma for telemetry.
- A tolerance on HGA pointing: A 2-deg off-point of the HGA was included in predicts for data-rate planning during surface operations.
- Allowing time for the station to lock up the downlink. For cruise, this time was 1 min; for surface operations it was changed to 3 min, then later back (sometimes) to 2 min.

Lesson: Establish consistent link-performance margin, timing, and operability criteria. The usual conflicting objectives are to make the criteria sufficiently conservative that no data will be lost, but not so conservative that the amount of planned data falls below what the project can tolerate. There may be no way other than gaining experience using the criteria in order to change them to meet the project's specific needs. The MER experience suggests the following:

- Although mean minus 2-sigma for downlink performance is standard, there was somewhat more data loss during the primary surface mission than the project was comfortable with. A larger link margin would have reduced replanning by accommodating such factors as weather worse than the defined 90 percent, worse-than-expected ground antenna pointing, some amount of occlusion of the HGA or RLGA by the PMA, etc.
- There is about a 2-dB difference between allowing for 2 deg and 4 deg for HGA off-point. Pointing error is an input to the TFP GUI. Perhaps

allowing for more HGA pointing error could have provided the necessary additional link margin described above.

- Unmodeled or insufficiently modeled effects, especially station-pointing error, on performance may make the criteria seem insufficiently conservative. Aberration effects on uplink performance became significant near maximum range in August through October 2004, with the station pointing its antenna based on the downlink currently being received, not on where Mars would be an OWLT later.
- The cruise value of 1 min for telemetry lockup proved insufficient on the surface, given the occasional longer-than-normal lockup time and consequent loss of the most valuable recorded data that comes down first. Midway through the primary mission, a comm window parameter value was changed so that only real-time data was transmitted for the first 3 min rather than 1 min (before valuable data started). Later, the data loss/opportunity balance again shifted. Particularly valuable windows now sometimes are planned to allow 2 min for telemetry lockup.

Thermal modeling. On MER-A sol 38, the HGA elevation-axis actuator stalled during the calibration portion of the morning comm window, causing the DTE to fail, with the HGA 30 deg off-pointed from Earth. Telemetry for problem evaluation and restorative commanding was via the RLGA. Subsequent analysis uncovered shading of the HGA by the PMA, which caused the motor to stall because it had not been sufficiently warmed up (see ISA Z83273 [18]). Following that incident, HGA heater tables were reconstructed to always assume worst-case shading, and HGA calibrations were removed from morning comm sessions.

Lesson: Occurrences like this dramatize the insufficiency of a prediction model that overlooks or oversimplifies certain factors. A sufficiently robust system design can withstand such surprises without permanent damage or irretrievable data loss.

Station antenna pointing. With no downlink confirmation in a blind-commanding session, the consequences of unexpectedly large station pointing error can be the loss of the commands. Except for aberration on the uplink, previously discussed, such station pointing error can largely be mitigated by Conscan if there is an orbiter downlink being received in MSPA mode (see Section 7.5.1.7.1).

The cause of station-pointing errors can sometimes be determined by project and DSN cooperative analysis of uplink signal level returned in later telemetry against the predicts, and by comparing times of large pointing errors with station logs.

Lesson: Follow up immediately on any suspected station-pointing error to minimize the impact on subsequent operations for the affected project or others being tracked by that station.

Lesson: Define a consistent Conscan strategy among the stations supporting a project. For example, MER experience has led to the following:

- Do not Conscan on the RLGA downlink. Neglecting rover tilt, the RLGA remains vertical to Mars, and there is a large signal variation resulting from Earth's going through a wide range of angles on the RLGA pattern.
- Always Conscan on an orbiter if one is available during an MSPA session.
- Conscan at all stations (of a given size). This was not the case during the MER primary mission due to DSN implementation and operational differences among the 70-m stations. At some stations there was at least the perception by operators that Conscan could at times drive the antenna off even a stable downlink.

Beep detection. At the beginning of the primary mission, the MER project negotiated beep detection by the DSN as a "best-efforts" activity, meaning that the formality of the JPL Discrepancy Report (DR) process could not be relied on to ensure timely assessment of missed beeps to reduce the chances of missing more beeps due to the same cause.

Lesson: Negotiate early with the DSN regarding the required level of support for any previously nonstandard capability. The DSN puts priority on analyzing problems that are covered by a DR. With limited problem analysis and resolution resources, problems involving best-efforts processes may also be resolved only on a best-efforts basis.

Project interaction at Mars. The group-buy of X-band SDSTs included several that operated on the same uplink/downlink DSN channel.

As each project acquired its SDSTs, the JPL frequency management organization took into consideration the locations of these missions (for example, at Mars) and the planned durations of the missions. Because MER's primary surface mission was planned to end in 2004, few anticipated that the rovers would still be operating strong more than five years after EDL.

Meanwhile, MRO, which arrived at Mars in March 2006, had been allocated channel 32 for its SDSTs, the same channel as MER-A (Spirit).[36]

Under the auspices of the Mars Program Office, a working group with representatives from the MER and MRO projects, the JPL Telecommunications Division, and the DSN developed a set of recommendations in May 2005 [19]. A plan incorporating these recommendations was based on the assumption that both rovers would still be active and with both UHF and X-band capability in March 2006 and for an indefinite period during the MRO prime mission afterwards. The plan required MER to develop and test a capability to command Spirit on UHF via Odyssey when critical MRO X-band operations (such as aerobraking) would be compromised otherwise.

Lesson: The group that developed the plan [20] also published the following lessons:

- Bandwidth is a program consumable (especially at Mars and the Moon).
- Bandwidth-efficient modulation approaches (for example, Gaussian-filtered minimum-shift keying [GMSK]) are needed at X-band.
- Continue to actively move high-bandwidth missions to Ka-band.
- MER command and telemetry operations should be conducted via UHF, but DTE should continue to be available as contingency and backup.
- The next-generation DSN and deep-space transponder should
    - Retain current SDST operational capabilities and flexibilities

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[36] The rover longevity also required a look at another possible interference case. The Deep Impact (DI) project used SDSTs operating on DSN channel 29, the same as Opportunity. The DI primary mission was from January 2005 through August 2005, overlapped a portion of Opportunity's surface mission. An extended mission (named Epoxi) using the Deep Impact spacecraft concluded at the end of 2010. In addition, the Dawn mission (launched in 2007) continues along with Opportunity's surface mission as of 2014. Epoxi, Dawn, and MER-B transponders all operate on DSN channel 29. The JPL multi-mission Spectrum Analysis Group ran predictions for these three missions to determine potential periods of interference between each pair of missions. Interference levels were a function of the relative received uplink or downlink signal power as well as the frequency offset resulting from the specific trajectories. When potential interference was identified, the projects would negotiate together to "deconflict" the interference through scheduling of tracking passes or cancellation of less critical tracking passes. In the 2005–2014 interval, this strategy has been effective, and no critical navigation, command, or telemetry data has been lost yet.

- Have synthesized frequency generation
- Be fully software-defined (for update after launch) while maintaining current SDST reliability against failures. Reconfiguration includes changes in the operating channel to meet needs unforeseen at launch. The benefits of transceiver software reconfiguration after launch are being realized in the Electra UHF transceiver on board MRO.

Solar conjunction. See ISA Z84599 [21]. To generate data for a radio propagation study intended to improve future near-Sun spacecraft commandability, the communications research section at JPL requested a test to send sets of no_op commands to the rovers during the 2004 solar conjunction at SEP angles down to the minimum of 1 deg. From previous similar uplink work [24] on the Near Earth Asteroid Rendezvous spacecraft in 1997 and the Cassini spacecraft in 2003, it was known that solar effects would degrade the uplink and introduce bit errors on the command waveform presented to the HCD.

Those evaluating the request did not consider the effects of multiple-bit errors within a single, 64-bit (actually 63-bit + 1-fill-bit) uplink code block. A particular vulnerability in the MER HCD setup caused the HCD to see a code block with three or more bit errors as zero or one error and “correct” the one error; then the FSW might correctly use the incorrectly decoded code block to write into sections of the program that it should not touch. In the ISA incident, a writing mistake caused the software to declare a fatal error, halt the sequence, and do a warm reboot.

Lesson: Evaluation of nonstandard command activities should involve representatives from all potentially affected subsystems. The evaluation should be particularly strict for an activity likely to induce errors on a command link.

7.6.2.4 UHF Development

Schedule and mass. During development, the MER project was informed of large pattern and polarization variations in its selected UHF monopole antenna. However, a better-performing UHF antenna weighed more. By the time the significance to mission planning of the performance differences became apparent, it was too late to implement the heavier antenna on the spacecraft. In hindsight, performance testing of the antenna was not sufficient. Consequently, MER retained a monopole design that was not characterized well enough for accurate data volume planning (including return link data rate selection) during surface operations.

Lesson: The UHF antenna measurement on a high-quality spacecraft mock-up should always be a high priority. This is particularly true when the antenna system has pattern amplitude and polarization variations as significant as those of the MER UHF monopole.

Lesson: Design decisions made for valid developmental reasons may have large operations impacts. When this becomes apparent, consider mitigation such as additional testing.

7.6.2.5 UHF EDL

Return bit rate. The UHF 8-kbps return-link performance to MGS during EDL was very good; however,

- MGS was required to phase its orbit so that ideally it would be directly over the planned rover landing site at the middle of the EDL UHF relay period. The orbit-phasing plan, which accounted for the expected prelanding and postlanding MER geometries during the period, was accurate to within 30 s of the ideal.
- The MGS UHF antenna needed to be pointed toward the landing site for optimum gain, and this would have required an MGS spacecraft reorientation.

Lesson: Consider a lower rate (perhaps 2 kbps) for future EDL links to minimize operational impact on the orbiter. And, in doing so, watch out for latency and frame size.

7.6.2.6 UHF Surface Operations

Antenna pattern workarounds. The rover UHF (RUHF) antenna asymmetry greatly increased operational complexity.

- Polarization loss for the monopole-to-orbiter antenna is challenging to model.
- The accuracy of the orbiters' antenna patterns remains unknown.
- Forward-link prediction has turned out to be less accurate than return-link prediction, and the reason is not yet determined.
- Even so, the Proximity-1 protocol allows the accuracy of UHF link prediction to be less critical than that of X-band link prediction.

Despite plans to the contrary during development, the Flight Team has reoriented the rover whenever possible to maximize the data return, particularly during the power-limited Martian winter.

Lesson: The pressure to increase data return during operations is unstoppable. The system must be calibrated and configurable to make that possible.

Using inherent capability. An error in the implementation of UHF carrier-only-mode communications behavior was discovered less than two months before EDL. Refer to Problem/Failure Report (P/FR) Z82586 [18]. For contingency operation, a pure-carrier UHF return-link mode is required. In the implementation, there was apparently confusion between the UHF transceiver nomenclature of “tone beacon” (rover return-link carrier-only output) and “command beacon” (an orbiter forward-link hailing-signal output). As implemented, the CBM incorrectly enables the command beacon in intended return-link carrier-only modes. This combination makes detection of the intended carrier-only return link by the orbiter very difficult and therefore has been prohibited by a flight rule.

Using different nomenclature for the two modes would probably have made the implementation error less likely. The project rejected a FSW update to fix the problem so close in time to the beginning of surface operations.

The UHF cognizant engineer developed and tested a workaround, which is to attach a sequence to all UHF carrier-only comm windows. (Any comm window can specify a sequence filename, and the sequence is then initiated when the window opens.) One minute after the window begins the erroneous UHF configuration, the attached sequence commands the transceiver to standby mode, waits 10 s, then enforces the correct carrier-only transmit mode.

Lesson: With a robust basic design, such as the comm windows, an operational workaround may be available that carries less risk than an in-FSW modification.

UHF link prediction. The prediction tools (DVCF and GTP) work well to help select low-elevation extra or alternative passes, significantly increasing data volume. In good areas of the rover UHF antenna pattern, the link can be closed at a 5-deg elevation angle. However,

- The ability to account for rover tilt in the rover-orbiter geometry was added by the end of the first extended mission. In a few cases, the expected data volume differed by a factor of 2 with and without tilt included in the prediction.
- Variability from pass to pass makes setting a margin criterion (for example, mean minus 1-sigma) challenging. It may differ for each rover as well as between MGS and Odyssey for a given rover.

Lesson: Projects with relay links must be capable of accurate prediction of data return commensurate with the accuracy required in sol-by-sol activity planning.

Data return latency. Creation of UHF comm windows was more hands-off than was the creation of X-band windows, but telecom analysts on the flight team still spent inordinate amounts of time in the primary mission answering queries about when the UHF data from each window would flow into the Mission Support Area (MSA). The mission planners required the data from one sol to plan the next sol. The comm window start time and duration accurately defined when the data left the rover on its way to the orbiter. However, the time the data reached the MSA varied greatly on the particular conditions on MGS or Odyssey, and in the orbiters' ground systems.

After the primary mission, this situation improved somewhat when Odyssey provided a bent-pipe mode for data relay, thus defining when the first data from a UHF window would be on the ground. It improved further when LMA developed scripts for Odyssey passes, taking into account buffer management, to define the latest time that all data from a UHF window would be on the ground.

Lesson: Projects with relay links (especially those that depend on other projects) need to design into the end-to-end ground system the capability to estimate the latency at each step in the process, again commensurate with the accuracy required in sol-by-sol activity planning.

7.7 Beyond the Extended Mission

The preceding sections discussed MER telecom operations and performance for the primary mission (through April 2004) and the first extended mission (through September 2004).

The source article for this chapter is in the Design and Performance Summary section of the DESCANSO website
http://descanso.jpl.nasa.gov/DPSummary/summary.html

Section 6.7 of that article, published in October 2005, provides summaries of telecom planning and performance as of that date. It also has information on planning and analysis tools developed and used by the telecom flight team to make operations more efficient with a reduced flight team staff.

The MER project website http://marsrovers.jpl.nasa.gov/home/index.html provides the current status of each rover. As of October 2014, the reports on Spirit and Opportunity were:

7.7.1 Spirit

Spirit remains silent at Troy, as of Sol 2621 (May 24, 2011). Spirit became bogged down at the edge of a crater in the area called Troy. At the time, Spirit had traveled 7.73 kilometers (4.80 miles) from her landing site. More than 1,300 commands were radiated to Spirit as part of the recovery effort in an attempt to elicit a response from the rover. No communication has been received from Spirit since Sol 2210 (March 22, 2010). The project concluded the Spirit recovery efforts on May 25, 2011.

7.7.2 Opportunity

Opportunity remains active as of Sol 3820 (October 22, 2014). Opportunity had just snapped images of Comet Siding Spring and was on the west rim of Endeavour Crater heading towards "Marathon Valley," a putative location for abundant clay minerals only a mile (1.6 km) to the south. She has once again come through a Southern Hemisphere dust storm that reduced solar-array output. Since landing on January 24, 2004, Opportunity has driven 40.79 km (25.35 miles).

References

[1] "Photojournal," *Mars Exploration Rover Mission*, website (planetary photojournal, including images of and by the MER rovers), Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California. http://photojournal.jpl.nasa.gov/index.html (accessed on April 19, 2010)

[2] *Mars Exploration Rover Mission*, MER public home page, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California. http://marsrovers.jpl.nasa.gov/home/index.html (accessed April 19, 2010)

[3] A. Makovsky, *X-Band Telecommunications Systems Operations Handbook*, version 4.0, D-21239 (internal document), Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, July 29, 2003.

[4] M. Danos, *UHF Telecommunications System Operations Handbook*, D-21240 (internal document, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, December 30, 2003.

[5] "MER Reports," *Quill MMO GDS Services*, internal web site, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California. https://quill.jpl.nasa.gov/ (accessed October 30, 2014)

[6] *Mars Exploration Rover* Library, internal website library, Jet Propulsion Laboratory, California Institute of Techhology, Pasadena, California, website accessed on April 19, 2010. http://mars03-lib.jpl.nasa.gov/ (internal JPL Web site).

[7] J. Ludwinski, *Mars Exploration Rover Project Mission Plan*, D-19659 (internal document), Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, March 3, 2003.

[8] *Proximity-1 Space Link Protocol—Data Link Layer, Recommendation for Space Data System Standards CCSDS 211.0-B-5 (Blue Book)*, Consultative Committee for Space Data Systems Secretariat, National Aeronautics and Space Administration, Washington, District of Columbia, December 2013. http://public.ccsds.org/publications/archive/211x0b5.pdf (accessed October 30, 2014)

[9] *Mars Exploration Rover (MER-1/2) Project Network Operations Plan*, DSMS 871-050, Rev. A, D-25967 (internal document), Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, June 30, 2005.

[10] R. Tung and P. Illot, *Uplink/Commands Can Get into MERs in Cruise if Sent with the Wrong Polarization*, ISA Z82482 (internal document), Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California.

[11] E. Satorius, P. Estabrook, J. Wilson, and D. Fort, "Direct-to-Earth Communications and Signal Processing for Mars Exploration Rover Entry, Descent, and Landing," *Interplanetary Progress Report* IPN PR 42-153, January–March 2003, pp. 1–35, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, May 15, 2003. http://ipnpr.jpl.nasa.gov/progress_report/42-153/153A.pdf (accessed October 30, 2014)

[12] T. Pham, C. Chang, E. Satorius, S. Finley, L. White, P. Estabrook, and D. Fort, *Entry Descent Landing Data Analysis (EDA)*, NASA Tech Brief NPO-41220 BR, National Aeronautics and Space Administration, October 13, 2004.

[13] D. Johnston, S. Asmar, C. Chang, P. Estabrook, S. Finley, T. Pham, E. Satorius, "Radio Science Receiver Support of the Mars Exploration Rover Landings," *European Space Agency Third Tracking, Telemetry, and Command Systems for Space Applications Workshop*, Darmstadt, Germany, September 2004.

[14] P. Estabrook, A. J. Barbieri, C. D. Edwards, Jr., R. M. Manning, M. J. Danos, P. A. Ilott, and A. Makovsky, "Mars Exploration Rovers: Telecom System Design and Operation Highlights," *The Journal of the Institute of Electronics Information and Communication Engineers*, June 2005.

[15] T. Pham, C. Chang, D. Fort, E. Satorius, S. Finley, L. White, and P. Estabrook, "Tracking Capability for Entry, Descent and Landing and Its Support to NASA Mars Exploration Rovers," *European Space Agency Third Tracking, Telemetry, and Command Systems for Space Applications Workshop*, Darmstadt, Germany, September 2004.

[16] R. Tung, *Telecom Forecaster Predictor/Unified Telecom Predictor, User's Guide*, version 2.1, D-21499 (internal document), Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, February 21, 2002.

[17] R. Gladden, P. Hwang, B. Waggoner, B. McLaughlin, P. Pieseler, R. Thomas, M. Bigwood, and P. Herrera, "Mars Relay Coordination Lessons Learned," *IEEE paper* 0-7803-8870-4/05, *Proceedings of the IEEE Aerospace Conference*, Big Sky Montana, pp. 170–190, March 5–12, 2005.

[18] R. Lindemann and H. Stone, *MER-A HGA Calibration Anomaly Sol 38*, ISA 30264 (internal document) Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, April 7, 2004.

[19] *MRO Uplink Coordination Plan*, viewgraphs in MER DocuShare (internal document, Jet Propulsion Laboratory, California Inst. of Technology, Pasadena, CA. https://mars03-lib.jpl.nasa.gov/docushare/dsweb/View/Collection-25395 (accessed February 2, 2011)

[20] *Frequency Sharing Channel 32 – Spirit and MRO working group,* viewgraphs in MER DocuShare (internal document), Jet Propulsion Laboratory, Pasadena, California. https://mars03-lib.jpl.nasa.gov/docushare/dsweb/View/Collection-24817

[21] R. Denise and J. Snyder, *Fatal Event, Opportunity Sol 229*, ISA 30437 (internal document), Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, May 2, 2005.

[22] A. Barbieri, *UHF Carrier Only*, PFR 34452 (internal document) Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, December 11, 2003.

[23] *Proximity-1 Space Link Protocol—Physical Layer*, *Recommendation for Space Data System Standards*, CCSDS 211.1-B-4 (Blue Book), Consultative Committee for Space Data Systems Secretariat, National Aeronautics and Space Administration, Washington, D.C., December 2013. http://public.ccsds.org/publications/archive/211x1b4.pdf (accessed October 30, 2014)

[24] D. Morabito, "Solar Corona Amplitude Scintillation Modeling and Comparison to Measurements at X-Band and Ka-Band," *Interplanetary Progress Report IPN PR 42-153, January–March 2003*, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, May 15, 2003. http://ipnpr.jpl.nasa.gov/progress_report/42-153/153E.pdf (accessed October 30, 2014)