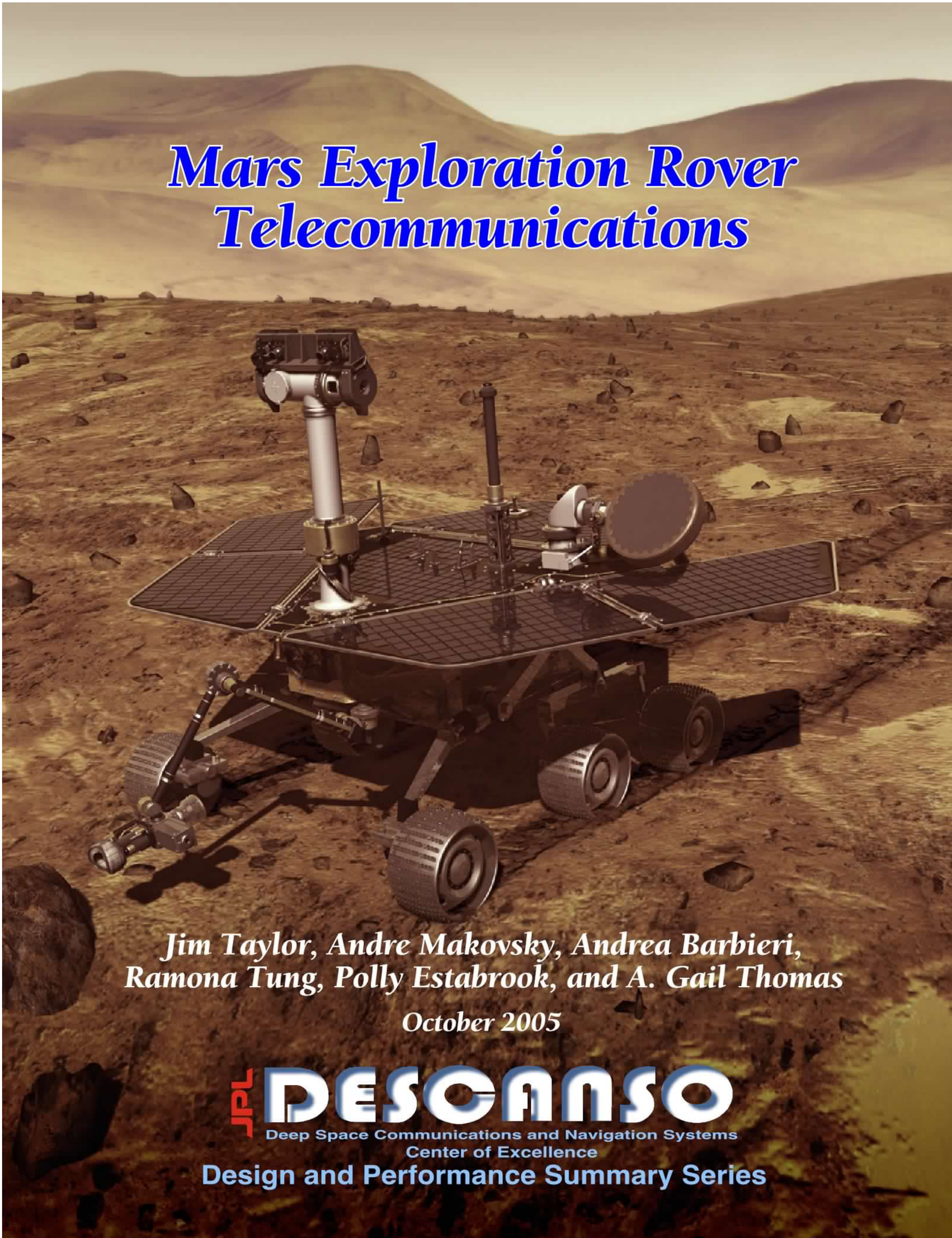
Mars Exploration Rover Telecommunications



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

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DESCANSO Design and Performance Summary Series

Article 10

Mars Exploration Rover Telecommunications

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October 2005

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Jet Propulsion Laboratory, California Institute of Technology,
under a contract with the
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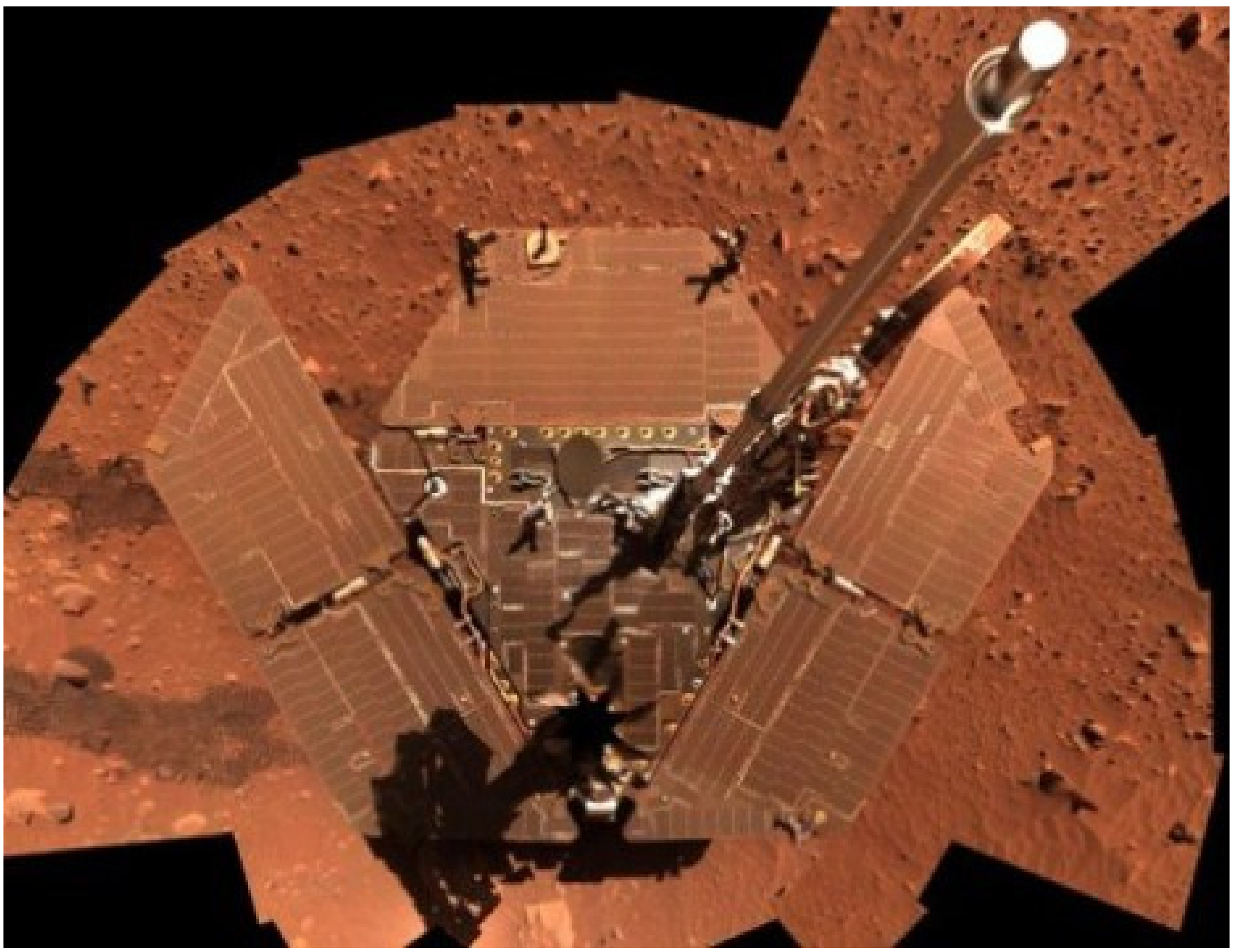
Prologue

Mars Exploration Rovers: Twelve Wheels on the Ground

The cover image is an artist's rendition of one of the rovers deployed on the surface of Mars. (A version of this picture with the parts called out appears at the end of Section 1.)

In the cover image, the communications antennas are prominent. The High-Gain Antenna (HGA) for direct-to-Earth (DTE) communications with the Deep Space Network (DSN) is the large disk to the right, facing up and out. The Low-Gain Antenna (LGA) is the mast to the left of the HGA. The Ultrahigh-Frequency (UHF) Antenna, for communicating with Mars orbiters, is the thinner vertical rod to the left of the LGA. The Panoramic Camera (Pancam) is mounted on the large, light-colored mast in the foreground, which was also a factor in the rover's communications with the DSN.



The picture above, from [1], is a self-portrait of the Spirit rover on the surface of Mars, a mosaic made up of about 100 separate images taken by the rover's Pancam on sols 329 and 330 (Dec. 7 and 8, 2004), and produced at Cornell University. The downward-looking view omits the mast on which the camera is mounted.

DESCANSO DESIGN AND PERFORMANCE SUMMARY SERIES

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Foreword

This Design and Performance Summary Series, issued by the Deep Space Communications and Navigation Systems Center of Excellence (DESCANSO), is a companion series to the DESCANSO Monograph Series. Authored by experienced scientists and engineers who participated in and contributed to deep-space missions, each article in this series summarizes the design and performance for major systems such as communications and navigation, for each mission. In addition, the series illustrates the progression of system design from mission to mission. Lastly, it collectively provides readers with a broad overview of the mission systems described.

Joseph H. Yuen
DESCANSO Leader

Preface

Sections 1 through 6 of this article describe and assess telecommunications in the 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 DSN, and it initiated a 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 September 2005 each rover had accumulated over 600 sols of surface operations. Both rovers remain healthy and continue to collect and transmit science data back to Earth, primarily through their UHF links to Odyssey.

Section 7, added in September 2005, describes notable Telecom-related activities of the most recent extended missions (October 2004 through September 2005 and continuing). Section 7 also includes engineering trend data for the Telecom subsystems.

The primary purpose of this article is to provide a description of the MER X-band and UHF Telecommunication subsystems, with an eye towards both their development and operational challenges and lessons learned. This article is not intended as a full reference on all subsystem aspects, rather it seeks to give a good overview.

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. The Odyssey and MGS orbiters are operated by Lockheed Martin Astronautics (LMA) in Denver, Colorado. Refer to http://marsrovers.jpl.nasa.gov/home/index.html [2] for current MER information.

Much of the Telecom design information in this article was obtained from original primary mission design documentation: the X-band Operations Handbook [3] and the UHF Operations Handbook [4]. [5] compiles the detailed sol-by-sol science and engineering reports, including Telecom. [6] is an online library of project reports and operational documents.

Acknowledgements

This article is an outcome of the Telecom Flight Team's contributions of time and data, ultimately supporting a surface mission with two rovers that function 24 Mars-hours per sol, 7 sols per week on opposite sides of Mars.

The authors would like to express their appreciation to Brian Cook and Monika Danos for their wealth of information about the heritage, performance and testing of the X-band and UHF systems. Thanks also to Bill Adams, the Odyssey and MGS Flight Team Telecom lead at LMA, and to Scott Toro-Allen of LMA, who provided the templates that MER Telecom used for the real-time displays of station monitor data. And thanks to Jan Ludwinski, whose excellent mission plan for the MER primary mission served well to organize the conduct of the mission, and served as the source of Section 1 of this article as well.

The authors are especially grateful to the other primary mission Telecom analysis, Telecom planners, and Telecom data-miner members of the MER Flight Team. Caroline Furman, a summer student for the Telecom Flight Team, generated the best-lock frequency (BLF) plots in this article.

In the first extended mission, as flight operations returned from "Mars time" shifts to Earth time, several of the data miners became full-fledged Telecom analysts as the original Telecom analysts moved on to other commitments. The authors, mostly no longer involved with day-to-day MER operations, appreciate the extended-mission material contributed to this article by Kris Angkasa and Tuan C. Tran. Patrick Ko, along with Monika Danos, wrote several of the scripts described in Section 7 to make the data from long months of flight operations consistent.

This photograph introduces the MER telecom subsystem at work on Mars. The Spirit rover imaged the local terrain with the HGA on its gimbal mount (lower right) and the RLGA on its waveguide mast (lower left) in the foreground. Deep into the extended mission on sol 637 (October 18, 2005), the rover had begun driving down from the summit of Husband Hill.

Section 1
Mission and Spacecraft Summary

1.1 Mission Objectives

The MER project had a 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.

1.2 Mission Description

Throughout this article, 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 “rover” after landing. MER-A and MER-B are identical. Each had a launch mass of 1,063 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. 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 hadn't 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.

Table 1-1, from the Mission Plan, summarizes the planned phases of the primary mission. The italicized phases at the end are for the two extensions of the mission—so far.

Table 1-1. Mission phases and planned dates for MER-A and MER-B.

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
End of Primary Mission	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*
Continuation 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.

Note: The initial extended mission was approved to the end of FY2004 (September 28, 2004). A six-month extended-extended mission began the next day and concluded March 27, 2005. Additional six-month extended mission segments are continuing (as of October 2005). In this article, the general term "extended missions" is used to refer to surface operations in the period May 2004 through October 2005.

1.3 The Spacecraft

The MER Flight System,[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 Figure 1-1.

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 [7]. Table 1-2 summarizes the assembly masses.

Table 1-2. Flight System mass breakdown.

	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

[1] The Flight System description is taken from [7]. See Figure 3-1 for a block diagram of the Telecom subsystem elements discussed in the following paragraphs.

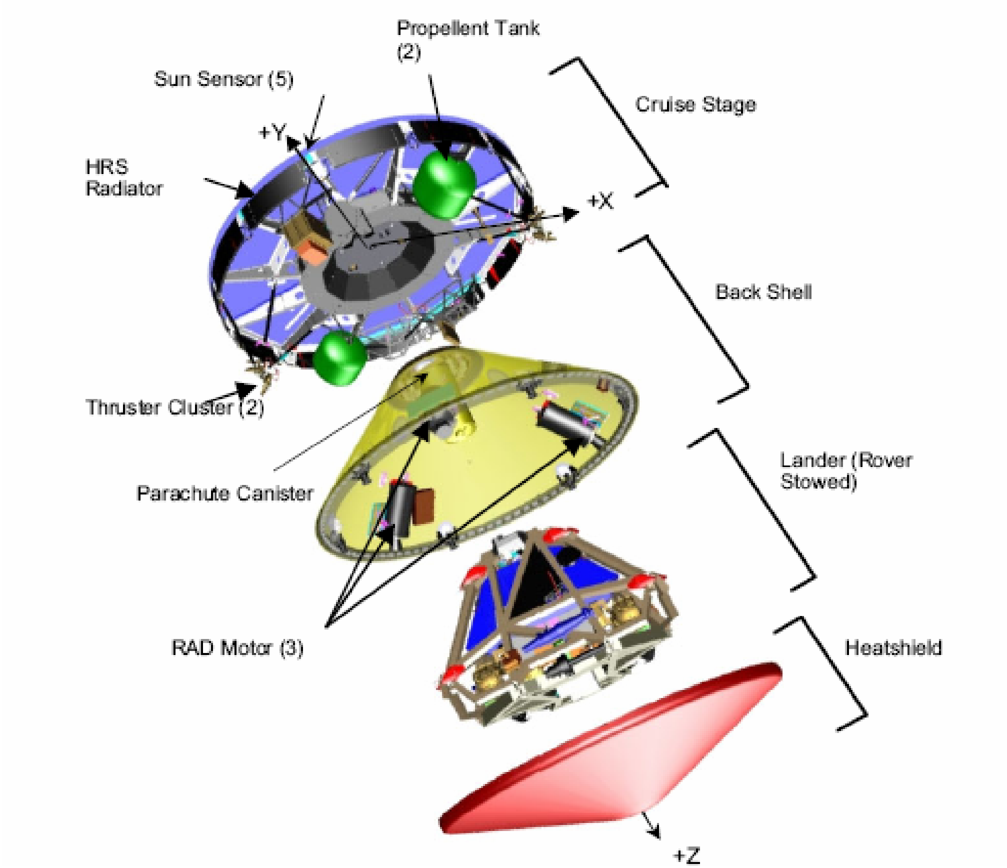

Figure 1-1. MER Flight System.

1.3.1 Cruise Stage

The spacecraft in its cruise configuration is shown in Figure 1-2.

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 rpm. Six trajectory correction maneuvers (TCMs) were planned during the flight to Mars, as well as payload and engineering health checks.

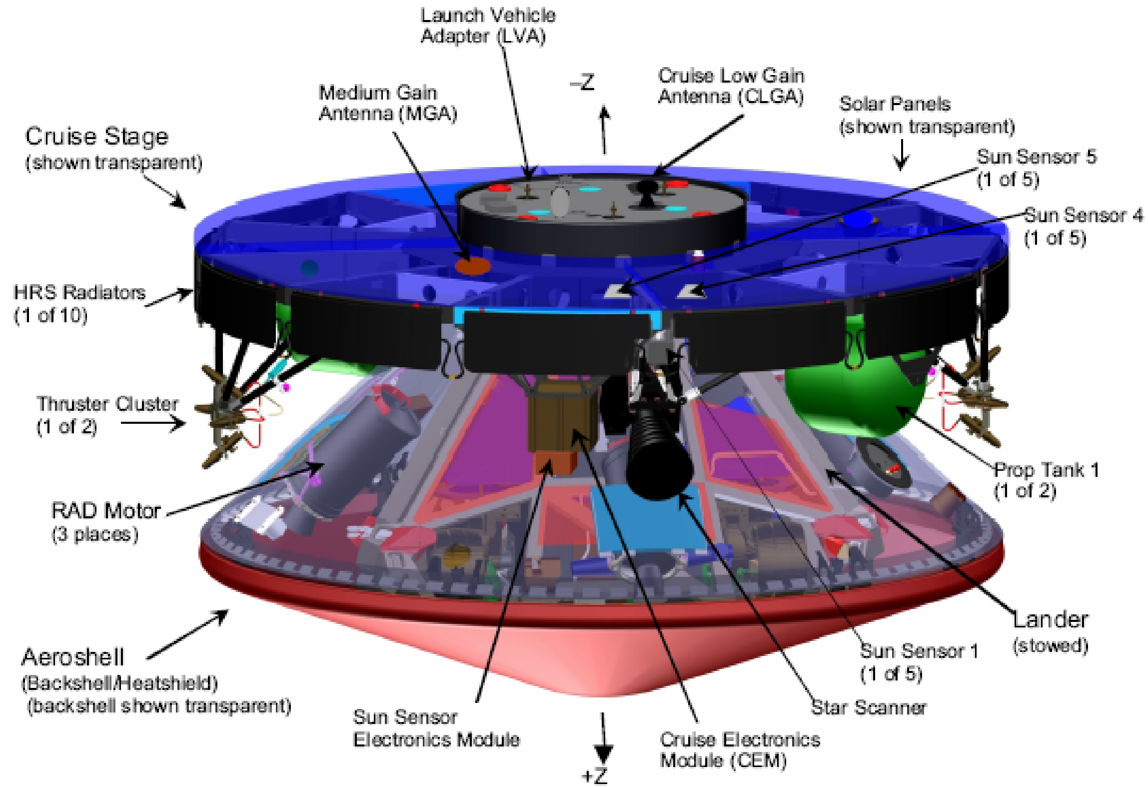

Figure 1-2. MER Spacecraft in cruise configuration.

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

Approximately 15 min prior to entering the Martian atmosphere, the cruise stage was separated from the aeroshell containing the lander and rover. The aeroshell, shown in Figure 1-3, 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 m in diameter to accommodate MER's heavier entry mass of 825 kg.

Several other components used during EDL were mounted on the backshell. These included the backshell 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.

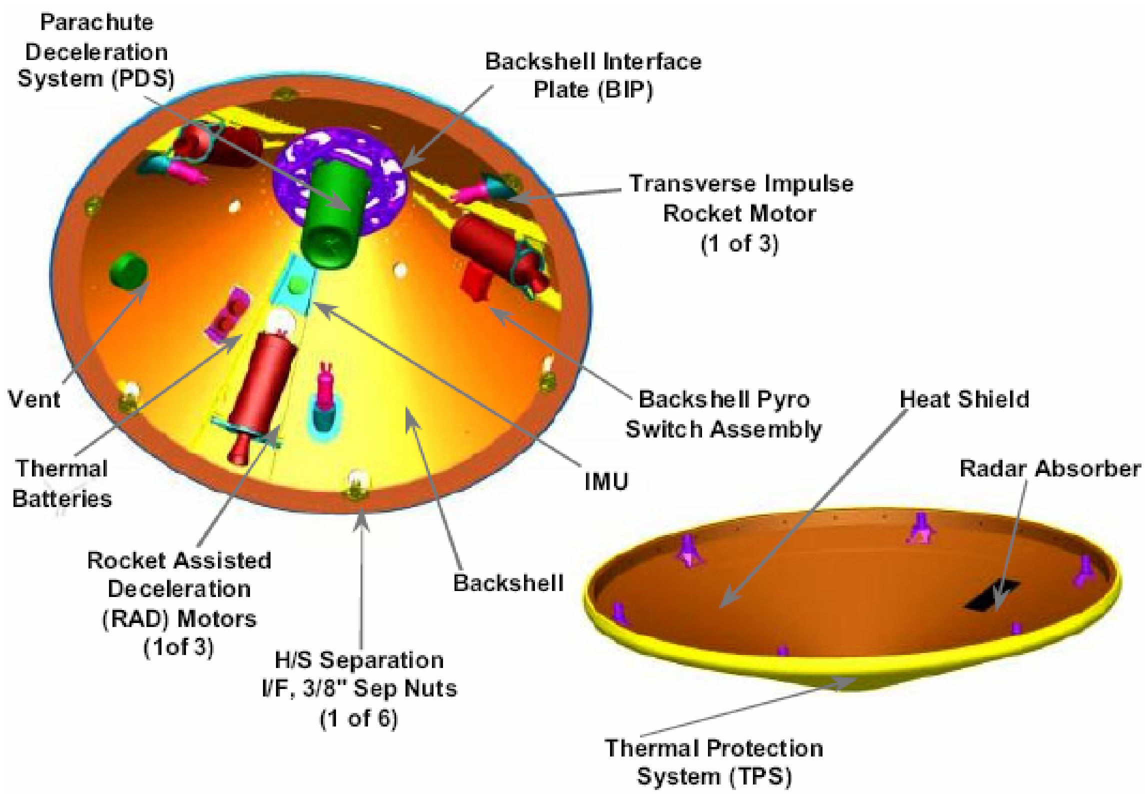

Figure 1-3. Aeroshell configuration.

After ~4 min of atmospheric deceleration, at an altitude of ~10 km and an atmospheric relative velocity of ~450 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] 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 1-4 shows the lander in its stowed configuration and Figure 1-5 in the extended position, ready for rover egress.

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[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. Vaguely related to Kevlar and nylon, Zylon is used in applications that require very high strength with excellent thermal stability.

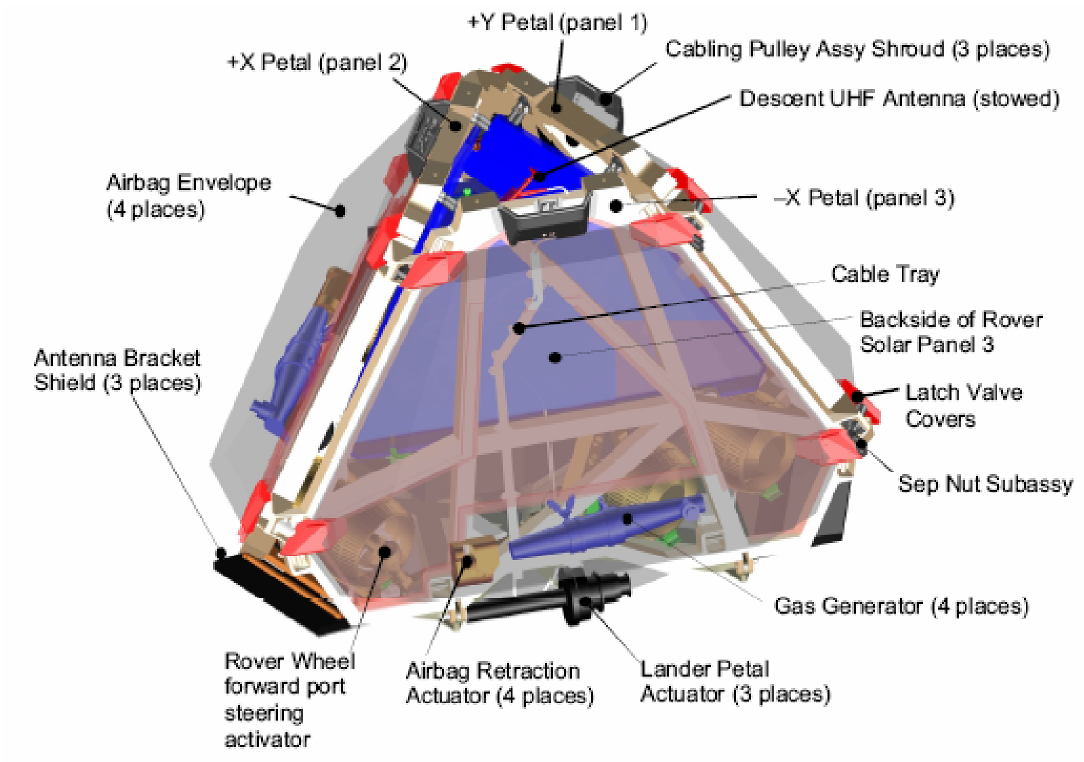

Figure 1-4. Lander in stowed configuration.

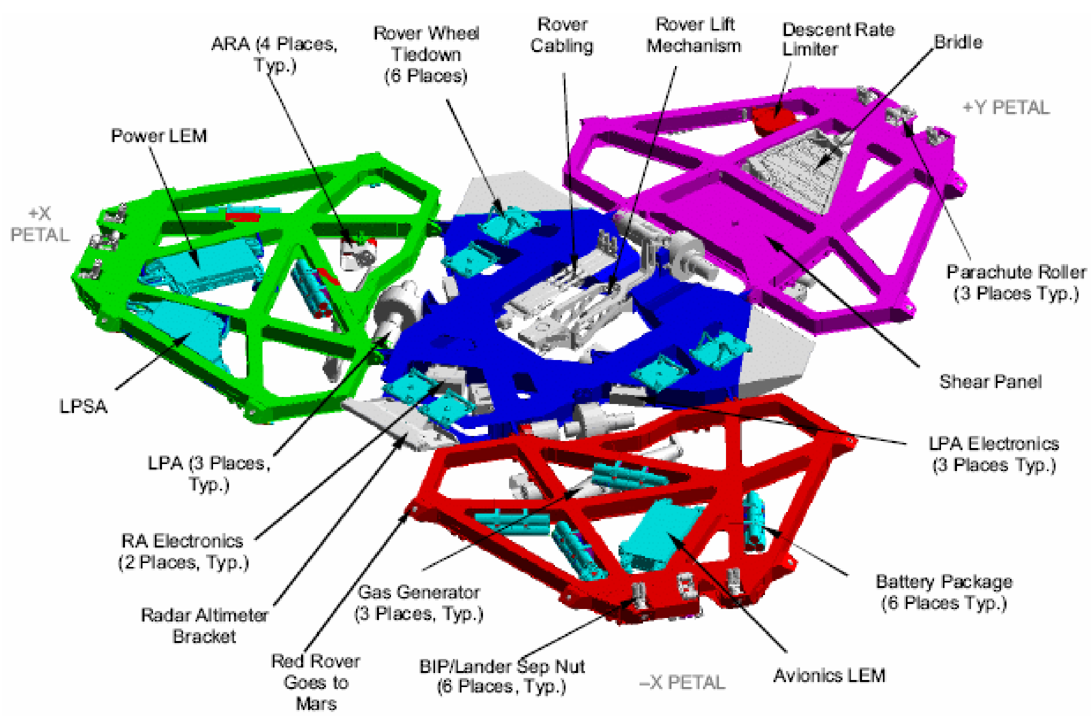

Figure 1-5. Lander in deployed configuration (for clarity, egress aids are not shown).

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.

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. After the radar was used to determine the RAD firing solution, but 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.

1.3.3 Rover

At the heart of the MER spacecraft is the rover, shown in Figure 1-6 in its stowed configuration, as it looked just after the lander had opened its petals.

Figure 1-7 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.

[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% air and is a stiff foam with a density of 3 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.

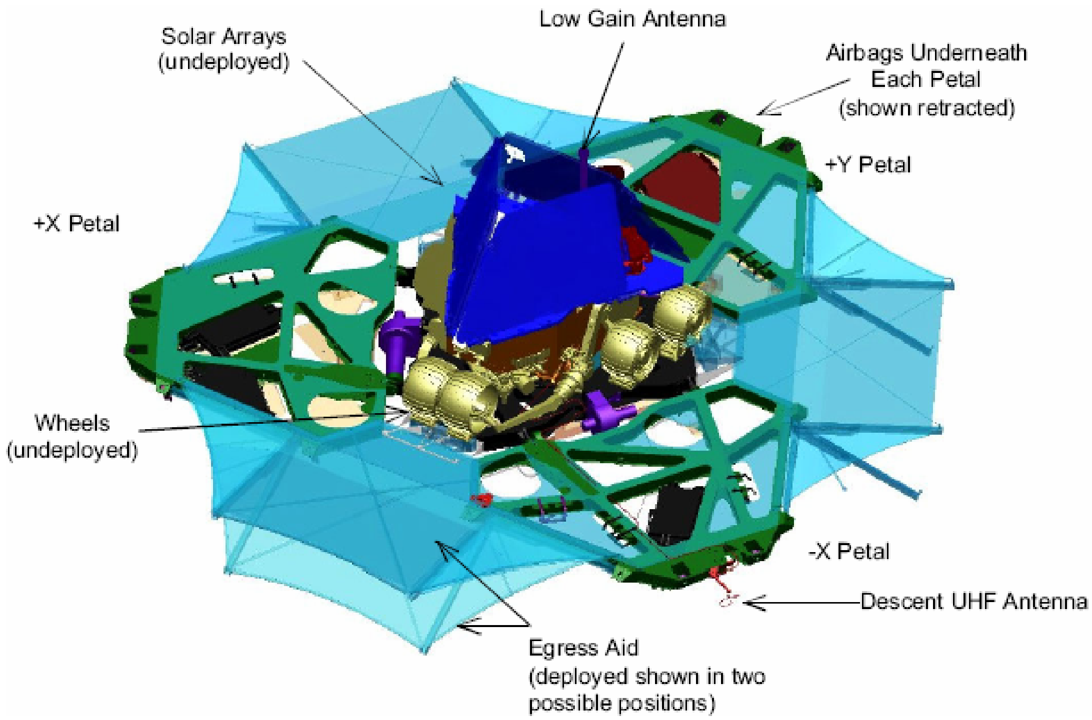

Figure 1-6. Rover stowed on lander after petal opening.

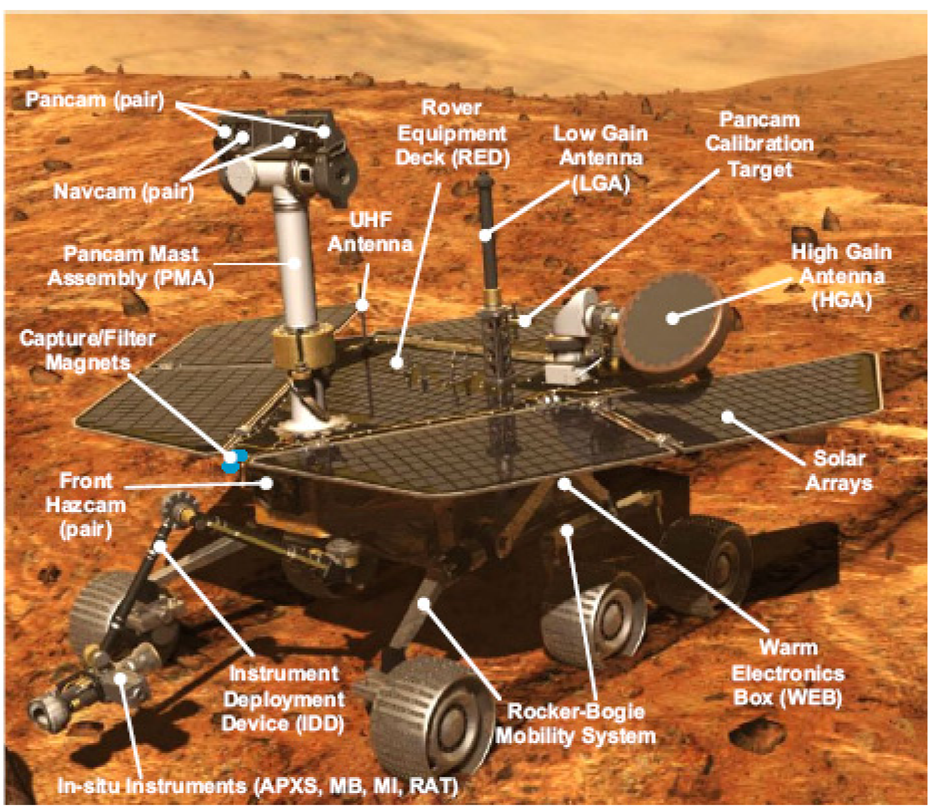

Figure 1-7. Rover in deployed configuration.

Section 2

Telecommunications Subsystem Overview

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 Figure 1-3) 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 (Figure 1-7). 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-kbps maximum and telemetry up to the 28.8-kbps maximum have been used.

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 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 CMC Electronics transceiver 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 5.2.4.

2.3 Direct-to-Earth Downlink Capability

Figure 2-1, from [7], shows the prelaunch predicted 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.

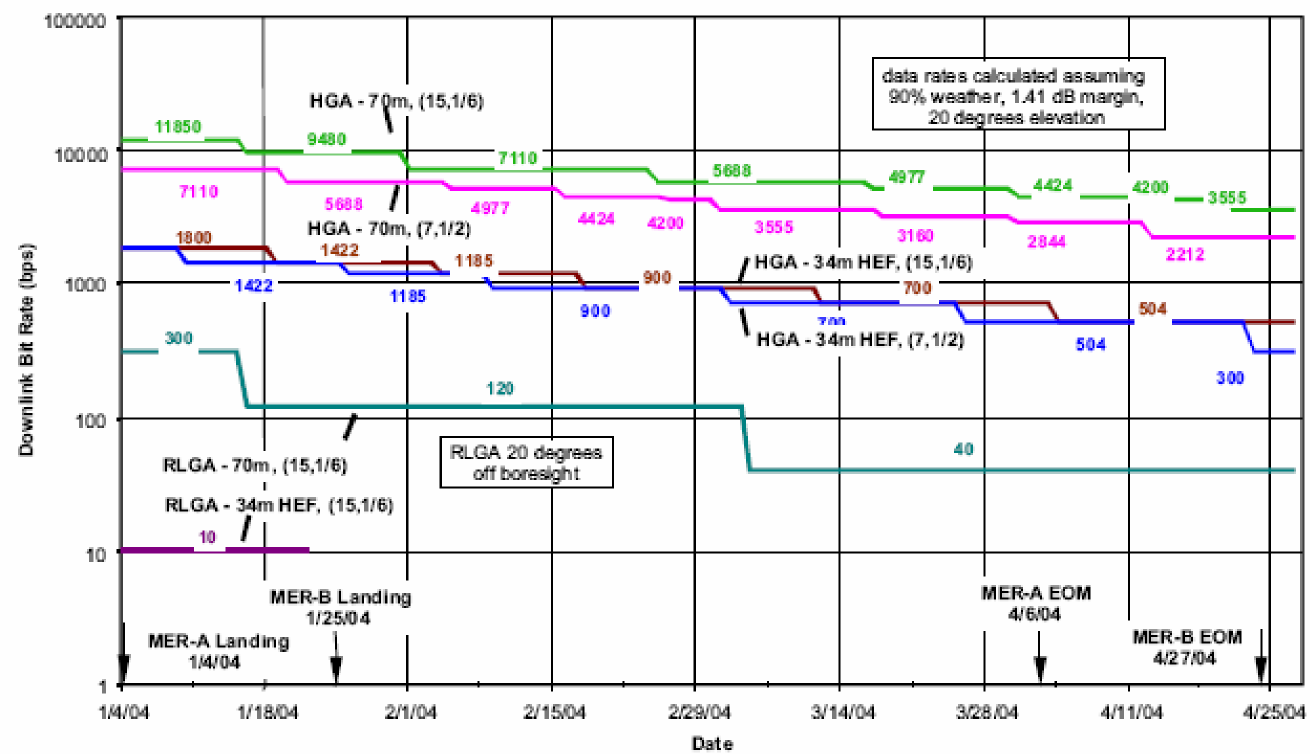

Figure 2-1. X-band predicted downlink capability for mission planning.

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. Over 60% 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° 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 two to eight minutes, and the return-link data rate from the rover to both orbiters was planned to be up to 128 kbps.[5] Maximization of the data downlink volume necessitates the use of as many of these UHF passes as possible.

The orbiter passes are distributed between midnight and sunrise, and from midday to late afternoon. Figure 2-2 shows a typical distribution of passes for both Odyssey and MGS in local solar time units and the corresponding maximum elevation of each pass.

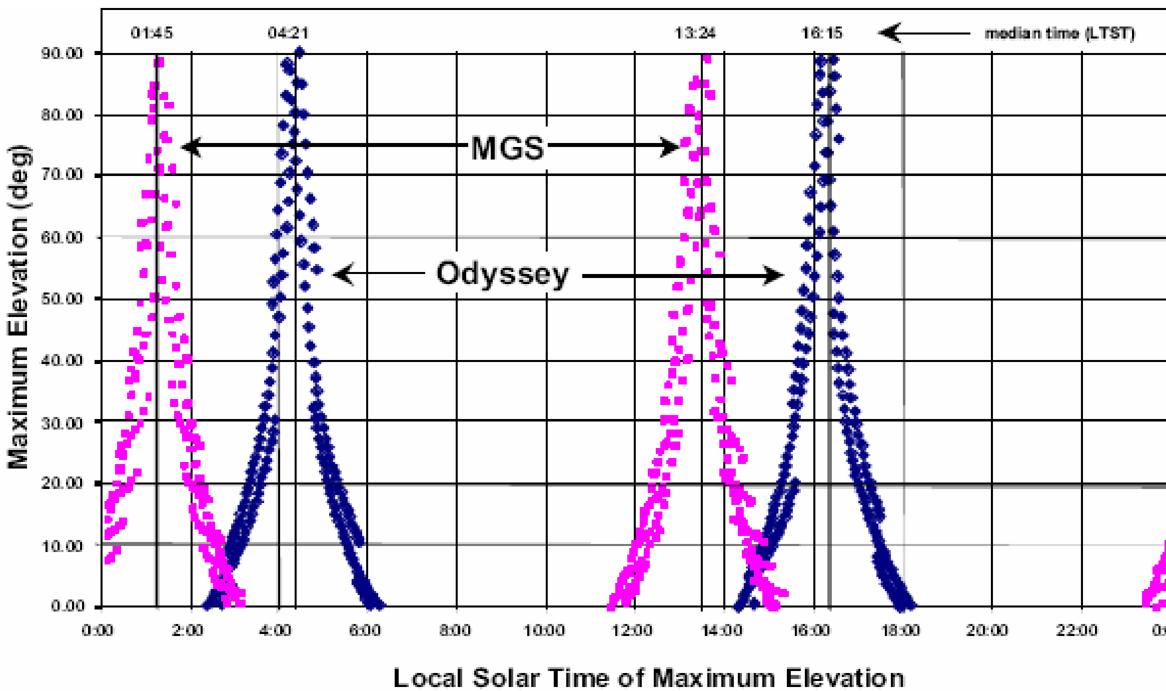

Figure 2-2. Distribution of Odyssey and MGS overflight times and maximum elevations (MER-A site).

[4] Data-return statistics for the MER missions through September 2005 are in Section 7. In summary, about 92% of the total data return was to Odyssey, 5% to MGS, and 3% over the X-band DTE link.

[5] The specific plan was to return data from the first few postlanding 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.

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 Mbits in a favorable azimuth, could see that return cut in half if the HGA assembly blocks the view. The average data-return volume is estimated to be about 56 Mbits/sol per rover for Odyssey and about 49 Mbits per sol per rover for MGS.

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 pass duration and rover orientation. Figure 2-3 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.

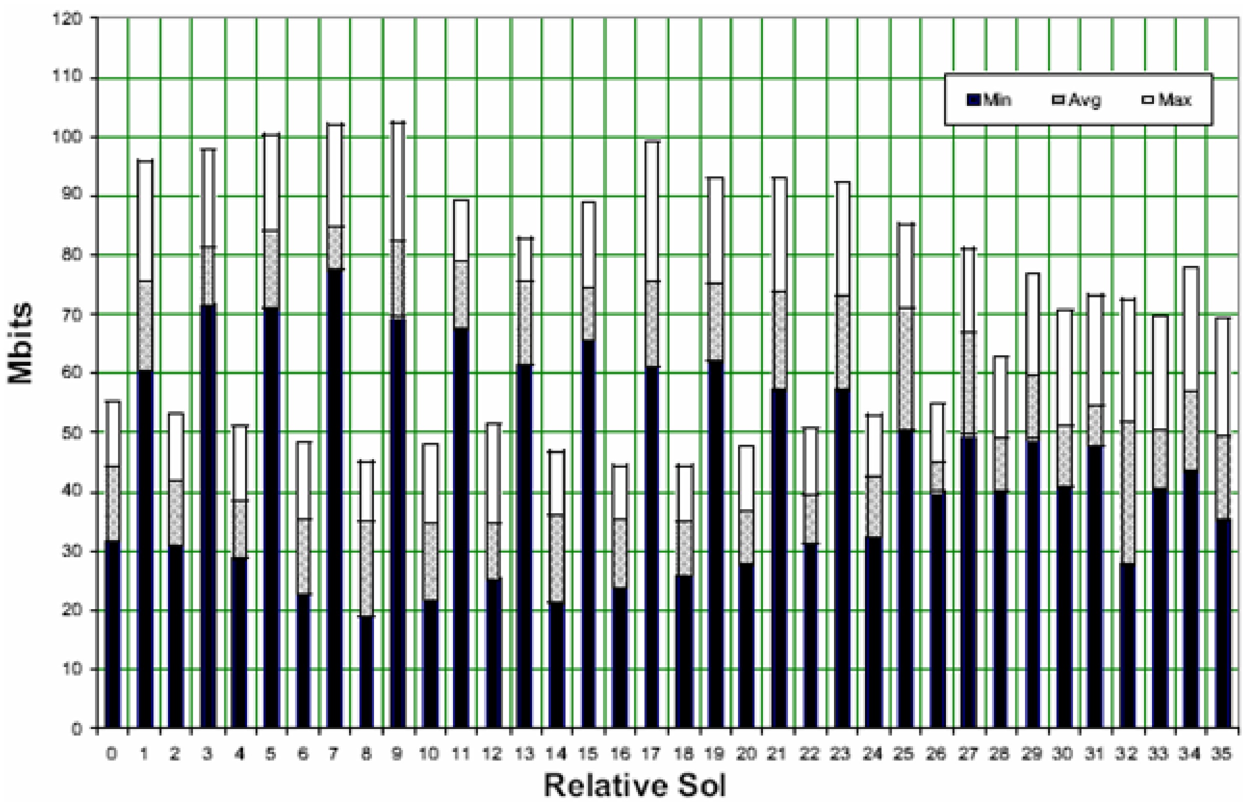

Figure 2-3. Odyssey 128-kbps data volume from MER per sol from a 0°-latitude landing site (averaged over all azimuths, no tilt).

[6] The first postlanding relay planning predicts were based on the average of those made for every 10 degrees 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° tilt predicts was 57.4 Mbits vs 41.5 Mbits.

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 12.5 MBytes (100 Mbits) of Odyssey onboard memory to both MER rovers (and to Beagle II, which did not operate). The allocation was later increased to 120 Mbits 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.

Section 3

Telecom Subsystem Hardware and Software

3.1 X-Band Flight Subsystem Description

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.
- 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 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 (i.e., which antenna should be used) and the operational mode of the subsystem (i.e., 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 RF transmitter, provide on/off power control to permit the conservation of power.

[7] The DSN is a global network of antennas and related support facilities, managed by JPL for NASA, that 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.

- 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 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.

3.1.2 Functional Block Diagram

Figure 3-1 is a block diagram of the X-band Telecom subsystem, with the functional elements as described in the four major assemblies of Figure 1-1.

3.1.3 Interfaces with Other Subsystems

The Telecom subsystem interfaces with the spacecraft are illustrated in Figure 3-2.

The interfaces with the Avionics and 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.

In each case, it is Avionics 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.

[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.

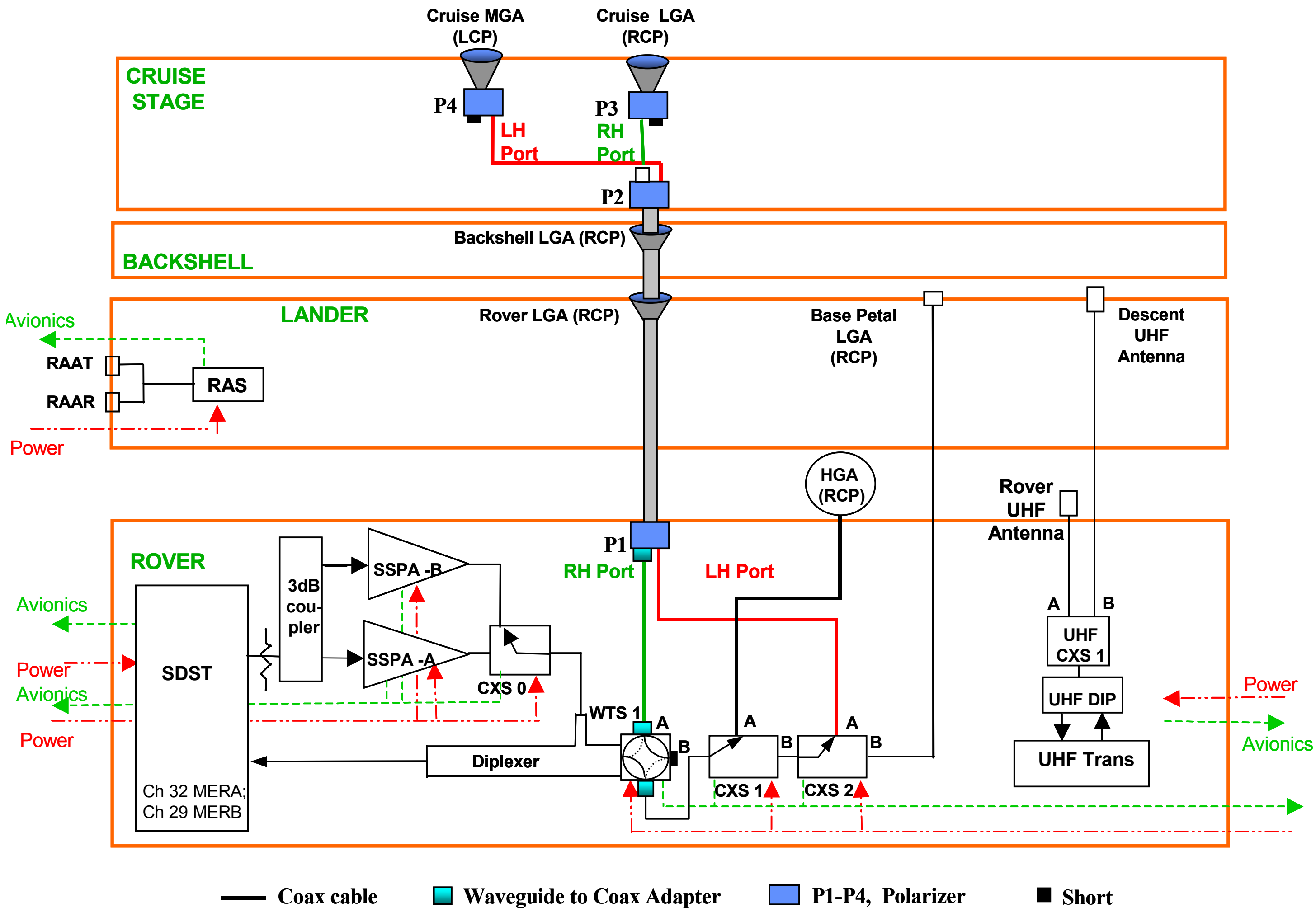

Figure 3-1. X-band Telecom subsystem block diagram.

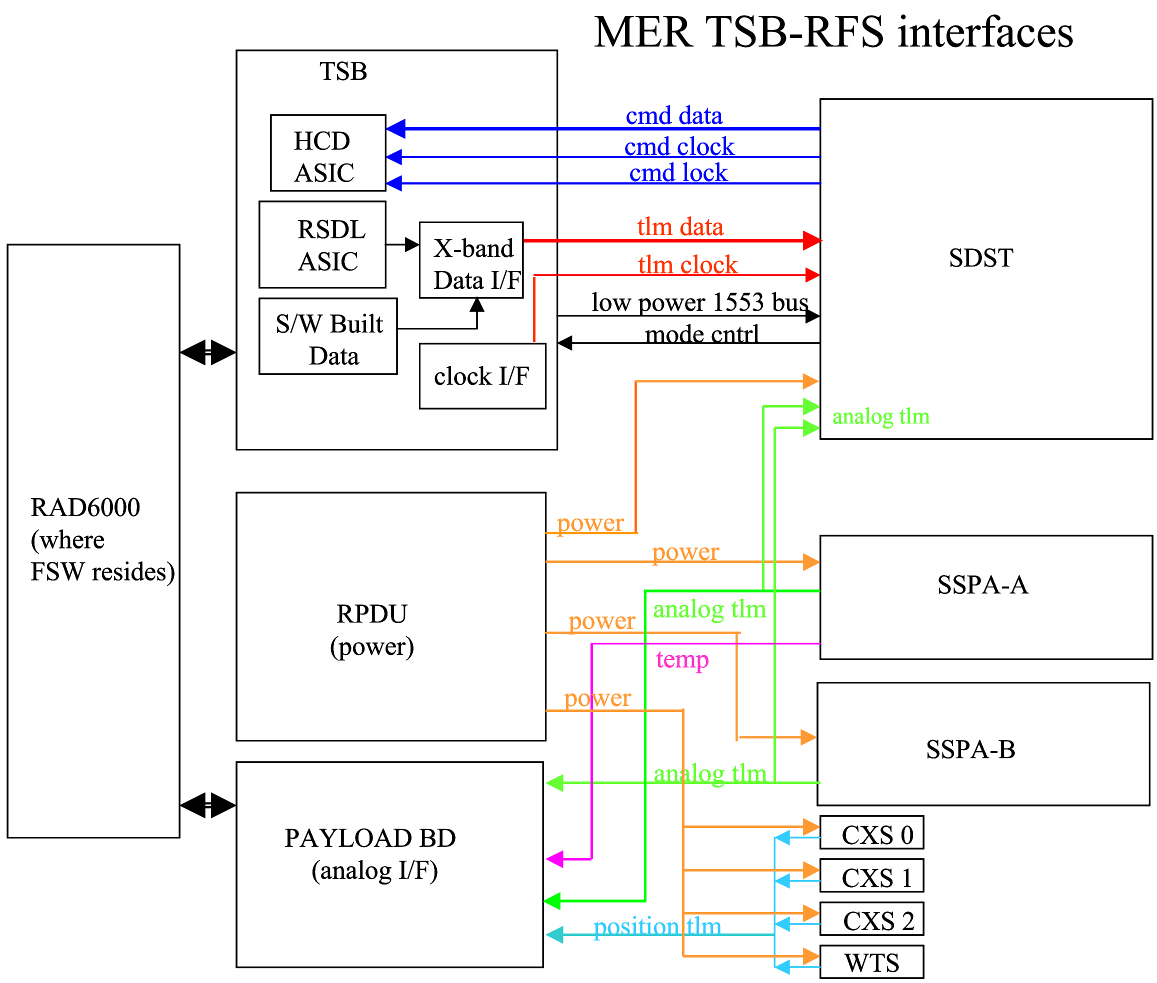

Figure 3-2. Telecom subsystem interfaces.

Avionics provides Telecom 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.

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 isn't.[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 Power to drive the waveguide transfer switch (WTS) and coaxial switches (CXSs), which select the X-band SSPA and the X-band and UHF antenna.

3.1.4 Description of X-Band Components

3.1.4.1 Antennas

As described in Section 1 and shown in the block diagram Figure 3-1, 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 3-1 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 Figure 3-3.

The CLGA, BLGA and RLGA are RF horns mounted on the same circular waveguide "stack" that is designed to break off in sections as described in Section 1. The RLGA is the shortest section of waveguide; hence, the RLGA circuit losses are the smallest while those of the CLGA are largest.

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

[9] We discovered one instance in the MER extended mission where the HCD and the flight software failed to handle properly a command containing multiple-bit errors. See Section 7.6 and ISA Z84599 [8].

Table 3-1. 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, degrees	±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 b/s: 7.70 dB RX 6.00 dB TX	20° off b/s: 6.29 dB RX 7.53 dB TX				
Design	Open-ended waveguide with choke	RF conical horn	Open-ended waveguide with choke	Microstrip array 1.5″ × 1.5″ square		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.

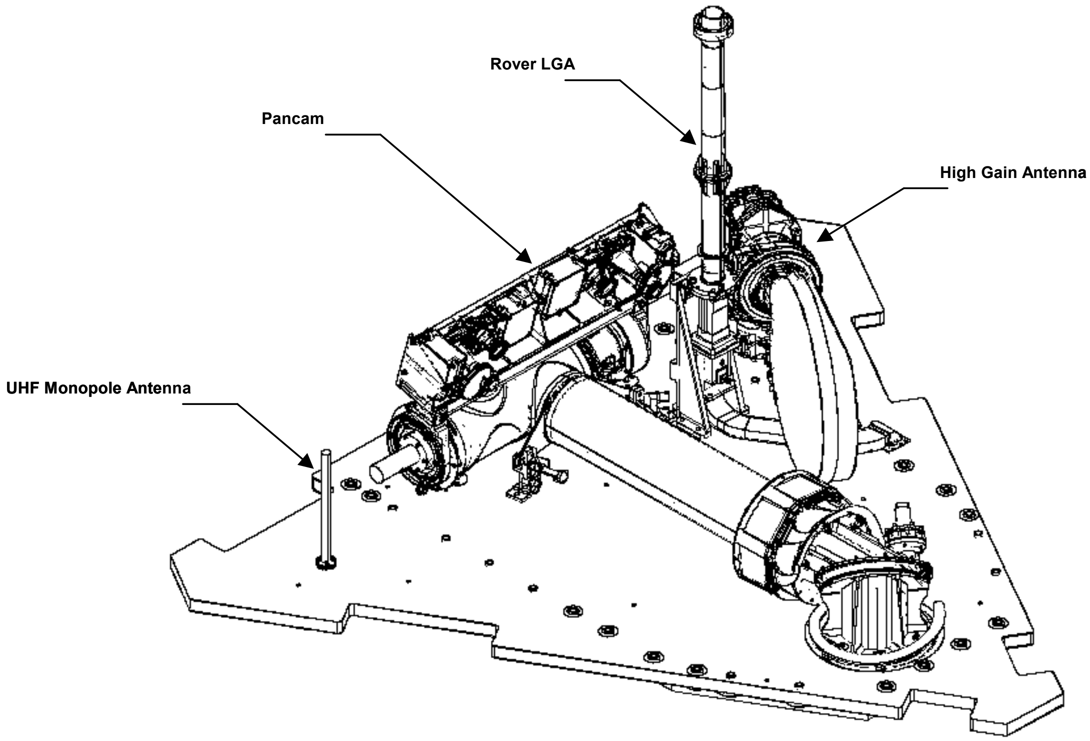

Figure 3-3. X-band and UHF antennas on the RED.

3.1.4.2 Radio Frequency Subsystem

The Radio Frequency Subsystem (RFS) is a general name that refers to the active (heat-producing) X-band elements of the Telecom subsystem. These include the SDST and the two SSPAs. Figure 3-4 shows how the SDST and SSPAs, along with the X-band switches and diplexer, are mounted on one side of the rover electronics module (REM), with a heat pipe, part of the Heat-Rejection Subsystem (HRS), between them. The other heat-producing Telecom element, the UHF transceiver, along with its diplexer, is mounted on the opposite side of the REM, as shown in Figure 3-4. The REM is inside the WEB, as Figure 3-5 shows. In Figure 3-5, the SDST and SSPAs are visible on the near side of the REM, and the UHF transceiver is visible on the far side.

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[10] because X-band and UHF heat-generating elements were so near each other on the REM. The amount of heat generated by

[10] The upper (hot) temperature limits were 50°C allowable flight temperature (AFT) and 60° protoflight qualification limit for SDST; 50° AFT and 70° protoflight qualification limit for SSPA; and 55° AFT and 70° protoflight qualification limit for UHF transceiver. (The trend data in Section 7.8 includes these temperatures.)

operating X-band and UHF elements limited the durations and intervals between successive X-band and UHF transmitter operations.

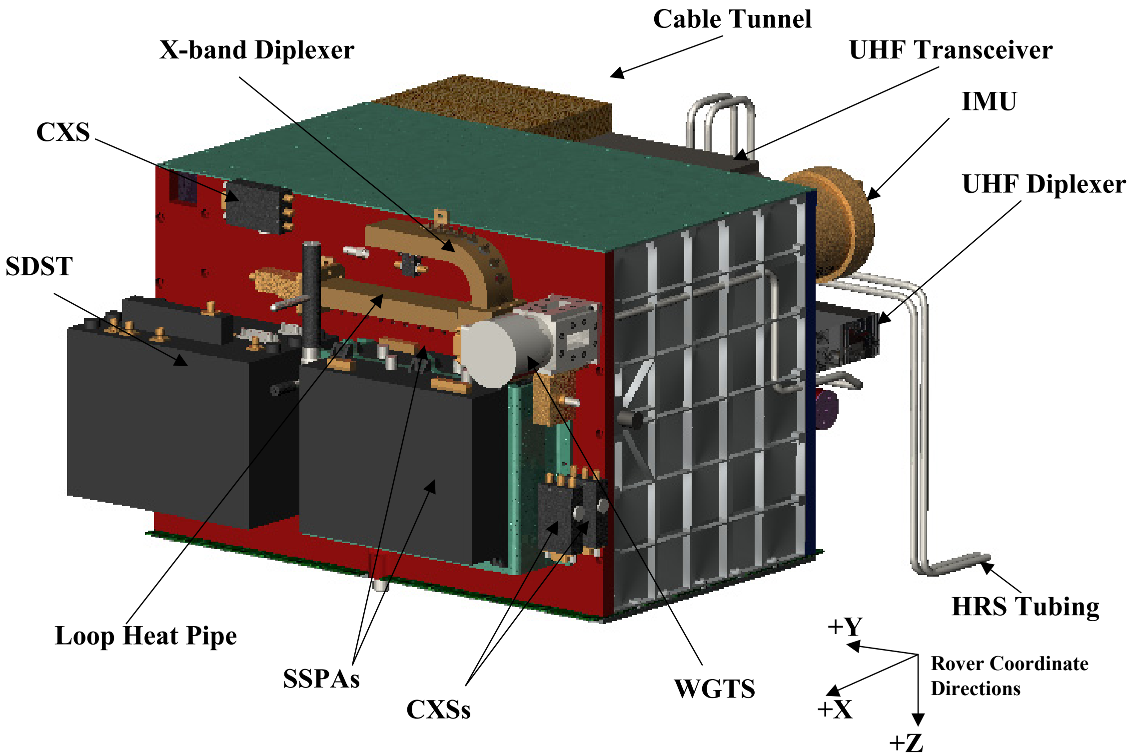

Figure 3-4. RFS mounted on the sides of the REM.

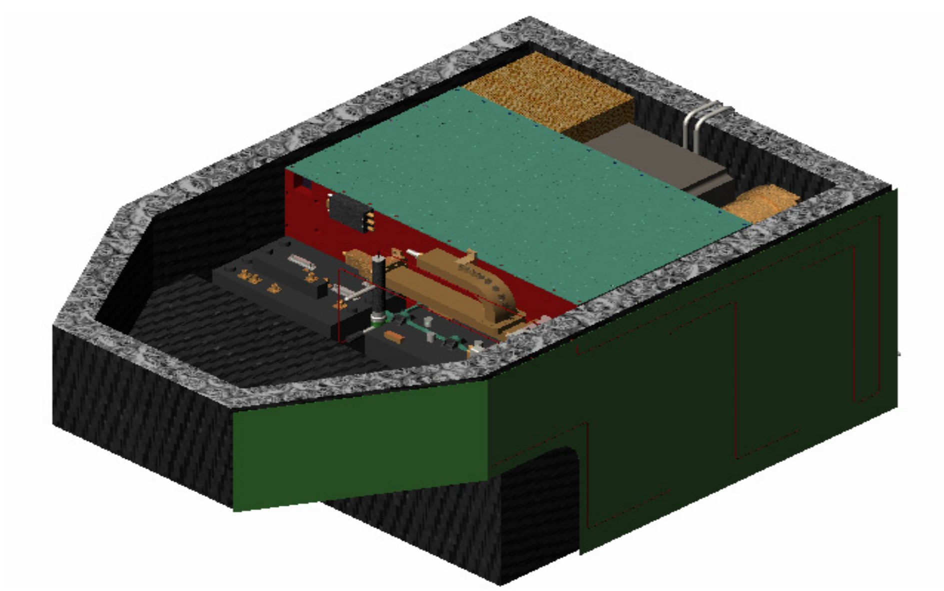

Figure 3-5. MER Warm Electronics Box.

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 rejection that the SSPA signal does not enter to damage or interfere with the SDST receiver. It allows the simultaneous transmit and receive signals to use the same antenna. X-band diplexer specifications are shown in Table 3-2.

3.1.4.4 Transfer Switches (WTS and CXS)

Refer to the block diagram in Figure 3-1. There are two types of transfer switches, coaxial and waveguide (CXS and WTS). The subsystem has three CXSs and one WTS. Switch specifications are shown in Table 3-3.

- 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.

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.

Table 3-2. X-band diplexer specifications.

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 3-3. Switch specifications.

Parameter	WTS	CXS
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, W	1000	70
Isolation	>60 dB	>60 dB
Switching Time	50 ms	50 ms

3.1.4.5 Solid-State Power Amplifier

The SSPA provides about 16.8 W (42.25 dBm) of RF output power, as shown by Figure 3-6, 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 DC power input for each SSPA is about 58 W. The DC input varies a little with temperature.

3.1.4.6 3-dB Coupler

The 3-dB coupler, specifications for which are shown in Table 3-4, allows the SDST to power both SSPAs by providing half the power from the SDST to each SSPA. The output from the SDST passes through an attenuator before entering the input of the coupler. SSPA selection is determined using CXS 0.

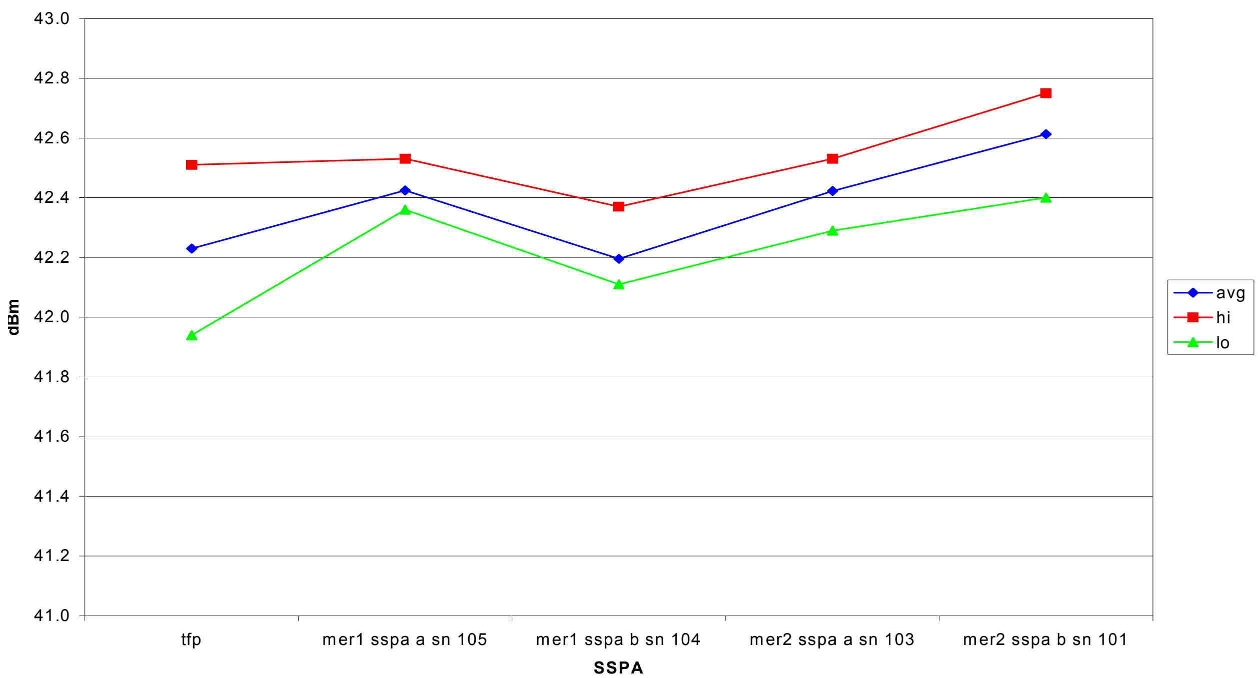

Figure 3-6. RF output of the two MER-B (MER-1) and two MER-A (MER-2) SSPAs.

Table 3-4. 3-dB Coupler specifications.

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

3.1.4.7 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's now a dual-stage modulator). Figure 3-7 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 3-5.

Figure 3-7. MER SDST.

Table 3-5. Receiver carrier loop.

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 Pt ≤–120 dBm			
Capture Range	±1.3 kHz			
Tracking Range	Greater than ±30 kHz at 200 Hz/s for uplink Pt 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 Pc/No = 100 dB-Hz			

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 3-6 shows the POR state for the SDST.

Table 3-6. 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
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

3.1.4.7.1 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, spacecraft antenna cabling, and the station ranging equipment.

Table 3-7 shows the delay the ranging signal experiences as it goes through the SDST. See Table 3-8 for total delay through the spacecraft.

In Table 3-7, one range unit (ru) = 1478/221 * 1/Ftx = 0.931 nanoseconds (ns) for MER-A and B.

3.1.4.7.2 Range Delay after Integration on Spacecraft

The total range delay through the spacecraft (Table 3-8) 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.

Table 3-7. 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 3-8. 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

3.2 UHF

The MER UHF subsystem, a block diagram of which appears in Figure 3-8, 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.

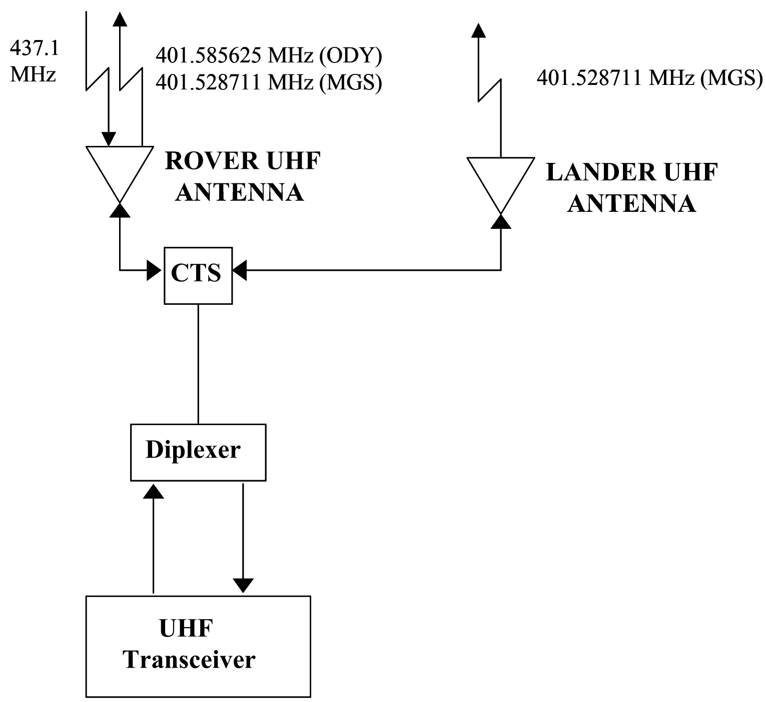

Figure 3-8. UHF subsystem block diagram.

3.2.1 UHF Antennas

The descent and rover UHF antennas are quarter-wavelength monopoles. Figure 3-9 shows photographs of the 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, the structures on the spacecraft create significant distortions to both gain and polarization. This is especially true for the RUHF, due to the vertical obstructions (mainly the LGA and PMA) present on the deck. A right-hand polarization pattern, as measured on a rover mock-up in the JPL antenna range, is shown in Figure 3-10.

Figure 3-10 shows the RUHF antenna pattern in polar coordinates, with the concentric grid markers (0 to 120°) representing the cone angle (angle from the boresight) and the radial grid lines (0 to 360°) 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.

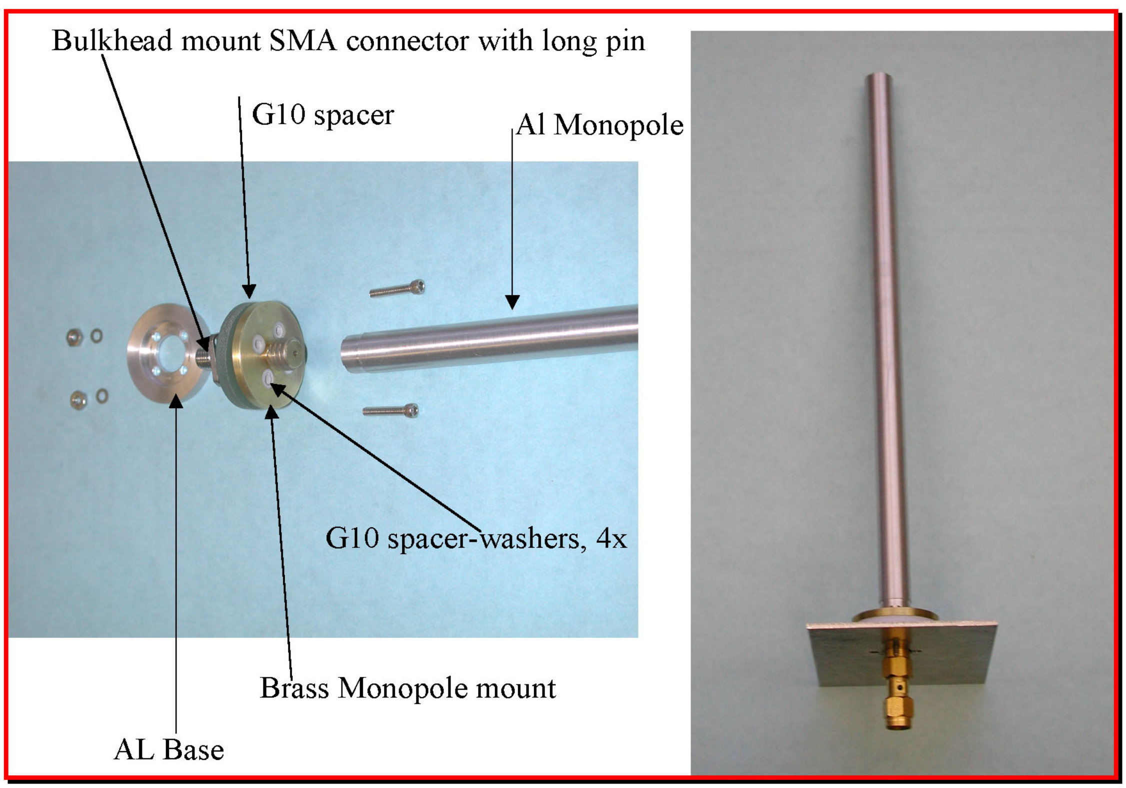

Figure 3-9. Rover UHF antenna.

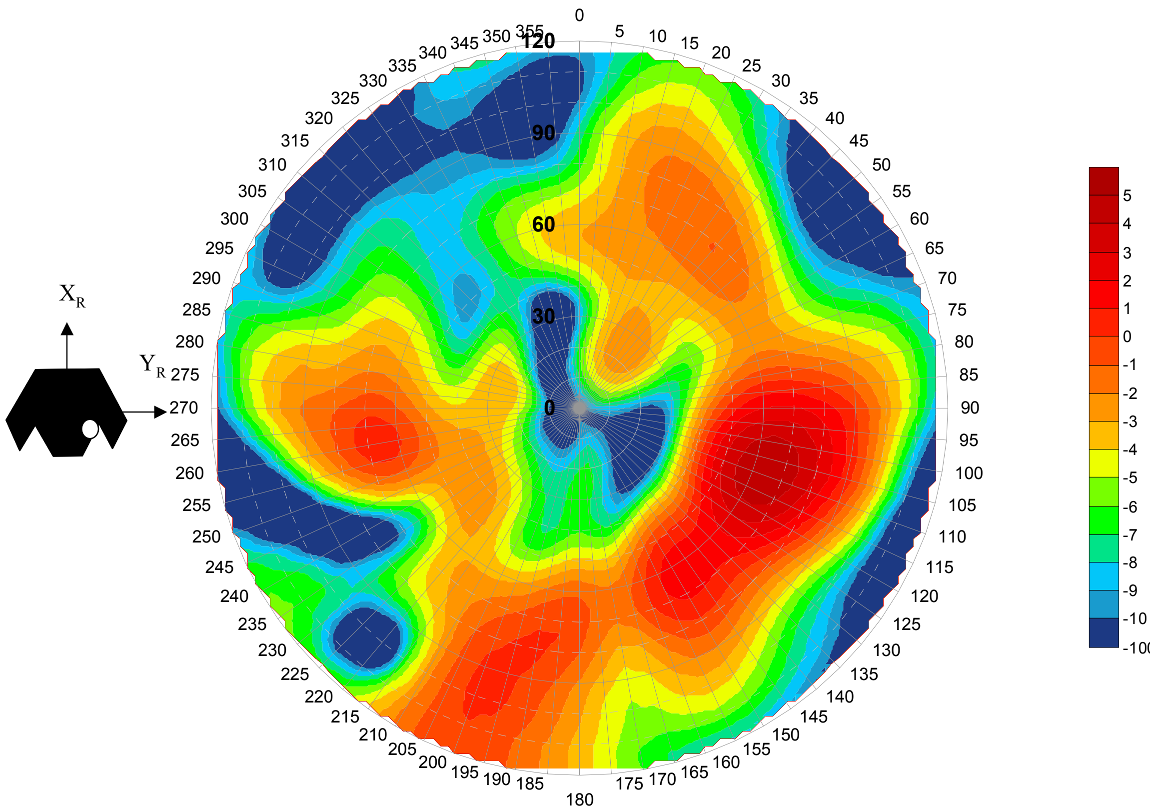

Figure 3-10. Rover UHF antenna pattern as measured on a mock-up at 402 MHz.

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 (Figure 3-11). 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.

Figure 3-11. Odyssey UHF transceiver.

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.

3.2.3 UHF System Operation

3.2.3.1 Physical Layer

At the physical layer, 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°)
- Data Rates
  - Forward link: 8, 32, 128, 256 kbps[11]
  - Return link: 8, 32, 128, 256 kbps[12]
- 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

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), which is the standard used for relay communications by all the missions currently at Mars, except MGS, launched in 1996.

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[11] 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.

[12] 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 4 of this article.

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 terms “receiving end” and “transmitting end” refer in context to either the forward link or the return link.

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 keep sending the 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. As of September 2005, with all forward- and return-link equipment operational on the orbiters and the rovers, the unreliable bit-stream mode had not been used since EDL.

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.[13] 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.

3.3 MER Telecom Hardware Mass and Power Summary

MER Telecom mass and input power are summarized in Table 3-9.

[13] 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 3-9. 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.						

Section 4
Ground Systems

4.1 Deep Space Network

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 didn't 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.

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.

4.1.3 DSN Changes Instituted during the MER Mission

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. These 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 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[14] or even damage to the SDST hardware.[15]

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.

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

[14] 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 (e.g., 8, 16, 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.

[15] 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.

tested by the 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°; in the second, the angle from the CLGA to Earth was about 8°.

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.

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[16] on the MER downlink signal in time for it to improve uplink pointing.

[16] 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.

Furthermore, when MER was downlinking via the RLGA, Conscan was generally not used. Ripples in the RLGA pattern (several dB 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 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.

4.2 Entry, Descent, and Landing Communications

Figure 4-1, from the Mission Plan [7], summarizes the events and representative relative times for MER-A and MER-B during the EDL mission phase.

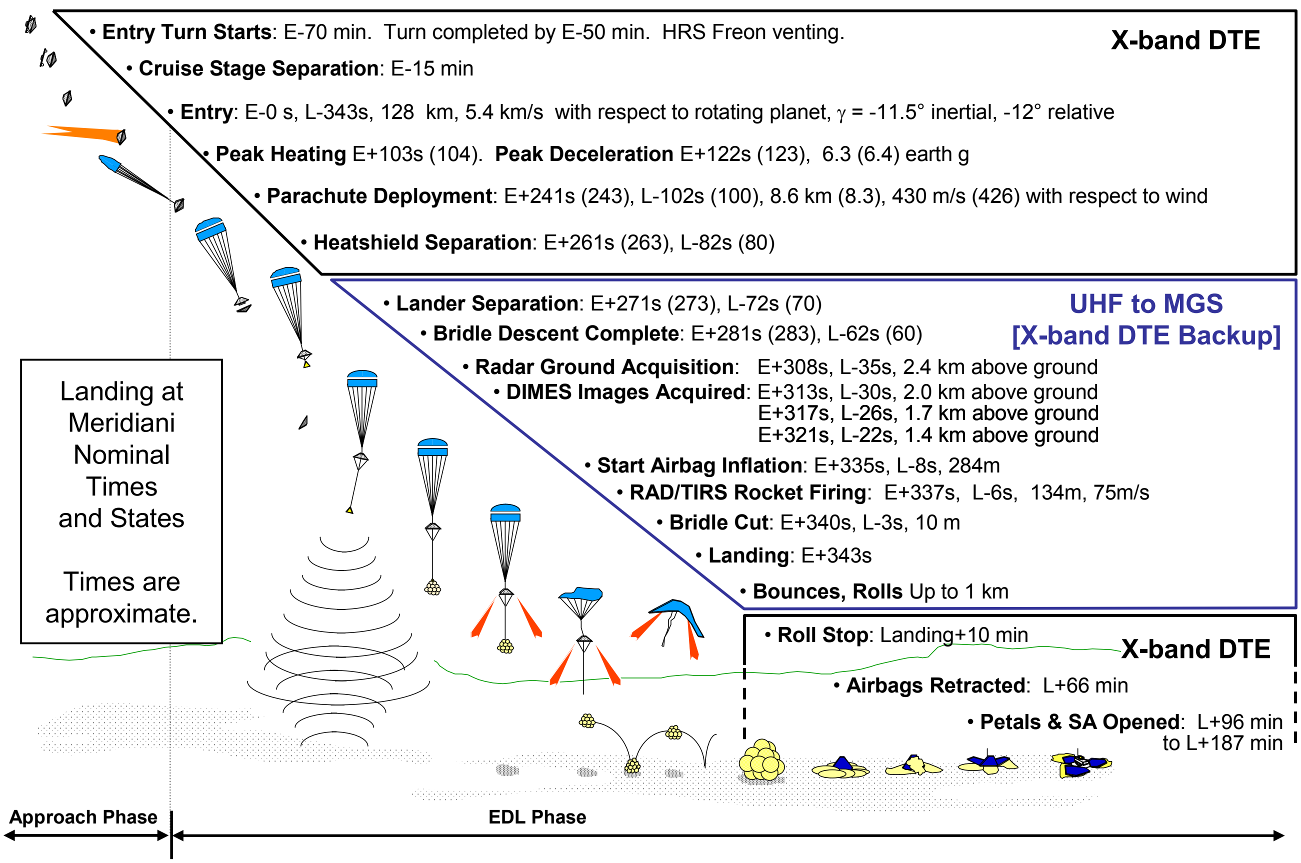

Figure 4-1. MER-A EDL representative timeline (MER-B times in parentheses).

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 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.

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 Figure 4-2. The profiles are shown for one of the candidate landing sites. Three different profiles are shown—in green for the nominal entry path angle and in red and blue for other path angles 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 Figure 4-2 (a). The range of Doppler shift is approximately 90 kHz, and the (two-sided) range of Doppler uncertainty is approximately 50 kHz. Figure 4-2 (b) shows the expected Doppler rate, or first derivative of Doppler frequency, due to acceleration.

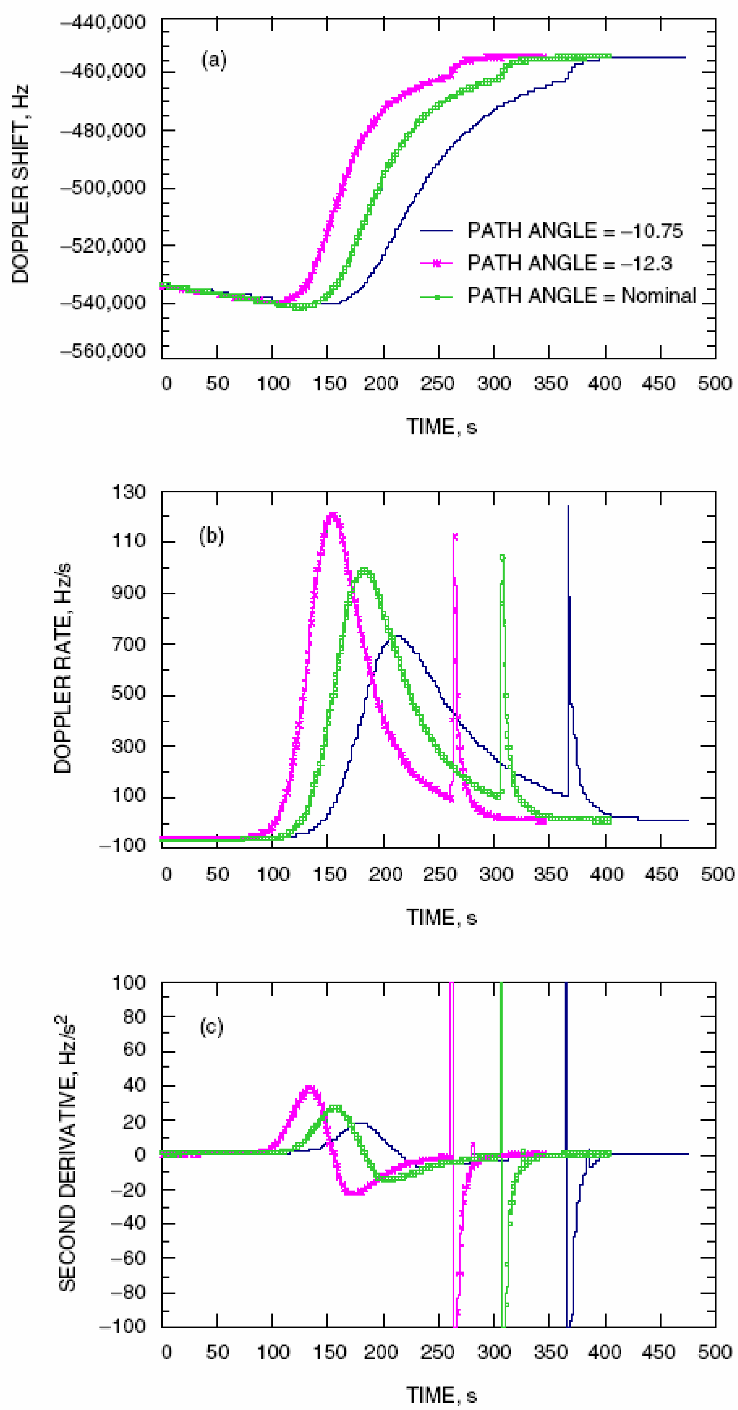

Figure 4-2. Doppler, Doppler rate, and Doppler acceleration during MER-B EDL.

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 4-2 (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.

The predicted SNR for the MER-B downlink signal during EDL is shown in Figure 4-3. 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 red (center) curve in Figure 4-3 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 green (upper) curve is the maximum SNR that might be achieved and is based on the most favorable orientation angle, and the blue (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.

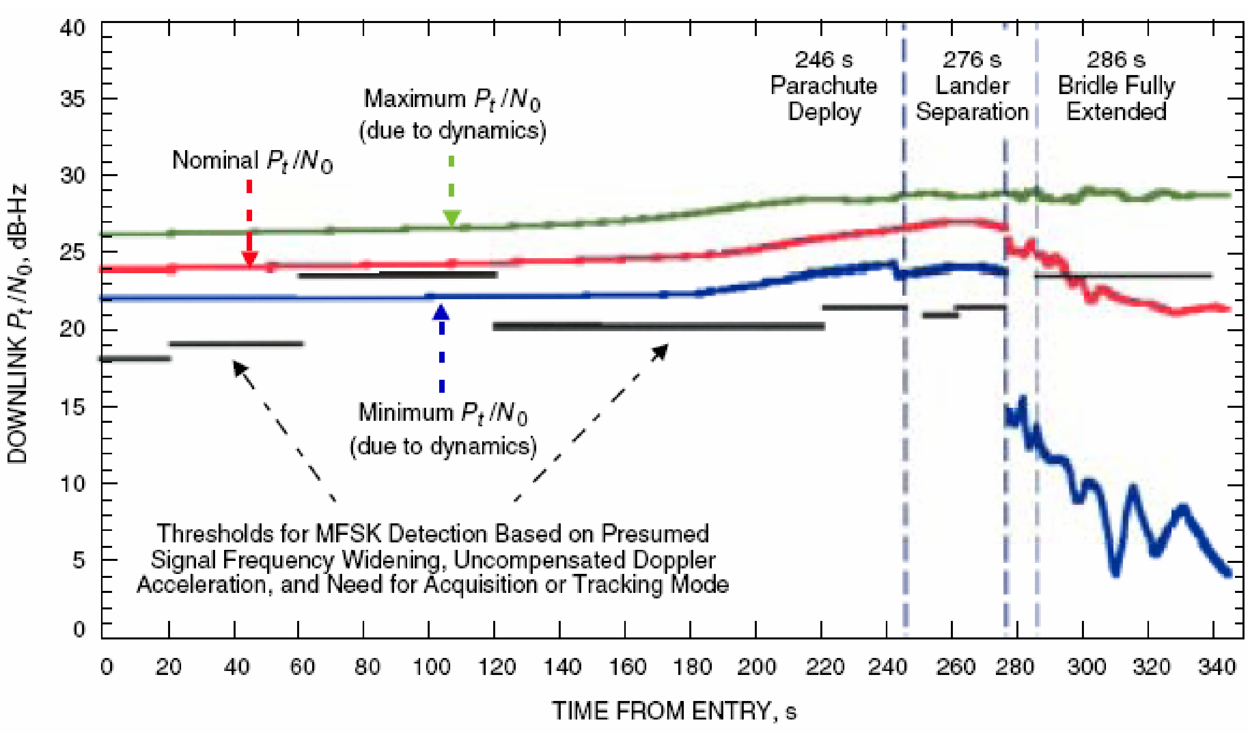

Figure 4-3. Predicted X-band downlink signal levels during MER-B EDL.

Figure 4-4 (a) shows the block diagram of the EDL data analysis (EDA) processor[17] and Figure 4-4 (b) the EDL tracking process.

During the higher-dynamics portions of EDL (preentry 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.

4.3 Relay Data Flow

Odyssey and MGS both 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.

4.3.1 Odyssey

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

At the beginning of the primary mission, each of the two rovers was allocated 120 Mbits.[18] 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, i.e., 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).

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[17] 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, fluctuating signals that are Doppler-shifted by amounts that are only partly predictable. The software supports both real-time 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.

[18] 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 up to 17 min, but due to antenna pattern and other link considerations, the best UHF pass at 128 kbps was on the order of 110 Mbits. The remainder of the memory was allocated to the Beagle 2 lander, but unfortunately no data was ever received.

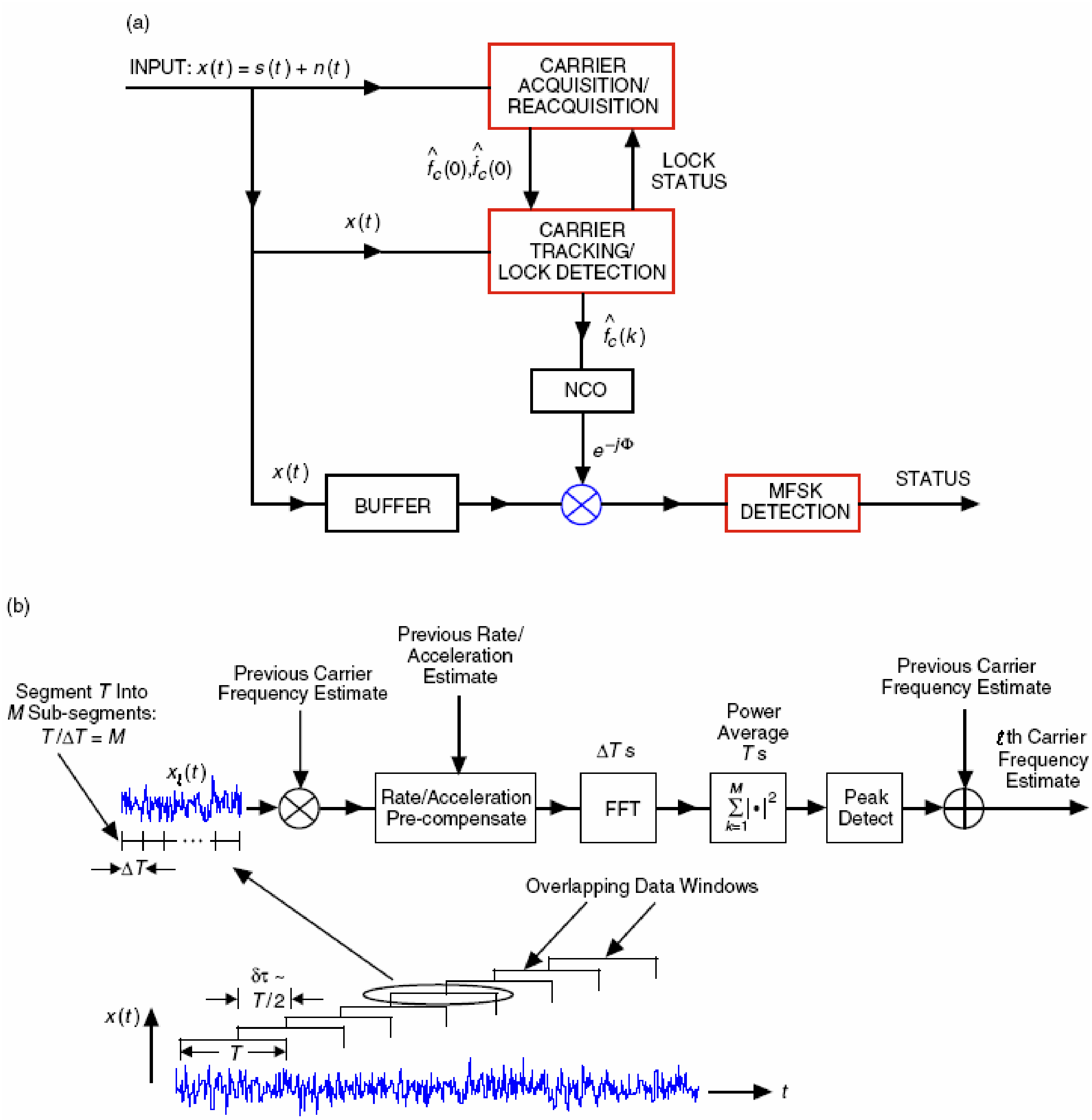

Figure 4-4. (a) EDL signal processor, (b) EDL tracking process.

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.

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 Mbits); 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 hrs apart.

With a minimum Odyssey X-band downlink rate of 14 kbps to the DSN, Odyssey could downlink approximately 50 Mbits 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.

4.3.2 Mars Global Surveyor

On the MGS spacecraft, the interface with the UHF radio is the Mars Orbiter Camera (MOC). Relay data from the rovers and the MOC images share the same buffer allocation. The total data volume available for MER relay during the primary surface mission was approximately 77 Mbits.[19] This allocation was routinely overflowed during MER operations at 128 kbps. In contrast to Odyssey relay storage, if the MGS MOC buffer has no additional space available, any new MER data is not recorded, and the old data is preserved.

The relay data in MOC packets reaches the principal investigator for the instrument (at Malin Space Science Systems in San Diego), where the relay data is extracted from the MGS-to-Earth downlink and sent at JPL for frame synchronization.[20]

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 cannot send data at UHF to a lander. Odyssey is the only backup to X-band available 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.

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

[20] For several reasons outlined in Section 7.3, as of September 2005, MER was not using MGS to return data from either rover.

Section 5
Telecom Subsystem and Link Performance

5.1 X-Band: Cruise, EDL, 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.

This section begins with Telecom performance during two critical mission phases: initial acquisition after launch, and EDL.

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 (up to ±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 postlaunch 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 Figures 5-1 and 5-2. 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 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 (Pc/No) estimator saturates at 80 to 90 dB-Hz. 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 Pc/No 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, No. 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 Pc/No.

For both MER-A and MER-B, the saturated SNR and Pc/No 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.

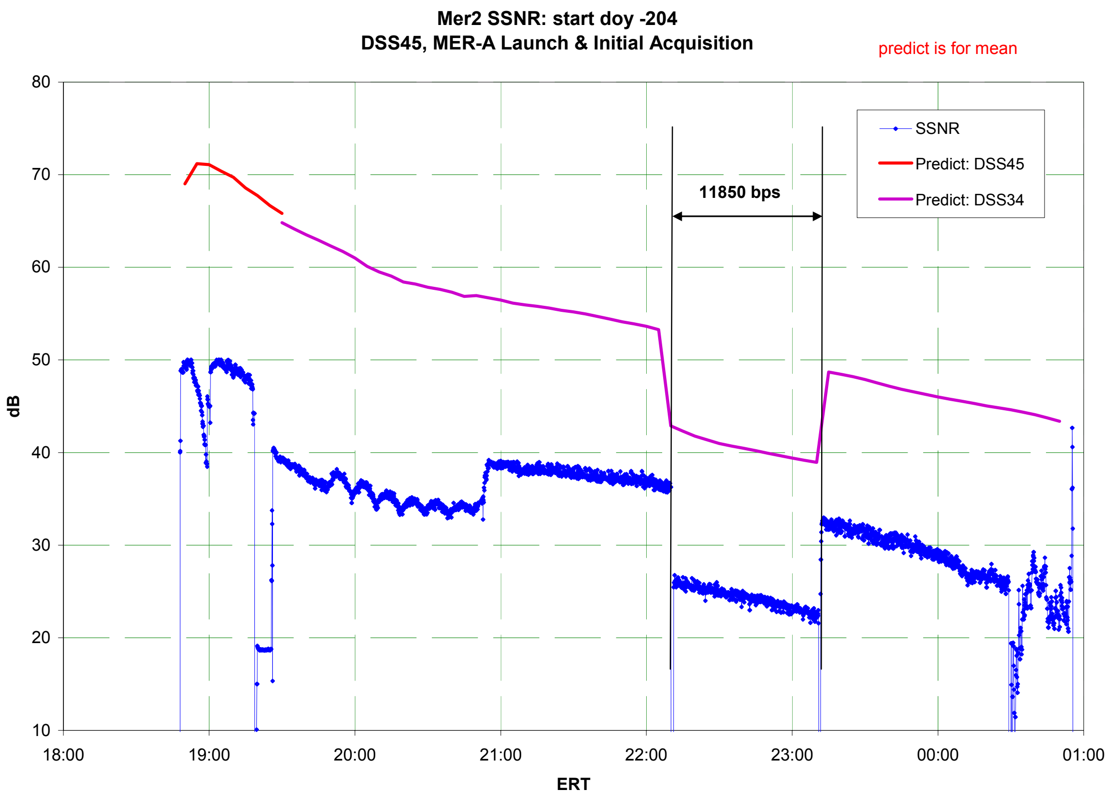

Figure 5-1. MER-A initial acquisition symbol signal-to-noise ratio.

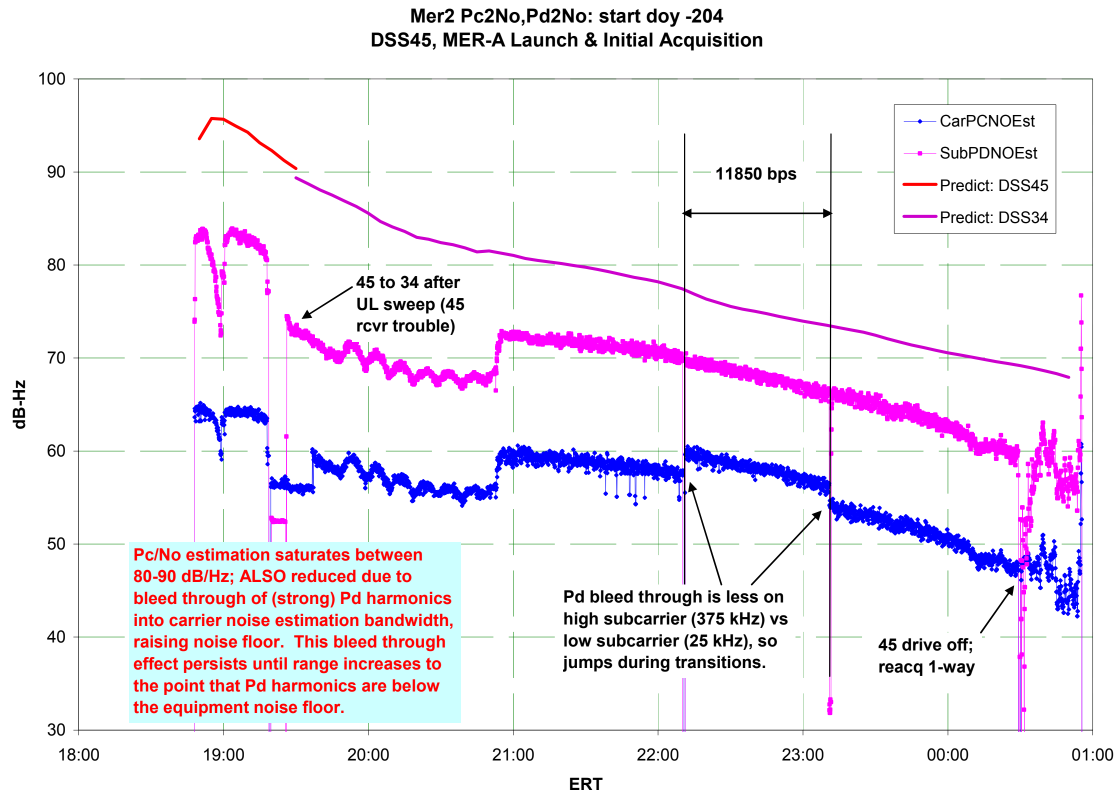

Figure 5-2. MER-A initial acquisition Pc/No and Pd/No.

5.1.2 X-Band Performance during EDL

Section 4.1 describes the special ground-system elements required to process the downlink modulation during EDL, and Figure 4-1 describes the spacecraft and Telecom transitions through the EDL sequence. The following summary of X-band carrier frequency changes is taken from [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 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 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, 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. The left half of Figure 5-3 shows a 2-rpm spin rate of the cruise stage superimposed as ripples on the aux osc drift and HRS cycling signatures.

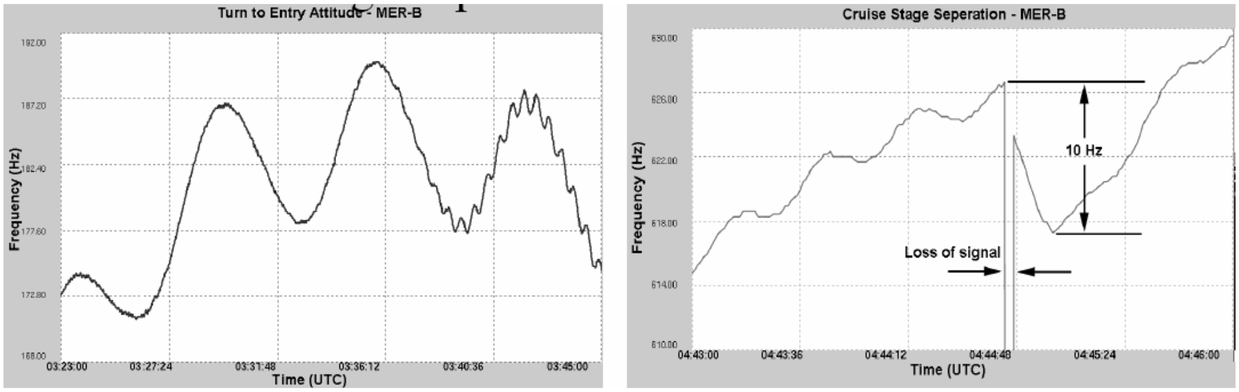

Figure 5-3. MER-B signature of CLGA spin and HRS cycling (left) and cruise stage separation (right).

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 turn to entry, the peak-to-peak one-way frequency variation was 3.3 Hz at 2 rpm.

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 the right half of Figure 5-3, 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 Figure 5-4 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 Figures 5-4 and 5-5, the correspondence between the two can be seen. RAD firing is –4 s in Figure 5-5. 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.

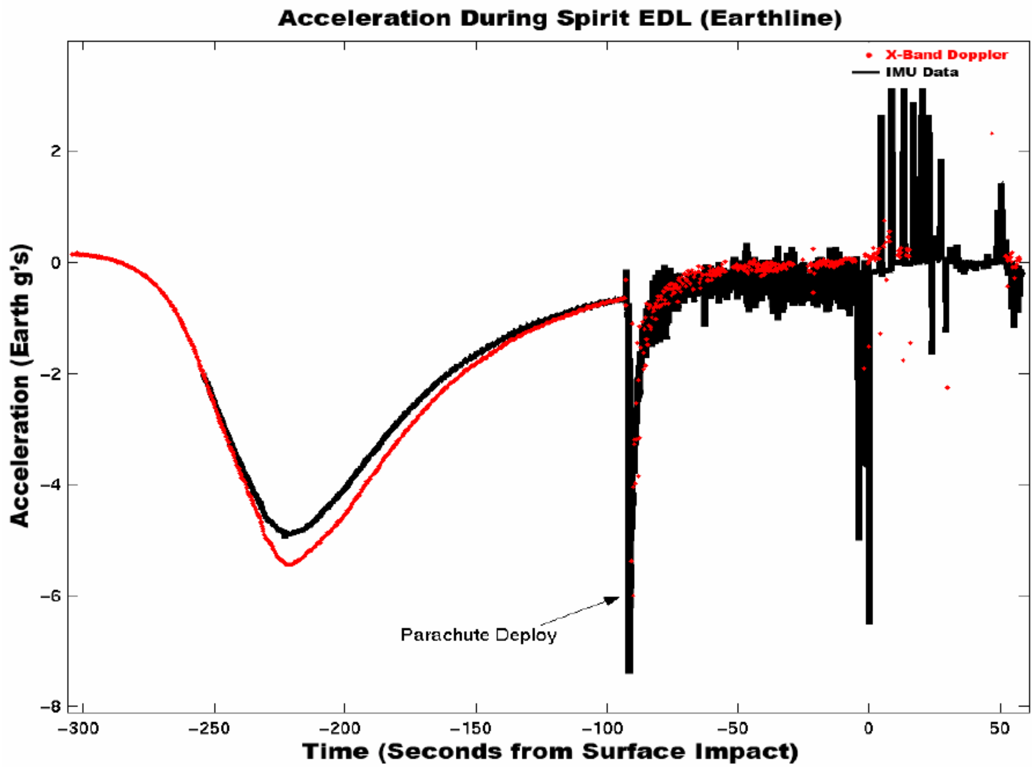

Figure 5-4. Spirit EDL Doppler frequency and accelerometer data: entry compared to landing.

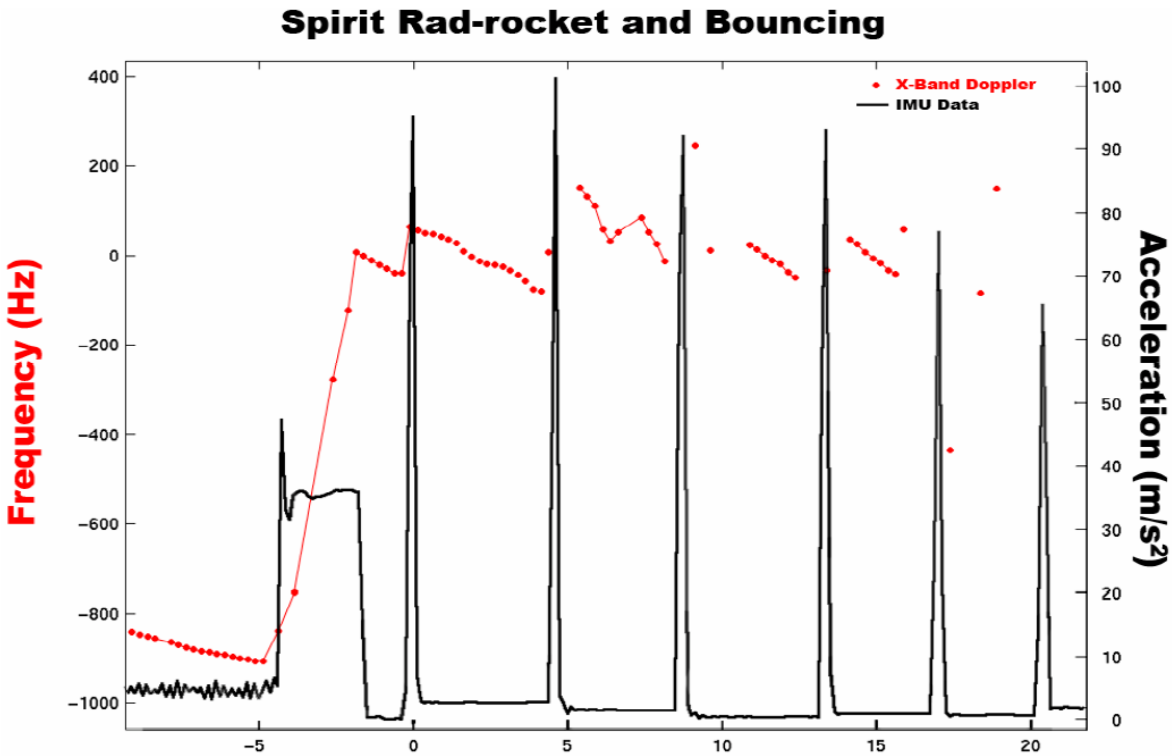

Figure 5-5. Spirit Doppler frequency and acceleration due to RAD firing and bounces.

The following summary of signal-level changes and the operation of the EDA is synthesized from [13,14,15]. Transmission of the M-FSK signal (described in Section 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. 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 5-6 shows the received carrier SNR per Hz (Pc/No) and the data SNR per Hz (Pd/No) in dB-Hz for the Opportunity EDL.

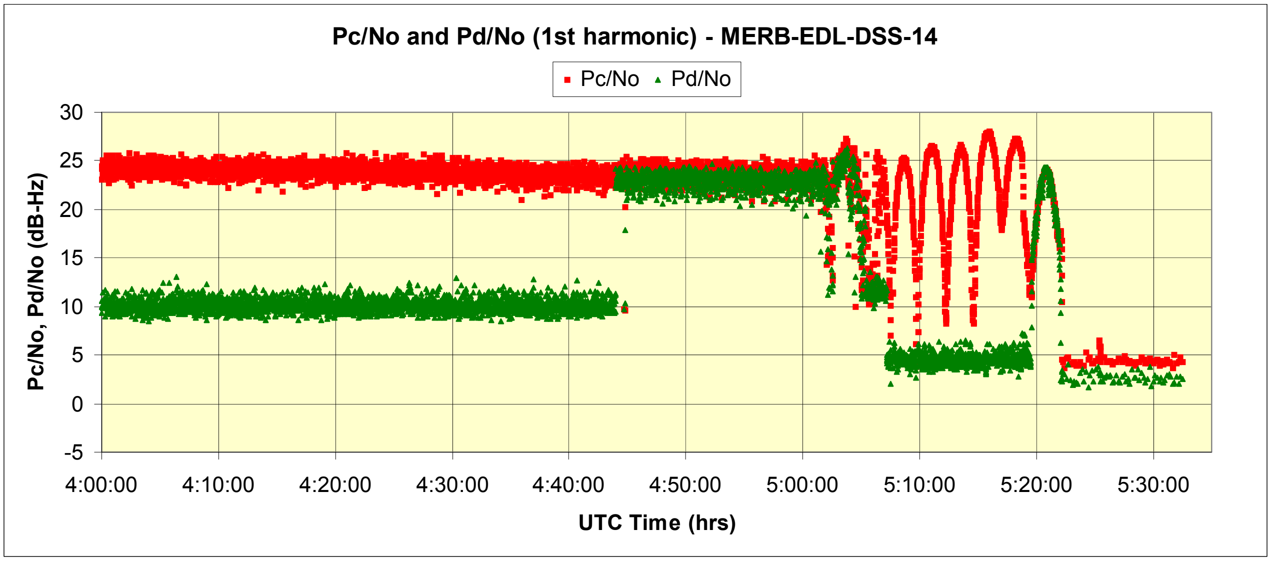

Figure 5-6. X-band received Pc/No during Opportunity EDL.

This Opportunity plot spans from about 44 min before cruise stage separation to 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 Figure 5-6). 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 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.

Figure 5-7 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.

[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.

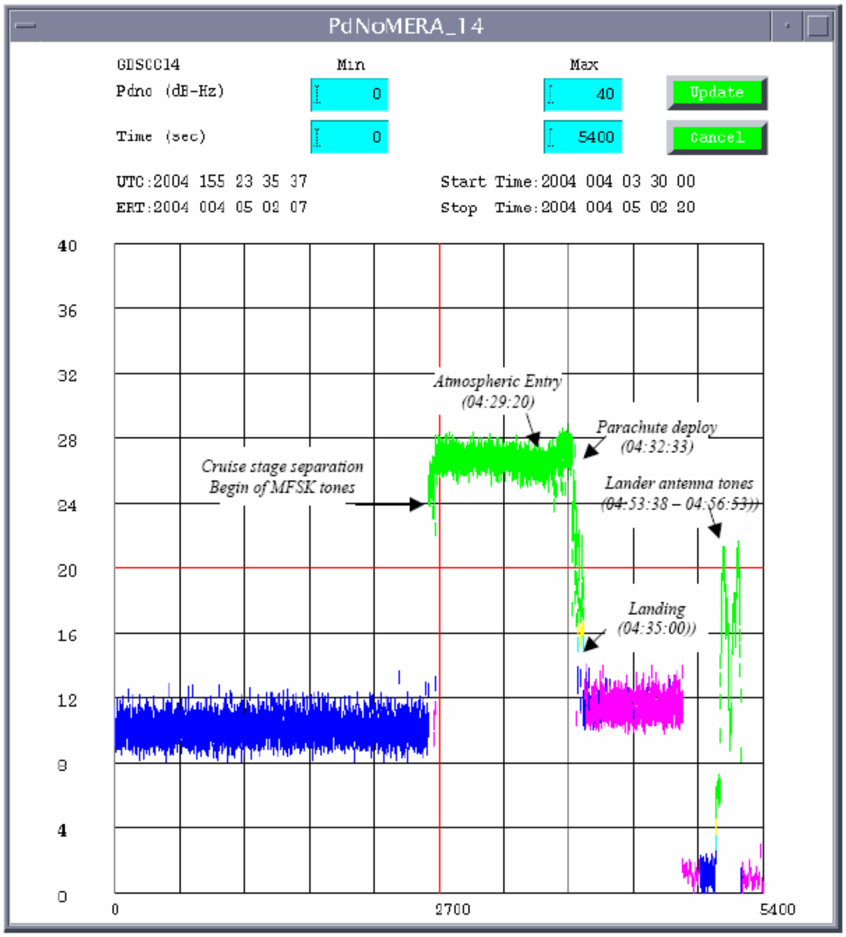

Figure 5-7. M-FSK tone power during Spirit's EDL.

Overall, the results from the actual EDLs were better than originally anticipated. All tones marking critical events such as cruise stage separation, parachute deployment, PLGA deployment, etc. 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.

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 postlanding 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 5-8 shows the comparative results of real-time and postpass processing. Green indicates valid processed data, and violet shows periods of receiver noise (lost data). In the right half of the figure, the segment over the period 5000 s to 5800 s after start is the recovered data, corresponding to the undetected data during that period in the left half.

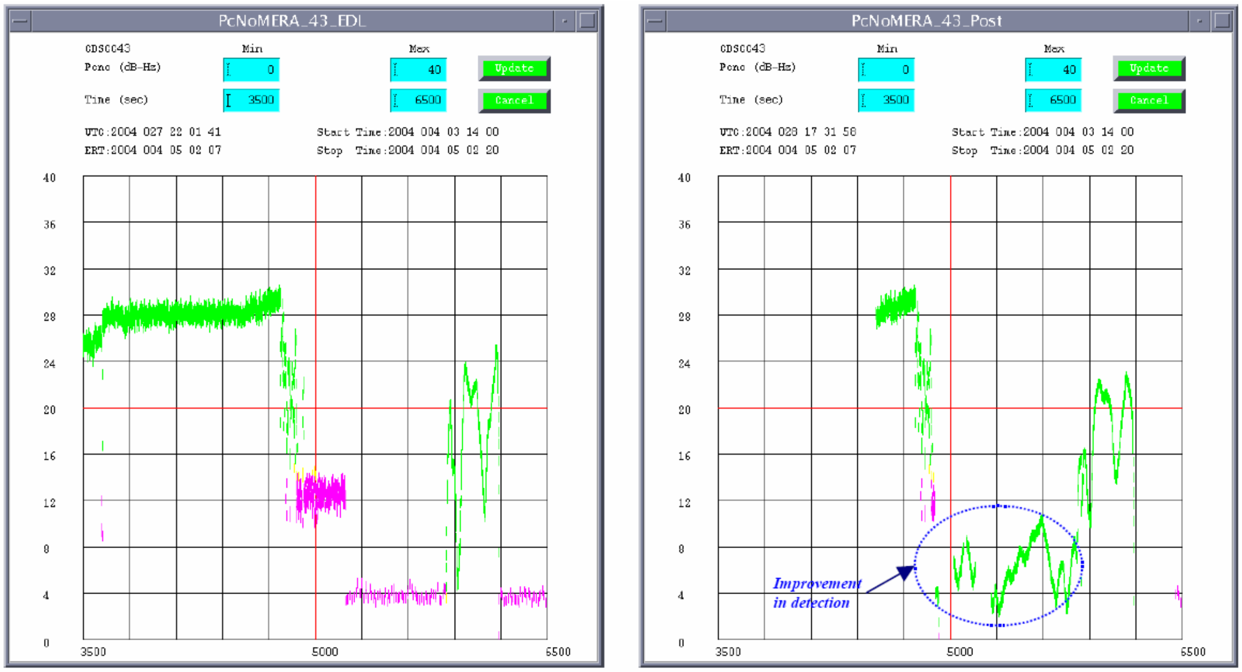

Figure 5-8. Comparison between real-time and postpass carrier detection for Spirit EDL.

During the 15-min outage, the Radio Science team reported unexpected detection of LH-polarized signal. Postlanding 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 5-9 shows the EDA carrier detection of Opportunity in oppositely polarized (RH and LH) channels. As in Figure 5-8, green indicates valid data, 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 of Spirit's. Again, all critical tones were detected. The posttouchdown outage was only ~1 min, compared to 15 min for Spirit. That outage occurred 3950 s after start, as shown in Figure 5-9.

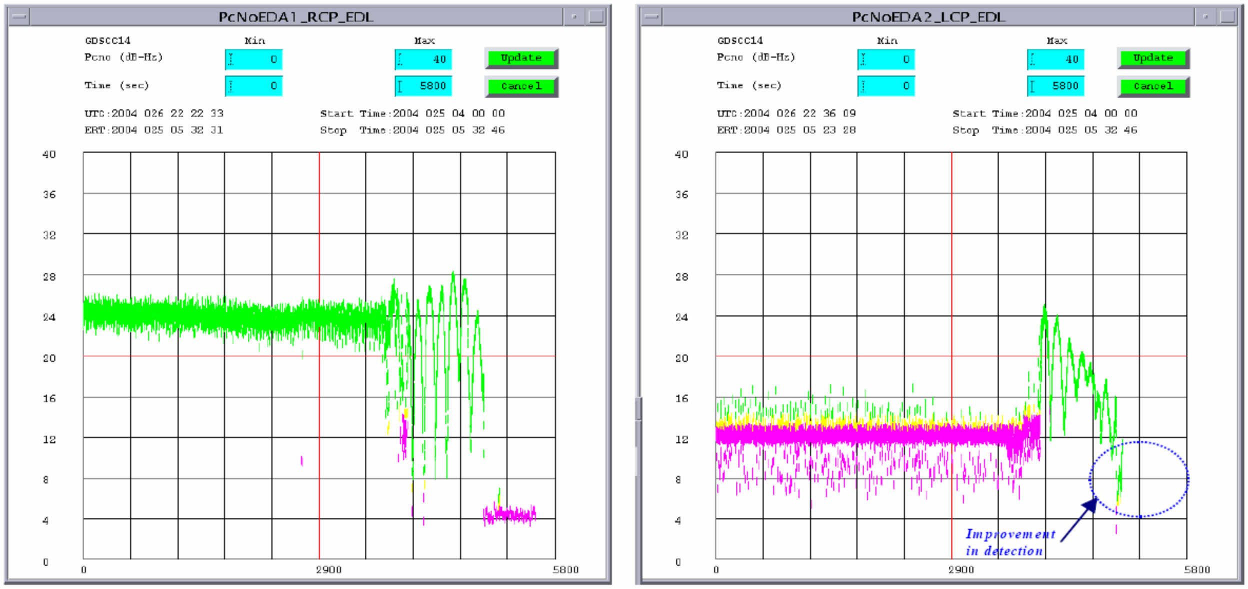

Figure 5-9. Comparison of RCP and LCP carrier detection during Opportunity EDL.

5.1.3 Performance vs. 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 TPF are initially based on prelaunch 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.

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 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 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°, to support the planned data rate of 40 bps.[22]

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.

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.

[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 Pt/No 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 doesn't 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 don't 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.

5.1.5 PMA 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 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 was not adequate to capture the magnitude of the problem.

During prelaunch development, both Telecom and ACS recommended characterizing and accounting for PMA occlusion, knowing that it would occur during surface operations. Analyzing and modeling occlusion wasn't 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.[23] 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.

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 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 executes a "run out" (canned science sequence), and sends its beep at the off-nominal time.

[23] 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). See Section 7.7.

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% of 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 Pt/No of 12 dB-Hz. Occasionally the DSN has been able to detect and lock up on slightly weaker beeps. Figure 5-10 shows the predicted Pt/No of the 11 a.m. (local solar time) beeps for MER-A through the end of 2004. The colors indicate the DSN sites: yellow for Goldstone, turquoise for Canberra, and blue for Madrid. The lower the station elevation angle at beep time, the lower the predicted Pt/No.

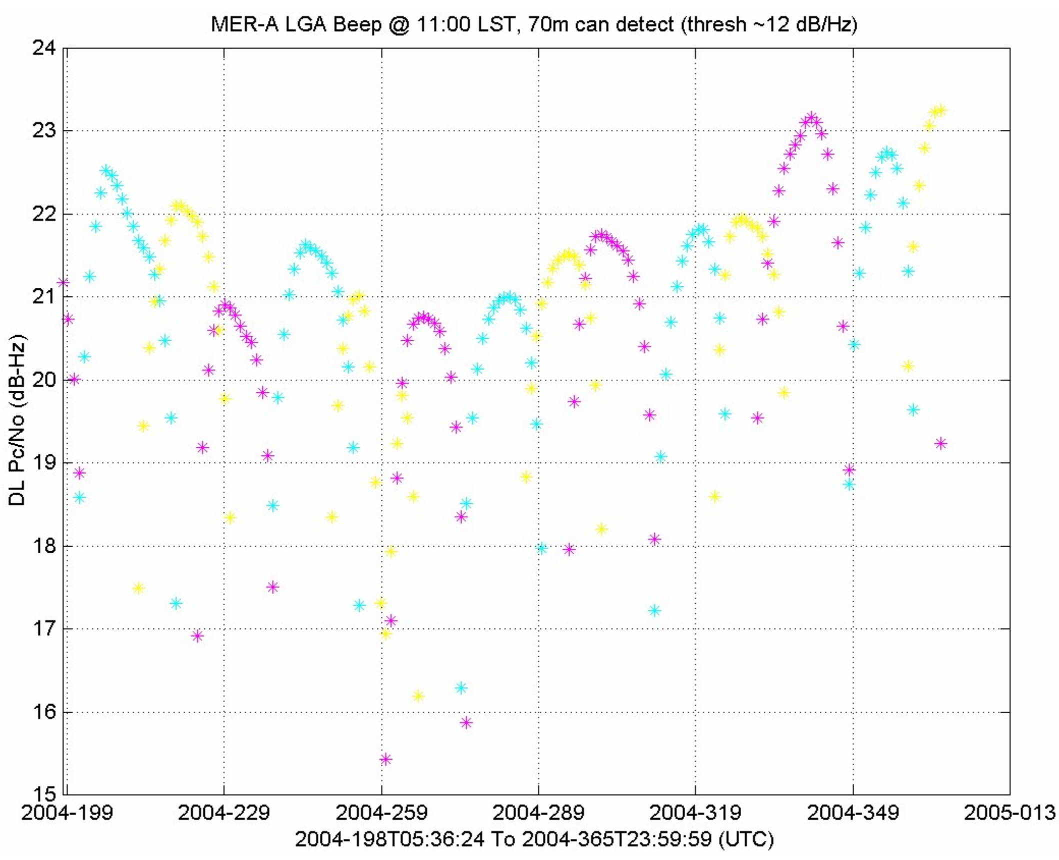

Figure 5-10. Predicted MER-A 11 a.m. beep received Pt/No at 34-m stations.

5.1.7 Antenna Pointing

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 an RTLT[24] 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. 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 5-11 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 5-12 compares the uplink pointing loss for 70-m and 34-m antennas that results from the pointing errors in Figure 5-11.

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°, 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°. 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°, with 0.02° due to spacecraft motion and 0.01 due to 70-m blind-pointing error. The effect of a 0.01° 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.

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

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.[25] 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.

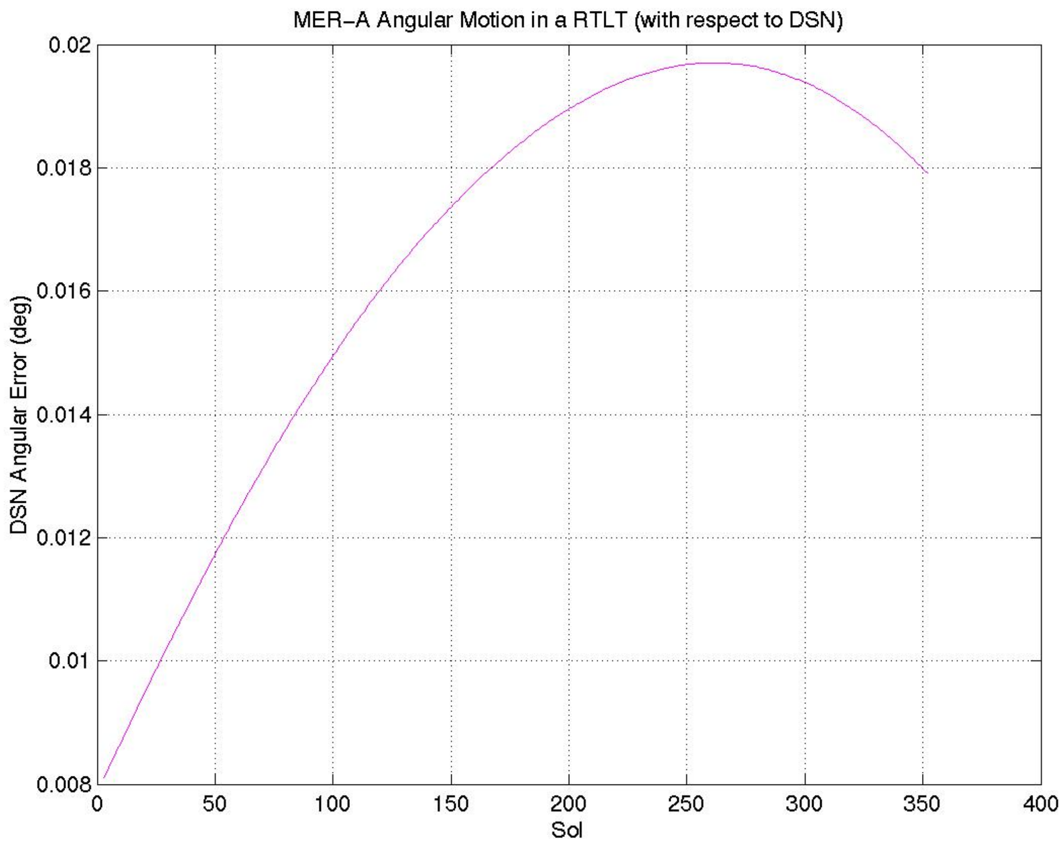

Figure 5-11. MER-A angular motion with respect to DSN during a RTLT.

[25] 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.

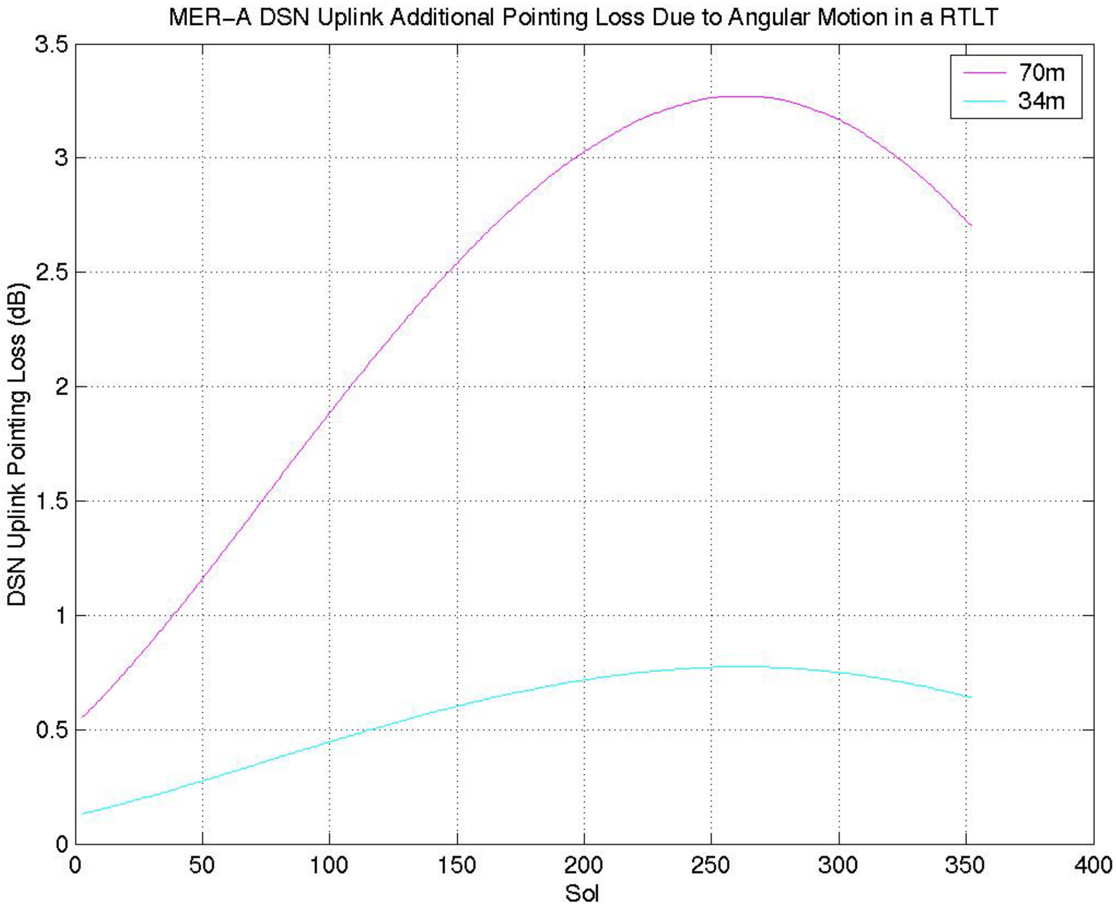

Figure 5-12. MER-A uplink pointing loss due to angular motion in RTLT.

5.1.7.2 Rover

The control of HGA pointing toward Earth is subject to ACS errors caused by such factors as temperature and bus voltage variations. ACS periodically corrects the HGA pointing through an activity called the fine attitude update. These updates are infrequent because science activity dominates the rover resources. Telecom 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° in the primary mission, and downlink data-rate capability planning has been based on a 2° error assumption.

Figures 5-13, 5-14, and 5-15 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 °C on the right axis.

The cla_snr from the HGA begins at about 20:30 UTC in Figure 5-13, 03:20 in Figure 5-14, and 01:35 in Figure 5-15. 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 Figure 5-14 with Figure 5-15 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.

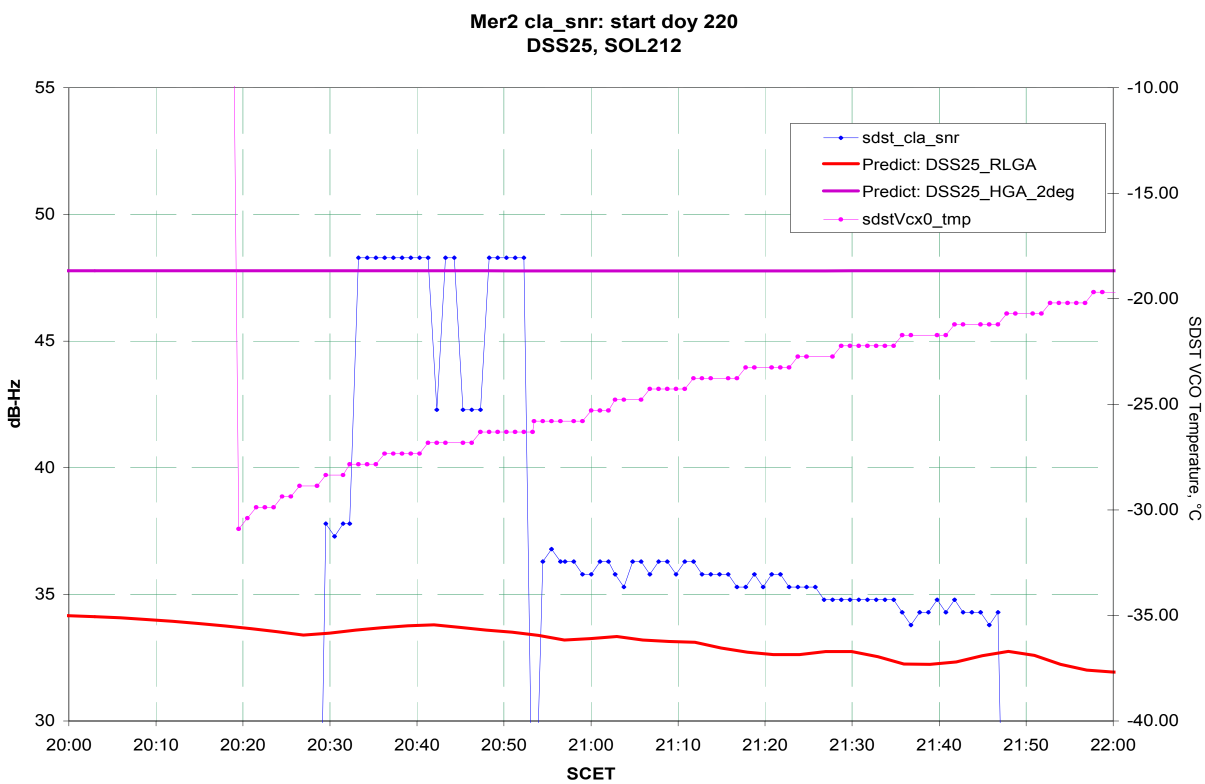

Figure 5-13. MER-A surface uplink performance from a 34-m station (without Conscan).

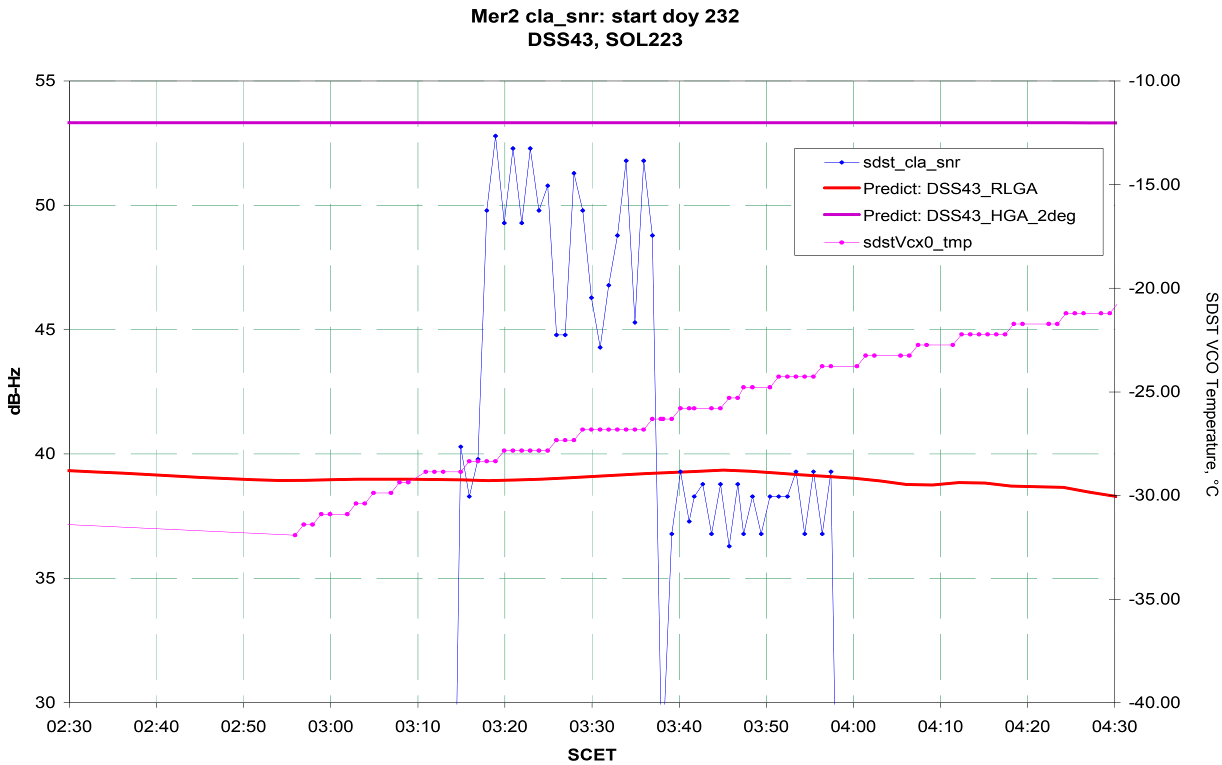

Figure 5-14. MER-A surface uplink performance from a 70-m station (with Conscan).

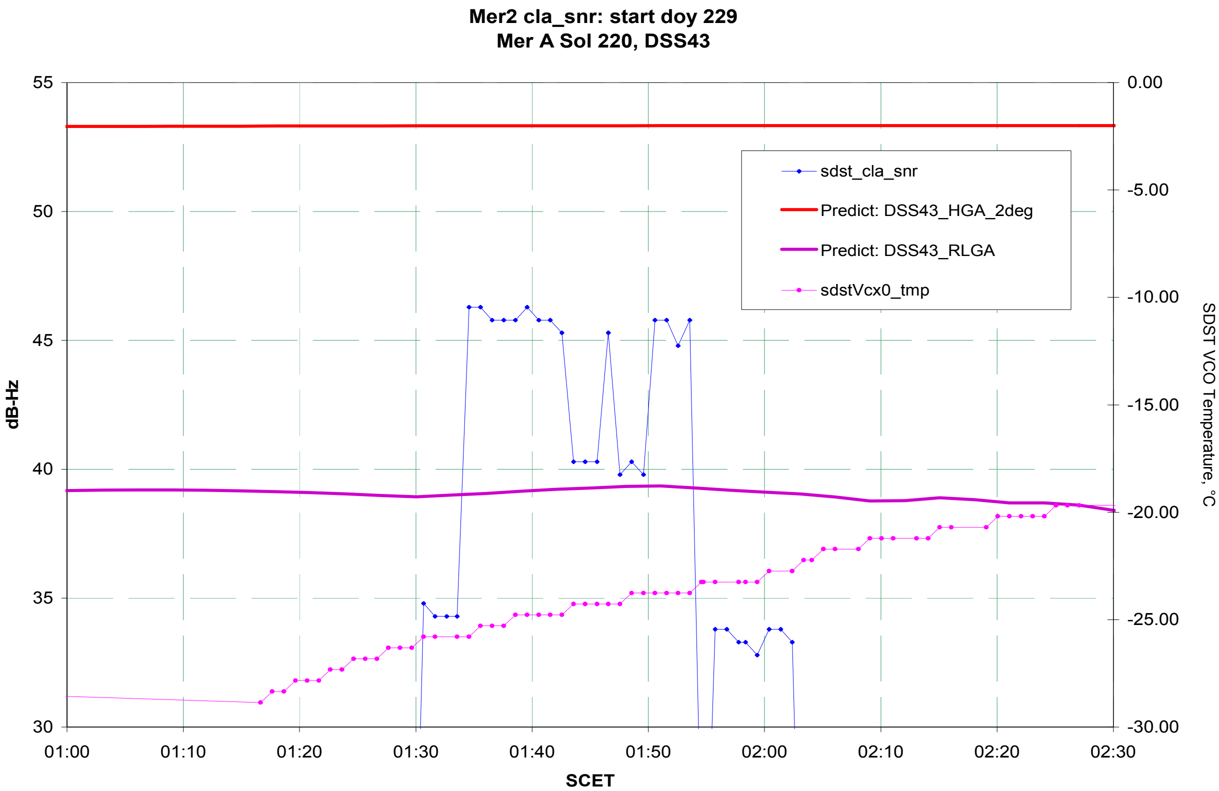

Figure 5-15. MER-A surface uplink performance from a 70-m station (without Conscan).

5.1.8 Uplink Acquisition Problems Caused by Rover Temperature Variations

The SDST 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 in that it produces a particular pattern of uplink frequency versus time. The tuning rate, the tuning distances above and below center frequency, and the dwell times between tuning segments are usually the same for each pass but can be changed without changing the template. After the acquisition template completes, the transmitted uplink is "ramped" so that its frequency changes with time to compensate for the Doppler shift induced by Earth's rotation and the spacecraft's motion. As a result, the frequency reaching the spacecraft remains nearly constant, at the predicted BLF through the rest of the pass. An uplink reaching the receiver at BLF facilitates tracking by the SDST although the SDST is capable of tracking 200-Hz/s frequency variations up to at least ±30 kHz away from BLF under normal circumstances.

During the first weeks of surface operations, the late-cruise BLFs were also suitable for both rovers. This is because the average SDST temperature on the surface was at first about the same as the SDST temperature during final cruise. MER-A sweep parameters (tuning distances as well as BLF) were adjusted multiple times during the surface mission (due to a MER-A SDST idiosyncrasy called "coherent leakage," described in Section 5.1.9.1), while the MER-B sweep parameters required little adjustment.

On the surface, there are several constraints on the timing of X-band communications. Earth has to be in view above the horizon at the rover's location. For power reasons, X-band communications are limited to daylight at the rover location. On Earth, the tracking station has to have the rover in view when the transmitted uplink reaches Mars. The standard procedure is to perform a single uplink acquisition in time to accommodate morning commanding. If stations at two locations share the Earth-facing view period of the rover, an uplink handover[26] between them might be required. On some sols, the uplink has to be interrupted, such as when the rover is sequenced to be asleep (central processor unit and SDST off) or for discontinuous station coverage. In those cases, the uplink station makes a new acquisition sweep after wake-up or at its beginning of track.

As Martian winter set in and the morning wake-up VCO temperature began to fall below –20°C, uplink acquisition strategies were necessarily more elaborate than those used earlier in the surface mission. At VCO temperatures lower than –15°C, the SDST is increasingly susceptible to DAC rollover glitches, so the tuning-rate parameter in the MAQ template was reduced to 100 Hz/s (from 200 Hz/s), and the total received power at the spacecraft was limited 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 for the duration of the winter (see Section 7.3.2).

Characterization of the BLF during surface operations, as compared with prelaunch testing data, yielded the plots in Figures 5-16 and 5-17.

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 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, it became necessary to use an uplink frequency reference offset (FRO) for the morning acquisitions.[27] Uplink FRO values of up to –6 kHz have been requested for MER-A.

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[26] In an uplink handover, the two stations, the outgoing one and the incoming one, each radiate an uplink simultaneously for 2 s, with the same frequency reaching the rover. That way the SDST remains in two-way lock, and the outgoing station can then turn off its uplink.

[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 a 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

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 (200 Hz/s).[28] For the MER-B SDST, which doesn't have coherent leakage or minimum temperatures as low as those of MER-A, no FROs have been necessary. The MER-B BLF has stayed within the nominal ±5-kHz SR for all VCO temperatures so far.

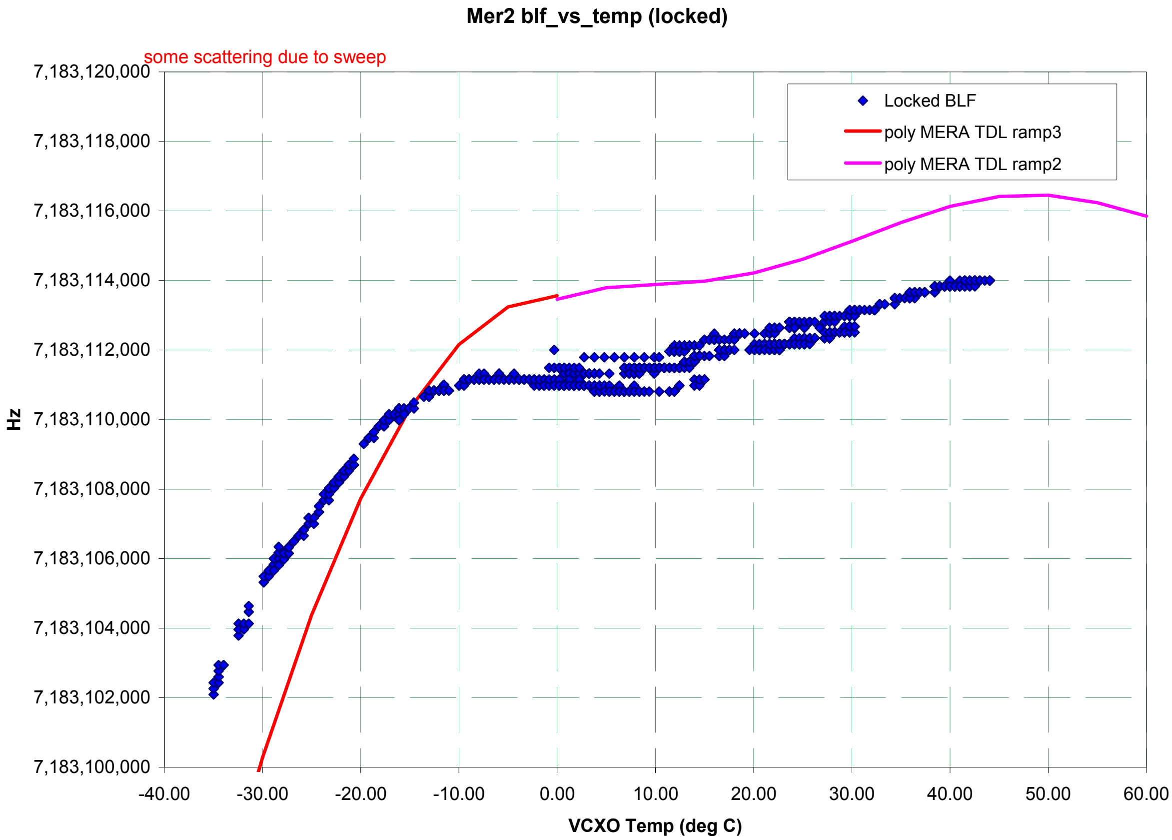

Figure 5-16. MER-A surface best-lock frequency (in flight vs. prelaunch test).

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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.

[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.

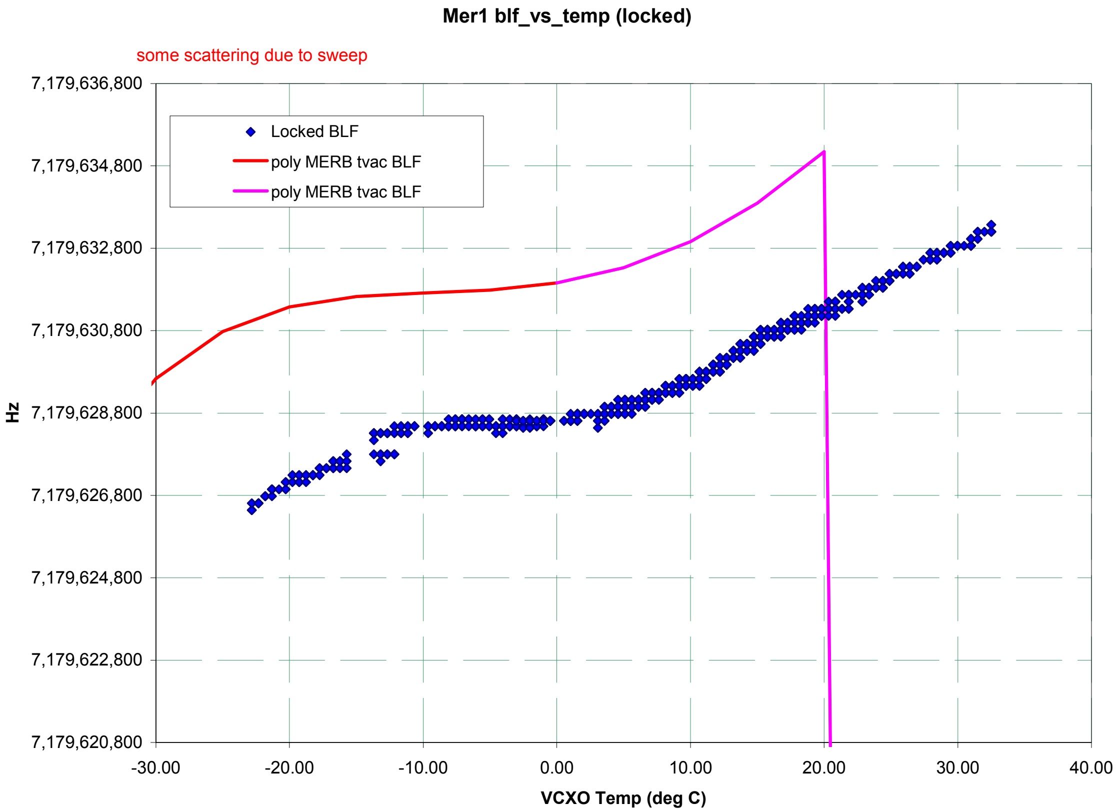

Figure 5-17. MER-B surface best-lock frequency (in flight vs. prelaunch test).

5.1.9 Other Key X-Band Technical Issues

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 5-18 is a plot of MER-A static phase error. The relatively smooth variation between 14:50 and 16:10 occurred when the receiver was in two-way lock with a station.

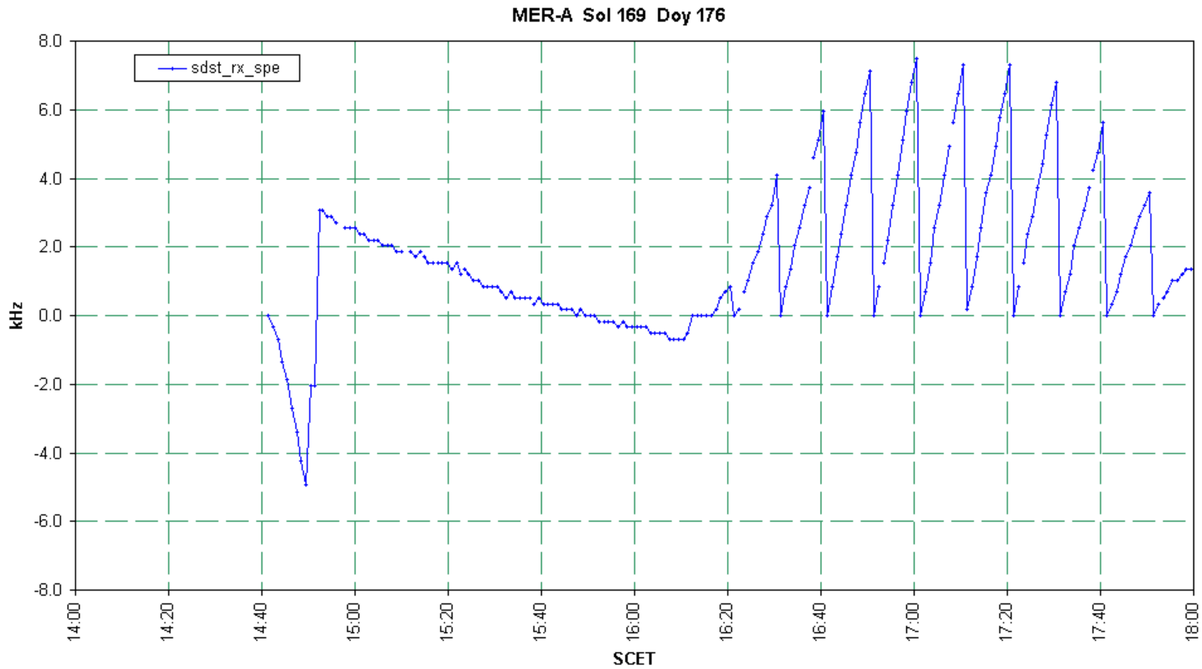

Figure 5-18. MER-A static phase error showing effect of coherent leakage in one-way.

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.

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.

5.2 UHF: EDL and Primary Mission Surface Operations

In this article, 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.

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 Mbits.

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 (e.g., 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 5-19 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° 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.

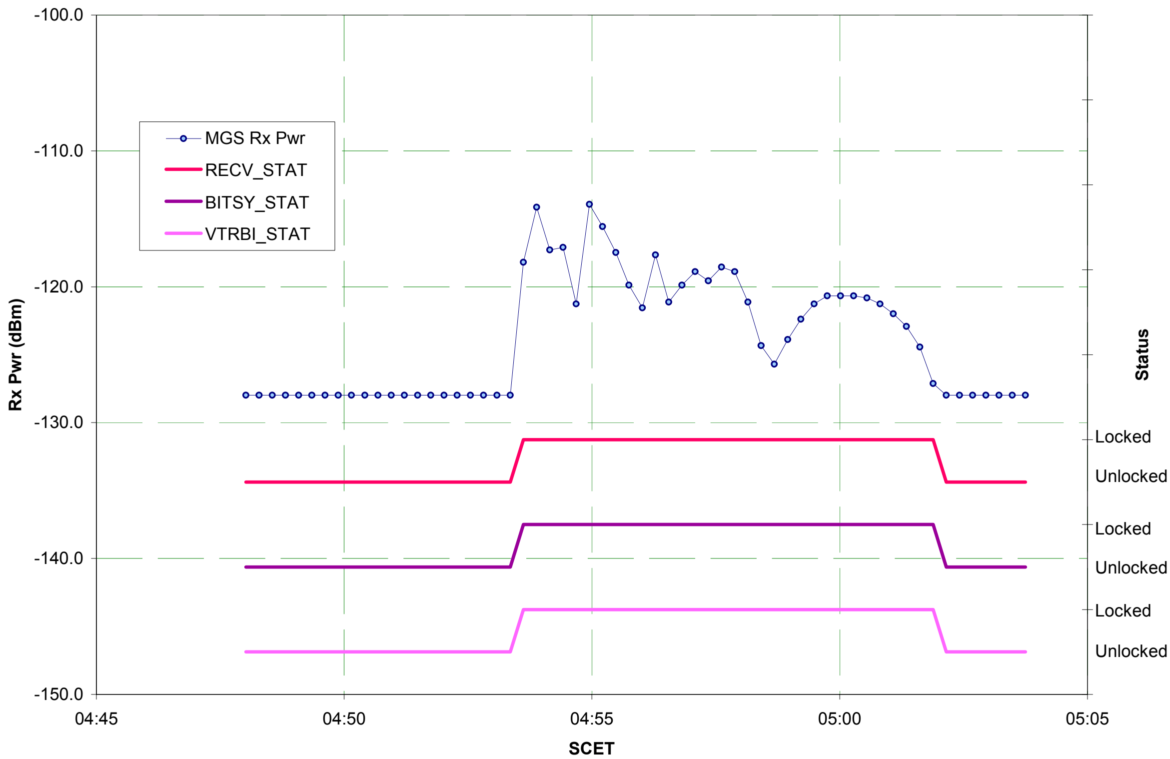

Figure 5-19. MER-B EDL (January 25, 2004), UHF received power and lock status.

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 Mbits) for each view period (potential relay pass) and for all rover yaw angles in steps of 10°. 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 can be displayed in several forms. Figure 5-20 shows at the left the predicted volume in Mbits at every 10° in azimuth on a polar plot, for each of two potential low-elevation passes. At the right is the geometry of each of these passes superimposed on the rover UHF antenna pattern (oranges and reds indicate higher

[29] For much of the primary and early extended mission, "no tilt" was a good approximation, with the actual tilt generally less than 4°. 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 of up to 31°. 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-sight blockage from the local terrain rather than using a simple, fixed, minimum elevation angle.

gains) for the actual yaw of 297°. Based on the yaw and the predictions, the pass shown to the right was selected, and it returned 75 Mbits.

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]

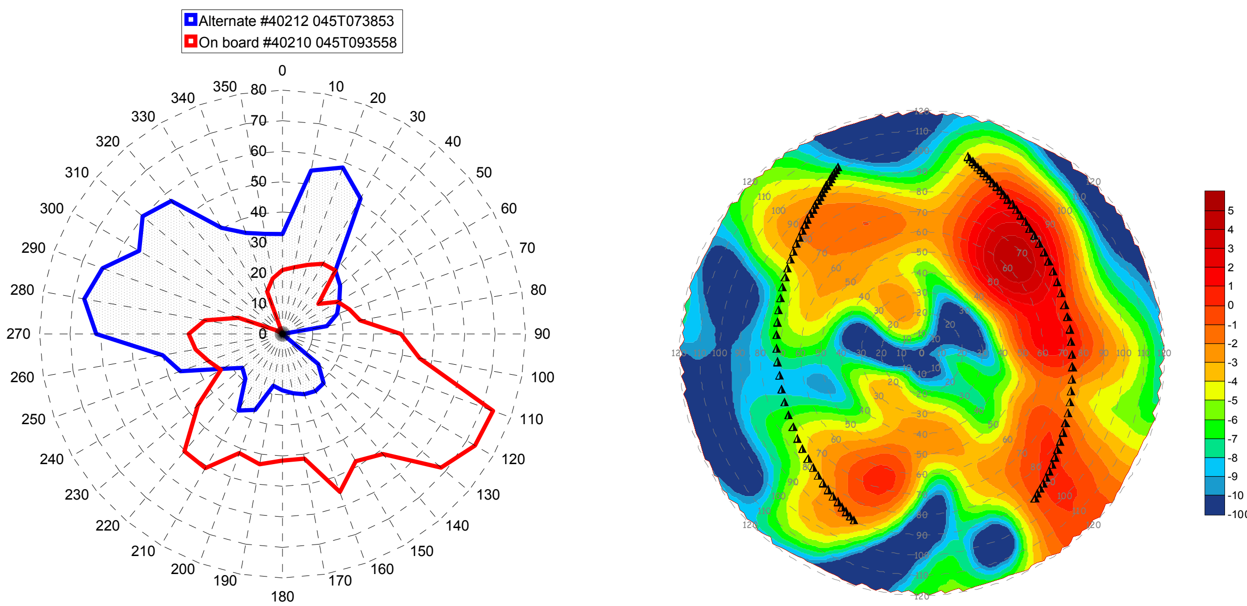

Figure 5-20. Example of tactical use of GTP/DVCF volume predictions.

[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 hrs 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.

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% of the total. Figure 5-21 (for Spirit) and Figure 5-22 (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.[31]

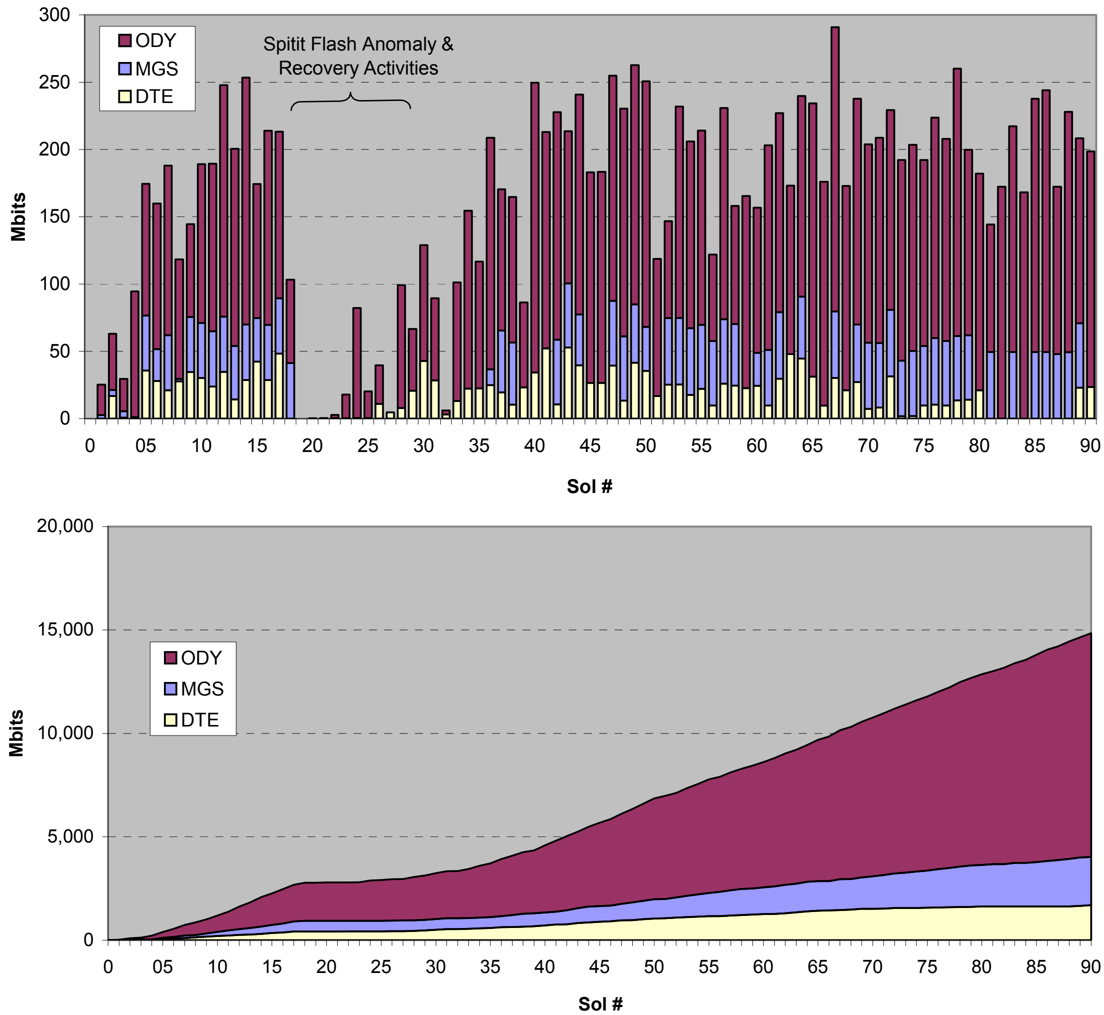

Figure 5-21. MER-A primary-mission data sources: volumes per sol (top) and accumulated (bottom).

[31] The conventions used in the top halves of these figures are also used in Figures 7-2 and 7-3, which show statistics on data returned from both rovers during the extended missions up to September 2005.

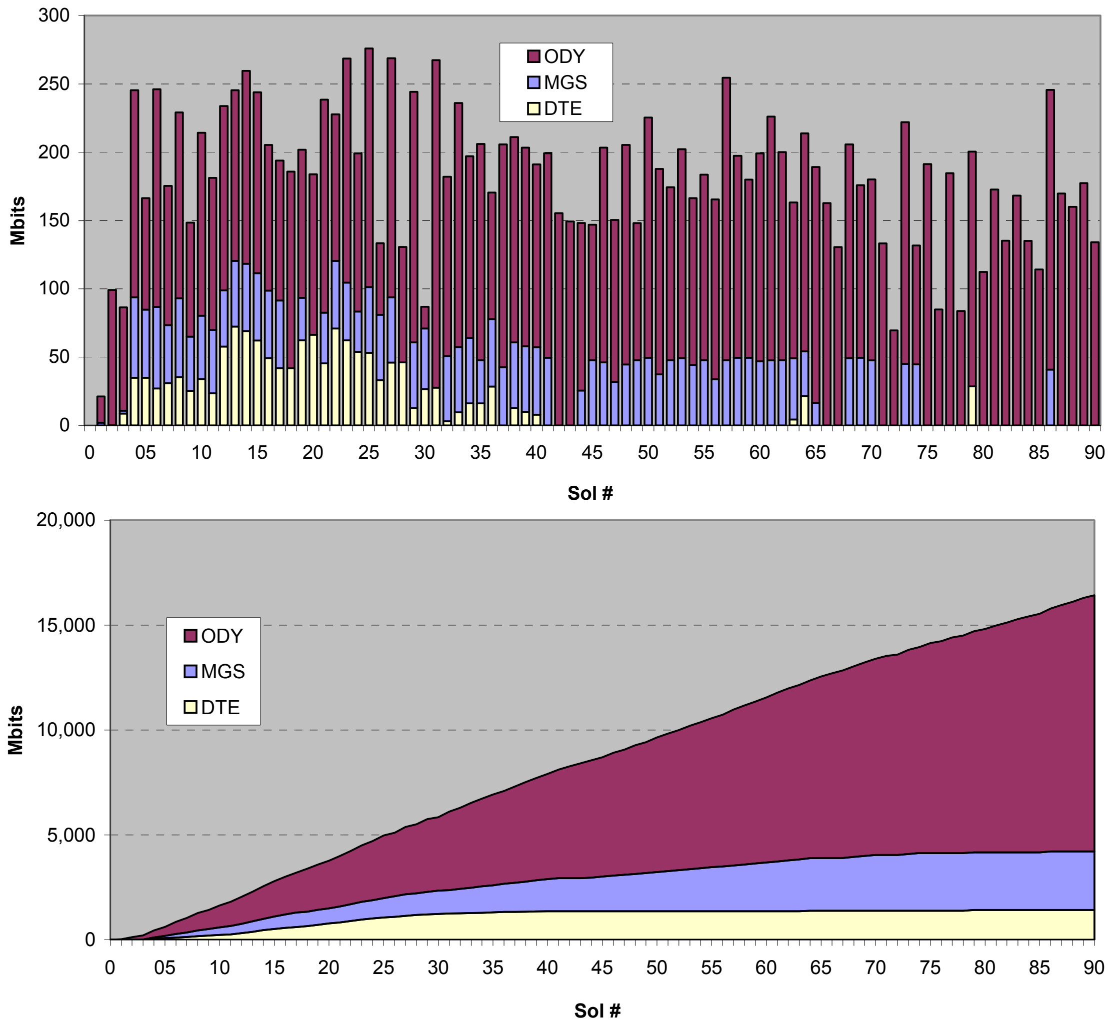

Figure 5-22. MER-B primary-mission data sources: volumes per sol (top) and accumulated (bottom).

During the first extended mission, the portion of total data returned via UHF increased to 95% and by October 2005 to 97%. 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.[32] 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.

[32] 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

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 multimission team of representatives from MER, Odyssey, and MGS.[33] 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 (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 Figure 5-12, it can be seen that if the rover were turned by 180°, the east pass would be on the high-gain region of the antenna pattern.

Odyssey uses the CCSDS Proximity-1 Space Link protocol (UHF1), 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% when the SNR in the link is high.

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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.

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

MGS, which was launched several years before Odyssey, implements the Mars Balloon Relay protocol (MBR or UHF2), 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.[34] 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 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 Mbits). 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.[35]

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), but once, MER also asked Odyssey to switch a few low-elevation passes from coherent to noncoherent. 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 have to 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.

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

[34] By the end of the initial extended mission (September 2004), all UHF passes were via Odyssey.

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

chances for success, recommendations were developed based on the results of the UHF forward-link verification activities. Recommendations include

- 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
- 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 has been 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.[36]

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 hrs 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 hrs 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, is being re-evaluated for 2006 to avoid X-band uplink interference with the Mars Reconnaissance Orbiter (MRO) mission at Mars. See Section 7.5.

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 Telecom). The data was

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[36] As detailed in Section 7.5, MER conducted UHF forward-link tests in September and October 2005 in preparation for a one-week UHF-only operational demonstration in late October 2005.

plotted using various Excel tools developed by MER Telecom. Generally, link volume predictions have compared well with actual data return (usually within 10-20%). 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, Figures 5-23 through 5-28 compare the performance of a high-volume and a low-volume UHF pass. In each case, 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 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. A third figure 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.

In the high-volume example (Figures 5-23, 5-24, and 5-25), 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.[37] The large dip in the return link just before 03:45 corresponds to the orbiter passing over the (dark blue) null in the pattern shown in Figure 5-25. This 256-kbps pass was predicted to return 83 Mbits, but the actual return was 125.5 Mbits. 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 dB better), allowing the return link to remain above threshold for a few extra minutes. This is shown in Figure 5-24.

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.

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[37] 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.

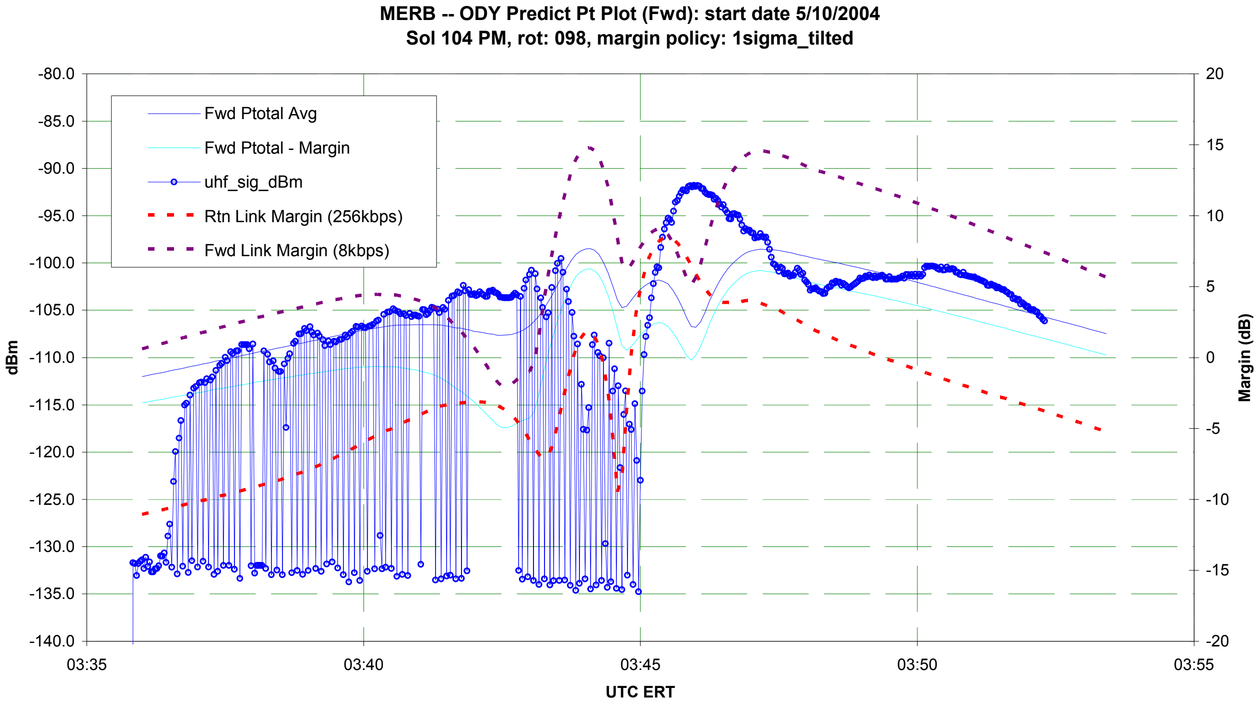

Figure 5-23. High-volume forward link—Odyssey to MER-B, sol 104 p.m. (5/10/2004).

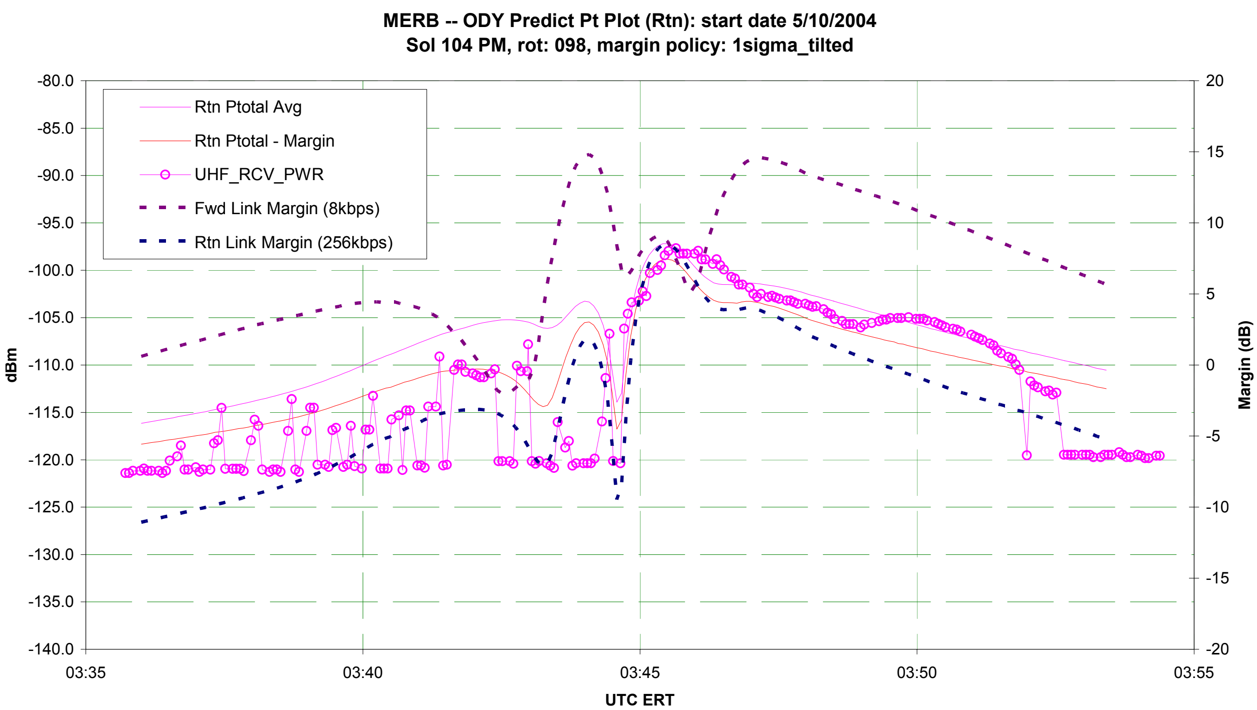

Figure 5-24. High-volume return link—Odyssey to MER-B, sol 104 p.m. (5/10/2004).

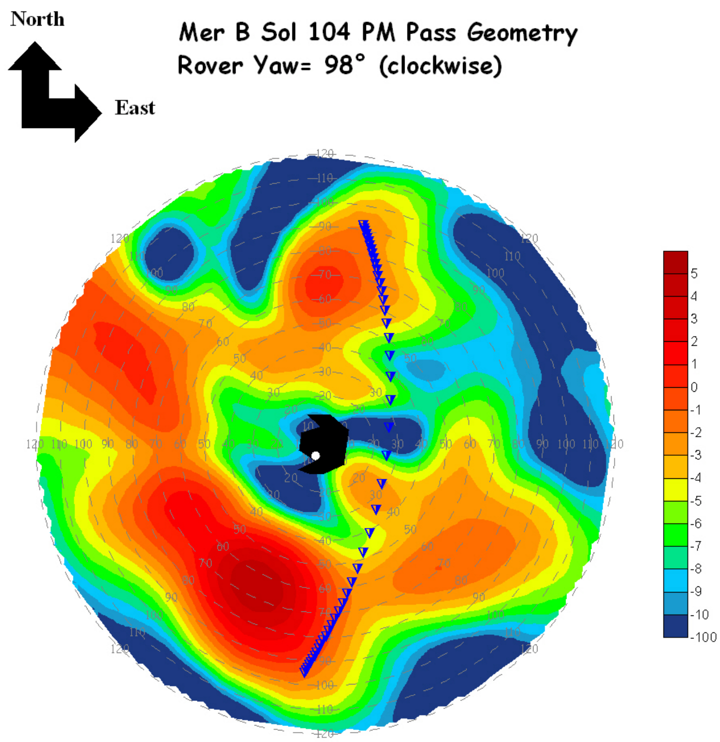

Figure 5-25. High-volume return-link geometry—Odyssey to MER-B, sol 104 p.m. (5/10/2004).

In the low-volume example (Figures 5-26, 5-27, and 5-28), 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 Figure 5-27, the link was expected to close and it did not. The predicted data volume for this 256-kbps pass was 80 Mbits, but the actual data return was 4.4 Mbits. When the link is analyzed, the performance is not too surprising despite the large discrepancy between predicted and actual data volume. Figure 5-28 shows the overflight geometry, with the predicted above-margin period highlighted. The geometry plot in Figure 5-28 shows that during the part of the pass highlighted in Figure 5-27, the overflight was in a steeper portion of the antenna-gain pattern. Because it's 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 Mbits 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.

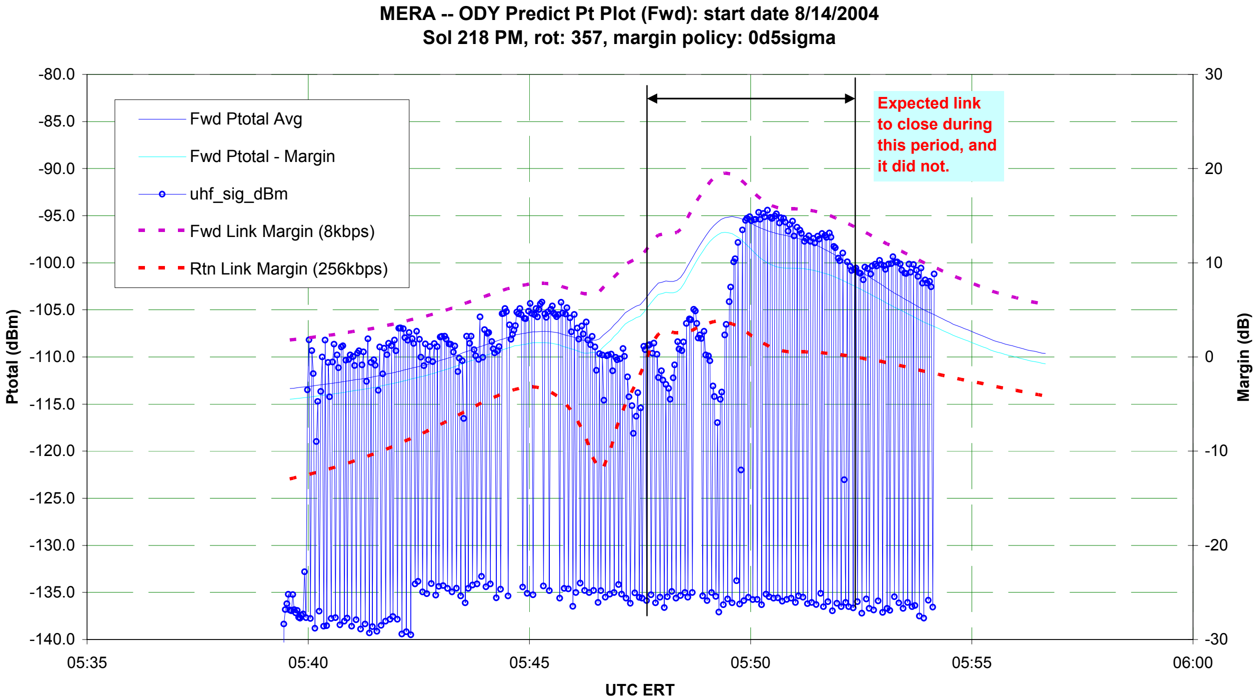

Figure 5-26. Low-volume forward link—Odyssey to MER-A, sol 218 p.m. (08/14/2004).

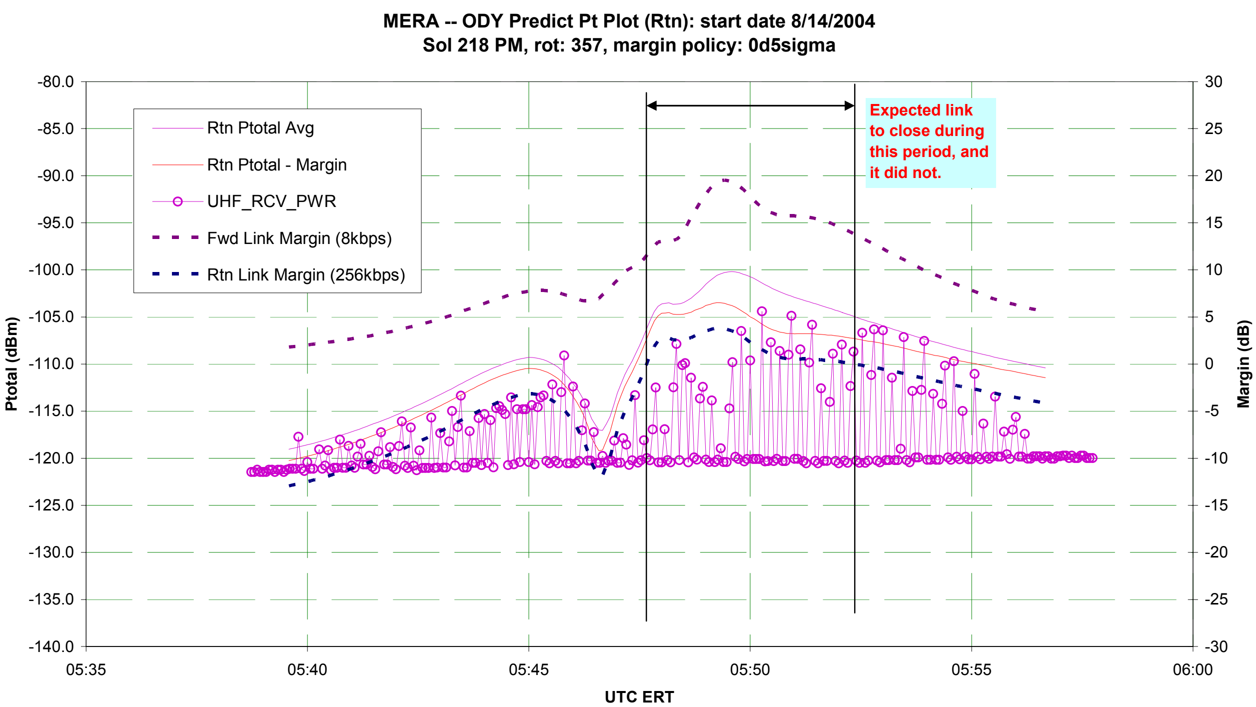

Figure 5-27. Low-volume return link—Odyssey to MER-A, sol 218 p.m. (08/14/2004).

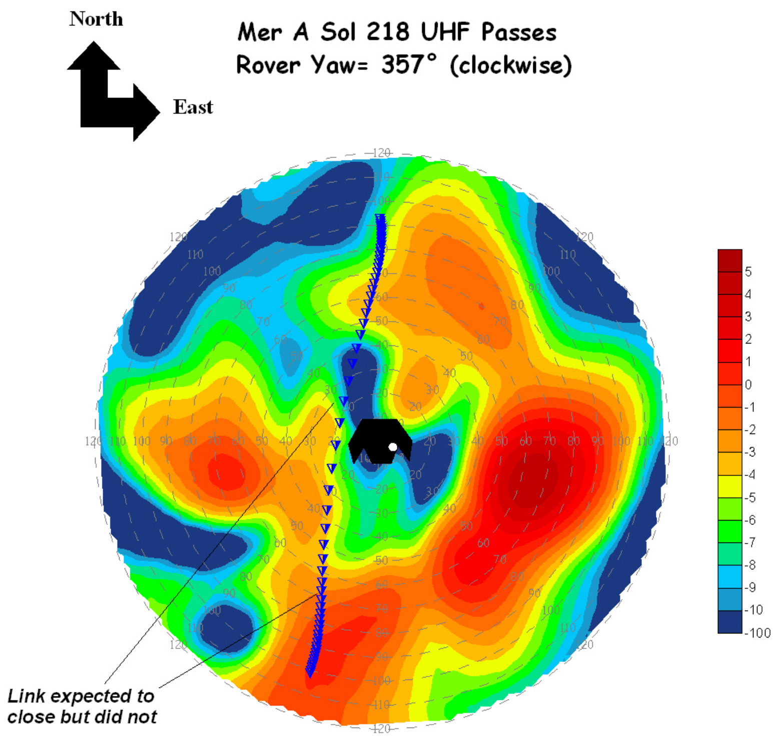

Figure 5-28. Low-volume return-link geometry—Odyssey to MER-A, sol 218 p.m.

Section 6

Lessons Learned

MER has been a fantastically successful mission, with both rovers reaching Mars' surface and embarking on explorations so far lasting more than 600 sols each, as compared to a full mission-success criterion of 90 sols each. In the telecom area, both the X-band and UHF systems 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.

6.1 What Could Serve as a Model for the Future

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. 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.

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 such development difficulties 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 differs enough from traditional telecom configuration sequencing 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. 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, like 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 (like 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 in other quantities (like SDST receiver sensitivity, SDST exciter RF output, or SSPA RF output due to aging). The telemetry plots in Section 7.8 show that any such trends during surface operations have been very small and likely the result of temperature changes. As the mission continues, it would be useful to confirm such conclusions.

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.

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 telecom 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 [DN] or engineering units [EU] 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 predicts. 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). Some work on scripts to do this began in July 2004. See Section 7.9 for a description of the Telecom scripts being used as of September 2005.

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.

6.1.3 X-Band EDL

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.

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). Telecom 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 MER's 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 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, Telecom 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 5.1.5 above) and the timing constraints imposed by HGA "flop" (described in Section 6.2.1, below).

Lesson: Consider telecom 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 don't 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. Telecom could reliably predict uplink and downlink performance and operate 80° from the RLGA boresight (10° 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 telecom planning for other missions where it may occur.

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's error-free data

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

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's 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.

6.2 What Could Be Improved

6.2.1 X-Band Development

FSW simulator. Because there was no Avionics simulator before the start of ATLO, the debugging of Telecom-related problems 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 an 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 5.1.4). The 3:1 ratio between 120 and 40 bps meant 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 don't 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 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 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 Figure 3-1, 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 didn't need higher downlink or uplink rates, with antenna characterization it could elect to conduct operations with smaller and less costly ground stations.

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 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 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 (see Section 7.9.9).

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 Telecom 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.

6.2.3 X-Band Surface Operations

Link margin criteria. Standard criteria were developed and used to set telecom 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° 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%, 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° and 4° 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. Windows now sometimes use 2 min.

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° 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 [17]). 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 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. See also Section 7.5.3.

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 last for only 90 sols, few anticipated that the rovers would still be operating strong almost two years after EDL. Meanwhile, MRO, which will arrive at Mars in March 2006, had been allocated channel 32 for its SDSTs, the same channel as MER-A (Spirit).[38]

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. A plan incorporating these recommendations is based on the assumption that both rovers will 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 expects 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 also published the following lessons:

- Bandwidth is a program consumable (especially at Mars and the Moon).

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[38] The rover longevity also required a look at another possible interference case. The Deep Impact (DI) project used SDSTs operating on channel 29, the same as Opportunity. The DI primary mission was from January 2005 through August 2005, overlapping a portion of Opportunity's surface mission. As of September 2005, an extended mission for DI that would continue through 2009 was under NASA consideration. However, the DI trajectory and Mars orbit (2005–2009) would obviate any uplink or downlink interference between DI and Opportunity.

- 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
  - 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 recently developed Electra UHF transceiver on board MRO.

Solar conjunction. See also Section 7.6 and ISA Z84599 [8]. 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 1°. From previous similar uplink work 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.

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.

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.

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 to 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° 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 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.

Section 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). This section describes the MER Telecom performance for the first full year since that extended mission (through September 2005). This period of the mission represents the majority of surface operating time for each of the rovers. As of September 30, MER-A (Spirit) was in sol 619, and MER-B (Opportunity) in sol 599.

In September 2004, OWLT to Mars was 22 min. Mars has been gradually getting closer, and now OWLT is less than 5 min. Figure 7-1 shows the seasons on Mars during the rover missions and the variation in the communications range between Earth and Mars (expressed in AU).

With primary surface missions for which full mission success was achieved at 90 sols, the rovers are approaching one full Martian year of operation, 670 sols. The anniversaries are November 20, 2005 for Spirit and December 12, 2005 for Opportunity.

7.1 Uplink Data Rates

September 29, 2004 marked the beginning of the extended-extended mission. The rovers were just beginning Martian winter and it was unknown whether they would survive until spring, over 160 sols (about six Earth months) away. Mars was also further away from Earth than it had ever been during the mission, with the OWLT being around 22 min. By this time, the spacecraft was being commanded on the HGA at 500 bps, and the background data rate (default data rate at which commands could be sent to the LGA) was 15.625 bps. It should be noted that because of the low data rate, commanding on the LGA cannot be too elaborate. LGA commanding has been reserved for short instructions such as opening up a high-priority comm window so that the rover can be commanded on the HGA at a time not previously scheduled in the comm windows or for resetting the uploss timer so that the rover doesn’t time out and go into fault mode.

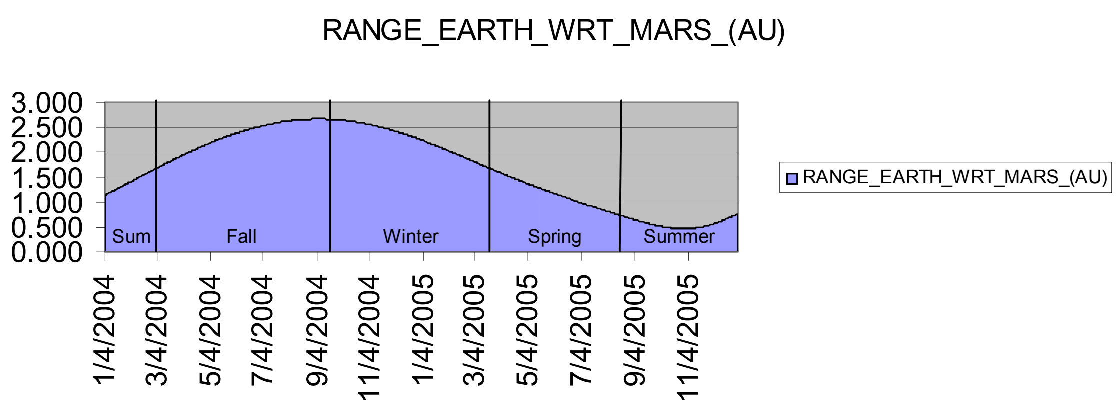


Figure 7-1. Mars-Earth distance for primary and extended surface missions.

In February 2005 when the OWLT was 15.5 min, on its way down again, mission planners began building HGA comm windows for 1000 bps when predicts indicated that this rate was not only supportable but had extra margin for those times when the HGA might be occluded by the PMA. In the middle of February 2005, each of the rovers had a FSW load for which the 2000-bps data rate was used.[39] Special care had to be taken by the planners that the HGA not be occluded during these uploads. Both loads were successful. At the same time, the background data rate for the LGA was increased from 15.625 to 31.25 bps. This higher data rate had not been used since shortly after landing.

7.2 Downlink Data Rates

The downlink data-rate capability of the X-band radio has also been steadily increasing since September of 2004 as Mars has come closer to Earth (Figure 7-1). In September 2004, DTEs were supportable at either 504 or 700 bps with 34-m stations, and at either 4200 or 4424 bps with 70-m stations. These supportable data rates were determined by running TFP. The predictions were found to be accurate by comparing expected power at a given data rate with the actual signal levels queried from the station data. At these data rates, a DTE, which is always scheduled on the HGA and typically has a duration of 30 min, would yield 1 Mbit or less on a 34-m station and between 6 and 7 Mbits on a 70-m station. DTEs had been seldom scheduled during the winter because the rover had to conserve power.

As of September 2005, Mars was closer than it had ever been during the surface mission and will continue getting closer until November 2005. The OWLT was about 4.5 min, and the rovers had just begun experiencing Martian summer a few weeks previously. The highest possible DTE data rate of 28,440 bps was used for the first time during the mission on Spirit sol 521 (June 21, 2005) on a 70-m station when OWLT was 8 min, 49 s. There have since been many successful DTEs on 70-m stations at this data rate, and they are currently providing approximately 6 to 8 dB of margin above threshold. A DTE at 28440 bps lasting 30 min will yield approximately 44.5 Mbits. DTEs are usually scheduled every time a rover is assigned a 70-m station, and the DSN schedulers have agreed to try to schedule a 70-m station for each rover at least once a week. The current supportable data rate for a 34-m station is ~14,220 bps.

7.3 Martian Winter

7.3.1 DTEs

During the Martian winter that was at its peak in September 2004, DTEs were seldom scheduled because of severe rover power constraints. The only time that DTEs were scheduled

[39] In the extended-extended mission, except for FSW uploads, the highest uplink rate is usually 1000 bps, even when the X-band link itself could support 2000 bps with ample margin. Mission planners on both rovers have concerns that sending uplink command bundles at 2000 bps could overload the avionics subsystem if the rover were doing anything else. The CPU is just barely able to keep up with the 2000-bps data rate. If another system, such as the Miniature Thermal Emission Spectrometer (Mini-TES), were also vying for CPU time during the processing of the commands, command codeblocks could be lost. This has never happened during the mission, but the mission planners want to be cautious, especially since uploading the next sol's command bundles at 1000 bps is usually sufficient.

was to do a "make-time packet" to enable the rover planners to ascertain the exact rover time, which tends to drift.

Martian winter, of course, also meant that the Telecom subsystems would be operating at significantly lower temperatures than planned for during the primary mission. With the SDST VCO temperature consistently below –30°C shortly after morning wake-up, it was necessary to use an FRO for reliable uplink acquisition (see Section 5.1.8). It was decided to begin scheduling uploads later in the day when the SDST would be warmer.

7.3.2 UHF Passes

Along with there being only a few DTEs during the Martian winter, many UHF passes were also cancelled. During times when the rover battery power was low, all telemetry transmission except for the afternoon Odyssey pass was cancelled.

It was at about this time that mission planners decided to stop using MGS as a relay. The last MGS pass occurred on sol 137 (May 22, 2004) for Spirit and sol 171 (July 17, 2004) for Opportunity.

There were several reasons for discontinuing the use of MGS passes. MGS has an overflight (potential pass) over each rover twice a day, once in the morning and once in the afternoon. The morning pass usually occurs between 2 and 3 a.m. LST. Because of an IDD heater problem that caused a low but constant drain on the battery, Opportunity needed to operate in a new mode, called "deep sleep." The deep sleep stopped the battery drain but precluded Opportunity from waking up for the morning MGS comm pass. Spirit also had significant power constraints during the winter, so most of its morning passes (both Odyssey and MGS) were cancelled.

The mission planners found that the afternoon MGS passes were inconveniently timed for relay passes. Drives and imaging activities could not be scheduled during a UHF Telecom pass because electromagnetic interference testing before launch indicated that these activities would sometimes interfere with the UHF receiver.

Also playing into the project's decision to cancel MGS passes was a large latency period that often occurred from the time when MGS received the rover transmission until the orbiter was able to relay the data to the MGS ground system, and the MGS ground system was able to process the data and send it to MER. This latency period was frequently 24 hours or more. Since planners need critical data for the next sol's planning, it was found that MGS was most useful for clearing out low-priority data.

The MGS protocol caused for there to be many gaps in the data. The maximum amount of rover data that MGS is able to receive is 60 Mbits. (See Section 5.2.4 for MGS protocol and data volume.) Before many of the data-management functions were automated, it had been a very laborious task to identify lost data and create commands to have the rover resend the lost data. Consequently, retransmits were usually done via Odyssey (ODY).

In January 2005, MGS went into "beta supplement mode," which consisted of an attitude adjustment to keep the spacecraft's Sun sensor out of its HGA shadow. MGS will be in this mode until November 2005. This attitude would make it necessary for MGS to do a maneuver each time to support a rover pass.

The MER mission planners are currently considering the scheduling of an occasional MGS pass. The purpose of these passes, which would occur about every 6 months, would be to verify that the MGS relay capability still exists.

7.4 Amount of Data Returned from UHF Relay vs. DTE

The charts in Section 5.2.3 show the primary-mission data volume returned from each rover per sol and cumulatively. Figures 7-2, and 7-3 extend the per-sol data return through the extended missions through September 2005. Figure 7-4 shows the cumulative data-return summary for each rover through September 2005.

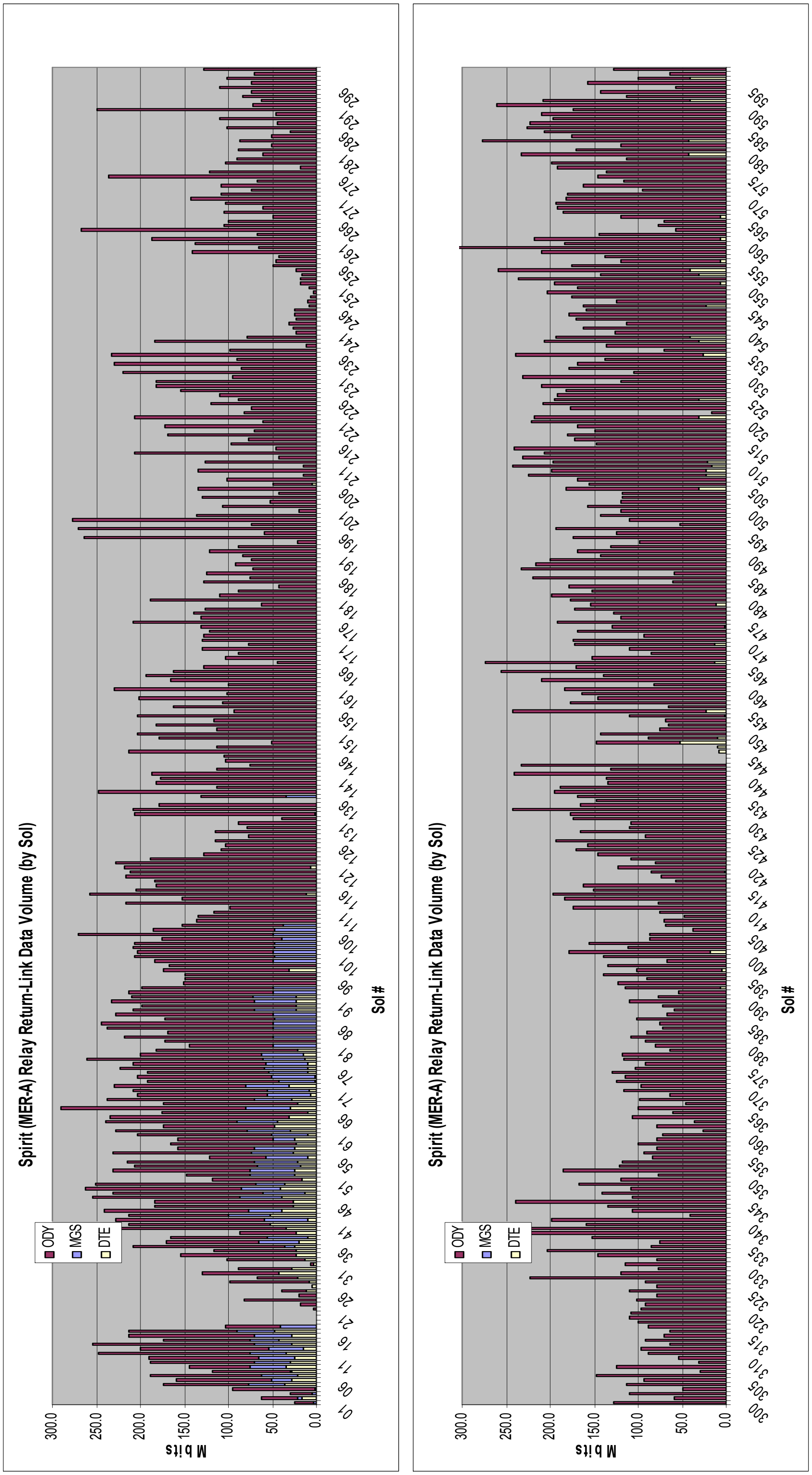


Figure 7-2. Data returned per sol from Spirit.

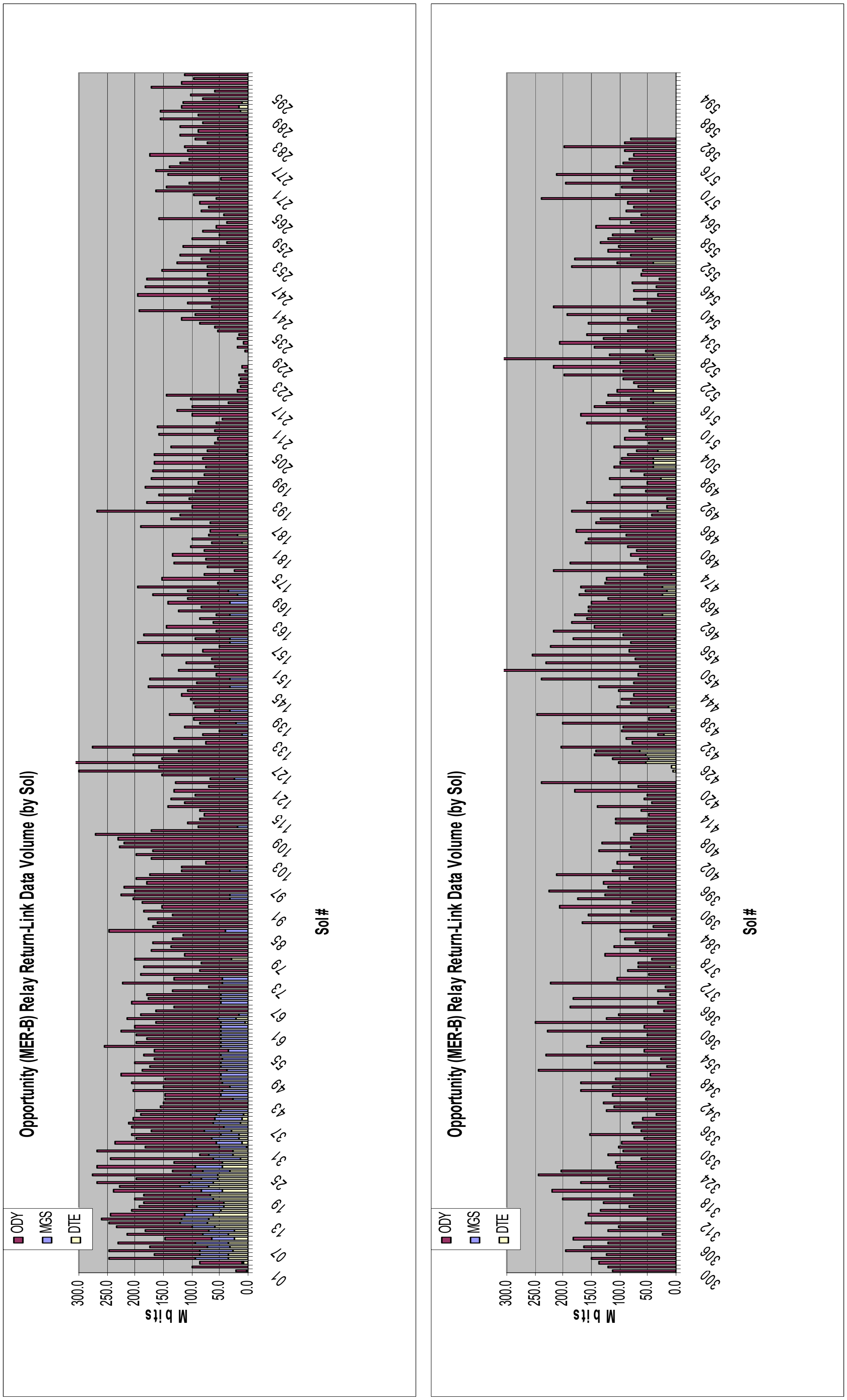
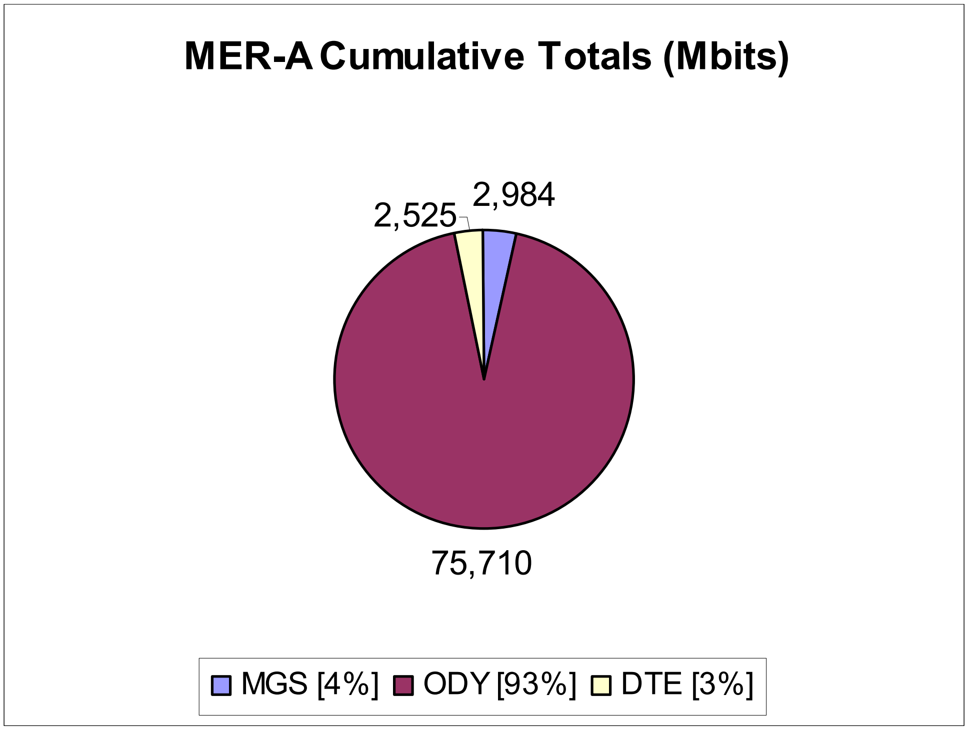


Figure 7-3. Data returned per sol from Opportunity.



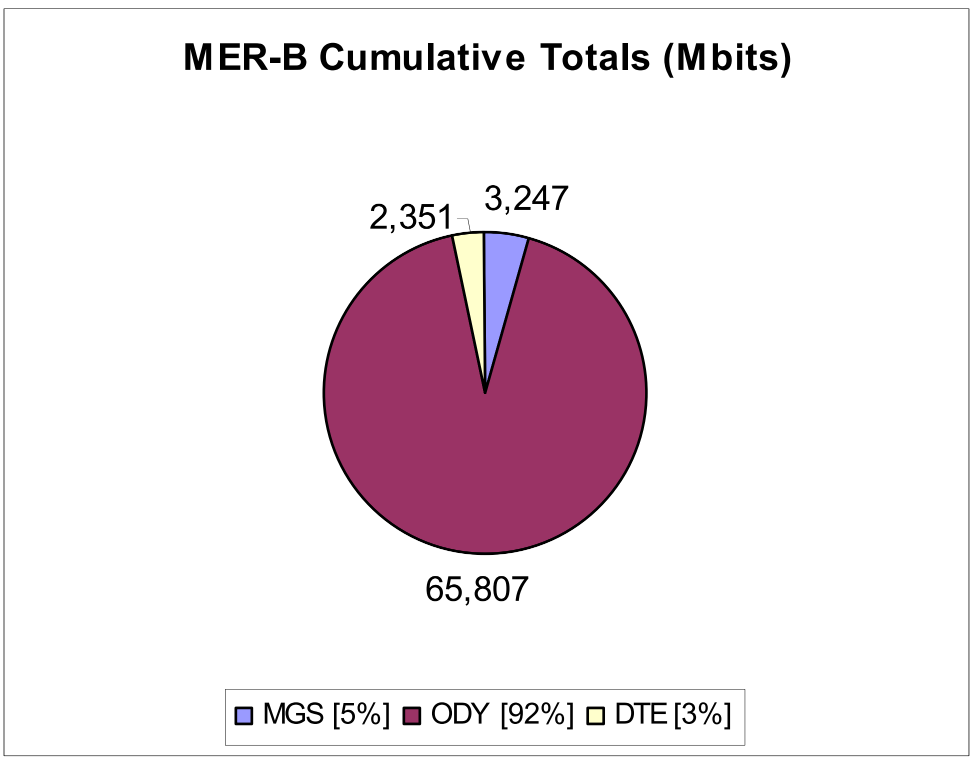


Figure 7-4. Spirit (top) and Opportunity (bottom) data volume via MGS, ODY, and DTE.

7.5 Constraints on MER Telecom Operations from Other Mars Projects

The previous section leaves no doubt that the UHF relay link returned an overwhelming fraction of the total data. In this light, three kinds of interproject factors became apparent during the extended missions. Two of these (Odyssey safe mode and the lack of a contingency Odyssey relay data-management capability) affected data to be returned via the relay link. The third (Spirit and MRO SDSTs on the same DSN channel) affects how each project operates its X-band links and may result in MER becoming a relay-only mission for some period in the future.

7.5.1 Odyssey Safe Mode

Odyssey went into safe mode on April 2, 2005. An e-mail from that project informed MER: “This is to notify the UHF Tactical group that Odyssey is currently in safe mode. No relay data will be available for the time being. Details are sparse right now.” Odyssey recovered to standard UHF operations by April 7.

Meanwhile, the MER project decided not to revert to using MGS as a relay vehicle because of the complexity of rebuilding sequences and because MGS presents another complicating factor in data return. For one second out of every 16, the Mars Relay Basic Telemetry Time Sequence (BTTS) protocol causes a data dropout.

The project elected to use X-band DTEs to return some data during the Odyssey outage. The plan was to convert the morning 20-min DFE to a 90-min DTE with the same start time. On a 34-m station, a 90-min DTE would provide a total of about 12.7 Mbits of data, including about 7 Mbits of critical engineering data to come down on each DTE first. This was much less than the tens of megabits of science routinely returned via UHF. The reduced data return can be seen around sol 446 in Figure 7-2 for Spirit and around sol 426 in Figure 7-3 for Opportunity.

7.5.2 No Relay Data Management Contingency Provisions on Odyssey Spacecraft

The transmission of data from each MER to the Odyssey spacecraft is part of each sol’s plan as implemented in the master sequence. However, if Odyssey or the DSN fail to get the data back to Earth, MER has no recourse for data recovery other than to first retransmit the data to Odyssey. That’s because once Odyssey radiates the MER data files, they are no longer kept on board Odyssey. On September 14, 2005, one relay pass from each rover was not received by the project. The DSN reported an Odyssey telemetry outage from rodent infestation in DSN fiber optical cables (refer to DSN DR G106060 [19]). In each case of this kind, when planning the next sol, the MER project takes into account the relative value of the lost old data and the new data in deciding whether to retransmit the lost data from the rover.

7.5.3 Spirit and MRO on the Same SDST Channel

MRO was successfully launched on August 12, 2005. By March 2006, as MRO nears Mars, the project and DSN plans must include the potential of MRO and MER-A being active in the station antenna beamwidth at the same time, both using the same frequency channel. The

MER Spirit SDST and both MRO SDSTs all operate on channel 32 for uplink and downlink. The MER Opportunity SDST is on channel 29, four MHz away.

A team representing the DSN, the JPL Telecommunications organization, and the MER and MRO projects presented the technical and contending operational factors to the Mars Program Office in May 2005. MRO plans to enter its critical aerobraking campaign shortly after arrival at Mars. With MER in an extended mission, and MRO early in its primary mission, MRO would be given priority. The MER project began considering UHF-only operation on both uplink and downlink to replace X-band for command uploads and rover data return.[40] Commanding MER via Odyssey UHF is operationally more complex because of the forward-link latency time, from a few hours to days, plus the frame-duplication idiosyncrasy.

In mid-2005, the typical MER X-band usage was as follows:

- Daily (per rover):
  - X-band commanding once a day for less than 2 hrs (at 1000 or 2000 bps).
  - X-band beep (carrier-only downlink) from LGA for 5 min within the 2 hrs shown above (coherent mode, requires an X-band uplink) to confirm uplink software load
- Weekly (at least once per week per rover):
  - X-band downlink data from HGA for about 20 to 30 min (for spacecraft time correlation and data return)

In January 2006, the Mars Program Office will evaluate the results of the MER UHF commanding tests and the MRO status and plans. The January 2006 decisions may involve some of the following technical means available to alleviate uplink and downlink contentions, in addition to having MER not operate on X-band during MRO critical periods.

7.5.3.1 Uplink

- Different Doppler profiles could provide some discrimination.
- LH polarization for MER RLGA[41] and RH polarization for MRO could provide some isolation.
- DSN uplink power could be turned down so that only MRO locks up.

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[40] The first UHF command tests of both rovers via Odyssey at 2 kbps were successful in February 2004 during the primary mission; however, these tests had been limited to a few commands. In preparation for the potential UHF-only mission in 2006, a complete test command upload simulating a one-sol plan was sent from the DSN to Odyssey, and then via UHF to Spirit on sol 605 (September 15, 2005). The commands included a set uploss timer, one real-time delete, and 42 sequences spread over three files. The test was successful. A second test the same week contained multiple sequences that simulated a more complicated three-sol planning day. The team sent old sequences and confirmed that the commands made it on board the rover; then the team deleted the files. As a final verification of the ability to conduct surface activities using UHF command only, Spirit will conduct a week-long UHF operational readiness test (with beeps and the sequences also sent on X-band for backup) in late October 2005.

[41] Refer to the Telecom subsystem functional diagram (Figure 3-1). The RLGA is normally RH. To make it LH, set the WTS in position 2, CXS1 in position 1, and CXS2 in position 1. This puts the RF signal in the LH port of the polarizer labeled P1. The polarizer is shown at the base of the waveguide section going to the RLGA.

- MRO and MER SDSTs could be set at different command data rates.
- When set to the same command rates, the unique spacecraft IDs should protect each from receiving wrong commands.

7.5.3.2 Downlink

- MER can operate when MRO is behind Mars, but the available times are short: ~40 min.
- When MER and MRO are in view simultaneously and MER requires an X-band downlink, MRO could
  - Turn its transmitter to standby,
  - Off-point the HGA,
  - Switch to LGA,
  - Lower its data rate so as to not interfere with MER's mode of operation,
  - Switch to the ultrastable oscillator to raise the center frequency by 110 kHz,
  - Set subcarrier frequency different from MER's,
  - Use a Ka-band downlink.

7.6 Solar Conjunction

Solar conjunction occurred late in the first extended mission. The Sun-Earth-probe (SEP) angle[42] was less than 3° from September 7 to September 24, 2004 (DOY 251–268). Solar conjunction occurs when the Sun is between the rover and the Earth, so it directly affected only the X-band links.[43] The SEP angle was at its smallest on September 15, 2004 (sol 250 for Spirit and sol 229 for Opportunity), about 0.96°. Figure 7-5 is a plot of the SEP angle (upper curve) and Sun-probe-Earth angle (SPE, lower curve). This plot is for Spirit with the date axis in sols.

At Mars distance, the Sun-station-rover angle is essentially the same as the SEP angle and applies to the rover that is in view of the Earth at the time.

Because the Sun obscures the communication path during solar conjunction, it is known that communications between Earth and Mars are unreliable. The effect on uplink and downlink communications has a good theoretical basis [20], but the actual magnitude of the effect is highly variable from day to day and even from moment to moment as the activity of the sun changes. Operational prediction of command or telemetry capability from day to day is not yet possible. Instead, projects apply broad constraints, called moratoriums. For example, MER did not expect to depend on telemetry within a 3° SEP angle and did not intend to command within 2°.

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[42] The SEP angle is the usual reference angle for solar conjunction analysis because it represents the angular separation of the center of the Sun and the spacecraft as seen from the center of the Earth.

[43] The rover-Odyssey UHF links have a different geometry with respect to the Sun. However, Odyssey's X-band links are degraded by solar effects just as the rover's X-band links are.

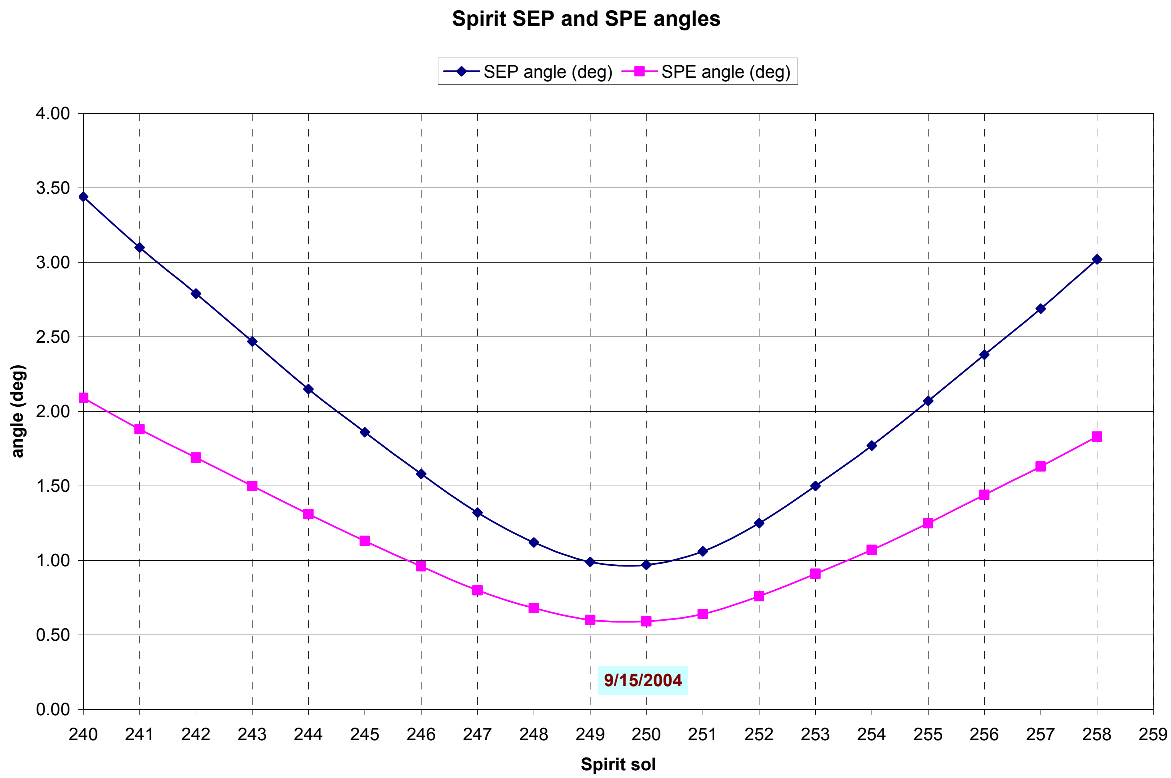

Figure 7-5. Spirit Sun-Earth-probe angle (top) and Sun-probe-Earth angle (bottom).

The MER Telecom team began noticing the solar effect in the narrowband AGC (nb_agc) telemetry on the DFE uplink starting on Spirit sol 240 (September 5, when the SEP angle was 3.44° and the SPE angle was 2.09°). Then, after one unaffected sol, during the command upload, the Spirit FSW telemetry data on sol 242 showed numerous corrected frames (71), uncorrected frames (44), and invalid frame counts (58).

The SDST telemeters two measures of uplink signal level for weak signals: nb_agc and cla_snr. The nb_agc does the better job of picking up solar scintillation effects because its integration time of 1 s is shorter than that of the cla_snr, which is 3 s. Absent solar effects, nb_agc and cla_snr track each other closely. If they do not, it can be a strong indication that solar effects are present. Figure 7-6 shows the significant solar effects on the uplink performance for Spirit on sol 242, while Figure 7-7, at nearly the same time, shows little solar effect on the downlink performance in terms of the station system noise temperature (SNT).[44] On sol 242, the nb_agc varied as much as 10 dB from peak to peak on the HGA around 18:15 UTC, while the cla_snr varied about 3 dB from peak to peak. (The variation from 17:30 to 17:50 was due to command modulation switching on and off during the regular command load.)

[44] The lack of apparent downlink degradation for this pass is not surprising. Solar-caused phase and amplitude disturbances on the modulated carrier affect the available telemetry (uplink indications) and station monitor and radiometric data (downlink indications) differently. The most sensitive downlink quantities would be two-way Doppler residuals and telemetry SNR, neither of which are available when the only downlink is a beep. The station SNT generally shows increases and variations only when sidelobes intersect the Sun as the main beam tracks the spacecraft. X-band sidelobe magnitudes become increasingly significant as the SEP angle goes below 1°.

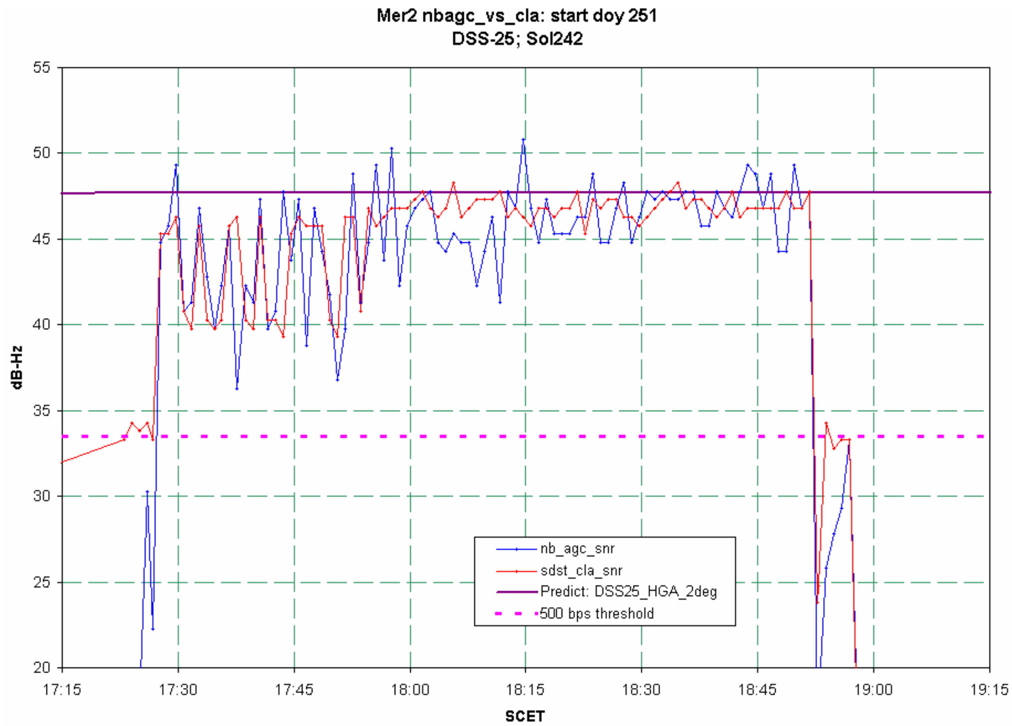

Figure 7-6. Spirit sol 242 uplink signal level (narrow-band AGC and CLA).

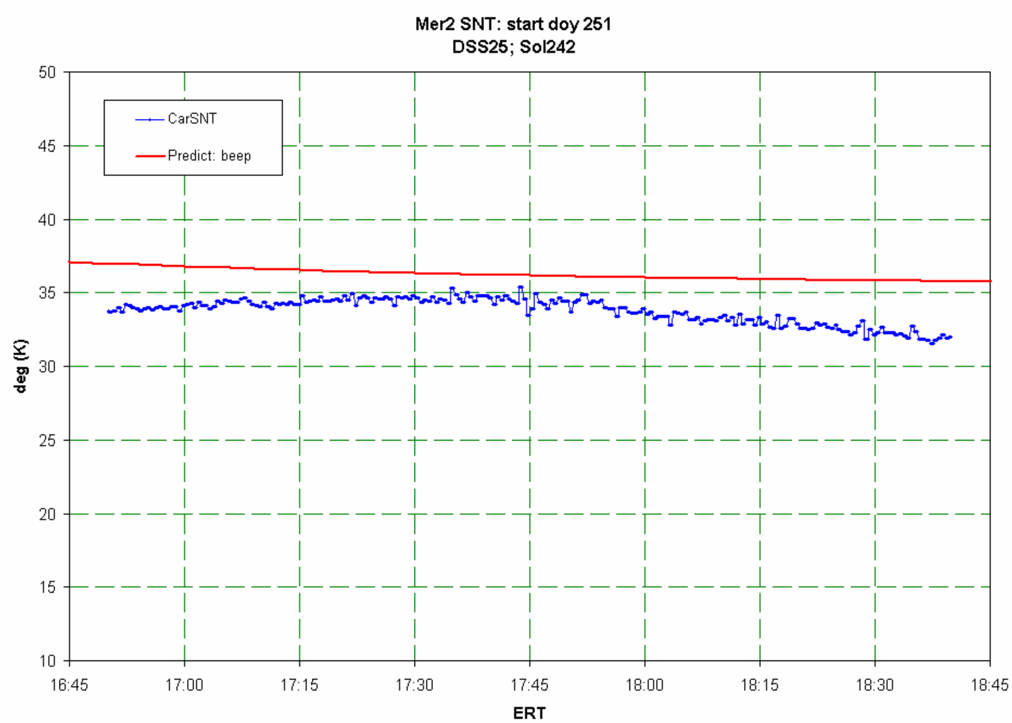

Figure 7-7. Spirit sol 242 DSS-26 station system noise temperature.

To gain additional data for use by the projects and Telecom analysts on future X-band missions that may need to operate actively at low SEP angles during their solar conjunctions, MER agreed to a series of uplink tests. For each sol's test on each rover, sets of no_op commands were radiated and the percentages of successfully received commands were charted as a function of time, and as a function of SEP angles. This MER commanding experiment request had been evaluated, coordinated, and approved by the project in a manner similar to that used for other requests for science or engineering activities in the extended missions.

Figures 7-8, 7-9, and 7-10 show the results of commanding to both rovers in terms of the fraction of transmitted no_op commands successfully received as a function of SEP angle. Except for two Opportunity outliers (on September 12 and 14), this experiment quantified the not-surprising conclusion that the smaller the SEP angle becomes, the less likely it is that commands will be received by the FSW. It also quantitatively confirmed that the experience-based 2° SEP command moratorium for X-band that is used by most projects is reasonable.

Spirit Uplink Test

Date	SEP (deg)	% of success
9/9/04 Th	2.15	89.2
9/10/04 F	1.86	n/a
9/11/04 Sa	1.58	90.1
9/12/04 Su	1.32	87.4
9/13/04 M	1.12	92.0
9/14/04 Tu	0.99	59.7

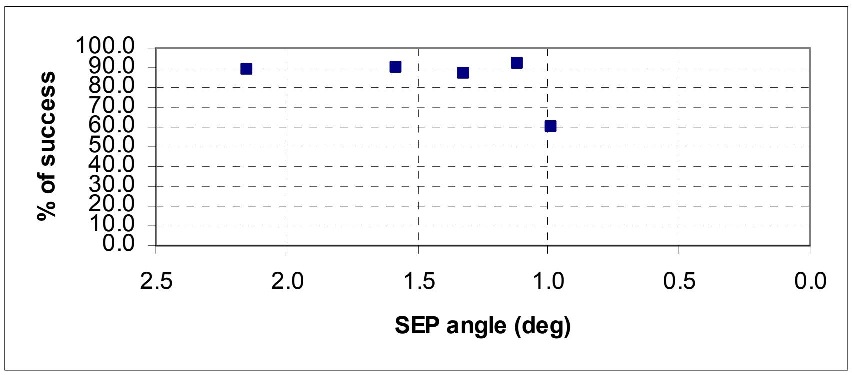

Figure 7-8. Spirit no_op conjunction testing results, success vs. SEP angle.

Opportunity Uplink Test

Date	SEP (deg)	% of success
9/10/04 F	2.01	98.6
9/11/04 Sa	1.71	86.5
9/12/04 Su	1.44	0.0
9/13/04 M	1.21	26.1
9/14/04 Tu	1.04	0.0
9/15/04 W	0.96	0.8

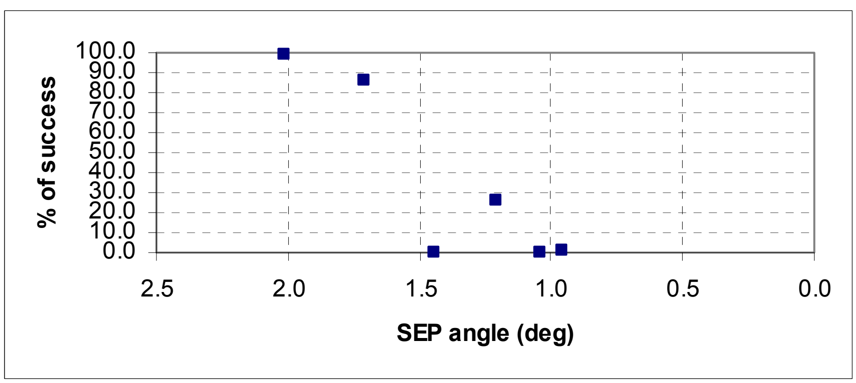

Figure 7-9. Opportunity no_op conjunction testing results, success vs. SEP angle.

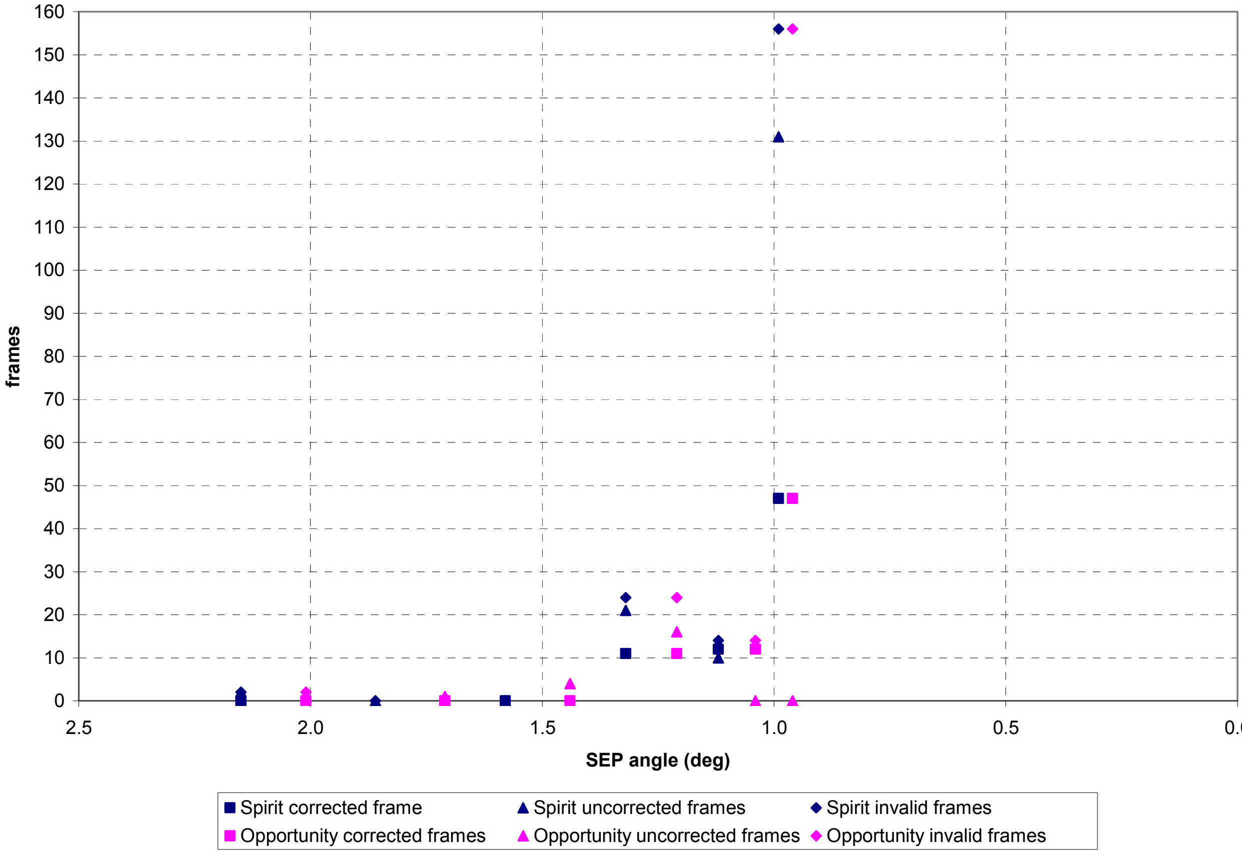

Figure 7-10. Error statistics of no_op commands improperly decoded as a function of SEP.

On Opportunity sol 229, when the SEP angle was at its minimum of 0.96°, Opportunity's FSW experienced a fatal error. The project immediately suspended the commanding experiment on both rovers.

The following symptom evaluation is paraphrased from ISA Z84599 [8]. The sol 229 telemetry via Odyssey (with good quality on the rover-orbiter link and on Odyssey's X-band) included one of the two EXC_INFO EVRs that accompany a "fatal." Though the telemetry didn't actually include the fatal EVR, it was clear the system had fataled and rebooted. Telemetry included an EVR for a sequence counter reset. The EXC_INFO indicated that the fatal occurred when FSW was in a task-context-switch from the task of processing uplink. Because these EVRs came down in the following Odyssey pass, by that time the FSW was up and healthy. However, the FSW was no longer running a master sequence.

Analysis of the symptoms showed a weakness in the HCD's interaction with the FSW. While the HCD corrects a single-bit error and flags double-bit errors, in the case where three or more bit errors exist in a received code block, the HCD may falsely interpret it as a single-bit error (or no bit errors), then wrongly "correct" it, and continue to hand off the corrupted code block to FSW for processing.

The analysis also showed that if the corruption to the code block turns a VC-1 command to a VC-0 command, and if the bit pattern is just right, it would be possible to initiate an unintended hardware command. Thus, at the small SEP angle still existing, the project was reluctant to send commands to restart the master sequence due to the possibility of causing the rover to do damage to itself. Other projects that might use similar FSW or a derivative thereof were contacted and informed of the bug. These included Odyssey, MRO, Stardust, Genesis, Phoenix, and the Spitzer Space Telescope. All responded that their code had been updated after MER's and did not contain the bug.

7.7 PMA Occlusion to Spirit's LGA in July–August 2005

Occlusion (partial or complete blockage) of the signal path to and from the X-band antenna (HGA or RLGA) by the PMA occurs at certain theoretically predictable orientations of the rover relative to Earth. Usually, however, the Flight Team Telecom analyst first sees an otherwise unexplainable variation in the uplink signal level in telemetry or in the downlink signal level in station monitor data. Consultation with the ACS analyst then determines whether the geometry had placed the antenna behind the PMA to cause the observed uplink or downlink degradation.

After a long period of occlusion-free operation after the primary mission, Spirit entered a period of PMA occlusion beginning on sol 557 (July 28, 2005). On that day, at a rover yaw angle of 76°, the received signal level from the RLGA was 7 dB below predicts during the acquisition sweep and subsequently fell 4 dB below predicted for a short period after the completion of the sol's command upload. On the next two sols (558 and 559), the RLGA uplink was 6 dB below predicts during acquisition and had dips of 7 dB and 8 dB at similar yaw angles.

For science operations, the rover was turned to a yaw of 88° during sol 562. By sol 564, at a yaw of 89°, the station acquisition sweep to the RLGA failed. Figure 7-11 shows the signal level variation on sol 664. The initial sweep is at the left, the HGA is the period of strong performance just left of center, and the remaining RLGA pass is from center to the right. Figure 7-12 is a representation of the occlusion in sol 564 as modeled by ACS using the TBall attitude visualization software model. In the figure, Earth is at the center of the bull's-eye partially obscured by the base of the white Pancam mast.

On sols 565 through 573, the acquisition sweep was made to the HGA to avoid PMA occlusion of the RLGA at yaw angles in the 84–89° range. The HGA signal level was normal. The subsequent RLGA signal level each day had dips, from 0 to 8 dB below predicts. On sol 573, the rover turned to a yaw of 293° for science, and the period of occlusion ended.

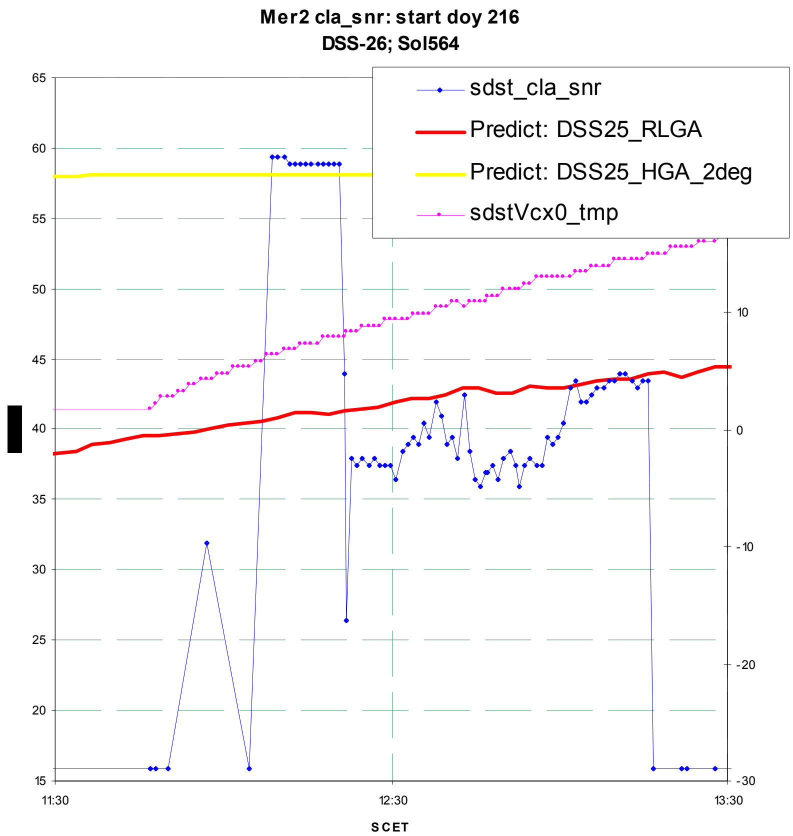

Figure 7-11. Signal-level (CLA) on HGA and LGA for Spirit, sol 564 at yaw 89°.

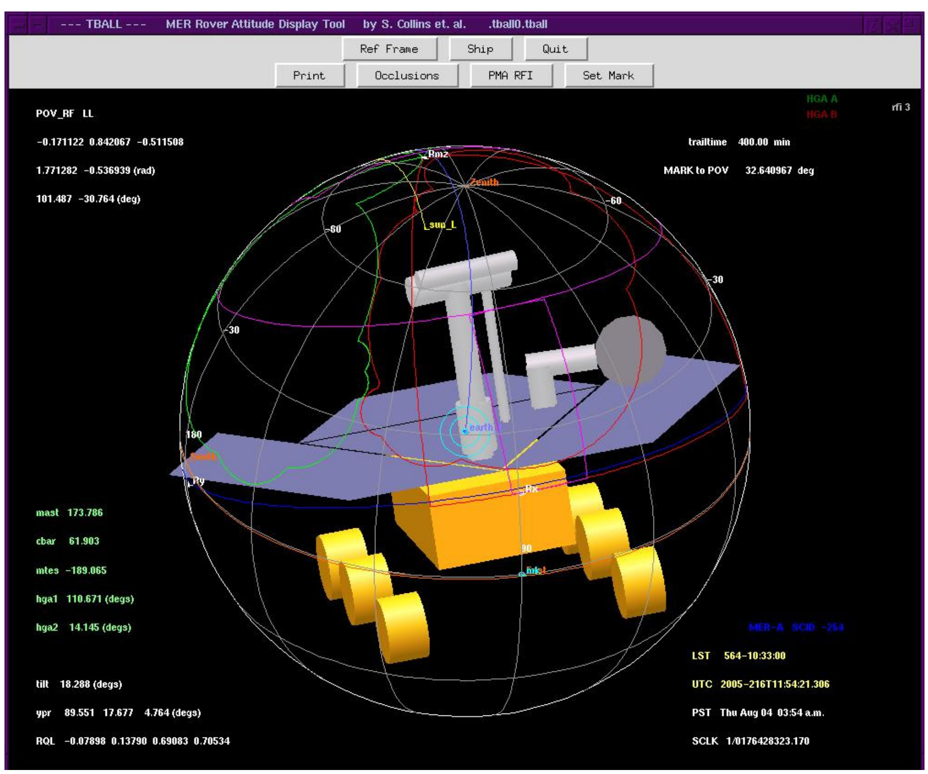

Figure 7-12. TBall representation of sol 564 geometry (PMA occlusion of RLGA).

7.8 Telecom Subsystem Trending Data

The MER rovers have each far exceeded their required lifespan of 90 sols of operation on the Martian surface. (Refer to Section 1.3 for the equipment layout on the rover and to Section 3.1 for the Telecom subsystem block diagram.)

With the excellent thermal protection of the WEB, the Telecom subsystem has operated within its qualification temperatures. In the extended missions, the X-band system has operated daily for about 17 min for upload, 5 min for the beep, and 20 min for DTE (when scheduled). Each UHF pass (typically two per day per rover, each with the Odyssey orbiter) is also about 17 min long.

The large volume of trend data for surface operations is summarized in the following figures. For each month, the figure includes an average of that channel's data values, along with the extreme maximum and extreme minimum value.

- Figures 7-13 through 7-15: SDST
- Figures 7-16 through 7-23: SSPA
- Figure 7-24 through 7-27: UHF

This section also includes a representative cruise mission trend plot (Figure 7-28), and the numbers of X-band and UHF component operating cycles (Tables 7-1 and 7-2).

7.8.1 SDST Surface Operations

Figure 7-13 shows the small variation in SDST power converter input current through the prime and extended missions for Spirit (MER-A). The variation in the maximum is caused by reductions in the bus voltage. The converter draws nearly constant power.

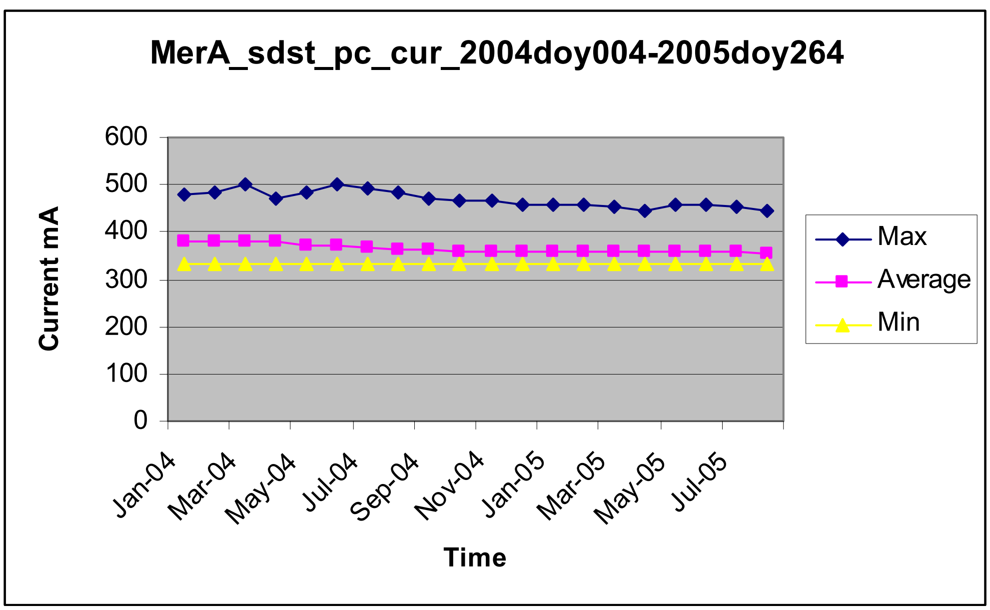

Figure 7-13. MER-A SDST power-converter input current during surface operations.

Figure 7-14 (Spirit) and Figure 7-15 (Opportunity) show the variations in temperature at the SDST VCO through the surface missions. The temperature profiles are only broadly similar, for the two rovers are on opposite sides of the planet and have experienced different constraints in power and temperature management during the Martian winter.

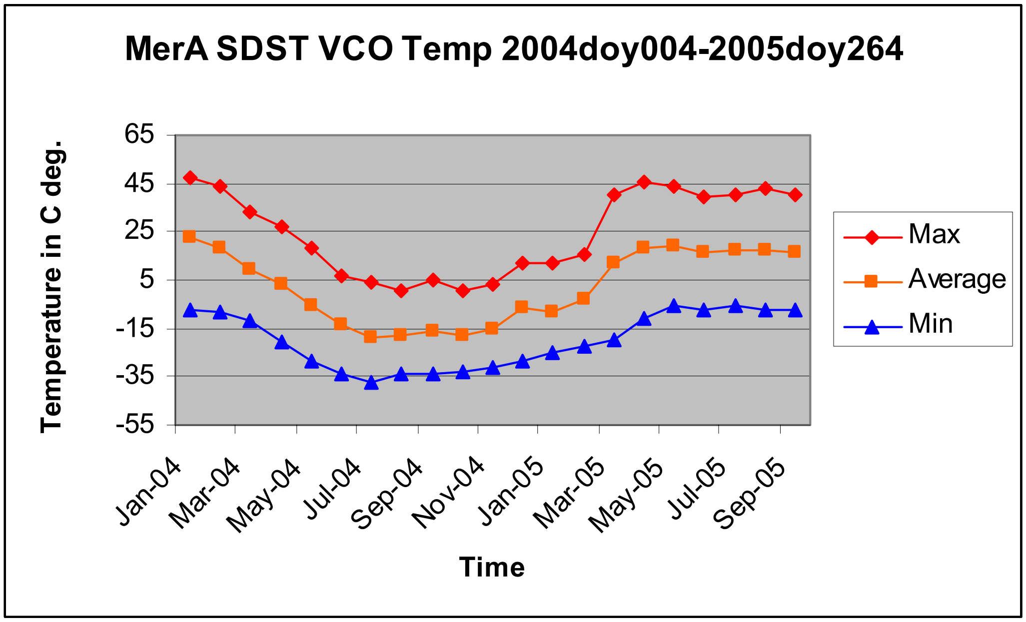

Figure 7-14. MER-A SDST VCO temperature during surface operations.

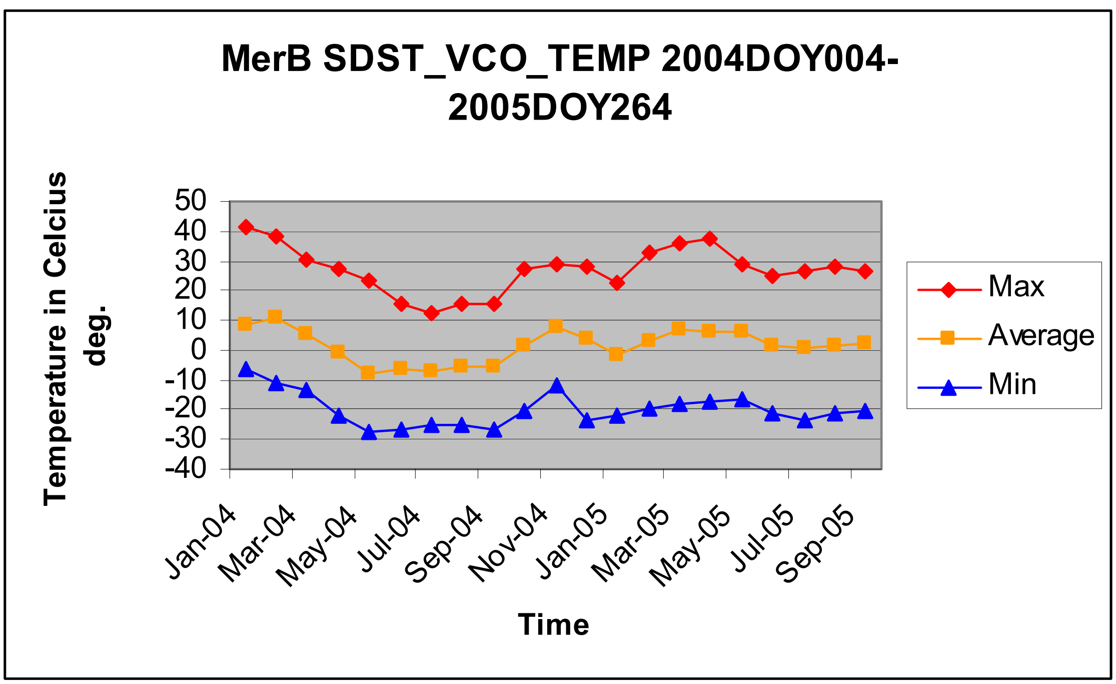

Figure 7-15. MER-B SDST VCO temperature during surface operations.

7.8.2 SSPA Surface Operations

SSPA-A on both spacecraft was powered-on continuously during cruise and power-cycled every sol on the surface. SSPA-B has not been used on either spacecraft.

Figure 7-16 for Spirit and Figure 7-17 for Opportunity show the monthly averages of SSPA RF output power. Spirit showed a ~0.25-dB reduction centered on the Martian winter while Opportunity did not. The variation may be real or a sensor artifact. A change this small would be difficult to see in the signal level received at the station. Station-related variations from day to day and from site to site would be larger.

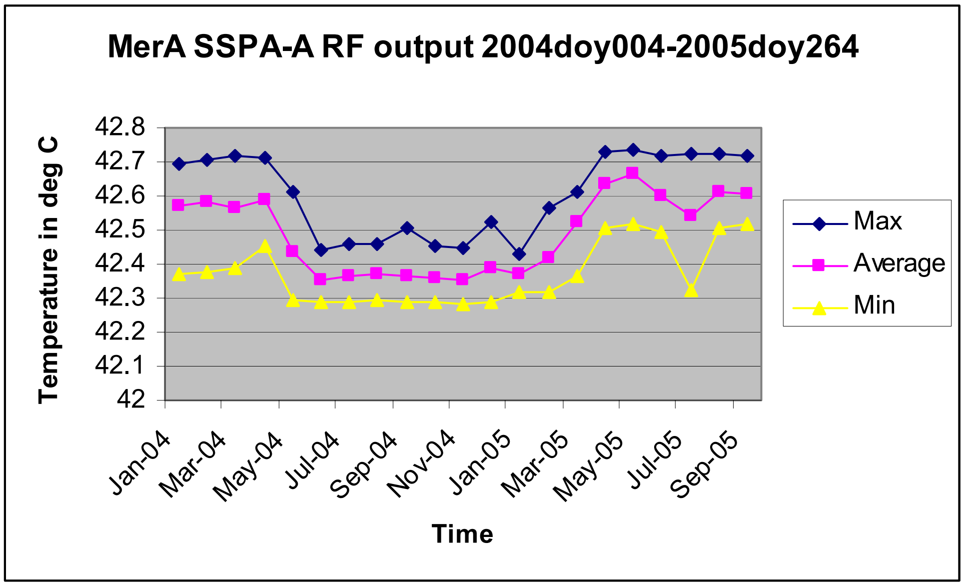

Figure 7-16. MER-A SSPA-A RF output during surface operations.

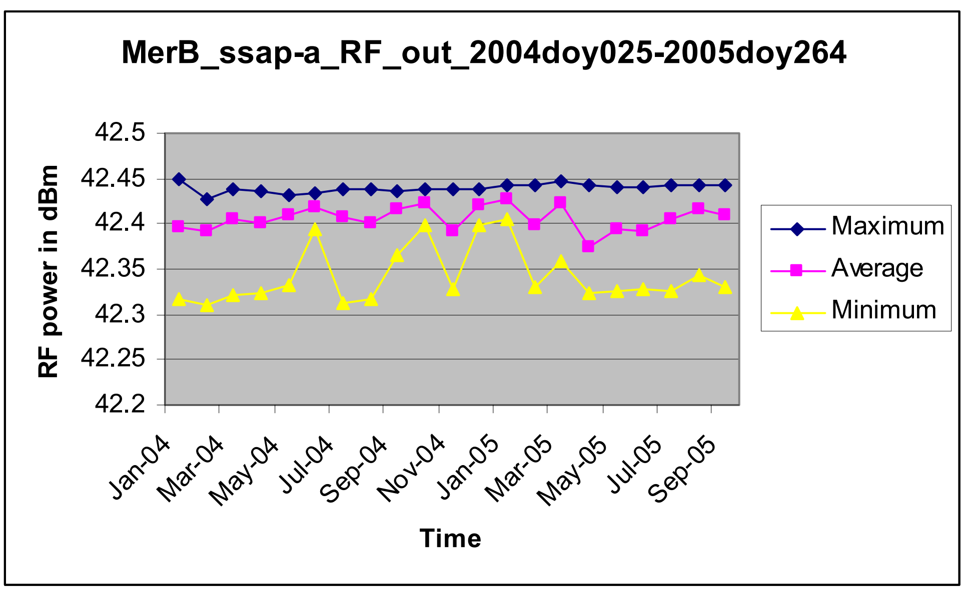

Figure 7-17. MER-B SSPA-A RF output during surface operations.

The prelaunch mission plan assumed a limit of 50°C for the maximum SSPA operating temperature at the mounting bracket (Figure 7-18 for Spirit and Figure 7-19 for Opportunity.) This limit was reached during the first two months of surface operations, and was approached again in April 2005. During the Martian winter, the lowest SSPA temperature (which occurred just before dawn, with the SSPA not operating) reached slightly lower than –30°C. The temperatures at the amplifier itself are shown in Figures 7-20 and 7-21.

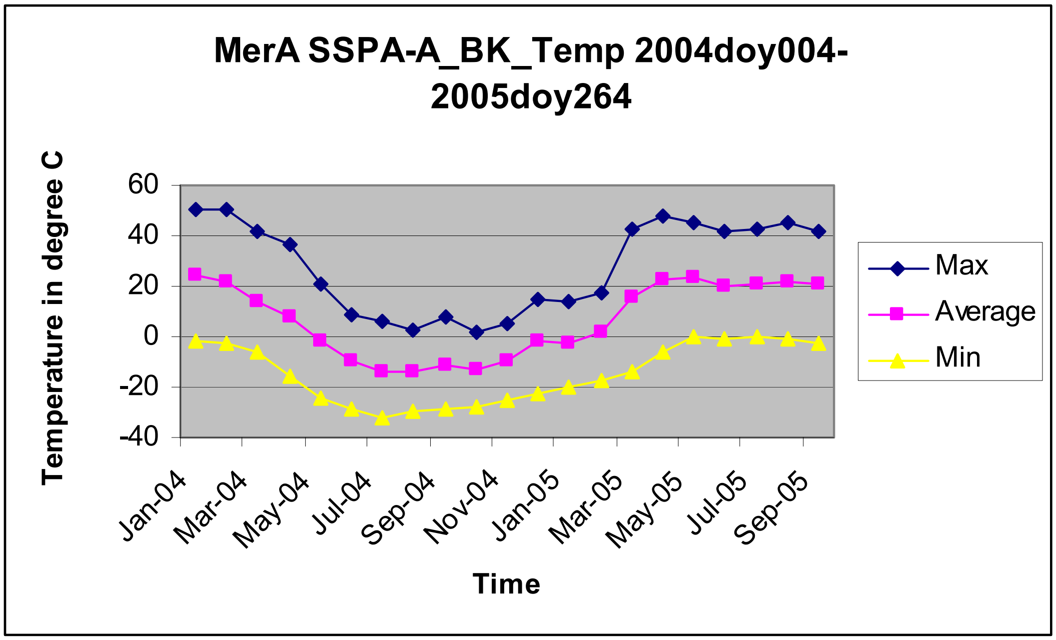

Figure 7-18. MER-A SSPA-A bracket temperature during surface operations.

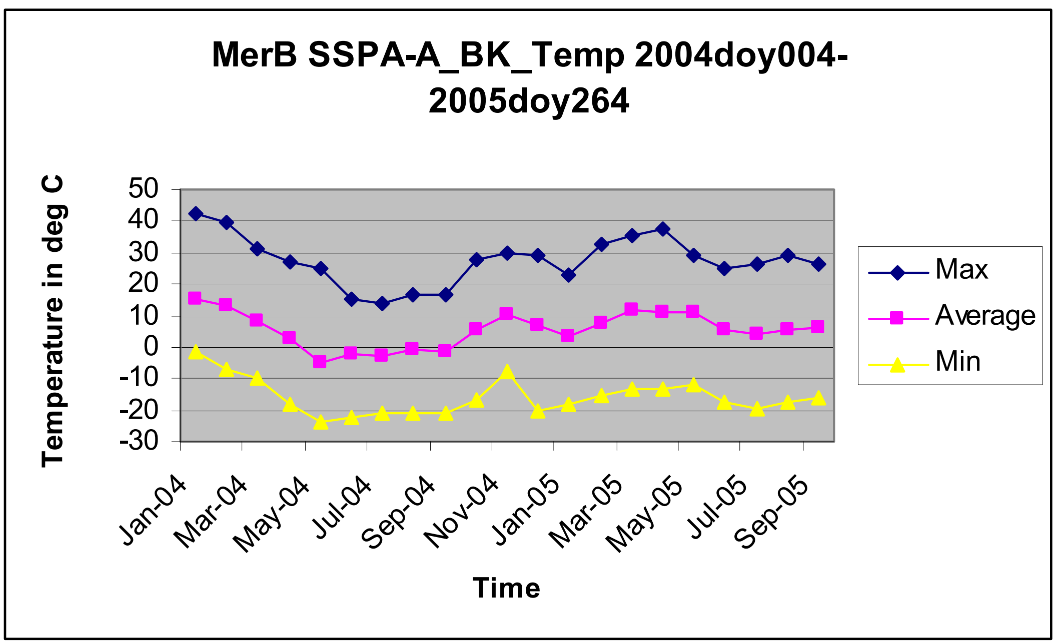

Figure 7-19. MER-B SSPA-A bracket temperature during surface operations.

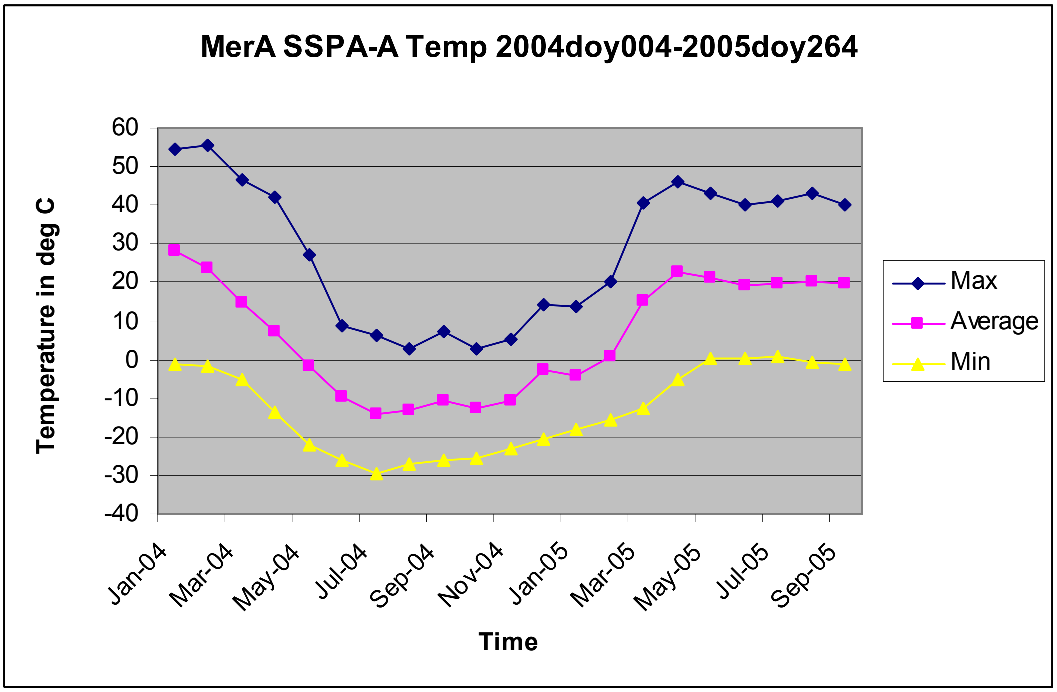

Figure 7-20. MER-A SSPA-A temperature during surface operations (compare with bracket).

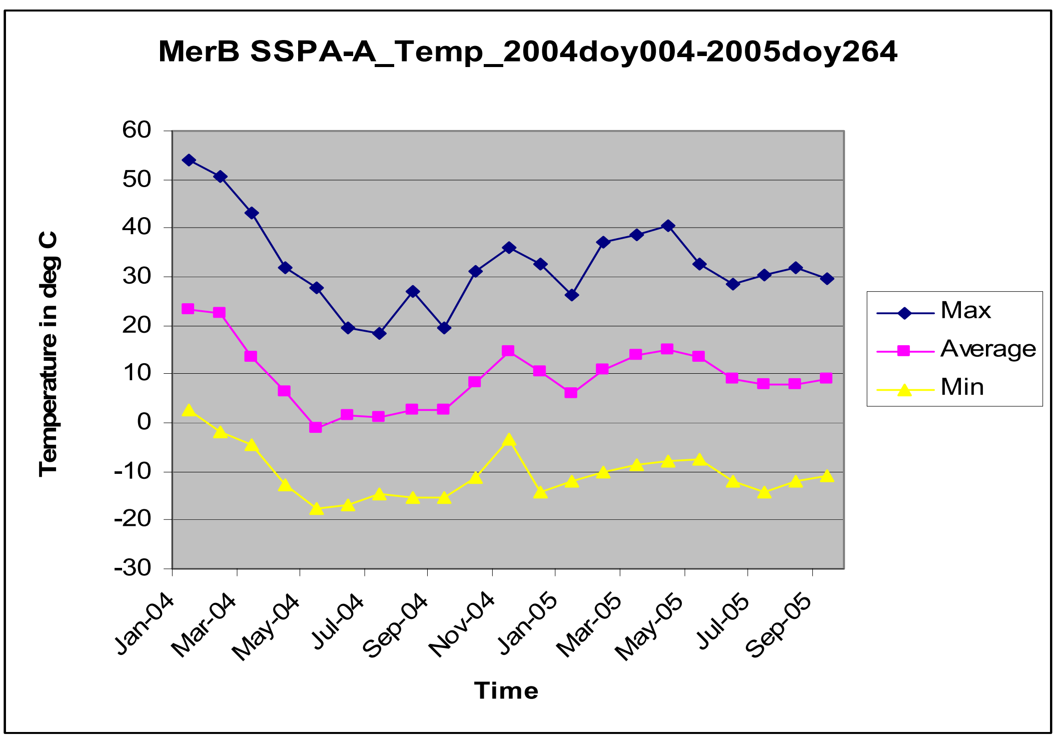

Figure 7-21. MER-B SSPA-A temperature during surface operations (compare with bracket).

Like the SDST, the SSPA consumes nearly constant power, with bus current increasing when bus voltage decreases. Figures 7-22 (Spirit) and 7-23 (Opportunity) show the variation in bus current for SSPA-A through the surface mission.

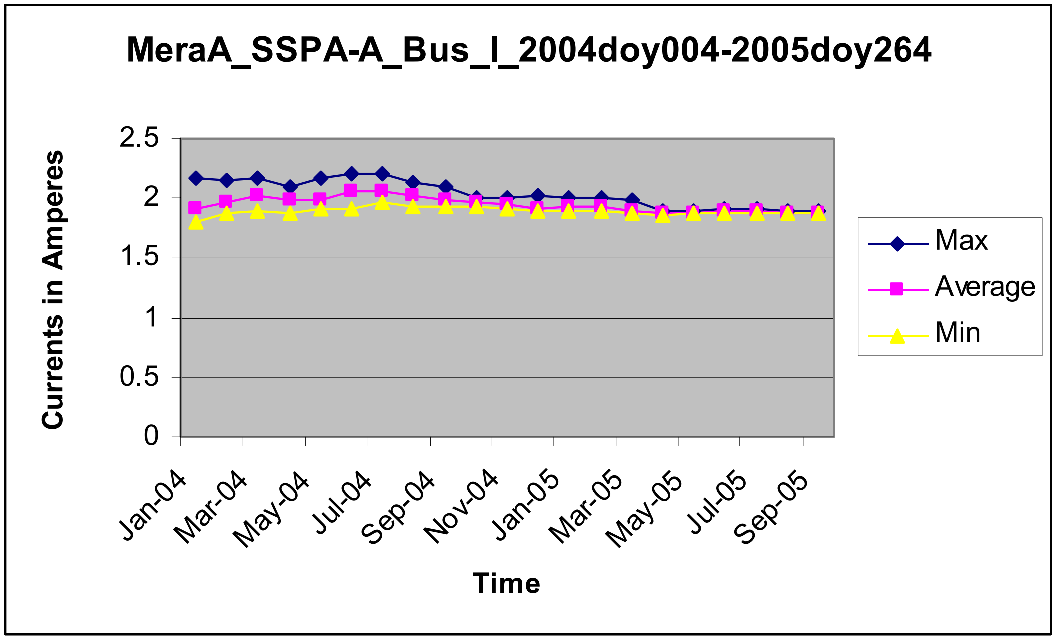

Figure 7-22. MER-A SSPA-A input current during surface operations.

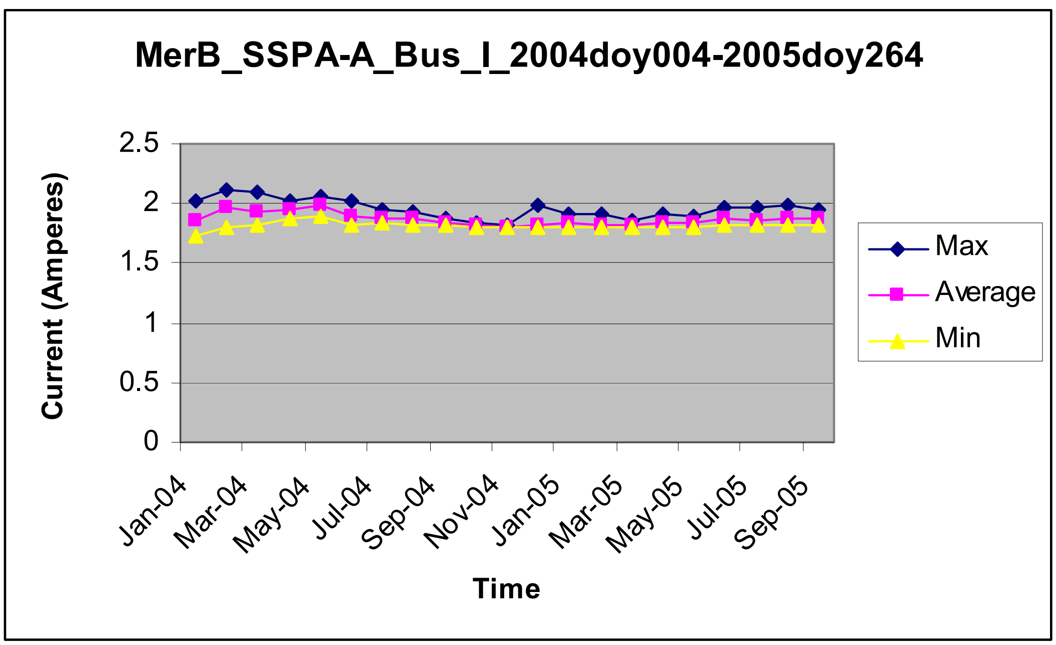

Figure 7-23. MER-B SSPA-A input current during surface operations.

7.8.3 UHF Transceiver Surface Operations

Figures 7-24 and 7-25 compare the temperature trends for the MER-A UHF power amplifier and UHF oscillator. The MER-B temperature trends (not shown) are somewhat smaller. Compare X-band VCO temperatures (Figures 7-14 and 7-15). UHF performance is expected to be slightly better at cold temperatures due to increased RF transmitter power (up to ~1 dB) and lower receive thresholds for a given bit error rate (BER).

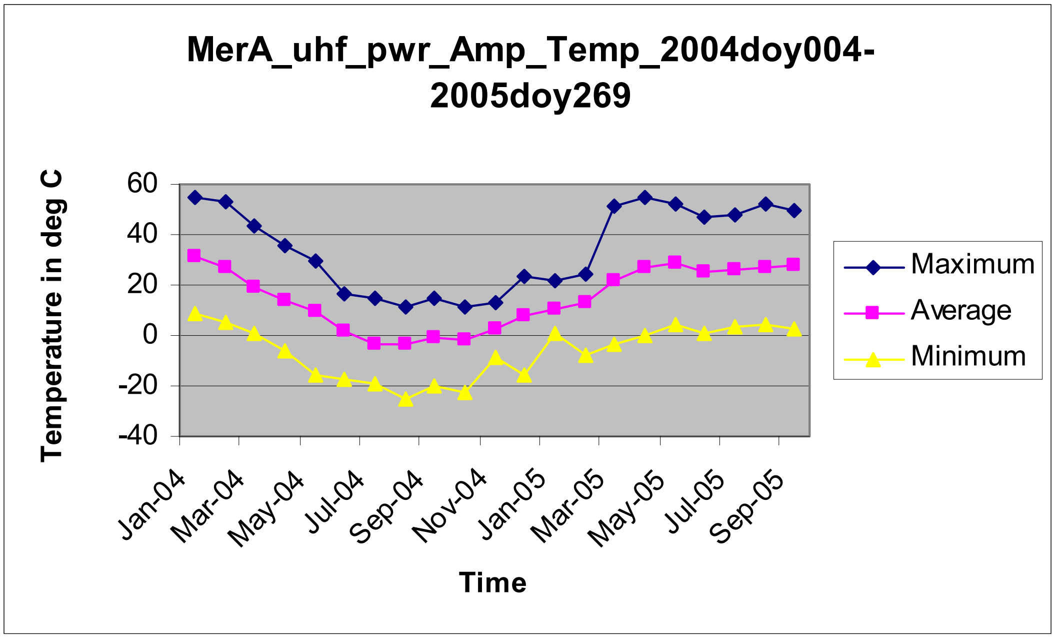

Figure 7-24. MER-A UHF power amplifier temperature.

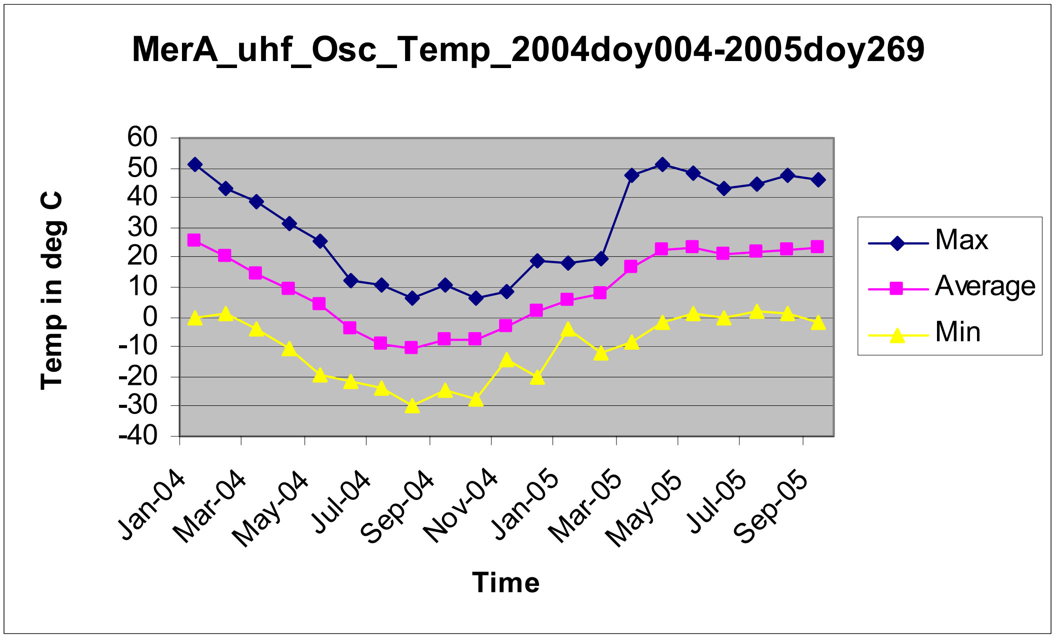

Figure 7-25. MER-A UHF oscillator temperature.

Figures 7-26 and 7-27 compare trends in the transmitter RF output for MER-A and MER-B. The causes for the outliers in the minimums (April 2005 for MER-A and March 2004 for MER-B) have not been evaluated. The MER-A average shows a little more variation (0.75 dB peak-to-peak) than does the MER-B average (0.5 dB peak-to-peak), possibly because of Spirit's wider temperature variations over the mission. Based on prelaunch test data, UHF transmit RF power was expected to be slightly higher (up to about 1 dB) at colder temperatures. This prediction is borne out in the RF output plots.

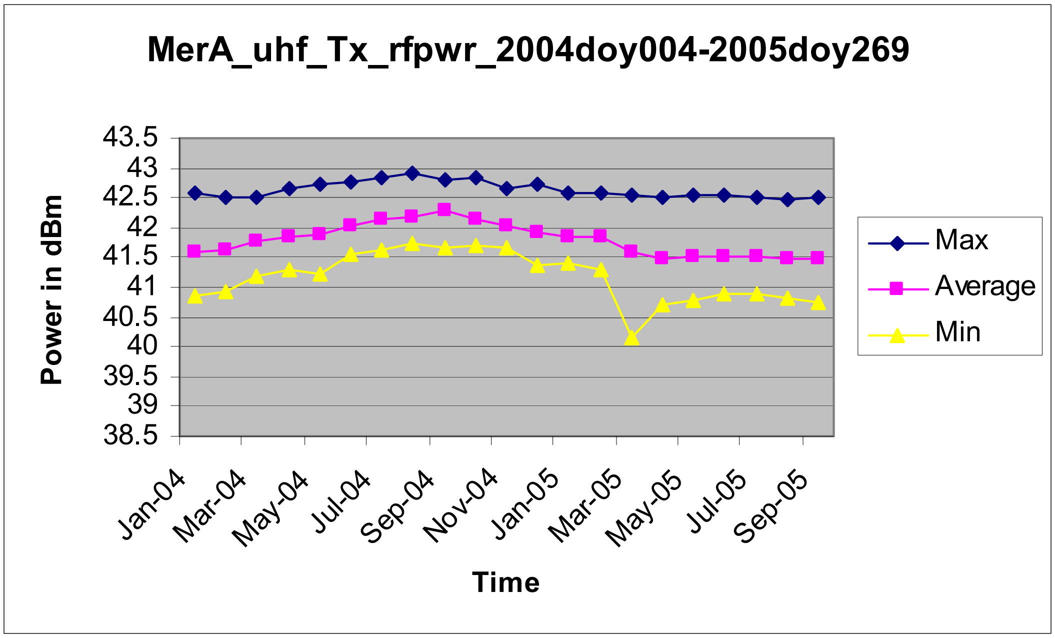

Figure 7-26. MER-A UHF transmitter RF power output.

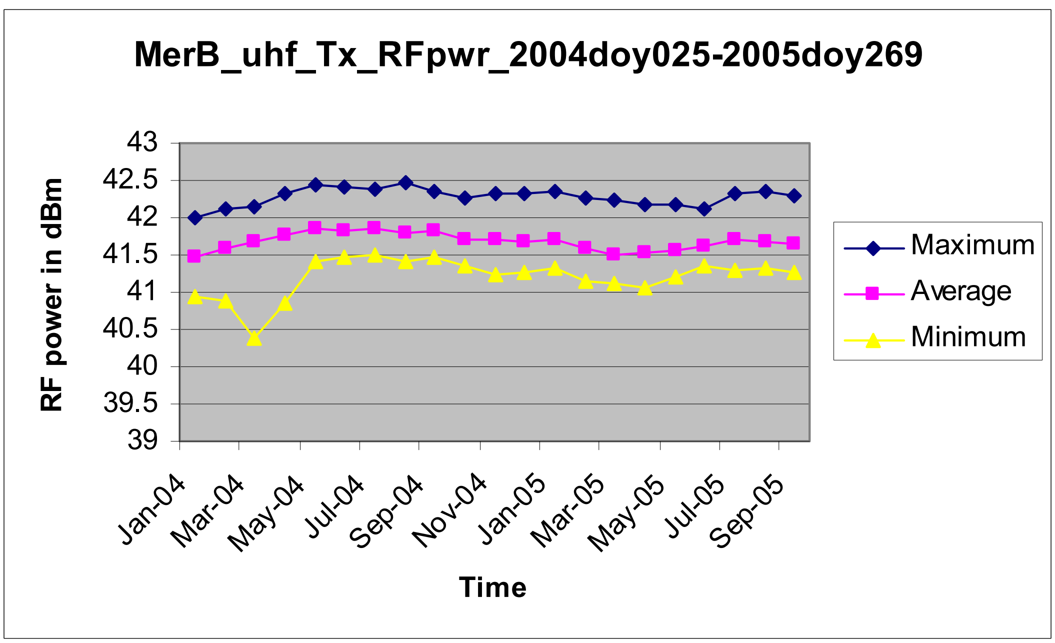

Figure 7-27. MER-B UHF transmitter RF power output.

7.8.4 SSPA Cruise Operations

The Earth-Mars cruise environment was thermally much more stable for the spacecraft than surface operations were for the rovers. As a representation of X-band subsystem performance trends during cruise, Figure 7-28 plots the RF output power of Spirit's SSPA-A from launch to EDL.

Variation in SSPA output power was less than 0.1 dB except for three times:

- Aug. 8, 2003: Switch from CLGA to MGA.
- Nov. 10, 2003: Cold reboot after solar effects (to correct possible FSW corruption), SSPA radiated on CLGA for a short period.
- Dec. 4, 2003: Reboot after FSW update, on CLGA for a short period.

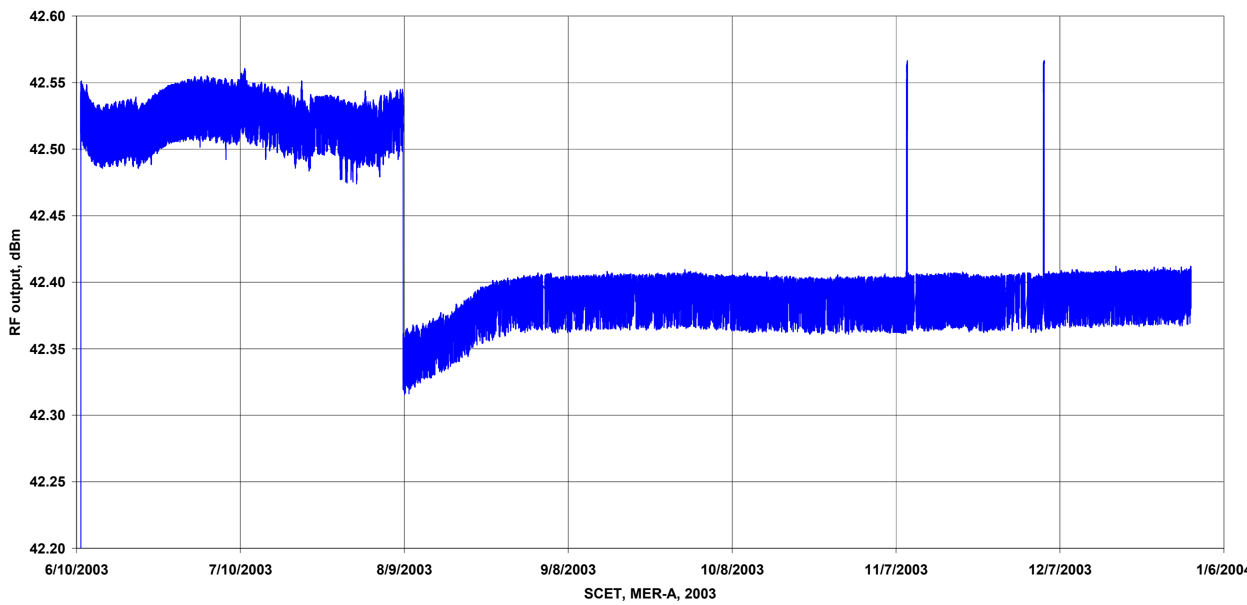

Figure 7-28. MER-A SSPA-A RF output power during cruise.

7.8.5 Subsystem Operating Cycles

Tables 7-1 and 7-2 show the number of operating cycles as of September 2005 for the X-band SDST and RF switches and the UHF transceiver. One cycle is defined as going from position 1 to position 2 and back to 1, or going from off to on and back to off.

- WTS: The waveguide transfer switch is used to toggle between rover LGA (for the RH-polarized path) and HGA. It switches daily during surface operations.
- CXS0: Coaxial switch #0 would be used to switch from SSPA-A to SSPA-B in case SSPA-A failed. It has not been used since launch.
- CXS1: Coaxial switch #1 is used to switch between HGA and CXS2 (to reach the LGA LH-polarized path or the PLGA).
- CXS2: Coaxial switch #2 was used to switch between the LGA LH-polarized path and the PLGA. After landing, the PLGA has no longer been in use.

Each UHF comm window, as it opens and closes, produces a transceiver power cycle. During the comm window, the transmitter status (power amplifier on/off) may cycle one or more times as the orbiter-to-rover forward-link signal goes above and below threshold.

Table 7-1. X-band subsystem, switch cycles.

X-Band Function	Number of Cycles MER-A	Number of Cycles MER-B
SDST power cycles	88	123
WTS	635	584
CXS0	0	0
CXS1	22	9
CXS2	1	1

Table 7-2. UHF transceiver, surface operating cycles.

UHF Function	Number of cycles MER-A	Number of cycles MER-B
Transceiver power cycles	1044	988
Transmitter status on/off	3001	2756

7.9 Telecom Scripts

This section discusses nine kinds of scripts that have been developed to make the Telecom Flight Team efficient in the use of their time and to make their outputs complete and consistent. The first four scripts query telemetry or station data about specific aspects of the subsystem, organize the data into plots or tables, and output the results as computer files stored in directories on the Telecom or project database, as printed pages, or as e-mail. The next four scripts invoke TFP or GTP to generate standardized predictions and data capability files. The last script described checks the parameters of X-band and UHF comm windows against a set of rules.

The scripts show the wide variety of data processing that the MER Telecom Flight Team members continue to do. Some of the performance figures in Sections 5 and 7 came from these queries.

7.9.1 SDST and SSPA Query

Telemetry data for the SDST and SSPA is received for each rover during the Odyssey “p.m. pass” (p.m. referring to the afternoon at the rover location). This script calls a standard program (Quickquery) provided by the MER Data Operations Team (MDOT). The script queries a defined set of SDST and SSPA digital and analog telemetry channels stored from the engineering data file received from Odyssey and put onto the system in a standard form by MDOT. The channels include status (digital) channels for subsystem configuration; and performance (analog) channels of SDST cla_snr and nb_agc (uplink signal levels) and static phase error, SDST and SSPA temperatures, currents and voltages, and SSPA input and output RF power levels.

The Telecom analyst inputs the rover ID, along with start time and end time, choosing a start time to slightly overlap the end time of the previous day’s end time. In this way there is a continuous record of each channel throughout the mission.

A typical script input is: **do_mer_query_ALL_daily Mer2 256 06:00 257 06:30 gt**

The digital outputs include tables with headers containing spacecraft ID, channel number, and parameter name. Table rows include times and channel values or configuration states. Analog outputs are written to a file in comma-separated value (CSV) format and also generated as plots. Output files are stored in the Telecom account and e-mailed to the analyst whose initials are specified at the end of the input. The output is also converted to PDF and e-mailed to Telecom team members and others on a mailing list. The e-mail enables anyone who cares to keep an eye on the Telecom data to do so.

The analyst loads the CSV file into a template which is an Excel (spreadsheet) macro written in Visual Basic (VBA). The template macro requests the user to input previously generated uplink signal-level prediction files to add to the plot of cla_snr. The data is then automatically plotted, and an output Excel workbook is produced that has each channel plot (versus time) in a separate spreadsheet. The template allows the analyst to rescale the time axis of all plots. Using Excel menus, the analyst can also rescale time or performance range on any plot and save the workbook. The analyst then uploads the workbook into a MER data storage area (DocuShare). The Telecom area of DocuShare is organized by sol for each rover.

7.9.2 Station Monitor Query

This script queries the monitor data received from the DSN station during a DTE or beep. The input process and plot output rescaling capabilities are the same as for the SDST and SSPA query. The only difference is that the data comes from monitor data rather than via telemetry from the rover. The monitor query can be run shortly after the DTE or beep ends.

The analyst specifies start and end time, and rover ID. A typical input to initiate the query is **do_mon_0158_mini_qry_daily Mer2 257 15:30 257 17:15 gt**

As for the SDST/SSPA file, the analyst loads the output CSV into a template that is an Excel macro written in VBA. The macro accesses the predictions for carrier power, telemetry SNR, and station SNT. The data is then automatically plotted. After reviewing the data and doing any rescaling, the analyst uploads the workbook to DocuShare.

7.9.3 UHF Report Generator

Early in the primary mission, data files concerning each relay pass were widely scattered. In fact, files were produced not only from MER telemetry, but also received from Odyssey operations at LMA and MGS data processing at Malin Space Science Systems. The most important pieces of information about a relay pass are the predicted data volume, the number of bits received at various stages along the way, and the orientation of the rover. Also of value are orbiter and rover transceiver received signal-level data and rover transceiver temperature, power amplifier RF output, and other engineering telemetry.

The analyst can invoke the script in either of two ways. The first is to use the "all" query command: **do_mer_query_ALL_daily_uhf Mer2 256 06:00 257 06:00 gt**

All UHF passes that occur between the specified start and stop times are included in the list and e-mailed to the person whose initials appear at the end of the command.

Alternatively, for a single, defined relay pass, by serial number: **uhfReport 46052 A**

An example of a UHF report output looks like this:

*** MER-B ODY SOL 582 PM (ID 45821), MRB_ODY_DOY256_1

128-k Pass, tilt = 1.17234, max elev = 28.36°, 29.54° with tilt

Yaw = 310.11644°, pitch = 0.40042°, roll = 1.10184°

Mean azimuth 103.88° no tilt

Pass is E

Max UHF t-4000 temperature = 30.73°C

MER estimated tx data volume = 94.57 Mbits (tac = 11602)

ODY data volume = ? Mbits, (? packets)

ODY telemetry queryplots = ? Mbits

MER GDS data volume = 89.8971 Mbits

DVCF 1-sigma predict = ? Mbits (@ 310.11644° yaw)

GTP tilted predict = 73.755 Mbits

It is left to the analyst to complete the report by filling in the question marks with data found in the DVCF summary, an e-mailed Odyssey query plot, and an e-mailed Odyssey daily relay pass summary to which the current script does not have access.

7.9.4 UHF Debug Generator

The name "debug" came from early in the primary mission when additional packets of engineering data were requested from the rover and the orbiter to enable a more in-depth analysis of certain relay passes, particularly ones that returned much less or more than the predicted data volume. The debug report, with GTP predicts, can be used to analyze both the forward and the return link. Because the transceiver frequencies are sensitive to the temperature, a debug report requires input of a temperature file. During the extended missions, the UHF comm windows have been defined to automatically request the additional packets for an overflight once a week.

The Telecom procedure to generate and process a debug report for any pass is as follows:

1. Request the Flight Team data management analyst to reprioritize data products for the pass so that the debug packets have a high enough priority to be sent down.
2. After the data is received on the ground, run a script that calls Quickquery.

   do_mer_query_UHF_NOPRINT Mer1 203 21:20 203 22:05 gt

   The outputs of the do_query are a temperature file and a data product file (in DN).
3. Run the uhfRpt tool

   Input: (1) temperature file, (2) data product file (in DN)
   Output: data product file (in EU)
4. Run GTP to get predicts for a rover given attitude
5. Get Odyssey output file (this query is run by Odyssey personnel)
6. Load data product file, GTP predicts file, and Odyssey file into the uhfRpt Excel template to produce plots of predicted and reported forward and return signal levels.

7.9.5 Predict Maker

This script operates TFP in batch mode to produce predictions for 8 weeks' worth of DTE and beep passes. It generates predicts for both LGA and HGA, with input from the DSN 8-week schedule.

Predict Maker takes inputs (such as start and end time, spacecraft, station, and so forth) from either the user or the DSN 8-week schedule file. To run the script to access the schedule file directly and generate predictions in a standard format for all passes in a particular 8-week schedule file, one specifies the directory path and file name, as in the following example:

predictMaker /home/mertel/dom254/dsn_8week_sched/MER205277_05308.SAF

LGA predicts are currently generated for the nominal uplink rate (31.25 bps in September 2005) and zero bps downlink for beeps. For the HGA, the uplink rate is currently set to 2 kbps. The downlink rate is set at the lowest level that the link can support at any time during the scheduled pass, and the SNR predicted for that rate. This may make the specified rate much lower than what the link could actually support at the time a DTE would be scheduled during that pass. The script also attempts to select the highest possible data rate for each pass and to predict the SNR for that rate. Prediction files in CSV format for both the highest and lowest data rates are generated. These files are placed in the Telecom account's directory structure under the appropriate rover and sol. A time-saving feature of this script is that it also automatically creates the directory for each rover/sol, if one doesn't already exist.

There are improvements that could be made to the current version of this script. First, it does not now create or modify GUI save files that would allow easy user modification of data rates, station transmitter power, or window times. Creating the HGA outputs requires a manual verification that the predictions reflect the comm window values before loading them into DocuShare. Second, manual checking often shows that the predicted highest rate is higher than the link can support.

7.9.6 DVCF Maker

This Perl script calls GTP and generates a file that contains all possible MER-A or MER-B passes with Odyssey or MGS within a given period of time. The script generates a DVCF that contains a summary and the detailed capabilities for both forward and return links.

To create a DVCF for a particular rover/orbiter combination for passes that span a particular period, the script requires the user to input a DVCF Request File that is generated by the rover planners. The request file is a series of text lines that define the conditions of the DVCF. The script selects the rover from the request file parameter "Mission" and the orbiter from the SCID in the request file's trajectory file directory. Following is an example of a DVCF request file:

Mission,MER-B

Start time,2004-120/00:00:00

End time,2004-134/00:00:00

Time step,00:00:05 (use 2 min in the view-period generation)

Orbiter-Mode_Modulation,ody-rel_bit

MER spice data,/domops/data/mer/253/main/spk_kernel/spk_b_s_040128-050125_040223.xsp.sfdu

MER_attitude_data,zenith

MER_sclk_scet_data,none

Orbiter_spice_data,/domops/data/m01/53/main/spk_kernel/spk_m_od09985-09988_11113_v1

Forward_criterion,mean-1sigma

Return_criterion,mean-1sigma

Attitude_alternates,alt0 (default)

Time_ref,UTC_at_MER

MER_elev_masks,5_10_20

MER frame kernel,/domops/data/mer/253/main/frame_kernel/mer1_v07.tf

File delivery location,/oss/merb/ops/ops/surface/strategic/ref/sret/telecom/dvcf/ody/

File Delivery deadline,2004-106/12

Unless suppressed by the "-s" option, the script will automatically create all of the files needed for the formal release of the DVCF and will copy the files into the delivery location in the project directory. It will also produce a File Release Form, "FRF.html," that can be opened in Microsoft Word.

To start the script: **dvcf [-s] [dvcf request file]**

The script will request at the beginning of the run for the user to run a multimission Navigation utility **spacit** to translate both the MER and Orbiter trajectory files that are in "transfer" form into SPK files.[45] This is the only interactive part of the script.

This script greatly reduces the DVCF setup time required of the user. The run that produces the DVCF itself is computationally intense and takes approximately 6 hrs. DVCFs are often set up to be run overnight, and the script makes it more certain that the correct outputs are available in the morning.

7.9.7 Tilted Rover Prediction Generator

The **run_gtp** script allows a user to run GTP in the batch mode. The input looks like this:

run_gtp Mer1 262 10:40:00 <yaw> <pitch> <roll>

This script is a quick way of making a "tilted predict" data-volume prediction taking the rover attitude into account. As previously noted, the delivered DVCF contains capabilities every 10° in yaw (angle from north at the rover site), but only for zero pitch and roll.

The output is the data volume to Odyssey predicted for the forward and return links. The output helps the mission planners decide which data rate to choose because it gives the link margin for the both the 128 kbps and 256 kbps passes. This script creates a file and sends a job to the printer to print the graph for the return-link margin (for 8, 32, 128, and 256 kbps) and the forward-link margin (for 8 kbps). This print job can also be suppressed.

The Rover Planners have a corresponding script that helps them pull out all of the information that they need to select return-link data rate. Their script calls **run_gtp**.

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[45] The Spacecraft, Planet, Instrument, C-Matrix Events (SPICE) kernel (SPK) file is the standard format used for trajectory data inputs by TFP and GTP.

7.9.8 DRCF Maker

The DRCF is a row-column-oriented text file that can be read into a spreadsheet for human evaluation or entered into the MER planning software. For either MER-A or MER-B, a DRCF defines the X-band capabilities to three DSN sites (Goldstone, Canberra, Madrid), three types of stations at each site (70-m, 34-m HEF, and 34-m BWG), and for CLGA and MGA (cruise) and RLGA and HGA (surface operations).

X-band capabilities include command, telemetry, two-way Doppler, turnaround ranging, and differential one-way ranging (DOR). The DRCF defines the maximum supportable command rates to the spacecraft or rover and the maximum supportable telemetry rates from the spacecraft or rover, and it indicates supportable signal levels for Doppler, ranging, and DOR. The capabilities are tabulated as a function of time and are defined for each of 13 specific configurations. They include uplink and downlink supportable data rate, uplink and downlink predicted Pt/No, ranging Pr/No, DOR Ptone/No, station elevation angle, and OWLT.

The user invokes the script by completing and running a GUI that includes such items as the spacecraft ID, start and stop time, and data-point spacing. Figure 7-29 shows the GUI filled out to produce a typical DRCF.

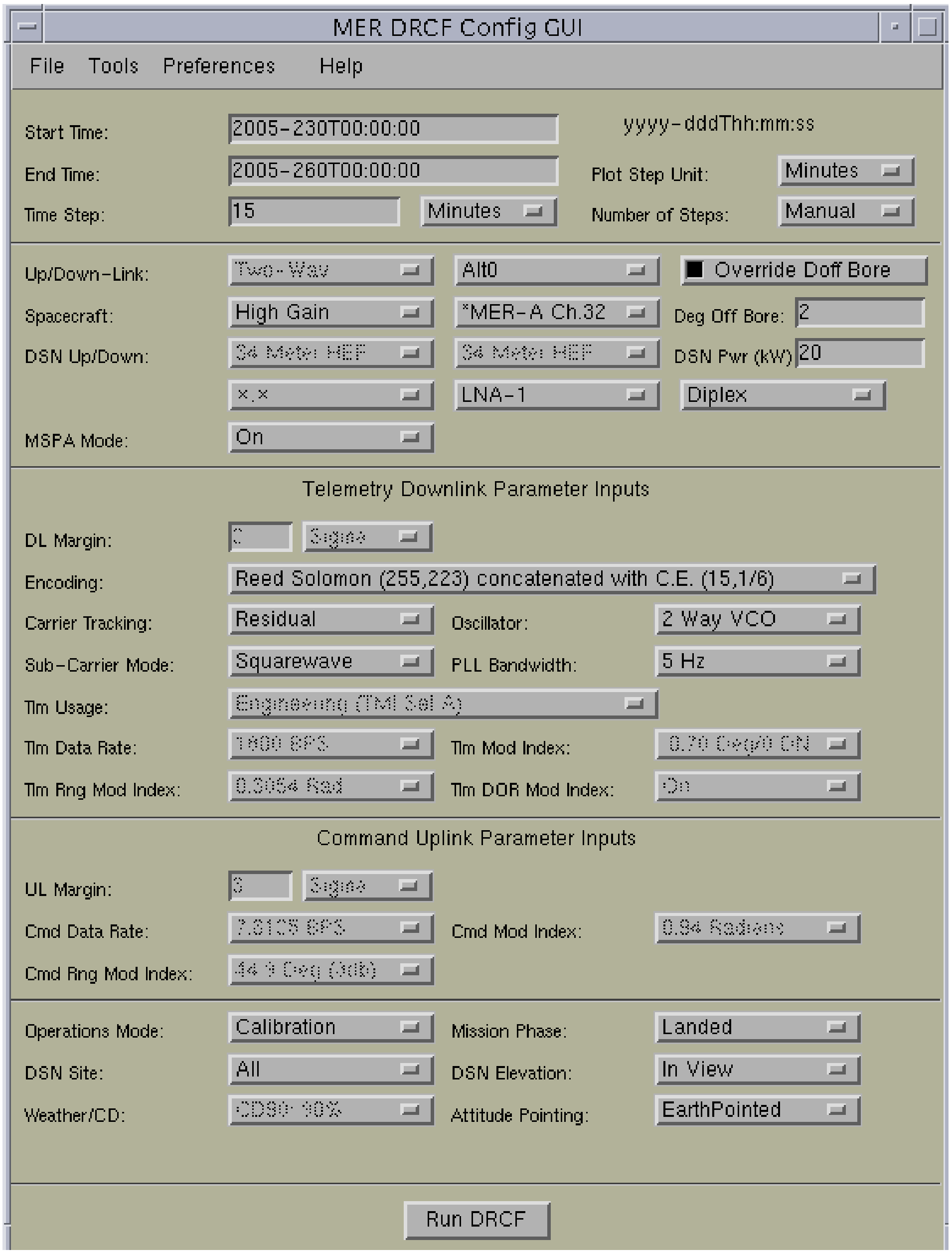

Figure 7-29. MER data-rate capability file-maker graphical user interface.

During the primary mission, the Telecom analyst ran, reviewed, and delivered the DRCF for mission planning. In the extended missions, mission planning has taken over running and using the DRCF for setting up DFE and DTE comm windows.

7.9.9 Comm Window Checker

In the primary mission, systems analysts on the strategic team (both rovers, longer-term, Earth time) produced most comm windows, and systems analysts on the tactical team (dedicated rover, sol-by-sol planning, Mars time) modified, added, and deleted comm windows based on how their rover was doing. The Telecom analysts (all on the tactical team) checked window parameter values and consistency with DSN station tracking times or UHF orbiter overflights, using a set of flight rules and the X-band and UHF predictions. After the windows were validated, they formed part of the command upload sent to each rover. Checking was manual.

In the extended missions, the Telecom team (now on Earth time, 5 days per week) is responsible for checking the comm windows. Telecom has developed a comm window checker script to eliminate some of the manual effort. This script took several work-months to produce, incorporating significant expert knowledge gained from the analysts who did manual checks; thus, it has a large source code relative to the other Telecom scripts. It is still a work in progress.

For X-band windows, the checker verifies that key parameters (durations, data rates) are correct or at least reasonable. It also verifies that each window occurs during times when station coverage has been allocated, using either the DSN Keyword File (DKF) or the DSN 8-week schedule produced by the project scheduling group. A DKF for any project is a time-ordered listing of station activities in support of the pass, including the begin-of-track (BOT) and end-of-track (EOT) times. The DKF for MER surface operations also includes the start and end times of nominal beeps, off-nominal beeps, and potential fault-protection windows.

For UHF windows, the checker verifies that each window occurs during orbiter overflights, from times produced by the GTP/DVCF program set.

The ADD_COMM_WNDW command parameters that are checked are in text in the following listing. The checker processes them in Rover Markup Language (RML).

<DURTRAN> = typ. 20 min. (a.m. DFE), 90 min. (long-range DFE). <DURTRAN> never more than 90 min. without thermal OK.

<HWCONF> = typ. 5 (a.m., long-term DFE) [receive-only, coherent, (7,1/2), 25 kHz]

<ULRATE> = typical 500 bps (a.m. DFE), 15.625 bps (long-term DFE). Must be X-band uplink rate.

<DLRATE> = typical 10 BPS (a.m., long-term DFE). Must be X-band downlink rate.

<INDEX> = typical 30 (a.m., long-term DFE). Must be per mi_look table for specified DLRATE & HWCONF

<DPT1> = rtOnlyDpt

<DUR1> = typical 0 (a.m., long-term DFE) else per table for specified DLRATE & HWCONF (or greater)

<DPT2> = rtOnlyDpt (a.m., long-term DFE) or sfcXDpt (DTE)

<DPT3> = rtOnlyDpt

<DUR3> = typical 0 (a.m., long-term DFE) else per table for specified DLRATE & HWCONF (or greater)

<EHACONF> = 6 (a.m., long-term DFE)

<ANT> = HGA (a.m. DFE), RPLGA_CLGA (long-term DFE)

<WMUP> = 0 (PM or LGA), per heating table* (DocuShare collection #12146) for a.m. HGA. Use <startran> - 3 min.for start of actuator movement. Heating Table Version:

____

<ATTFLG> = NONE (LGA, HGA a.m.), CAL (HGA PM), ATT (Rarely used. Comment.)

<MODE> = RS_L_SDST (a.m., long-term DFE), RS_L_SDST (when downlink rate >10 BPS)

* The analyst still manually verifies the X-band comm windows start times using the HGA warm-up tables provided by the thermal analyst.

Two files are checked together. The first is an RML file of the primary UHF and X-band (DTE) windows that will be uploaded to the rover to cover a span of sols. The second file contains long-range UHF windows (also called morning “keep alive” windows) for emergency. At any given time, the long-range windows all have start times in the future and are available to be used to keep the spacecraft alive if the team loses communication with it. The long-range windows are deleted by the team on a daily sol basis as the rover continues to remain healthy.

In addition to the primary and long-range window RML files, the script requires that the following files be collected or produced by the analyst and used as input.

The **DKF** or the **DSN 8-week schedule,** covering the period of the RML files. The checker inputs the BOT and EOT times. If both files are input, the DKF takes precedence.

Onboard Windows. The onboard file of windows is also in DocuShare and is created by the rover planners for each sol when there is an upload. The checker compares the windows in the RML files against the windows that are already on the rover.

Apgen notes. This is a text file that documents all of the Odyssey and MER agreed-to windows. This file contains all of the UHF pass information. It is used to double-check the comm window times in the RML file.

The output of the checker is a checklist (text file that can be printed). The checklist flags violations of the criteria in the parameter list above. The analyst reviews the checklist and resolves (as a real problem or not) what the checker has flagged. Telecom signs the checklist and forwards it to the uplink team, pointing out any warnings that represent remaining concerns.

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Abbreviations and Acronyms

1553 bus	MIL-STD-1553 Time-Division Command/Response Multiplex Data Bus
$2Bl_0$	carrier-loop bandwidth at threshold
34-m, 34m	DSS antenna with diameter of 34 meters
70-m, 70m	DSS antenna with diameter of 70 meters
ACE	call sign of the real-time MER interface with the DSN (not an acronym)
ACK	acknowledgment
ACS	Attitude Control Subsystem
AFT	allowable flight temperature
AGC	automatic gain control
APID	application process identifier
APXS	Alpha Particle X-Ray Spectrometer
ARA	Airbag Retraction Actuator
ARQ	automatic repeat request
ASIC	Application-Specific Integrated Circuit
ATLO	assembly, test, and launch operations
aux osc	auxiliary oscillator
avg	average
b/s	bits per second
BER	bit error rate
BIP	Backshell Interface Plate
BLF	best-lock frequency
BLGA	Backshell Low-Gain Antenna
BPSA	Backshell Pyro Switch Assembly
BPSK	binary phase-shift keying
BTTS	Basic Telemetry Time Sequence
BVR	Block V Receiver
BWG	beam waveguide station
C	Celsius
CBM	Communications Behavior Manager
CCAFS	Cape Canaveral Air Force Station
CCSDS	Consultative Committee for Space Data Systems

CEM	Cruise Electronics Module
CLA	carrier-lock accumulator
cla_snr	carrier-lock accumulator signal-to-noise ratio measurement
CLGA	Cruise Low-Gain Antenna
CMC	Canadian Marconi Corporation
conf	configuration
Conscan	conical scanning
cPROTO	compensated Pitch-and-Roll Targeted Observation
CPU	central processing unit
CRC	cyclic redundancy check
CS	check sum
CSV	comma-separated value
CTS	coaxial transfer switch
CXS	coaxial switch
DAC	Digital-to-Analog Converter
dB	decibel
dBm	decibels with respect to 1 mW
DDUT	drop-dead uplink time
deg	degree
DESCANSO	Deep Space Communications and Navigation Systems Center of Excellence
DFE	direct-from-Earth
DI	Deep Impact
DIMES	Descent Image Motion Estimation System
DIP	diplexer
DKF	DSN keyword file
DL	downlink
DMD	data monitor and display
DN	data number
DOR	differential one-way ranging
DOY	day of year
DPT	data-priority table
DR	Discrepancy Report
DRCF	data-rate capability file
DS1	Deep Space 1
DSN	Deep Space Network

DSS	Deep Space Station
DTE	direct-to-Earth
DTF-21	DSN Test Facility 21
DUHF	Descent UHF Antenna
DVCF	data-volume capability file
EDA	EDL data analysis
EDL	entry, descent, and landing
EH&A	engineering health (or housekeeping) and accountability
EMC	electromagnetic compatibility
ESA	European Space Agency
EU	engineering unit
EVR	event report
FFT	fast Fourier transform
FRF	file release form
FRO	frequency reference offset
FSW	flight software
Ftx	transmit frequency
fwd	forward
GDS	Ground Data System
GHz	gigahertz
GMSK	Gaussian-filtered minimum-shift keying
GTP	Generalized Telecom Predictor
GUI	graphical user interface
HCD	Hardware Command Decoder
HEF	high-efficiency station
HGA	High-Gain Antenna
HPCW	high-priority comm window
HRS	Heat-Rejection Subsystem
Hz	hertz
I/F	interface
ID	identification

IDD	Instrument Deployment Device
IMU	Inertial Measurement Unit
ISA	Incident, Surprise, Anomaly report
ITE	impact through egress
JPL	Jet Propulsion Laboratory
Ka	frequency band (about 32 GHz)
kbps	kilobits per second
LCP	left-hand-circular polarization (also known as LHCP)
LEM	Lander Electronics Module
LGA	Low-Gain Antenna
LH	left-hand (polarization)
LHCP	left-hand circular polarization (also known as LCP)
LMA	Lockheed Martin Astronautics
LPA	Lander Petal Actuator
LPSA	Lander Pyro Switching Assembly
LST	local solar time at rover site
LTST	local true solar time
LVA	Launch Vehicle Adapter
MAQ	Magellan acquisition tuning template
MB	Mössbauer spectrometer
Mbit	megabit
MBR	Mars Balloon Relay protocol (also known as UHF2)
MCD	maximum likelihood convolutional decoder
MDOT	MER Data Operations Team
MER	Mars Exploration Rover
MEX	Mars Express
M-FSK	multiple-frequency shift-keying
MGA	Medium-Gain Antenna
MGS	Mars Global Surveyor
MHz	megahertz
MI	Microscopic Imager
MIL	military

MOC	Mars Orbiter Camera
mod	modulation
MON	monitor data
MPF	Mars Pathfinder
MRO	Mars Reconnaissance Orbiter
ms	milliseconds
MSA	Mission Support Area
MSPA	multiple spacecraft per aperture
MSR	Mars Sample Return
n/a	not applicable
NASA	National Aeronautics and Space Administration
NCO	numerically controlled oscillator
No	noise spectral density
nom	nominal
ns	nanoseconds
NSP	Network Simplification Project
ODY	2001 Mars Odyssey
ORSC	orbiter relay state change
OWLT	one-way light time
P/FR	Problem/Failure Report
Pancam	Panoramic Camera
Pc/No	ratio of carrier power to noise spectral density
PCM	pulse code modulation
Pd/No	ratio of data power to noise spectral density
PDF	Portable Document Format
PLGA	Petal Low-Gain Antenna
PM	phase modulation
PMA	Pancam Mast Assembly
PN	pseudonoise
POR	power-on reset
PSK	phase shift-keyed
Pt	total power
Pt/No	ratio of total power to noise spectral density

RA	radar altimeter
RAAR	radar altimeter antenna receive
RAAT	radar altimeter antenna transmit
RAD	rocket-assisted deceleration
RAS	radar altimeter subsystem
RAT	Rock Abrasion Tool
RC	request command
RCP	right-hand circular polarization (also known as RHCP)
RED	Rover Equipment Deck
REM	Rover Electronics Module
RF	radio frequency
RFS	Radio Frequency Subsystem
RH	right-hand (polarization)
RHCP	right-hand circular polarization (also known as RCP)
RLGA	Rover Low-Gain Antenna
RML	Rover Markup Language
rot	rotation
RS	Reed-Solomon code
RS422	also known as EIA422, data interface standard
RSDL	Reed-Solomon downlink
RSR	Radio Science Receiver
RT	remote terminal, real time
RTLT	round-trip light time
rtn	return
ru	range unit
RUHF	Rover UHF Antenna
Rx	receive
S/N	serial number
S1	ID of a time-out signal in the SDST
SCET	spacecraft event time
SCID	spacecraft identifier
SDST	Small Deep-Space Transponder
SEP	Sun-Earth-probe angle
seq	sequence

sig	signal
SLC	Space Launch Complex
SMA	subminiature version A (connector)
SNR	signal-to-noise ratio
SNT	system noise temperature
sol	Martian day (24 hr 39 min long)
SPE	static phase error, Sun-probe-Earth angle
SPICE	Spacecraft, Planet, Instrument, C-Matrix Events
SPK	SPICE kernel
SR	sweep range
SSNR	symbol signal-to-noise ratio
SSPA	solid-state power amplifier
STE	system test equipment
TC	transmit command
TCM	trajectory correction maneuver
temp, tmp	temperature
TFP	Telecom Forecaster Predictor
TIRS	Transverse Impulse Rocket System
tlm	telemetry
TPS	Thermal Protection System
TSB	Telecom Support Board
Tvac	thermal vacuum
Tx	transmit
UHF	ultrahigh-frequency
UHF1	Proximity-1 Space Link protocol
UHF2	also known as MBR (Mars Balloon Relay) protocol
UL	uplink
UTC	Universal Time, Coordinated
VBA	Visual Basic
VC	virtual channel
VCO, VCXO	Voltage-Controlled Crystal Oscillator
VME	Versa-Module Europa

W	watt
WEB	Warm Electronics Box
WTS, WGTS	waveguide transfer switch
X-band	frequency range (7 to 9 GHz for MER)