Mars Exploration Rovers: Telecom System Design and Operation Highlights

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1. Introduction

The two identical Mars Exploration Rovers (MER), Spirit and Opportunity, landed on Mars on January 4, and January 25, 2004 and have now begun geologic exploration at their two distinct sites at Gusev Crater and Meridiani Planum respectively. The rovers' prime scientific objectives are to identify the ancient geologic and climatic history and to search for the presence of water, past or present, at these two sites on the red planet. To accomplish this, the Athena Science Payload on-board each rover is composed of a suite of five instruments capable of performing remote and in-situ science observations. At this time, both Spirit and Opportunity have successfully roamed around their new homes, and scientists on Earth have received data from each of their instruments about conditions at Gusev Crater and Meridiani Planum.

To arrive at this day, work was begun 3 and 1/2 years ago on the design of a spacecraft which could support a 7-month interplanetary Cruise, a 16-minute Entry, Descent and Landing, a 10-sol Critical Deployment, and an 80-sol Surface Mission. This paper describes the telecommunications subsystem of the MER spacecraft and will highlight some of the telecom operational issues.

Figure 1 shows the MER spacecraft. It is composed of a cruise stage and an aeroshell. The aeroshell is comprised of a backshell which houses the parachute, bridle deploy mechanisms, and the Retrorocket aided descent system, and a heatshield. The rover in its stowed configuration is located inside the tetrahedral lander which itself is protected inside the aeroshell.

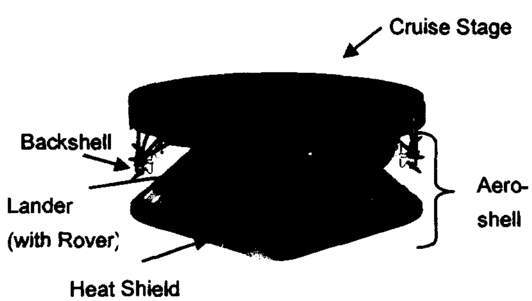

Figure 1. The MER Spacecraft

2. Overview of MER Telecom Subsystem

The MER Telecommunications subsystem consists of an X-band and a UHF band subsystem. The X-band subsystem is designed to support communications directly from NASA/JPL's Deep Space Network, receiving commands at 7.18 GHz and transmitting engineering housekeeping and science data at 8.4 GHz. The X-band communication systems for Spirit and Opportunity operate on different channels assignments in order to eliminate the possibility of interference during cruise, and to a lesser extent surface operations. The UHF subsystem supports communication with the Mars '01 Odyssey (ODY), the Mars Global Surveyor (MGS) and the Mars Express (MEX) orbiters. The frequency plan for Spirit and Opportunity is shown in Table 1.

Table 1. MERA and MERB Radio Frequencies

	Spirit / Opportunity
X-band Channel Assignment	Channel 32 / Channel 29
Transmit	8439.444445 MHz / 8435.370371 MHz
Receive	7183.118056 MHz / 7179.650464 MHz
UHF Frequency Assignment	
Transmit to ODY and MEX	401.585625 MHz
Transmit to MGS	401.528711 MHz
Receive	437.1 MHz
Radar Altimeter Frequency	4.3 GHz Pulsed CW

The X-band subsystem was designed to provide communications between the spacecraft and the DSN during cruise, to transmit a signal during Entry, Descent, and Landing, and to provide a two-way link during surface operations for real-time command and telemetry reception of the rover by the Mission Operations team.

The UHF subsystem was designed to provide telemetry during EDL after backshell jettison via the Mars Global Surveyor (MGS) spacecraft; to provide the bulk of science data return from the surface via the MGS and Mars Odyssey NASA's orbiters; to serve as a backup to the X

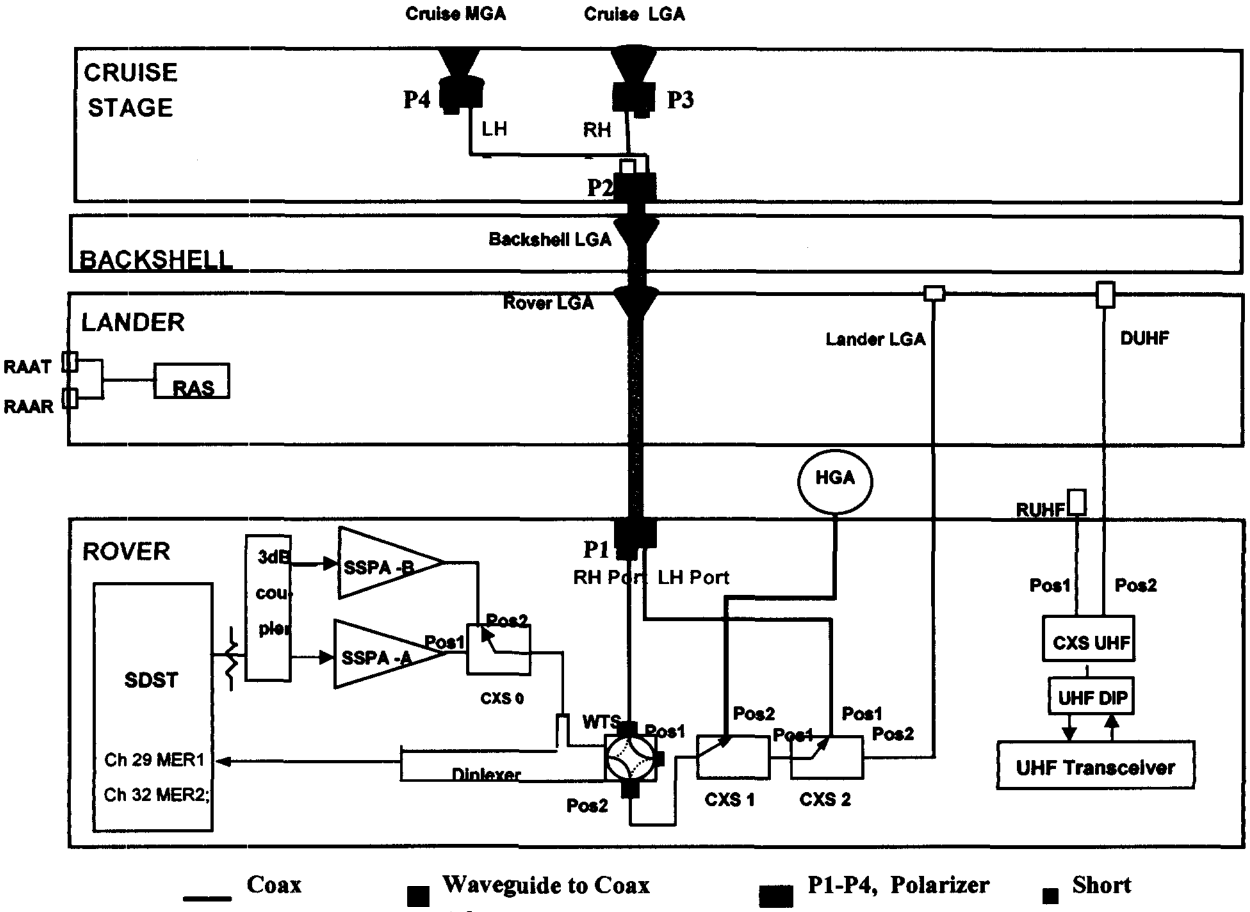

Figure 2. The MER Telecommunications Subsystem

band for commands; to demonstrate interoperability with the ESA's Mars Express orbiter.

The block diagram of the MER telecom subsystem is shown in Figure 2. The brain of the X-band radio frequency system is the Small Deep Space Transponder. In order to receive commands from the DSN at Earth-spacecraft ranges of 2 AU, the SDST possesses a very low input power threshold of -155 dBm. It can demodulate a 16 kHz sine-wave command subcarrier and detect uplink data rates from 2000 bps to 7.8125 bps. The transponder encodes the incoming telemetry bit stream from spacecraft avionics using either a k=7, r=1/2 or k=15, r=1/6 convolutional code, BPSK modulates the ensuing symbol stream onto a square-wave subcarrier either at 25 KHz or 375 KHz subcarrier, and phase modulates the downlink carrier with this composite telemetry signal. Downlink data rates tested vary from 10 bps to 28.44 Kbps. The transponder can also generate a carrier and unmodulated subcarrier where the subcarrier frequency, set by avionics, can vary from 2 KHz to 4000 KHz. In this mode, the transponder is effectively generating a M-ary FSK signal where the bit rate is determined by the number of possible frequencies and the rate at which the frequencies are varied. During EDL, the transponder was used in this mode to generate a carrier and an MFSK signal. The transponder is capable of receiving a ranging signal from the DSN, demodulating and transmitting the ranging tones, and generating Differential One-way Ranging Tones. These signal types enable highly accurate navigation of the spacecraft.

The X band subsystem also possesses redundant 15 W Solid State Power Amplifiers and various microwave components to enable signal reception and transmission from six X band antennas. The Cruise Low Gain Antenna (CLGA) was designed to support near-Earth communications and spacecraft safing. The Cruise Medium Gain Antenna (CMGA) was designed to support ranging and telemetry at max. approach distance (1.33 AU for Opportunity). The same LGA waveguide stack design as used for the Mars Pathfinder spacecraft was employed to produce a Backshell LGA (BLGA) and a Rover LGA (RLGA) capable of supporting signal transmission during EDL. The RLGA circular waveguide is long enough to guarantee that the RLGA can be used effectively when lander petals are closed.

Table 2. X-Band Signal Parameters – Cruise Phase

Parameter	CMGA	CLGA
Near Earth Data Rates (Launch to approx. L+ 60 days – Spirit; to approx. L + 40 days – Opportunity)		
Command Rate	Not used	7.8 - 250 bps
Telemetry Rate	Not used	40 - 300 bps
Cruise Data Rates		
Command Rate	125 - 2000 bps	7.8125 bps
Telemetry Rate	120 - 11850 bps	40 bps
Antenna Type	Horn	Open-ended W/G
Antenna Pattern	Conical Beam	Conical Beam
Receive G/T	-13.4 dB/K	-18.6 dB/K
Transmitter Power, nominal	16 W	16 W
Transmit Losses, nominal	3.5 dB	2.3 dB
Transmit Antenna 3 dB Beamwidth	+/- 9 °	+/- 42 °
Peak Transmit Antenna Gain	19.2 dBic	7.2 dBic
EIRP, Nominal	27.7 dBW	16.9 dBW
Polarization	LCP	RCP

Table 3. X and UHF Signal Parameters - EDL

Parameter	Backshell LGA and RLGA	Lander LGA	DUHF (used with MGS)
Command Rate	Not applicable	Not applicable	Not applicable
Telemetry Rate	MFSK	MFSK	8 kbps BPSK
Antenna Type	Open-ended W/G	Patch	Monopole
Antenna Pattern	Conical Beam	Conical Beam	Toroidal Beam
Receive G/T	-19.6 dB/K / -18.6 dB/K	-17.6 dB/K	Not applicable
TX Power, nom.	16 W	16 W	12 W
TX Losses, nom.	1.3 dB	2.7 dB	0.6 dB
TX Ant. 3 dB BW	+/- 42 °	+50° / -60 °	Not applicable
Peak Ant. TX Gain	8.0 dBic / 7.0 dBic	6.0 dBic	5 dBic
EIRP, Nominal	18.7 dBW / 17.7 dBW	15.3 dBW	15.2 dBW
Polarization	RCP	RCP	Linear

The lander antenna, a patch located on the outside of the base petal of the lander tetrahedron, was designed to support carrier and MFSK signal transmission post landing. Finally, a High Gain Antenna (HGA) identical to that designed for Mars Pathfinder was flown to enable high data rate communications once successful lander petal deployment has been achieved.

The UHF subsystem is also depicted in Figure 2. The core of the subsystem is the UHF transceiver, manufactured by CMC Electronics, Cincinnati which implements physical and data layers compatible with both the MGS Mars Relay protocol and the CCSDS Proximity-1 Space Link Protocol [1]. Both Mars Odyssey and Mars Express relays implement the CCSDS Proximity-1 protocol recommendations, enabling interoperability and interagency cross-support. The carrier acquisition threshold is -118 dBm. The diplexer allows the use of a single antenna for the transmitting and receiving frequency. The RF output of the diplexer is in the order of 12 W.

Table 4. X and UHF Signal Parameters - Surface

Parameter	Rover LGA	Rover HGA	RUHF
Command Rate	7.8125 – 31.25 bps	250 (A) – 2000 bps	8 kbps
Telemetry Rate	10 bps – 300 bps	1850 (A) – 22120 bps	ODY: 8, 32, 128, 256 kbps MGS: 8, 128
Antenna Type	Open-ended WG	Printed Dipole Array	Monopole
Antenna Pattern	Conical Beam	Conical Beam	Toroidal Beam
Recieve G/T	-18.6 dB/K	-9 dB/K	-26 dB/K
TX Power, nom.	16 W	16 W	12 W
TX Losses, nom.	1.3 dB	3.15 dB	0.3 dB
TX Ant. 3 dB BW	+/- 42°	+/- 4.1°	Not applicable
Peak Ant. TX Gain	7.0 dBic	24.8 dBic	5 dBic
EIRP, Nominal	17.7 dBW	33.6 dBW	15.5 dBW
Polarizat'n	RCP	RCP	Linear

Note A: Data rate is achievable with 70m DSN station and k=15, r = 1/6 convolutional code on sol 90 of the Opportunity Surface Mission.

Two UHF antennas are present. A quarter wavelength monopole, known as the descent UHF antenna or DUHF, is mounted inside the wall of one of the lander's petals. During the final phase of EDL, the DUHF is used to transmit an 8 kbps data stream to MGS. A second monopole, called the rover UHF antenna or RUHF, is mounted on the rover deck to support communications with the ODY, MGS, and MEX. This antenna can only be used post-landing after the rover has deployed its solar panels. The Rover UHF antenna design has the advantage of being simple, lightweight and possessing good gain at low elevation angles. However, the disadvantage of this linearly polarized antenna is its interaction with all the other vertical structures on the rover deck such as the panoramic camera and the X-band RLGA. Consequently, the RUHF antenna pattern is very asymmetric causing the data return of a given pass to depend greatly on the rover orientation.

Tables 2 - 4 give the X-band-and UHF transmit and receive signal parameters for cruise, EDL, and surface operations. The X-Band and UHF hardware was specified to operate and tested over an unprecedentedly wide temperature range in order to prepare for surface operations. Table 5 lists the allowable flight temperatures for the active Xband and UHF components.

Table 5. Allowable Flight Temperatures

Item	Allowable Flight Temperatures			
	Operational		Non-Operational	
	Min	Max	Min	Max
SDST	-25 C	50 C	-40 C	50 C
SSPA	-25 C	50 C	-40 C	50 C
UHF Subsystem	-40 C	55 C (B)	-40 C	55 C

Note B. The UHF transceiver was specified and tested to a maximum. operational temperature of 50 °C however, once on the surface, the max. allowable was increased to permit late Mars afternoon use on active days.

Lastly, a 4.3 GHz Radar Altimeter Subsystem (RAS) is depicted. The RAS is used during EDL in order to provide measurements of lander altitude which are used by flight software in the computation of airbag inflation, retrorocket ignition, and bridle cut times.

3. Mars Global Surveyor and Mars'01 Odyssey UHF Subsystems

MGS and Mars Odyssey are in near-polar, sun-synchronous circular orbits at approximately 400-km altitude. They have been orbiting Mars since 1997 and 2001 respectively. The UHF subsystem on MGS, called Mars Relay (MR), was provided by the Centre Nationale d'Etudes Spaciales (CNES) in France. The MR was designed to support retrieval of science data from a Russian probe. Although the probe was never flown on MGS, the MR system has been very useful to MER. However, as the capability for data transmission from orbiter to probe was not built into MR, MER can use MR only for telemetry reception; no commands can be sent from MGS to MER using the MR UHF link [2].. MER can transmit to MGS at data rates of 8 kbps and 128 kbps, and the data can be uncoded or coded with a rate 1/2, constraint length 7 convolutional code.

The UHF radios on Odyssey were built to communicate with MER-style lander radios using the Proximity-1 link protocol. In this link there is the capability of sending. In this link there is the capability of sending commands at 8 kbps; science and telemetry data can be sent in the return link with a data rate up to 256 kbps. As in the MGS case, this link can be convolutionally encoded.

As Spirit and Opportunity have both landed near the Mars equator – Gusev Crater being at 15 South, 175 East and Meridiani Planum being at 2 South, 354 East – there are typically two overflights in the morning and two in the afternoon for each rover - orbiter pair. The duration of the overflights is between 12 and 17 minutes for passes above 10° elevation.

4. MER Telecom Operations Highlights

A. Cruise

Spirit was launched on June 10, 2003 from Cape Canaveral, Florida. Opportunity followed on June 29, 2003. To support launch and near-Earth operations, the CLGA was used for all communications due to the close range to Earth and the possibility of saturating both the DSN's and the spacecraft's receivers. By mid-August, both spacecraft were commanded to switch to the CMGA for all nominal communications. During this phase of the mission, there were two main issues that the telecom system designers had prepared for: ensuring that the maximum supportable downlink data rate through the MGA was not violated, and that the spacecraft attitude in 'safing' would support the 'safing' downlink rate of 40 bps. Figure 3 illustrates the spacecraft attitude turns that were necessary to balance the off-Sun needs for the thermal subsystem and the minimum off-Earth requirements for use of the MGA.

Although it had been planned to operate the CMGA less than 5° off-boresight, the CMGA was actually operated as much as 10° off-boresight due to the desire to reduce workload on the operations team. As a consequence the downlink data rate was lower than initially anticipated. During the design and test of the MER spacecraft, it was difficult to arrive at the max. off-boresight angle that would be seen if the spacecraft was put in 'safe' mode. This occurs when flight software detects certain types of faults, primarily related to pointing or power malfunctions. Then on-board thrusters are fired to point the spacecraft at or near the Sun and the telecom system is reconfigured to use the CLGA. Although a downlink rate of 10 bps had been selected for safing, flight software was reconfigured prior to launch to select 40 bps for this 'safing' rate due to its superior data return and ease of use. As the range to Earth grew to 1 AU in the final months prior to EDL, the 40 bps downlink rate could be supported through the CLGA with a 70m DSN station at a maximum of 32 deg. off-boresight, or 10 deg less than the Sun-Probe-Earth angle. Luckily, neither MER spacecraft ever went into 'safe' mode during cruise.

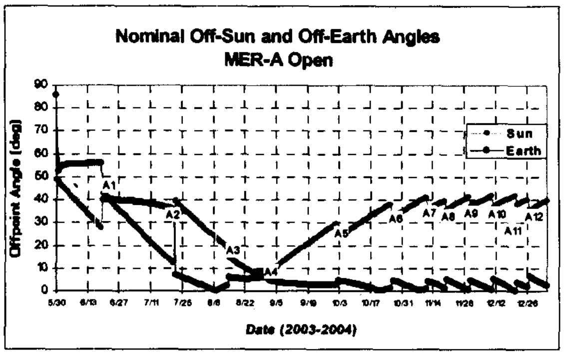

Figure 3. Off Sun and Off Earth Angles Resulting from 12 Planned Attitude Update Turns [3]

B.: Entry, Descent and Landing

MER's Entry, Descent, and Landing phase is defined to begin when the spacecraft reaches the atmospheric entry interface point at 3,522.2 km from the center of Mars. It ends when flight software declares the vehicle to have reached Rollstop. This time has been preset in flight software to be 10-minutes greater than the actual time of bridle cut. At this time, flight software transitions control of the vehicle from the EDL software to the Critical Deploy software. The latter causes the vehicle to autonomously initiate the events that will, with luck, allow the rover to reach a thermally stable, positive energy balance, commandable configurations.

Figure 5 depicts the EDL sequence of events starting at the beginning of the entry turn at Entry – 70 minutes. All of the events shown in the figure are performed autonomously by the spacecraft. At this time, the spacecraft's telecom system is configured to support up- and down-links via the CLGA (prior to this time the telecom system had been configured for communications via the CMGA), a downlink data rate of 10 bps is used to enable communications through the entry turn, In addition the SDST is set to use an internal frequency reference to generate the downlink carrier. The entry turn results in an off-boresight angle on the CLGA of 22° for Spirit and 40° for Opportunity. At Entry – 40 minutes the spacecraft vents all the freon from its thermal control subsystem (or heat rejection system). At this time the temperature in the lander begins to rise from about 0°C and the downlink carrier frequency, related to the output frequency of the SDST oscillator, begins to rise. 50-sec prior to cruise stage separation (CSS), the telecom subsystem is configured to transmit the MFSK signal – consisting of the carrier and an unmodulated subcarrier. The subcarrier freuqnecy can be changed every 10 sec to indicate spacecraft status. The MFSK transmission is continued until ignition of the retrorockets (RAD) at which point only a carrier is transmitted.

Nominally 15-minutes after CSS, the spacecraft hits the atmospheric interface point. At this point, the spacecraft begins to decelerate from 12,000 mph down to 1,000 mph in the Martian atmosphere. The outside temperature of the heatshield reaches over 1000°C but the rover electronics are only about 10°C. About 4 minutes after entry, the spacecraft deploys a parachute which decelerates the vehicle to about 250 mph. It then jettisons the heatshield, permitting the radar altimeter to acquire the lander's altitude. The lander is lowered from the backshell on a 20-m long bridle and begins to sway beneath the backshell-parachute system.

As the lander separates from the backshell, transmission of an 8 kbps signal from the DUHF to the MGS orbiter is begun. Transmission of both the MFSK signal directly to Earth via X band and the 8 kbps signal to MGS continues until RAD firing. At that time, the X band telecom subsystem is configured to transmit a carrier only signal. Both X band and UHF signals are transmitted through touchdown and the subsequent bouncing on the surface of Mars. Spirit and Opportunity each bounced for about 90 sec post touchdown until they came to rest on Mars. When the lander's flight software transitions into the Critical Deploy state, the UHF transmitter is turned off and the lander is commanded to transmit a set of 5 subcarriers – each 30 sec long – via the RLGA, switches to the lander antenna and transmits carrier only for 3 minutes then the 5 subcarrier are repeating. These signal the lander state prior to the critical mechanical deployments.

Figure 6 shows the received carrier signal-to-noise ratio in dB-Hz for Opportunity's EDL. The plot begins at E – 86 sec and ends after the second set of landed tones are transmitted. Each division in the plot represents 3 minutes. The Entry point occurred 3586 sec past the beginning of the track and landing occurred at 3937 sec. Bouncing occurs until 4040 sec whereupon 6 peaks of

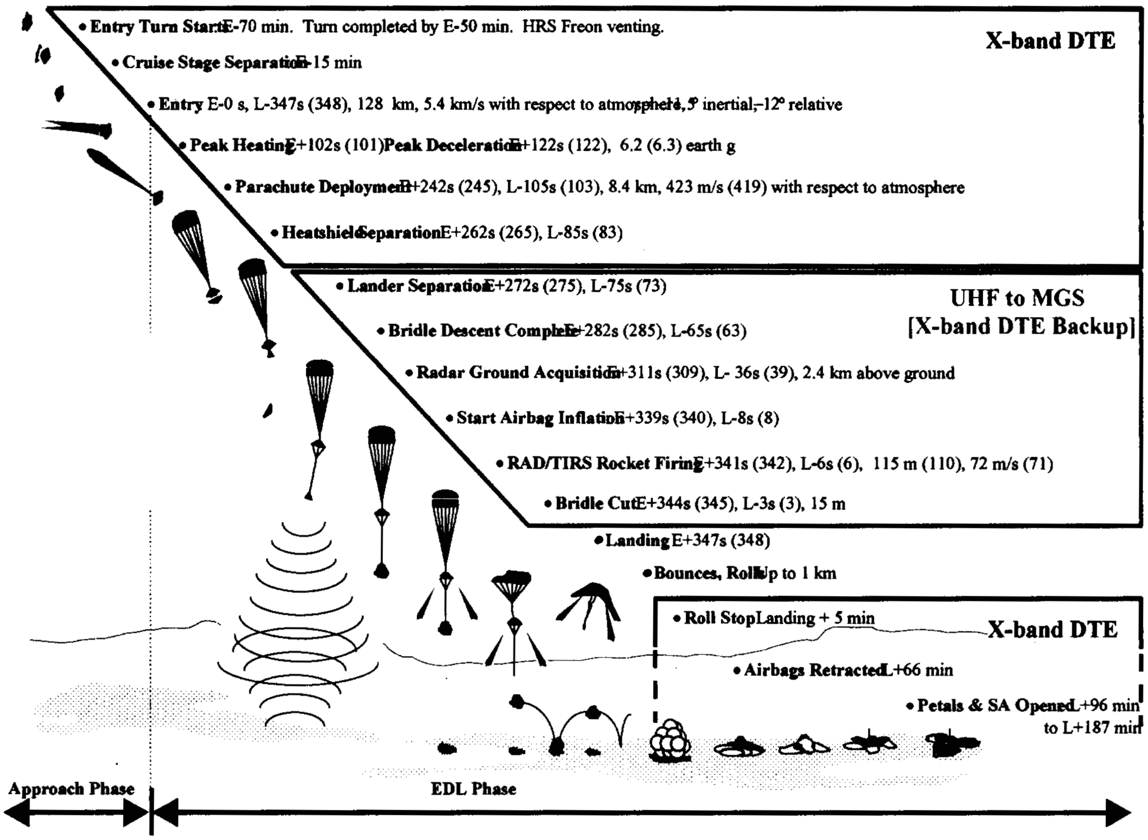

Figure 5. Entry, Descent, and Landing (EDL) Phase

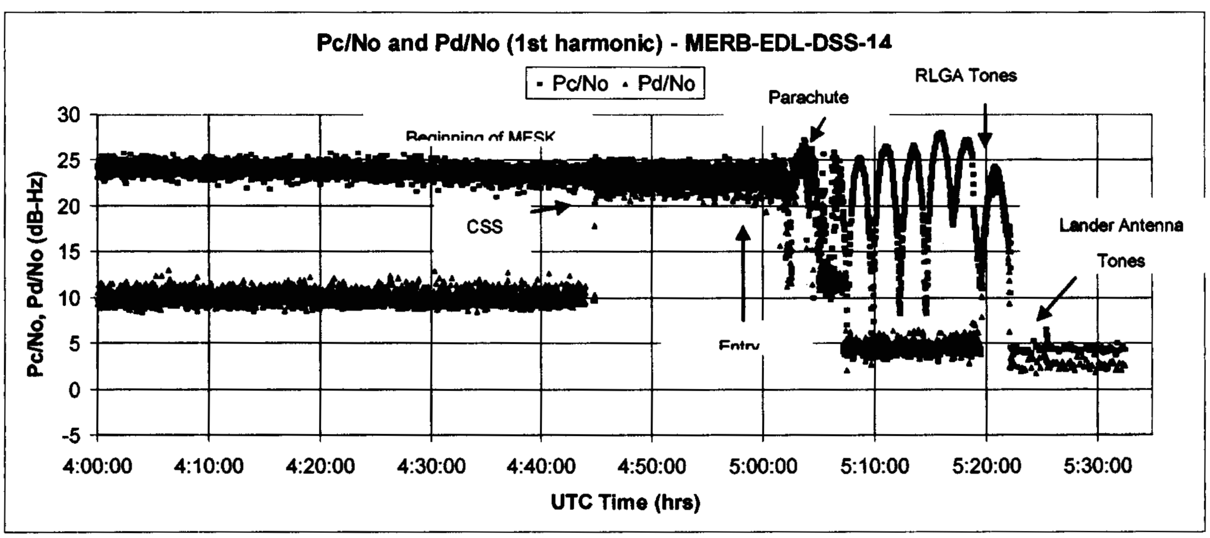

Figure 6. X-Band Recieved Pc/No during Opportunity EDL

the received signal can be seen. These correspond to multipath of the transmitted X band signal due to the Earth's setting.

Both 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 16-minute loss of signal after landing corresponding to the RLGA transmissions 130 ° off-boresight. This outage was removed in post-EDL signal processing.

The UHF 8Kbps signal was received by MGS from lander separation through the time of MGS setting for both Spirit and Opportunity.

C. : Surface

A typical sol on Mars for Spirit and Opportunity is as follows: the rover, depicted in Figure 6, wakes up for about 30 minutes at 0200 Local Solar Time (LST) as the MGS spacecraft passes overhead, it wakes up a second time for another 30 minutes at 0400 LST for the ODY pass. Both of these telecom passes use 128 kbps as the telemetry rate. At 0900 LST, the rover wakes again for the morning's work. It receives an uplink from Earth via the RLGA. Data is then downlinked via the HGA. The master sequence for the sol is executed and the rover performs science or mobility tasks until about mid-sol. It takes a 1 – 2 hour siesta to cool down the rover. About 1400 LST, the rover wakes and performs some afternoon acitivities and downlink data via the HGA to Earth and at about 1600 LST to downlink science data via ODY.

The X band link is used for commands to the rover and to downlink housekeeping telemetry and any 'critical' science data needed to plan the next sol's activities. Due to the unexpected ease of operation and large data return achieved with the UHF telecom subsystem, 'critical' data is also sent back over the UHF relay link.

The typical data volume returned per Sol is approximately 170 Mbits (excluding the recovery period from the Spirit software anomaly), with peaks up to 250 Mbits. Table 6 presents a breakdown of data return via the three different paths: Direct to Earth (DTE), via Mars Global Surveyor (MGS) and via Mars Odyssey orbiters.

Table 6. Data Volume Returned in Mbits as of 2/17/04

	Spirit Sol 44	Opportunity Sol 22
DTE	821 (15%)	913 (21%)
Relay - MGS	739 (14%)	831 (19%)
Relay - Odyssey	3736 (71%)	2647 (60%)

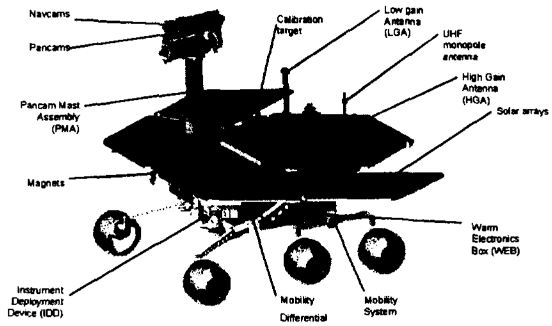

Figure 4. Deployed Rover

The telecom operations team is responsible to select which of the possible UHF passes to use on a given sol.. This choice is based on the predicted data return. It is interesting to note that given the asymmetry in the rover UHF antenna pattern, sometimes a low-elevation pass, using a good portion of the rover antenna pattern, can return more data than a higher-elevation pass. For a few selected UHF ODY passes on both Spirit and Opportunity, the maximum data rate of 256 kbps has been used, returning up to 150 Mbits of data in a single pass.

It is also important to mention the capability of sending commands at 8 kbps to the rovers using the Odyssey spacecraft; while this capability was mainly designed as a backup it has been fully validated after landing and it has occasionally been used in the morning pass, in order to have an head start in the sol's activities of the rover.

Finally a successful UHF overflight between Spirit and Mars Express was conducted on February 6, 2004. By transferring data in both direction, this communications session demonstrated the compatibility of the two implementation of CCSDS Proximity-1 link standard and the first realization of an international network of orbiters and landers at Mars which can provide cross-support between space agencies.

Some thoughts of future scenarios as the mission becomes more energy constrained and the Mars-Earth range increases

Communications with the orbiters constitutes the bulk of the data volume returned for both rovers (more the 80%); it is expected that as the Mars-Earth distance increases with the mission, the contribution of data coming via UHF will increase. As the two missions become more energy-constrained there will also be important trades to be made: for example all the morning passes might be deleted and the mission will rely heavily on one MGS pass and on one Odyssey pass in the afternoon to return science data.

5. Conclusions

MER Telecom subsystem has met design objectives. The UHF subsystem outperformed expectations given the operational complexity. Due to the rigorous operational test program that all MER hardware underwent, the telecom operations team has a wealth of data to understand nuances of operating equipment over wide power, temperature, and range of environments. Lastly, the MER telecom operations team has created new paradigms for telecom system operation: commanding in the blind, turning both X-band and UHF communications hardware off whenever the rover is 'sleeping'.

6. Acknowledgments.

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7. References

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