An Overview of the Telecom System for the Mars Exploration Rovers: Design Challenges and Performance Highlights

DESCANSO Seminar
by Polly Estabrook
2/21/03
## Project Timeline

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<th>Phase</th>
<th>Definition</th>
<th>MER-A Open Phase Start</th>
<th>MER-B Open Phase Start</th>
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<td><strong>Launch</strong></td>
<td>Launch to thermally stable, positive energy balance state, launch telemetry played back</td>
<td>May 30, 2003</td>
<td>June 25, 2003</td>
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<td><strong>Cruise</strong></td>
<td>End of Launch phase to Entry-45 days</td>
<td>May 31, 2003</td>
<td>June 26, 2003</td>
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<td><strong>Approach</strong></td>
<td>Entry-45 days to Entry</td>
<td>November 20, 2003</td>
<td>December 11, 2003</td>
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<td>Entry to end of critical deployments on Sol 1</td>
<td>January 4, 2004</td>
<td>January 25, 2004</td>
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<td><strong>Post-Landing Through Egress</strong></td>
<td>End of EDL to receipt of DTE following successful placement of rover wheels on the Martian surface</td>
<td>January 4, 2004</td>
<td>January 25, 2004</td>
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<td><strong>Surface Operations</strong></td>
<td>End of Egress to EOM</td>
<td>January 8, 2004</td>
<td>January 28, 2004</td>
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<td><strong>End of Mission (EOM)</strong></td>
<td>Successful receipt of last scheduled UHF data return the night of Sol 91</td>
<td>April 6, 2004</td>
<td>April 27, 2004</td>
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</table>
Where are the Rovers going?

Prime Sites for MER-A:  Hematite, Isidis, Gusev
Prime Sites for MER-B:  Hematite, Isidis, Elysium
Why Go?

- Search for and characterize a diversity of rocks and soils that hold clues to past water activity (water-bearing minerals and minerals deposited by precipitation, evaporation, sedimentary cementation, or hydrothermal activity)
- Investigate landing sites, selected on the basis of orbital remote sensing, which have a high probability of containing physical and/or chemical evidence of the action of liquid water
- Determine the spatial distribution and composition of minerals, rocks, and soils surrounding the landing sites
- Determine the nature of local surface geologic processes from surface morphology and chemistry
- Calibrate and validate orbital remote sensing data and assess the amount and scale of heterogeneity at each landing site
- For iron-containing minerals, identify and quantify relative amounts of specific mineral types that contain H$_2$O or OH, or are indicators of formation by an aqueous process, such as iron-bearing carbonates
- Characterize the mineral assemblages and textures of different types of rocks and soils and put them in geologic context
- Extract clues from the geologic investigation, related to the environmental conditions when liquid water was present and assess whether those environments were conducive for life
Telecom’s Mission
(AKA Level 1 Requirements)

• Mission Success Criteria:
  – The spacecraft shall approach Mars on a posigrade trajectory designed to support direct communications with Earth during EDL through roll stop. The spacecraft shall provide direct communications of data during EDL through roll stop at a rate and volume sufficient to provide support for fault reconstruction
  – The MER-2003 rovers shall be designed to utilize direct-to-Earth X-band communications for surface operations
  – The MER-2003 Project shall be designed to utilize two-way UHF communications through the MER-2001 Orbiter as an operational capability

• Science Requirements
  – Drive the rovers to at least 8 separate locations and use the instrument suite to investigate the context and diversity of the Mars geologic environment.

• Technology and Program Feed-Forward Requirements
  – To validate the NASA-compatible international telecommunications infrastructure, the MER-2003 Project shall demonstrate telecommunications capabilities through the Mars Express orbiter.
Support DOR tone transmission for Delta-VLBI for all Mission Phases (used only in Cruise)

Near-Earth (Launch to L+14 days):
- Nominal: 250 bps Command, 300 bps Telemetry, Ranging (2m for 1 sigma, 600 sec) into a 34 m DSN, 60 deg off CLGA boresight
- Safing: 7.8 bps CMD, 10 bps TLM, no ranging into a 70m DSN, 60 deg off CLGA boresight

Cruise and Approach:
- Nominal: 125 bps CMD into 34m DSN (10 deg elev, 90% weather), 5 deg off CMGA boresight, max. range (1.33 AU)
- Nominal: Ranging (4m, 600 sec) into 34m DSN, with CMD off, 40 bps TLM into 34m DSN, 5 deg off CMGA boresight, max. range (1.33 AU)
- Safing: 7.8 bps CMD, 10 bps TLM, no ranging, into a 70m DSN, 55 deg off CLGA boresight for CMD, 20 deg off CLGA boresight for TLM, max. range (1.33 AU)

Surface:
- Nominal into a 34m DSN: 125 bps CMD, 400 bps TLM
- Nominal into a 70m DSN: 250 bps CMD, 1850 bps TLM
- Safing: 7.8 bps CMD, 10 bps TLM, no ranging, into a 70m DSN, 70 deg off RLGA boresight for CMD, 30 deg off RLGA boresight for TLM, max. range (2.14 AU)

Details: DSN Passes assumed at 10 deg elev during cruise, 20 deg elev during surface, 90% weather for all non-EDL links, (7, ½) code for all safing and cruise ops, (15,1/6) code for HGA links on surface only
Telecom Level 3 Link Requirements: EDL and UHF

- **EDL – X band:**
  - Turn to Entry to CSS separation: 10 bps TLM, max off point CLGA 46 deg, into a 70m DSN, 20 deg elev, 90% weather
  - From CSS to Lander Separation: Transmit 10 sec tones, with 90% probability of correct receipt, max off point angle 70 deg, 30 deg DSN elev, 95% weather
  - Bridle deployment to Rollstop: Transmit 10 sec tones, best effort basis
  - At Rollstop: Transmit 20 sec tones with a 40% prob. Of correct receipt, max offpoint angle 70 deg, 30 deg DSN elev, 95% weather

- **EDL – UHF:**
  - From Lander Separation to Airbag inflation: Transmit one way 8 Kbps link to MGS - best effort basis

- **Surface – UHF:**
  - Transmit 100 Mbits on average over 2 sols to MSP’01 Orbiter
  - Receive 2 Mbits on average over 2 sols to MSP’01 Orbiter
MER Rover Operations - Telecom
Overview

1. DSN-ROVER FORWARD LINK 7.8 bps-2 kbps 7140 MHz (P)
2. ROVER-DSN RETURN LINK 10 bps-2 kbps 8440 MHz (P)
3. ROVER-M’01 RETURN LINK 8, 32, 128, 256 kbps 401.585625 MHz (P)
4. M’01-ROVER FORWARD LINK 8 kbps 437.1 MHz (B)
5. ROVER-MARS EXPRESS FORWARD 8 kbps 437.1 MHz (B)
6. ROVER-MARS EXPRESS RETURN 8, 32, 128 kbps 401.585625 MHz (B)
7. ROVER-MGS RETURN 8, 128 kbps 401.528711 MHz (B)
MER-A Entry, Descent, Landing - Telecom Overview

- Entry Turn & HRS Freon Venting: E - 1:30:00
- Cruise Stage Separation: E - 0:30:00
  - Entry: E - 0 s, 129 km, 5.4 km/s wrt atmos., γ = -11.5° inertial, -12° relative
  - Peak Heating / Deceleration: 34 W/cm², 6.5 earth g
  - Parachute Deployment: E + 237 s, 10.8 km, 449 m/s wrt atmos.
- Heatshield Separation: E + 257 s
- Lander Separation: E + 277 s
  - Bridle Deployed: E + 287 s
  - Radar Ground Acquisition: L - 34 s, 2.4 km above ground
  - Airbag Inflation: ~450 m, L - 10 s
- Rocket Firing: L - 6 s, 125 m, 76 m/s
  - Bridle Cut: L - 3 s, 16 m
  - Landing: E + 359 s
  - Bounces: >15, Rolls Up to 1 km
  - Roll to a Stop: Base Petal Down, Landing + 2 min
  - Earth Set: Landing + 69 min
  - Deflation / Petal Latch Firing: Landing + 90 min

Launch = 6/3/03
Arrival = 1/4/04
Landing at 5N Nominal Times and States
Project PDR baseline
What have we built?
MER-2 Ch.32 Xband Radio Frequency System in ATLO 10/01/02
What have we built?
UHF Transceiver S/N 002 Before and After Taping
MER SC-1 Telecom Support Test Equipment: X band and UHF
MER Antennas !!
(see cover page for view on Rover)

PLGA: Petal Low Gain Antenna
Peak Gain Free space = 7 dBi

HGA: Printed dipole antenna (made by Ball Aerospace), similar to MPF

DUHF: Pop-up Monopole using MPF actuator on lander mockup
CLGA, BLGA, RLGA and MGA Hardware
Exploded View

CLGA Assembly
- CLGA
- Polarizer P3
- Dual E-Bend
- Polarizer Adapter

BLGA
- WG-to-Coax Adapters
- Polarizer P2
- WG Slip Fit interface
- (significantly longer than shown in this picture)

MGA Horn
- MGA
- Polarizer P4
- Dual E-Bend
- Polarizer Adapter
- WG-to-coax Adapter

RLGA Assembly
- RLGA (base section and sprung section, held together by spring retainer)
- Spring Retainer
- Polarizer P1
- WG-SMA Polarizer Adapter
- Antenna Bracket

From MER Antenna Subsystem Peer Review, 5/3/01
**Cruise Stage Antennas**
- **CMGA** - Cruise Stage MGA
  - Used during Cruise
- **CLGA** - Cruise Stage LGA
  - Used during early & late cruise
- **P2-P4** - Polarizer with dual E-Bend Adapter

**Descent & Landing Antennas**
- **RUHF** – Rover UHF LGA
  - Used during ground ops for link with orbiter
- **HGA** – High Gain Antenna
  - Used during ground ops as prime data link

**Antenna Stack**
- **BLGA** - Back Shell LGA
  - Used during Mars entry after cruise stage eject
- **RLGA** - Rover LGA
  - Used during parachute descent & ground ops
- **P1** - Polarizer with WG-SMA Adapter

**RAS Antennas**
- **RAAT** - Transmit
- **RAAR** - Receive
  - Used during final descent
Design Challenges:
X band Cable Routing and Associated Cable Losses

Concern over X-band cable routing and Level 3 specification to support ranging, command, and telemetry at Mars Approach led to change in CMGA from Mars Pathfinder baseline to higher gain horn prior to PDR.

<table>
<thead>
<tr>
<th>Antenna</th>
<th>Transmit Loss (dB)</th>
<th>Peer Review 5/23/01</th>
<th>Present 7/22/02</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLGA</td>
<td>1.75</td>
<td>2.53</td>
<td>2.31</td>
</tr>
<tr>
<td>BLGA</td>
<td>1.39</td>
<td>1.64</td>
<td>1.30</td>
</tr>
<tr>
<td>RLGA</td>
<td>1.38</td>
<td>1.62</td>
<td>1.30</td>
</tr>
<tr>
<td>CMGA</td>
<td>4.29</td>
<td>4.53</td>
<td>3.44</td>
</tr>
<tr>
<td>HGA</td>
<td>4.22</td>
<td>4.28</td>
<td>2.79</td>
</tr>
<tr>
<td>PLGA</td>
<td>4.28</td>
<td>5.01</td>
<td>2.71</td>
</tr>
</tbody>
</table>

Cable Losses reflect use of 4 PLGA and associated switches.

Concern over X-band cable routing and Level 3 specification to support ranging, command, and telemetry at Mars Approach led to change in CMGA from Mars Pathfinder baseline to higher gain horn prior to PDR.
Design Challenges: Spacecraft Pointing

- Trade studies on solar array vs. CMGA pointing performed to balance power vs. telecom needs and to establish CLGA pointing during safing.

- Maximum CMGA offpoint is 8 degrees (2.2 dB down from max. gain)
- Maximum CLGA offpoint is 55 degrees post near-Earth (6 dB down from max. gain)

Sun and Earth Offpoint Angles

MER-B Close

Worst Case Safing Angles (1/02)

Max Angle = 55.5 deg (Close) on 12/15/03
• Post PDR, UHF Baseline Antenna, a monopole located on Rover Solar Panel, was measured on a rover mockup and found to have very asymmetric pattern
  – Resulted in widely varying Data Return vs. Rover Orientation and ODY pass geometry

• Breadboard models of 5 other antennas were made, tested on the Rover mockup, some found to possess more azimuthally symmetric patterns but were deemed too difficult to implement given tight MER timeline

• Baseline antenna was kept
  – Level 3 Requirements can be met (on average can achieve 100 Mbits/2 sols, but minimum may be 60 Mbits/2 sols!);
  – MGS support is planned to achieve additional data return;
  – Data return for a given day cannot be predicted
UHF Rover Antenna Patterns Measured on Rover Mockup
UHF Surface Performance: Telemetry Link
(MER2 to ODY at Hematite)

Data Return Bars show minimum, average, and maximum data return per sol for ‘worst’, average, and ‘best’ rover orientation.
UHF Surface Performance: Command Link (ODY to MER2 at Hematite)

Data Return Bars show minimum, average, and maximum data return per sol for ‘worst’, average, and ‘best’ rover orientation.
MER2-ODY
Monopole FM1, Max Elevation per Pass vs Data Volume, 128 kbps, 2dB Fixed Margin
Certain science instruments (PMA, and Micro Imager) have been found to create EMC which degrades UHF transceiver’s receiver threshold. Flight Rules have been made so that these instruments will NOT operate during a UHF pass.
X-band EDL Design Issues

- Signal Structure
- Expected Pt/No at 70m DSN
- Residual Doppler (and Doppler Acceleration)
- Dynamics
- Plasma
- EDL Data Analysis (EDA) System
Landing Ellipse Size

From Rob Manning
EDL Signal Structure and EDA Performance

- Spacecraft telecom system transmits carrier and MFSK signals (RCP) using
  - Backshell LGA (BLGA) used from entry to lander separation
  - Rover LGA (RLGA) used from lander separation to landing
- MFSK Signal Format
  - Desired carrier suppression 3 dB ONLY (desired modulation index of 45deg for all subcarrier frequencies) during entry and descent; 3.5 dB for post-rollstop tones
  - MFSK alphabet is 256 (each MFSK signal denotes particular state or event on spacecraft)
    - Small Deep Space Transponder (SDST) can generate subcarriers in steps of 0.7 Hz
  - MFSK Duration:
    - Every 10 sec from Entry to Bridle Deploy
      - Specific events trigger immediate generation of MFSK signal, e.g. parachute deploy
      - These signals override currently transmitted tone
    - Every 20 sec post roll-stop
- DSN configured with Radio Science Receivers to digitize received signal for subsequent post processing to determine carrier and identify transmitted MFSK tone
- EDL Data Analysis (EDA) System has been developed to recover carrier and tones from digitized data using FFT-based analysis techniques.
- EDA Algorithm performance depends on the following signal characteristics:
  - $P_c/No$ and $P_d/No$, residual Doppler acceleration, tone duration
Fluctuation in Pt/No arise due to change in BLGA and RLGA antenna off-boresight Angle during EDL; Variations in Required Threshold due to changes in EDA algorithm (FFT BW, coherent vs. non-coherent Integration time) during the phases of EDL.

DESCANSO Talk: MER Telecom
Doppler Residuals Expected during EDL

Difference in Doppler MER A Predicts
- Difference in Doppler between Nominal and Steep (Hz)
- Difference in Doppler between Steep and Shallow (Hz)

Difference in Doppler Rate MER A Predicts
- Difference in Doppler between Nominal and Steep (Hz)
- Difference in Doppler between Steep and Shallow (Hz)

Difference in Doppler Acceleration MER A Predicts
- Difference in Doppler between Nominal and Steep (Hz)
- Difference in Doppler between Steep and Shallow (Hz)
Plasma: Is it an Issue?  
Mars Pathfinder Comm. during EDL

**Pathfinder Electron Density Profile**

Critical Electron Density to cause comm outage at X-band = $8.8 \times 10^{11}$

**Conclusion:** Comm blackout more or less aligned with time period when electron density in wake region (where BLGA is located) greater than critical density.

(Courtesy D. Morabito)
Electron Density around MPF Entry Vehicle at Entry + 60 sec

Critical Electron Density to cause comm outage at X-band = $8.8 \times 10^{11}$

Conclusion: For MPF, comm signal path from BLGA to Earth would pass through regions of plasma containing an electron density greater than critical density.
MER B Electron Density Prediction at S/C -z axis Wake and Stagnation Region Points

Velocity and altitude profile provided by P. Desai (8/13/2001)

**Conclusion:** It is unlikely that there will be a communications blackout due to ionized charged particles for MER-B.

From D. Morabito
MER Level 2 Reqs.: 70m at one DSN station with a goal of arraying all available antennas; rx and process data tx via UHF to MGS during EDL

DESCANSO Talk: MER Telecom
EDA Displays Seen at MER MSA: Freq and Freq. Acceleration (from Test Run)

From Tim Pham / Dave Fort
Each rectangle represents freq estimate produced by processing 1 sec of processed received signal (i.e., with Dynamics removed). Color of rectangle indicates signal strength.

From Tim Pham / Dave Fort

DESCANSO Talk: MER Telecom
MER on MARS
For More Information: Documents

- MER Telecommunications System Handbook
  - Covers X-band telecom system, performance, test results, idiosyncrasies
- MER UHF Telecom Handbook
  - Covers UHF telecom system, performance, compatibility with MGS, ODY, and Mars Express, idiosyncrasies
- MER Mission Plan
  - Description of MER Mission Plan by Mission Phase
- MER Entry Descent and Landing Performance Assessment Report
  - EDL geometry for DTE and UHF link, S/C to Earth range rates,
- MER Interplanetary Trajectory Characteristics Document
  - Range, pointing angles, DSN station elevation,
- MER Detailed Mission Requirements
  - Covers DSMS support agreements
- Many test results on MER Docushare
For More Information: Telecom Team

- Telecom System and Project Interaction: Jeff Hilland
- X band System Engineering Issues: Andre Makovsky
- UHF System Engineering Issues: Andrea Barbieri
- MER Antennas: Joe Vacchione
- X band Radio Frequency System: Brian Cook
- UHF Telecom System: Peter Ilott
- X band Integration and Test: Ernie Stone, Adolfo Valerin, Tuan Tran
- Radar Altimeter System: Scott Shaffer
Backups
CLGA Pattern on Cruise Mockup

Transmit Gain and Receive Gain vs Angle of Boresight

On-Boresight Gain:
- Receive Gain = 7.7 dBi
- Transmit Gain = 7.2 dBi
Test Article: PLGA under Airbags
Interaction of Airbags and PLGA Performance

- PLGA pattern with inflated airbags
- PLGA pattern with deflated airbags
Measured Pattern/Gain Data
Inflated Airbag

Gain Requirement

Coverage Requirement

Azimuth – degrees from boresight

No Airbag
Inflated Airbag 0 deg roll cut with 3/4 inch spacer
Inflated airbag +20 deg roll cut with 3/4 inch spacer
Inflated Airbag 40 deg roll cut with 3/4 inch spacer
Inflated airbag -20 deg roll cut with 3/4 inch spacer
Inflated Airbag 0 deg roll cut with MLI cover
Deflated Airbag Over Antenna

2 Folds

4 Folds

5+ Folds

Packed w/ MLI Cover
Measured Pattern/Gain Data
Deflated Airbag

Gain Requirement

Coverage Requirement

Azimuth – degrees from boresight

-80 -60 -40 -20 0 20 40 60 80

Gain (dBiC)

-35 -30 -25 -20 -15 -10 -5 0 5 10

No Airbag
Airbag with 1 fold & 3/4 inch spacer
Airbag with 2 folds & 3/4 inch spacer
Airbag with 3 folds & 3/4 inch spacer
Airbag with 4 folds & 3/4 inch spacer
Airbag with >5 folds & 3/4 inch spacer
Other Telecom System Engineering Trade Studies and Test Issues

- Frequency interference issues with Deep Impact
- Telecom H/W interaction with FSW
  - Telecom Support Board Issues
    - Clock rate
    - Uplink FPGA
- UHF EMC performance in Screen Room
- Communication Behavior Manager
- EDL Comm. Manager