Relay Support for the Mars Science Laboratory and the Coming Decade of Mars Relay Network Evolution

Charles D. Edwards, Jr., Bradford W. Arnold, David J. Bell, Kristoffer N. Bruvold, Roy E. Gladden, Peter A. Ilott, Charles H. Lee
Jet Propulsion Laboratory, California Institute of Technology

March 8, 2012

chad.edwards@jpl.nasa.gov
Outline

• Benefits of a Mars Relay Network
• Current Mars Relay Network description
• Electra Proximity Link Payload
• MSL Relay support
  – Critical Event Communications during EDL
  – Curiosity Rover Surface Operations
• MAVEN
• ExoMars/Trace Gas Orbiter
• Relay Support for the 2018 Mars Joint Rover Mission Concept
• Summary
Benefits of a Mars Relay Network

- **Increased data return**
  - Significantly increase science return from the Martian surface
  - *MER*: >97% data return via relay

- **Energy efficiency**
  - Enable small, low-cost mission concepts
  - *MER*: 10-100x lower energy-per-bit compared to X-band DTE
  - *PHX*: UHF-only mission

- **Connectivity**
  - Support interactive, *in situ* ops
  - *MER*: Contacts during Martian night
  - *PHX*: up to 10 relay contacts/sol

- **Critical event telemetry**
  - Capture engineering telemetry during high-risk mission phases
  - *PHX*: 32 kbps telemetry during EDL

- **Radio-based navigation**
  - Utilize radio metric observables on comm links for *in situ* nav
  - *PHX*: <30m (3σ) surface position determination
Current Mars Relay Network

**Odyssey**
- **Launched**: 2001
- **Orbit**:
  - 400 km sun-synch
  - 93° inclination
  - ~4 AM LMST asc node
- **Deep Space Link**:
  - X-band
  - 1.3 m HGA
  - 15 W SSPA
- **Relay Link**:
  - CE-505 UHF Txcvr
  - Quadrifilar Helix Antenna
  - 8, 32, 128, 256 kbps
  - CCSDS Prox-1 Protocol

**Mars Express**
- **Launched**: 2003
- **Orbit**:
  - 250 x 10,142 elliptical
  - 86° inclination
  - Non-sun-synch
- **Deep Space Link**:
  - X-band
  - 1.65 m HGA
  - 65W TWTA
- **Relay Link**:
  - Melacom UHF Txcvr
  - Patch Antennas (2)
  - 2, 4, ..., 128 kbps
  - CCSDS Prox-1 Protocol

**MRO**
- **Launched**: 2005
- **Orbit**:
  - 255 x 320 km sun-synch
  - 93° inclination
  - ~3 PM LMST asc node
- **Deep Space Link**:
  - X-band
  - 3 m HGA
  - 100 W TWTA
- **Relay Link**:
  - Electra UHF Txcvr
  - Quadrifilar Helix Antenna
  - 1, 2, 4, ..., 2048 kbps
  - Adaptive Data Rates
  - CCSDS Prox-1 Protocol
Electra and Electra-Lite UHF Transceivers

- **Software-defined radio architecture**
  - Flight-reprogrammable digital baseband processor w/ Sparc microcontroller and Xilinx FPGA
- **Frequency-agile operation over 390-450 MHz UHF band**
- **CCSDS Proximity-1 Space Link Protocol**
  - Enables interoperability with other Mars proximity radios (CE-505, Melacom)
- **Data rates: 1, 2, 4, … 2048 kbps**
  - Uncoded and (7,1/2) convolutionally coded modes
- **Adaptive Data Rate capability**
  - Return link data rate is
- **Additional services**
  - Open-loop recording capability
    - 8-bit I&Q samples @ up to 150 kHz sample rates
  - Phase/Power sampling
    - Supports Doppler-based lander position determination
  - Time correlation services
- **Mass:**
  - Electra (MRO): 5.0 kg
  - Electra-Lite (MSL): 3.1 kg
Guided entry corrects for atmospheric variability and improves landing accuracy.

“Sky Crane” design places the rover directly on Martian soil while keeping the rockets away from the ground.
MSL EDL Arrival Geometry
MSL EDL EDL Telecommunications Overview

Cruise Stage Sep

Turn to Entry

Exo-Atmospheric

Jettison Cruise Balance Mass

Entry Interface

Entry, Descent and Landing

Parachute Deploy

Backshell Sep

Landing

MEX sets just prior to Landing

Potential UHF Plasma Blackout

High-Fidelity Open Loop Recording, Post-EDL Playback to Ground for Post-Processing (Carrier-Only; few hrs latency)

Potential Short (~1s) UHF Dropouts Due to MSL Powered Descent Dynamics

HiRISE Imaging

X-band: Transmit MFSK Tones (~one 8-bit symbol every 10 sec)

UHF: Transmit 8 kbps MSL Telemetry

MEX sets just prior to Landing

Canberra 70m/34m Reception; Real-time Playback to JPL for MSL Carrier & MFSK Tone Demodulation

8 kbps Demodulation & Bent-Pipe Relay to Earth

Real-time visibility of MSL Carrier and Telemetry

"Canister Mode" Open Loop Recording, Post-EDL Playback to Ground for Post-Processing (Carrier-Only; few hrs latency)
MSL Surface Relay Support

• Curiosity Rover’s rich science instrument suite drives need for increased data return

• Time-critical rover commanding primarily via X-band Direct-From-Earth link each Martian morning
  – Augment with ODY/MRO UHF forward link for non-time-critical commanding and s/w uploads

• Data return primarily via MRO and ODY UHF relays, based on high instantaneous data rates and low energy cost
  – MEX offers back relay support if ODY and/or MRO become unavailable
MSL Surface Communications

Overnight planning cycle

AM contact opportunities

PM contact opportunities

Daytime lander activity

X-band (Direct-From-Earth Uplink)

ODY (4 PM descending node)

MRO (3 PM ascending node)

Midnight

Noon

6 AM

6 PM
MSL Relay Data Return

- **Nominal Curiosity surface mission** is based on average return of 250 Mb/sol
- **Key MSL UHF link assumptions**
  - Best AM + Best PM pass
  - 2-sigma statistical link margin (~2 dB)
  - 10 deg elevation mask
  - **ODY:**
    - Fixed data rate, selected from 8, 32, 128, 256 kbps coded for each pass
    - Fixed ODY nadir orientation
  - **MRO:**
    - Adaptive Data Rate
    - 4 dB link degradation due to EMI from MRO science instruments (@ 391 MHz channel)
    - MRO roll-steering to +/- 30 deg to improve MRO antenna gain
MAVEN

• **Second Mars Scout mission**
  – Focused aeronomy science
  – AO requires orbiter to carry MEP-provided Electra payload (single-string)
  – MAVEN Team:
    • PI: Bruce Jakosky, UC Boulder
    • GSFC: Project mgmt, NGIMS
    • LMA: S/C system contractor
    • Instruments: GSFC; UC Berkeley/SLL; LASP
    • JPL: Electra, Relay Ops, Navigation, MGSS, DSN

• **Mission summary**
  – Launch Nov 18 – Dec 7, 2013
  – MOI Sep 16 – 24, 2014
  – One earth year primary science mission
  – Elliptical orbit for aeronomy science
    • 150 x 6200 km orbit
    • 75 deg inclination
    • Apsidal and nodal precession
MAVEN Relay Assessment Summary

Key assumptions:
- Electra Adaptive Data Rate
- LDPC coding (provides ~ 3dB performance advantage)
- Nadir MAVEN antenna pointing
- 3 dB link margin

Results:
- MAVEN orbit offers 1-4 passes per sol for +-30 deg latitude range
- However, elliptical orbit results in significant variability in relay statistics depending on latitude and local time of periapsis
  - Northern Hemisphere /Southern Hemisphere asymmetries
  - Day/Night asymmetries
- Highly variable slant range
  - 150 km - 8400 km
  - Results in wide range of supportable data rates
  - For some orbit orientations, long passes at low rates are required to achieve large data return

<table>
<thead>
<tr>
<th>Metric</th>
<th>Summary (for +-30 deg Lat)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of passes per sol</td>
<td>1-4</td>
</tr>
<tr>
<td>Avg duration per pass</td>
<td>25-150 min</td>
</tr>
<tr>
<td></td>
<td>N-S, day/night asymmetries</td>
</tr>
<tr>
<td>Max comm gap</td>
<td>10-20 hr</td>
</tr>
<tr>
<td>Total contact time per sol</td>
<td>50 min - 10 hr</td>
</tr>
<tr>
<td></td>
<td>N-S, day/night asymmetries</td>
</tr>
<tr>
<td>Data return for best 10-minute pass</td>
<td>5-300 Mb/sol</td>
</tr>
<tr>
<td></td>
<td>(Avg ~ 85 Mb/sol)</td>
</tr>
<tr>
<td></td>
<td>N-S, day/night asymmetries</td>
</tr>
<tr>
<td>Data return for two best 30-min passes</td>
<td>30-400 Mb/sol</td>
</tr>
<tr>
<td></td>
<td>(Avg ~ 150 Mb/sol)</td>
</tr>
<tr>
<td></td>
<td>N-S, day/night asymmetries</td>
</tr>
</tbody>
</table>
ExoMars/Trace Gas Orbiter

- n.b. Based on the President’s FY13 Budget, NASA has withdrawn from the proposed NASA/ESA 2016 EMTGO and 2018 Joint Rover missions. We present the mission concepts as they were understood at the time this paper was submitted, to illustrate potential Mars relay capabilities.

**Mission summary**
- Launch Jan, 2016
- Deploy ESA EDL Demonstrator Module (EDM) @ E-4d
- MOI Oct, 2016
  - Orbiter provides critical event comm support to EDM during EDL
  - Aerobrake to 400 km circular orbit, 74 deg inclination (non-sun-synch)
- One Mars year primary science
- Extended relay ops through Dec, 2022

**Relay Payload**
- Dual-string Electra UHF Transceiver
- Build-to-print of MAVEN Electra design
Relay Support for the 2018 Mars Joint Rover

- n.b. Based on the President’s FY13 Budget, NASA has withdrawn from the proposed NASA/ESA 2016 EMTGO and 2018 Joint Rover missions. We present the mission concepts as they were understood at the time this paper was submitted, to illustrate potential Mars relay capabilities.

- **MSL-class rover with ESA Pasteur in situ payload and NASA sample caching payload**
  - -15 to +25 deg latitude

- **Baseline ESA QinetiQ UHF transceiver**
  - Also assessed Electra-Lite option for comparison

### Table: Comparison of QinetiQ and Electra-Lite

<table>
<thead>
<tr>
<th>Item</th>
<th>QinetiQ</th>
<th>Electra-Lite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmit Power</td>
<td>6 W</td>
<td>8.5 W</td>
</tr>
<tr>
<td>Coding</td>
<td>(7, ½) CC</td>
<td>LDPC</td>
</tr>
<tr>
<td>Max bit rate</td>
<td>1024 kbps</td>
<td>2048 kbps</td>
</tr>
</tbody>
</table>

Key Assumptions: 24 deg N latitude, 10 deg horizon mask, MSL Quad Helix antenna, best 3 passes/sol, 1-hr constraint on pass duration.
Summary

- Mars Relay Network is prepared to support MSL
  - ODY/MRO/MEX will all provide critical event comm support during EDL
  - New Electra/Electra-Lite capabilities on the MSL-MRO link will support >250 Mb/sol MSL data return

- 2013 MAVEN orbiter will replenish on-orbit relay infrastructure as prior orbiters approach end-of-life

- While NASA has withdrawn from the 2016 EMTGO and 2018 Joint Rover missions, analysis of the potential link shows a path to Gbit/sol relay capability
Backup
# Key Model Parameters for 2018 Joint Rover

<table>
<thead>
<tr>
<th>Item</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landing site</td>
<td>24 deg N Lat, 352 deg E Long</td>
</tr>
<tr>
<td>Horizon mask</td>
<td>10 deg</td>
</tr>
<tr>
<td><strong>UHF Transceiver</strong></td>
<td><strong>QinetiQ (Baseline)</strong></td>
</tr>
<tr>
<td>Transmit Power</td>
<td>6.0 W</td>
</tr>
<tr>
<td>Transmitter Circuit Loss</td>
<td>1.7 dB</td>
</tr>
<tr>
<td>Supportable data rates</td>
<td>8 – 1024 kbps</td>
</tr>
<tr>
<td>Surface antenna</td>
<td>MSL Quadrifilar Helix</td>
</tr>
<tr>
<td>Coding</td>
<td>(7, ½ )</td>
</tr>
<tr>
<td></td>
<td>Electra-Lite (Option)</td>
</tr>
<tr>
<td></td>
<td>8.5 W</td>
</tr>
<tr>
<td></td>
<td>1.7 dB</td>
</tr>
<tr>
<td></td>
<td>1-2048 kbps</td>
</tr>
<tr>
<td></td>
<td>MSL Quadrifilar Helix</td>
</tr>
<tr>
<td></td>
<td>LDPC (3 dB coding gain)</td>
</tr>
</tbody>
</table>
# Key Model Parameters for Mars Relay Orbiters

<table>
<thead>
<tr>
<th>Item</th>
<th>MRO</th>
<th>MAVEN</th>
<th>EMTGO</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Orbit</strong></td>
<td>255 x 320 km</td>
<td>250 x 6200 km</td>
<td>400 km circular</td>
</tr>
<tr>
<td></td>
<td>Incl = 92.6 deg (Sun-Synch)</td>
<td>Incl = 75 deg</td>
<td>Incl = 74 deg (Non-Sun-Synch)</td>
</tr>
<tr>
<td></td>
<td>3 PM LMST Asc Node</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>UHF Antenna</strong></td>
<td>Litton Quad Helix</td>
<td>3 dB Quad Helix</td>
<td>3 dB Quad Helix</td>
</tr>
<tr>
<td></td>
<td>4.1 dB Ant Sys Loss</td>
<td>1.5 dB Ant Sys Loss</td>
<td>1.5 dB Ant Sys Loss</td>
</tr>
<tr>
<td><strong>Antenna Pointing</strong></td>
<td>+30 deg Roll Steering</td>
<td>Nadir</td>
<td>Nadir</td>
</tr>
<tr>
<td><strong>Polarization Loss</strong></td>
<td>0.8 dB</td>
<td>0.8 dB</td>
<td>0.8 dB</td>
</tr>
<tr>
<td><strong>EMI Degradation</strong></td>
<td>4.0 dB</td>
<td>0.5 dB</td>
<td>0.5 dB</td>
</tr>
</tbody>
</table>

**Electra UHF Configuration**

(Referenced to (7,5) convolutional code, 10° BER, w/out EMI losses, measured at Electra input connector)

<table>
<thead>
<tr>
<th>Data Rate (kbps)</th>
<th>Modulation</th>
<th>Threshold Power (dBm)</th>
<th>ADR Switching Time (s)</th>
<th>Prox-1 Efficiency (Return)</th>
<th>Prox-1 Efficiency (Forward)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Residual carrier</td>
<td>-133.3</td>
<td>5</td>
<td>0.8111</td>
<td>0.8347</td>
</tr>
<tr>
<td>2</td>
<td>Mod Index = 60 deg</td>
<td>-130.3</td>
<td>5</td>
<td>0.8111</td>
<td>0.8347</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>-127.2</td>
<td>5</td>
<td>0.8111</td>
<td>0.8347</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>-124.2</td>
<td>5</td>
<td>0.9500</td>
<td>0.8347</td>
</tr>
<tr>
<td>16</td>
<td></td>
<td>-121.2</td>
<td>5</td>
<td>0.9500</td>
<td>0.8347</td>
</tr>
<tr>
<td>32</td>
<td>Suppressed carrier Mod Index = 90 deg</td>
<td>-119.5</td>
<td>5</td>
<td>0.9730</td>
<td>0.8347</td>
</tr>
<tr>
<td>64</td>
<td></td>
<td>-116.5</td>
<td>5</td>
<td>0.9890</td>
<td>0.8290</td>
</tr>
<tr>
<td>128</td>
<td></td>
<td>-113.5</td>
<td>4.5</td>
<td>0.9940</td>
<td>0.8175</td>
</tr>
<tr>
<td>256</td>
<td></td>
<td>-110.5</td>
<td>4</td>
<td>0.9713</td>
<td>0.7946</td>
</tr>
<tr>
<td>512</td>
<td></td>
<td>-107.3</td>
<td>3.5</td>
<td>0.9880</td>
<td>0.7487</td>
</tr>
<tr>
<td>1024</td>
<td></td>
<td>-104.2</td>
<td>3</td>
<td>0.9450</td>
<td>0.6570</td>
</tr>
<tr>
<td>2048</td>
<td></td>
<td>-101.0</td>
<td>2.5</td>
<td>0.8180</td>
<td>0.4735</td>
</tr>
</tbody>
</table>

**Link Margin**

- MRO: 2.3 dB
- MAVEN: 3.0 dB
- EMTGO: 3.0 dB