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Jet Propulsion Laboratory
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Relay Support for the Mars Science Laboratory Mission

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Agenda

- MSL
  - Mission Overview
  - Relay Telecom Requirements
- Mars Relay Network
- Critical Event Communications During EDL
- Relay Communications for Curiosity Surface Operations
- Key Lessons Learned
- Conclusions

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Curiosity Rover

Cameras	• Mast Camera (Mastcam) • Mars Hand Lens Imager (MAHLI) • Mars Descent Imager (MARDI)
Spectrometers	• Alpha Particle X-Ray Spectrometer (APXS) • Chemistry & Camera (ChemCam)
Analytical Instruments	• Chemistry & Mineralogy X-Ray Diffraction/X-Ray Fluorescence Instrument (CheMin) • Sample Analysis at Mars (SAM) Instrument Suite
Radiation Detectors	• Radiation Assessment Detector (RAD) • Dynamic Albedo of Neutrons (DAN)
Environmental Sensors	• Rover Environmental Monitoring Station (REMS)
Atmospheric Sensors	• Mars Science Laboratory Entry Descent and Landing Instrument (MEDLI)

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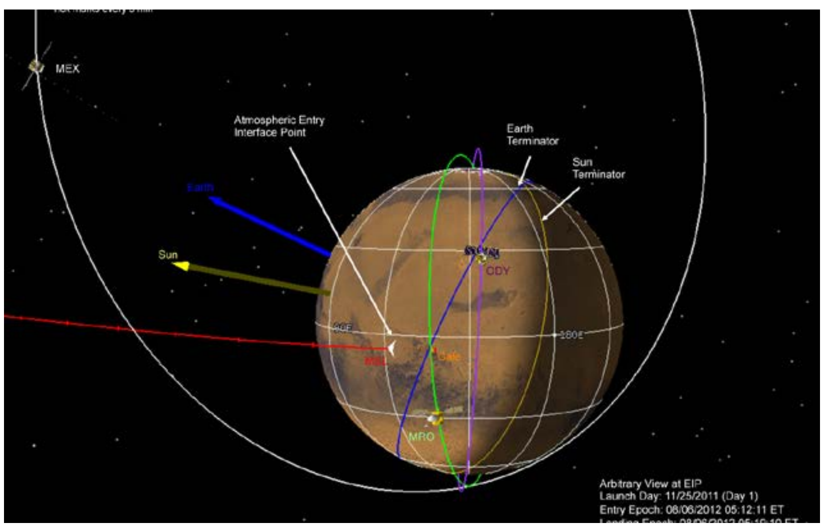
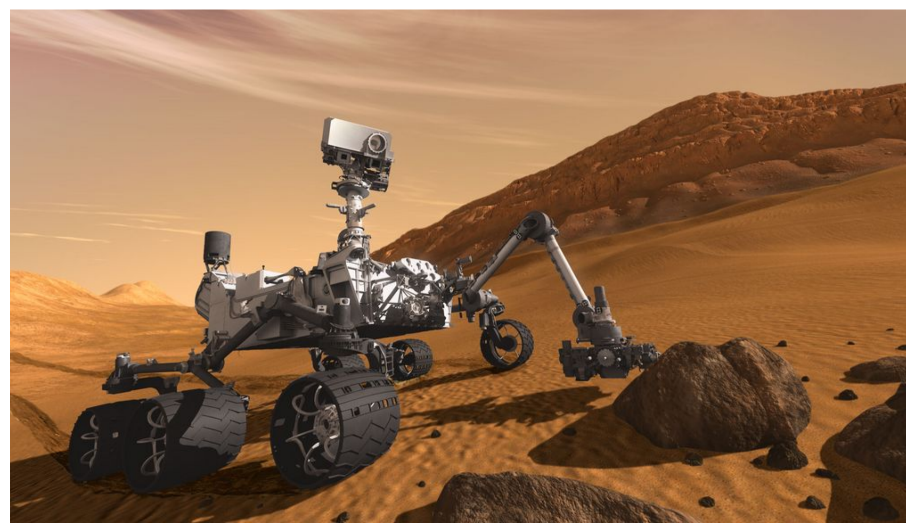
Key MSL Relay Telecommunications Requirements

- Critical event communications during MSL Entry, Descent, and Landing
  - *"sufficient to determine the state of the spacecraft in support of fault reconstruction"*

- Command and telemetry relay services during Curiosity surface operations
  - *250 Mb/sol via MRO**
  - *75 Mb/sol via ODY**

  *(*Average return assuming two passes per sol)*





Mars Relay Network

Odyssey

NASA

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
- Fixed Frequency

Mars Express

ESA

Launched 2003

Orbit:

- 250 x 10,142 elliptical
- 86˚ inclination
- Non-sun-synch

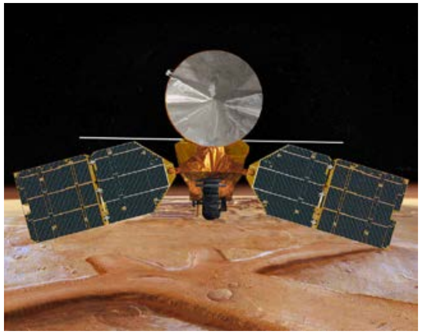
Deep Space Link:

- X-band
- 1.65 m HGA
- 65W TWTA

Relay Link:

- Melacom UHF Txcvr
- Patch Antennas (2)
- 2, 4, …, 128 kbps
- CCSDS Prox-1 Protocol
- Fixed Frequency

MRO



NASA

Launched 2005

Orbit:

- 255 x 320 km sun-synch
- 93˚ inclination
- ~3 PM LMST asc node

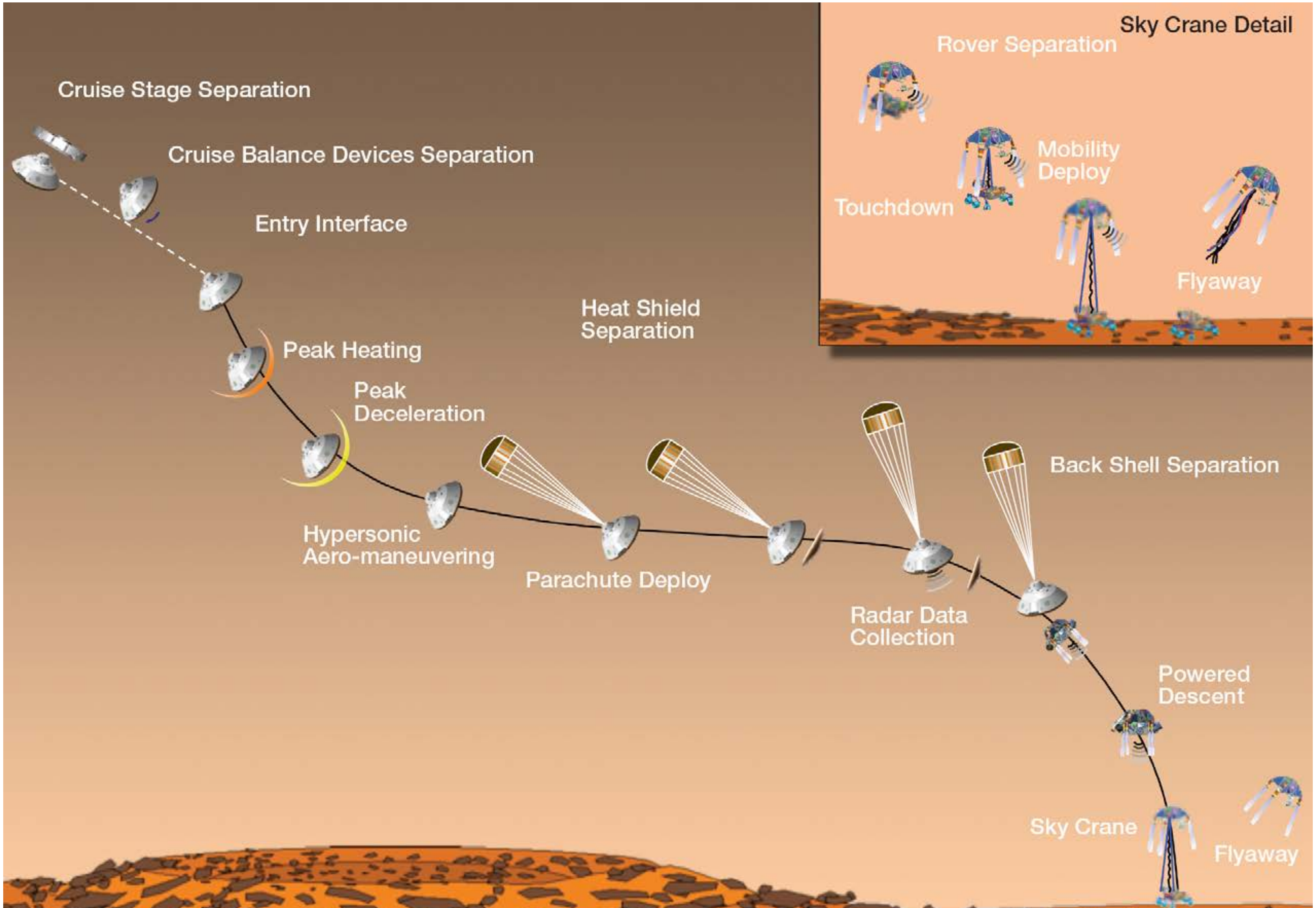
Deep Space Link:

- X-band
- 3 m HGA
- 100 W TWTA

Relay Link:

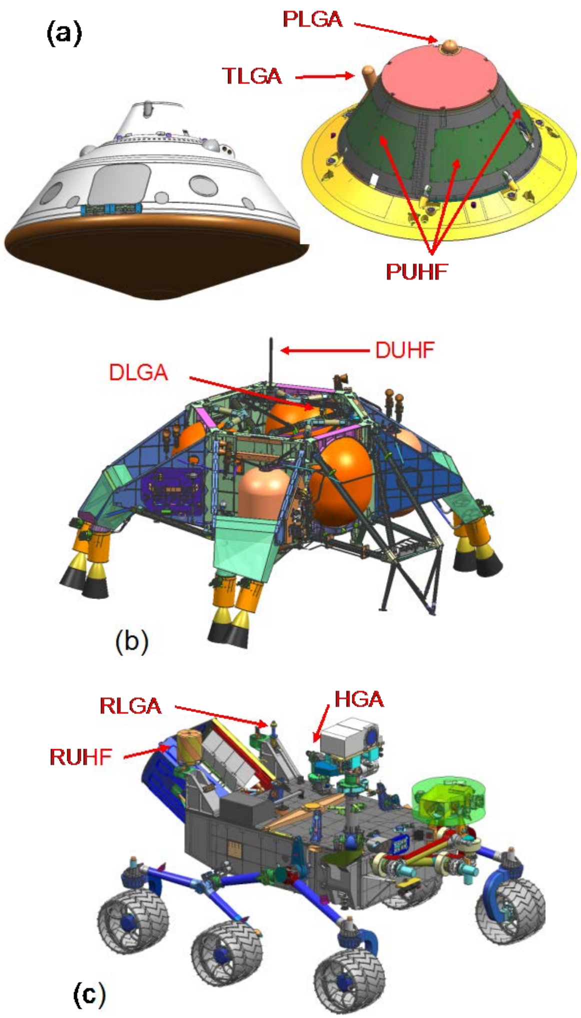
- Electra UHF Txcvr
- Quadrifilar Helix Antenna
- 1, 2, 4, …, 2048 kbps
- CCSDS Prox-1 Protocol
- Frequency-agile
- Adaptive Data Rates

MSL Entry, Descent, and Landing

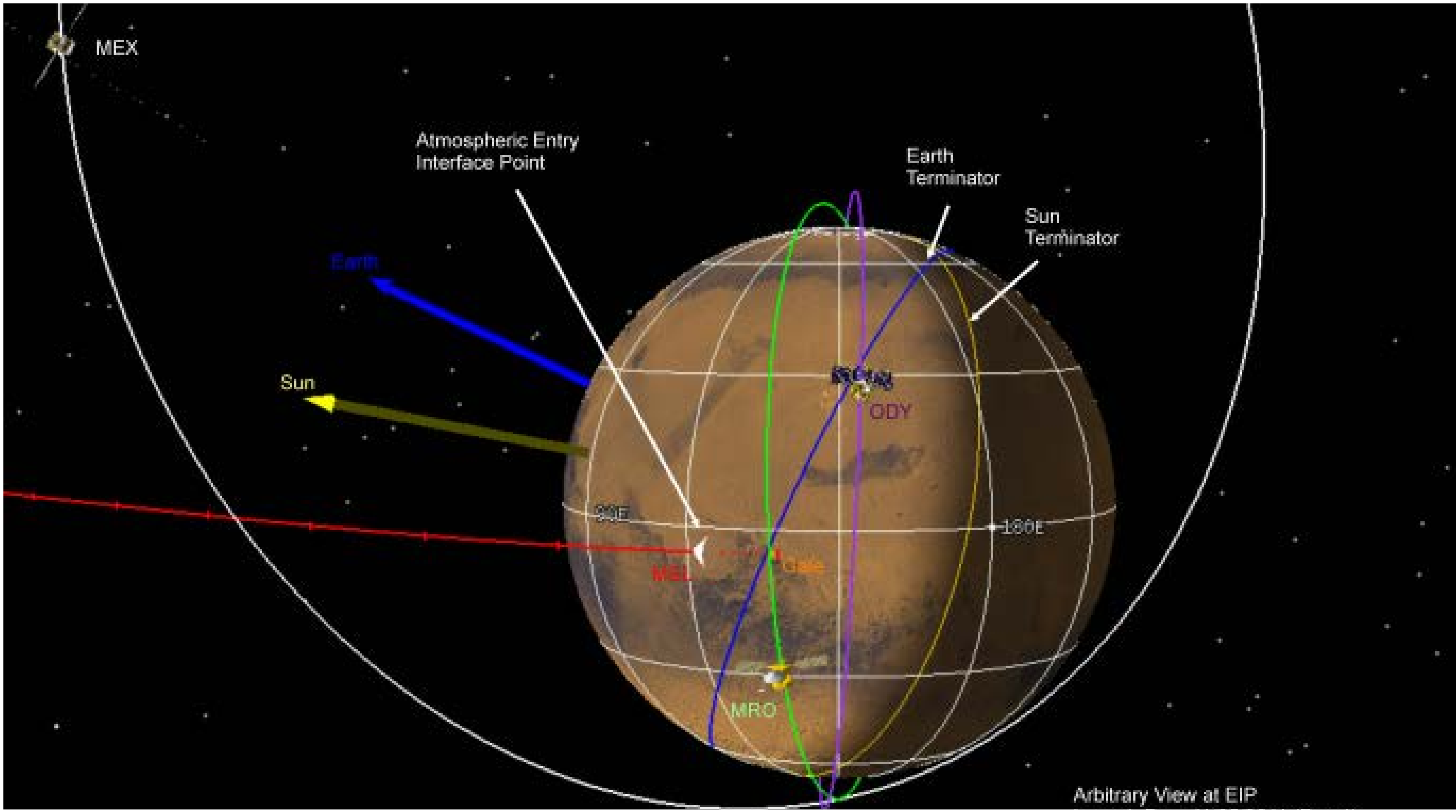


MSL Telecommunications

- After cruise stage separation, MSL uses a combination of X-band and UHF transmissions
  a) Entry phase
    - X-band Parachute LGA and Tilted LGA
    - Wrap-around Parachute UHF antenna patch array
  b) Powered descent phase
    - X-band Descent LGA
    - Descent UHF dipole antenna
  c) Skycrane and Surface phase
    - X-band Rover LGA (and HGA for surface only)
    - UHF quadrifilar helix antenna



MSL EDL Geometry



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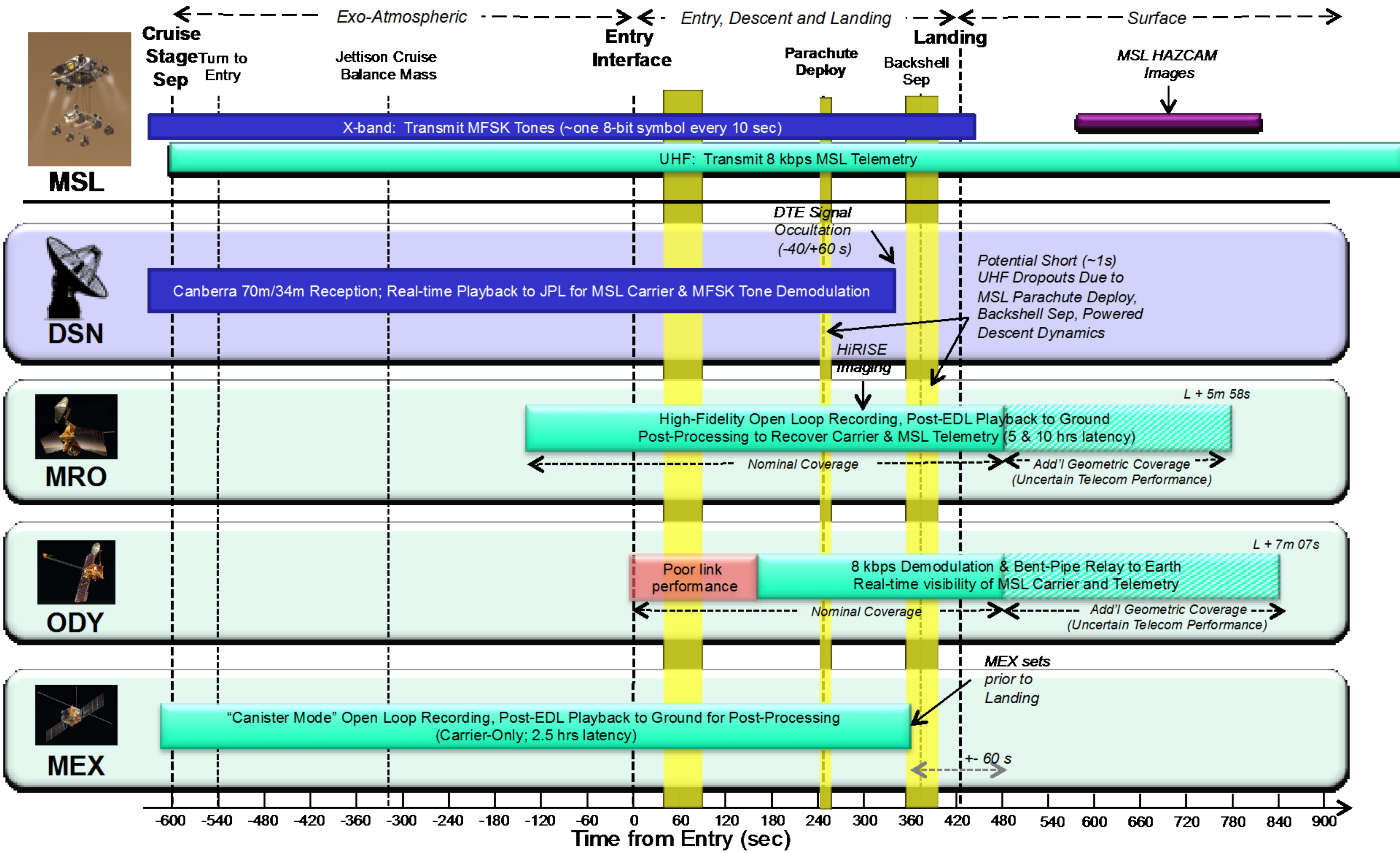
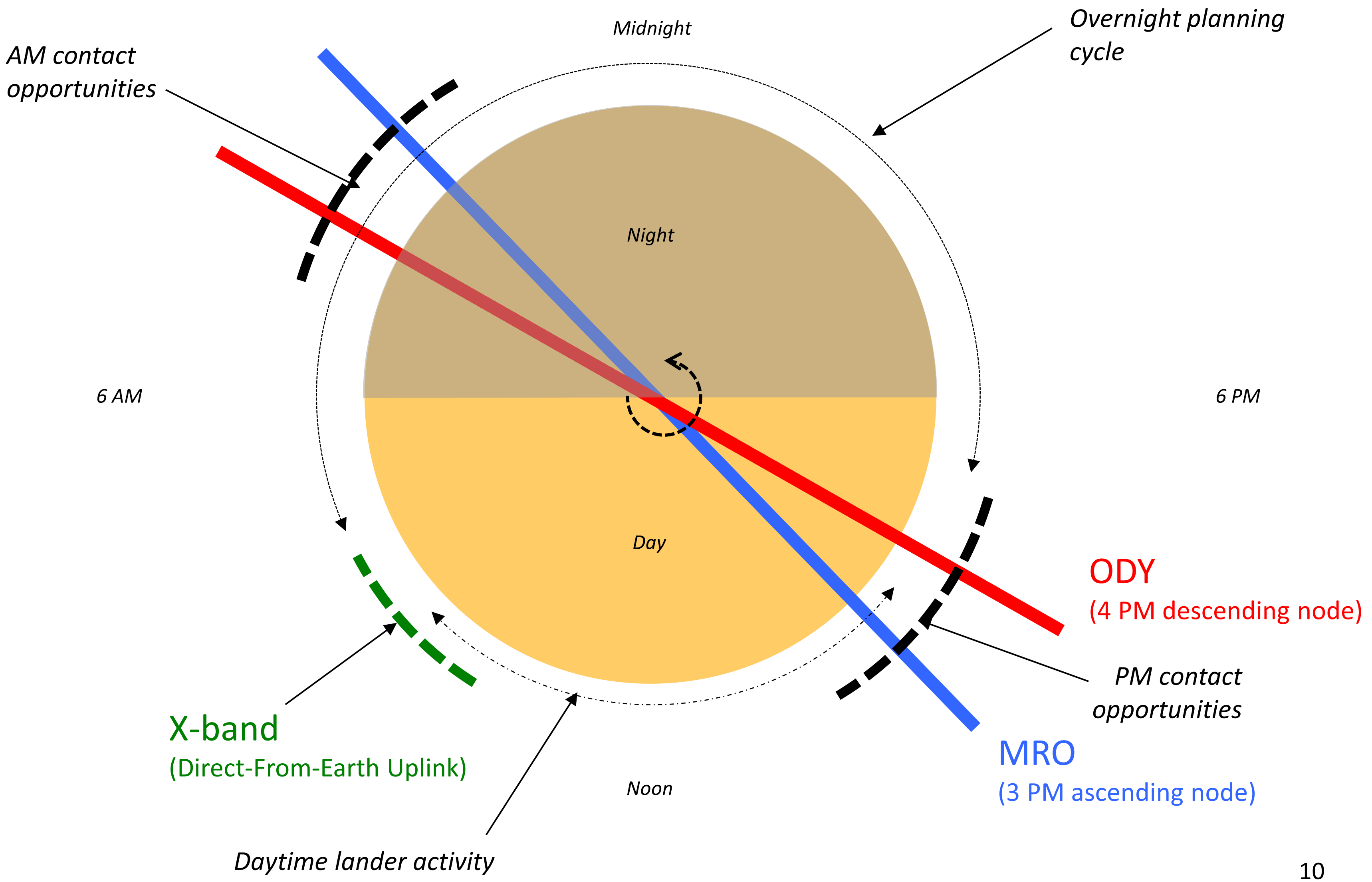
Overview of EDL Communications

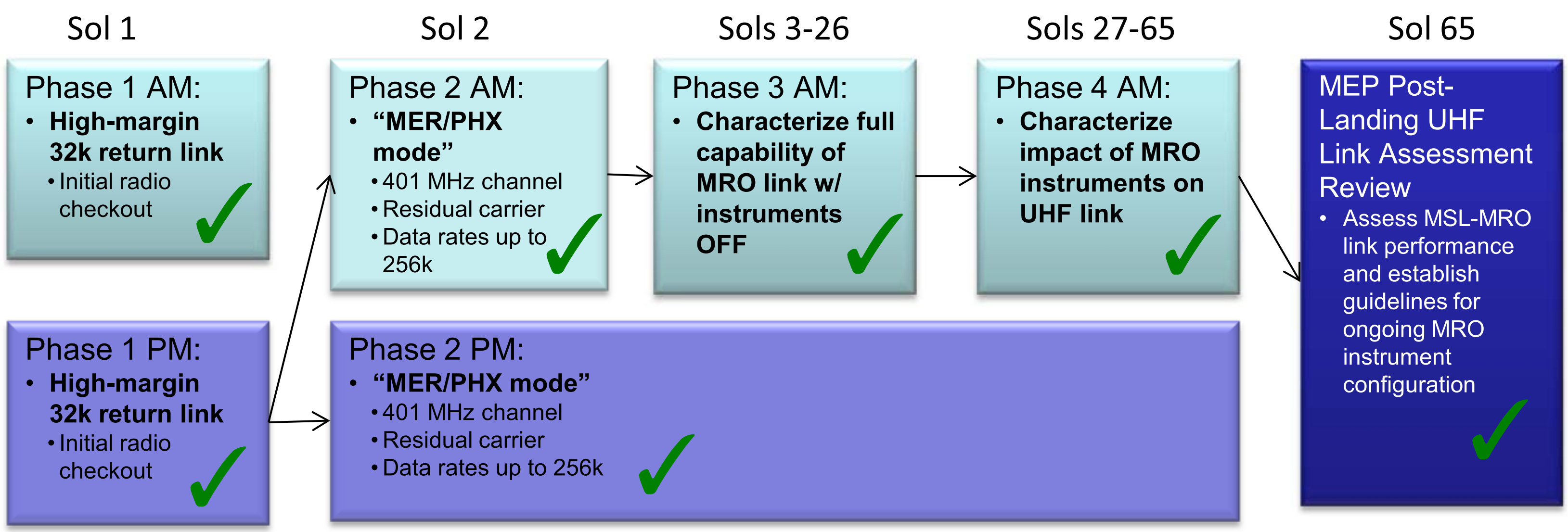


MSL Surface Communications



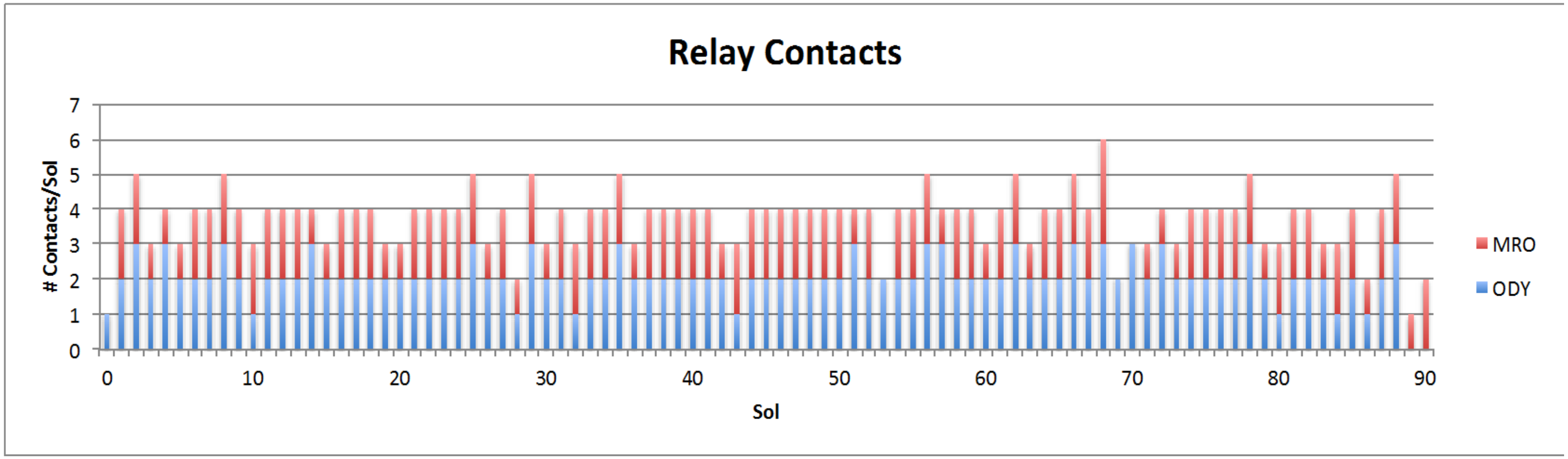
MSL Link Characterization Overview

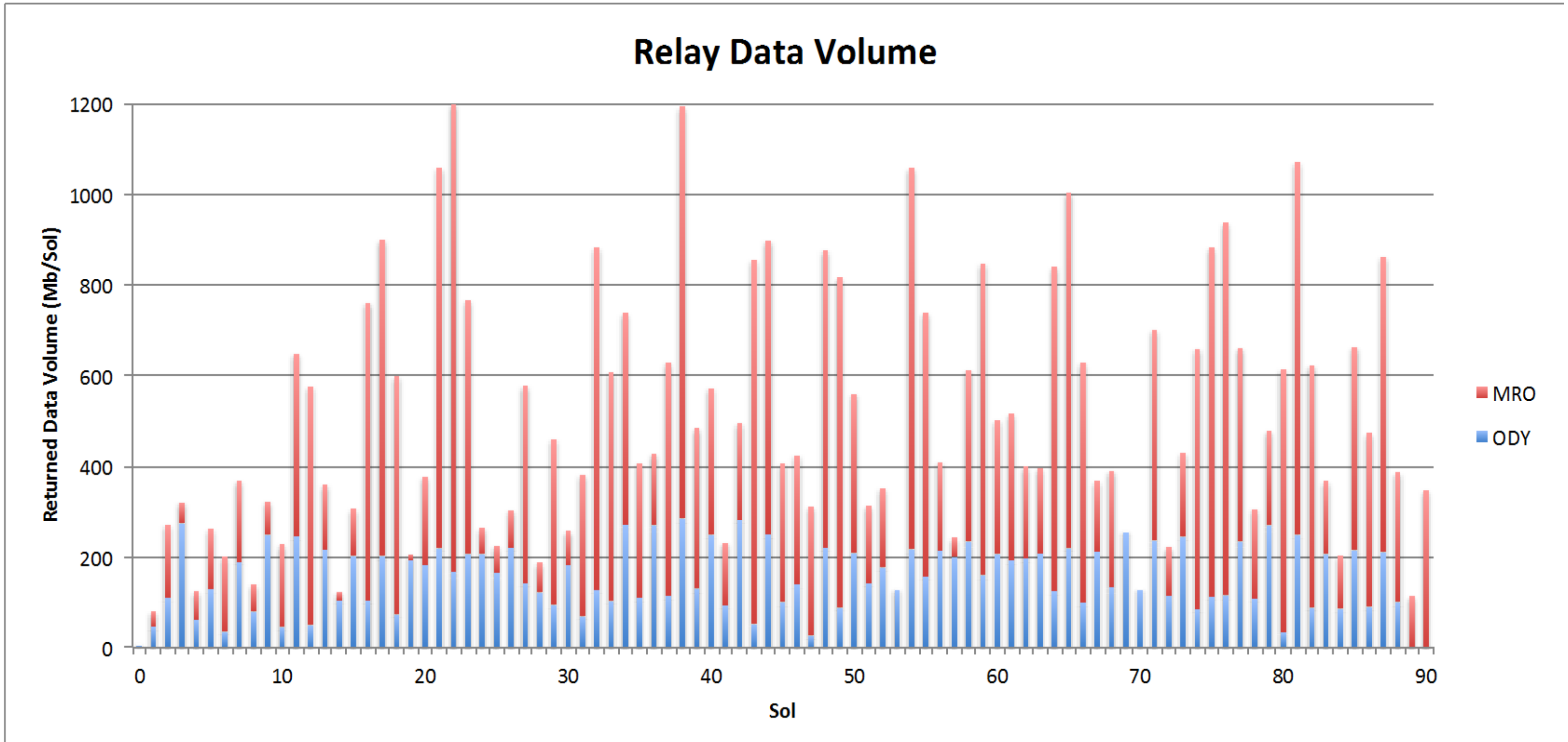
- To understand the performance of the MSL-MRO link, new capabilities were introduced gradually, and MRO science instruments were powered on sequentially to quantify EMI impacts



MRO Instrument Configuration:

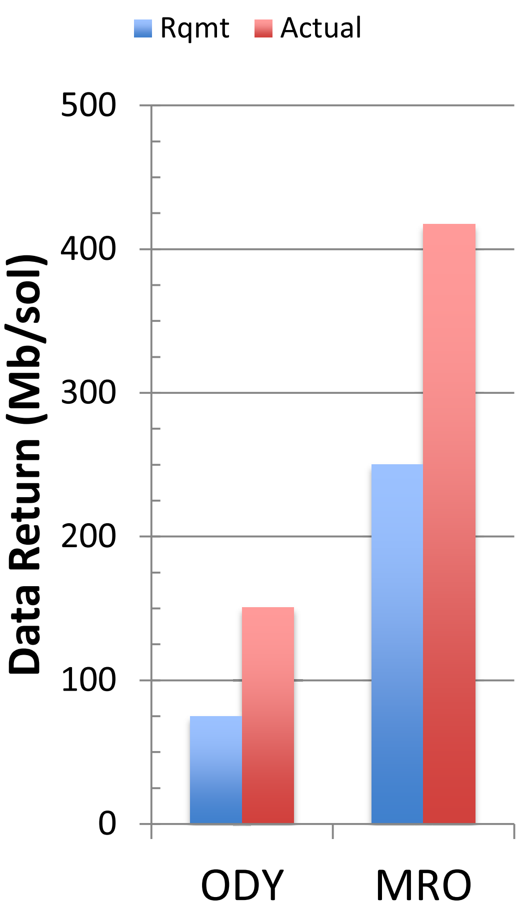
MSL Data Return Metrics





Relay Performance vs Requirements

- MSL relay requirements:
  - ODY: 75 Mb/sol (average over 2 wks, assumes 2 passes/sol)
  - MRO: 250 Mb/sol (average over 2 wks, assumes 2 passes/sol)
- MSL relay performance:
  - ODY: 157 Mb/sol (for 2.1 passes/sol)
  - MRO: 353 Mb/sol (for 1.7 passes/sol)
- *Observed performance exceeds requirements with margin*



1) Data volumes normalized to 2 passes/sol

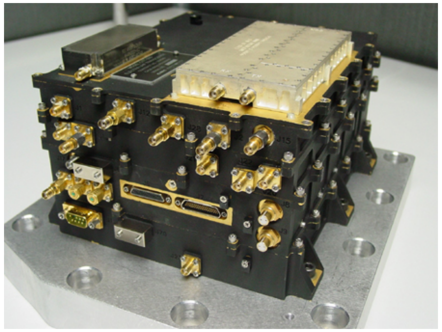
All Passes Through Sol 90

	ODY	MRO	Total
Total # Passes	187	152	339
Total Data Return (Gb)	14.1	31.7	45.8
Average # Passes/sol:	2.08	1.69	3.77
Average Return Data Vol/Sol (Mb)	156.61	352.67	509.28
Average Return Data Vol/Pass (Mb)	75.37	208.82	135.21

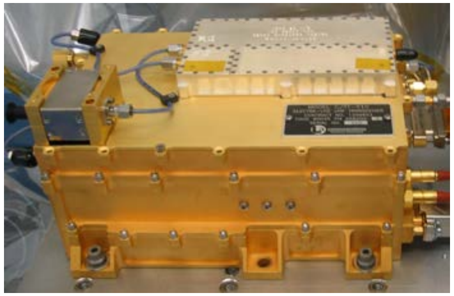
Over 500 Mb/sol average MSL data return

New Electra Capabilities on the MSL-MRO Link

- Higher data rates
  - Support for data rates up to 2048 kbps (8x higher than previous 256 kbps maximum for MER)
- Frequency agility
  - Operate MSL-MRO return link at 391 MHz to mitigate known CRISM EMI @ 400 MHz
- Suppressed carrier modulation
  - Provides increased power in data channel and enables higher symbol rates
- Adaptive Data Rates
  - Maximizes data return by varying the lander transmission rate based on the actual comm channel capability
    - Orbiter Electra monitors return-link quality (symbol tracking loop SNR) throughout relay pass
    - Based on observed SNR, orbiter sends Prox-1 “COMM_CHANGE” directives to lander to increase/decrease data rate, always operating at the max possible rate the channel can support
  - n.b. The ADR technology was originally developed for the Mars Telecommunications Orbiter; it was uploaded to the MRO EUT *after* MRO launch, illustrating the benefits of a software-defined radio

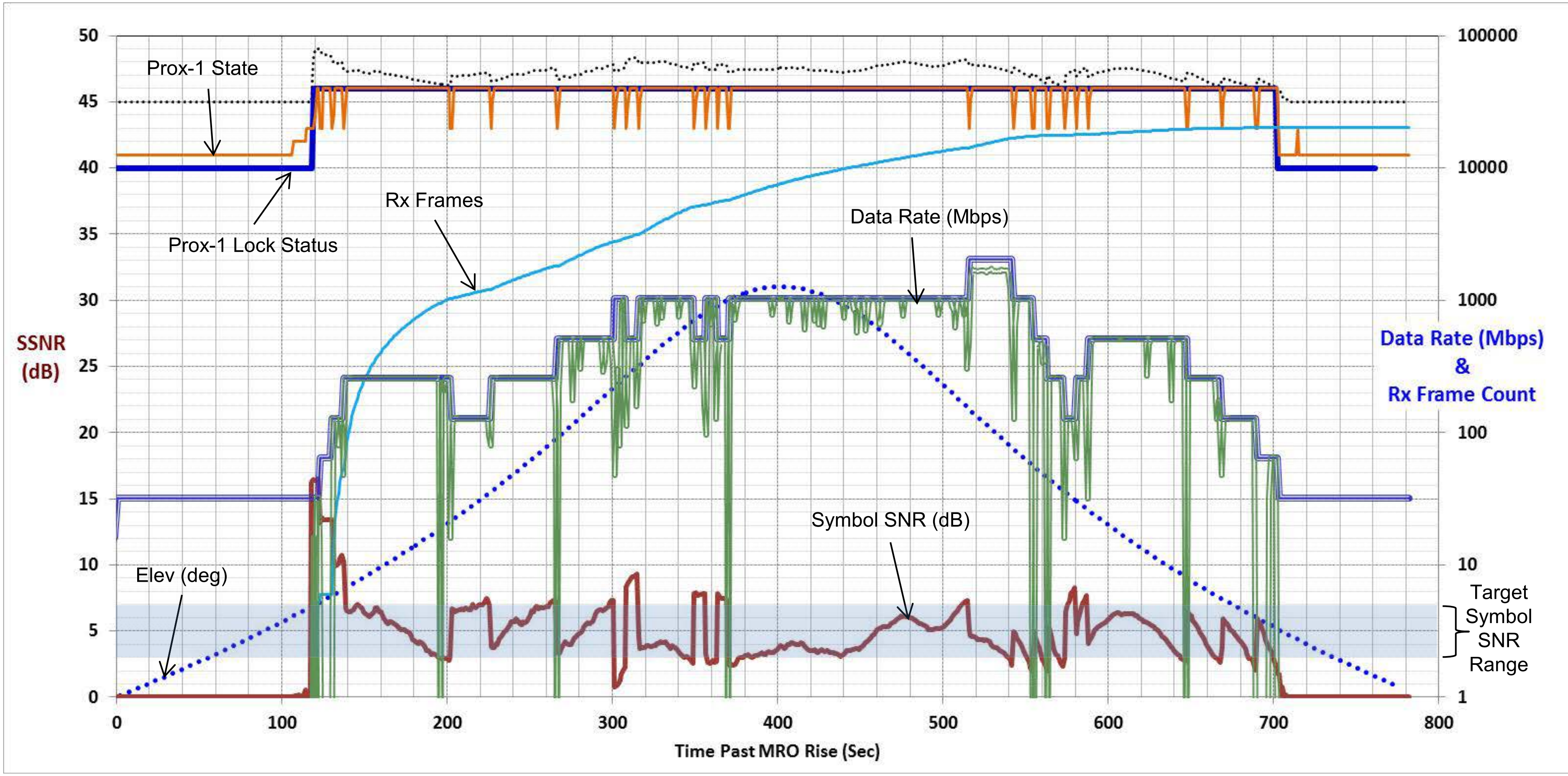


MRO Electra UHF Transceiver



MSL Electra-Lite UHF Transceiver

ADR Example


Prox-1 State
Prox-1 Lock Status
Rx Frames
Data Rate (Mbps)
Symbol SNR (dB)
Elev (deg)
SSNR (dB)
Data Rate (Mbps) & Rx Frame Count
Target Symbol SNR Range
Time Past MRO Rise (Sec)
0
100
200
300
400
500
600
700
800
50
45
40
35
30
25
20
15
10
5
0
100000
10000
1000
100
10
1

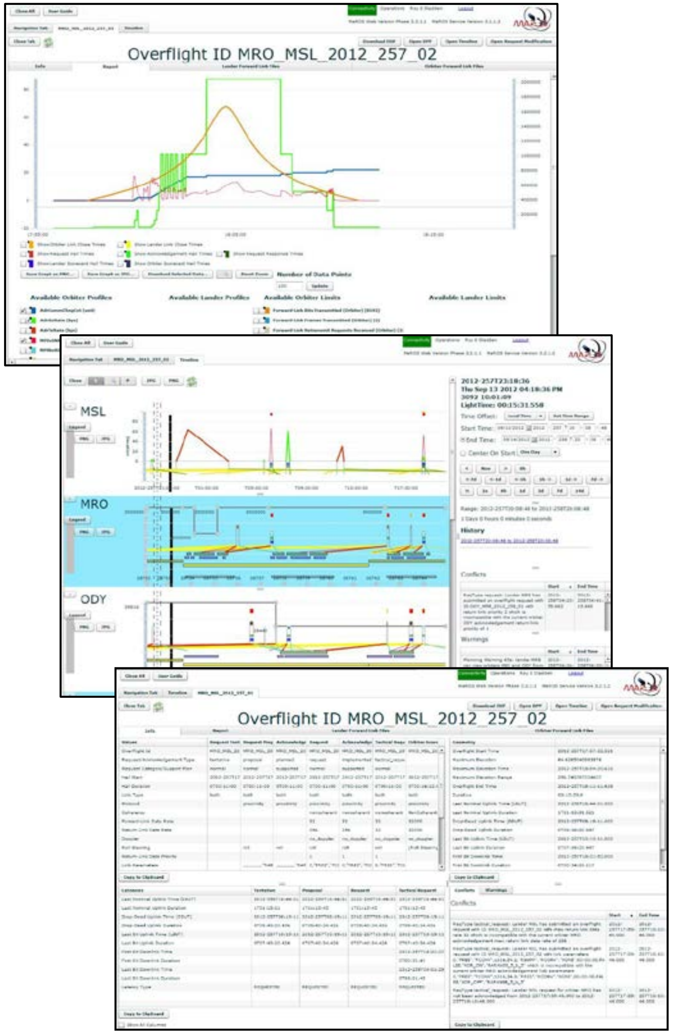
Mars Express Demonstration Passes

- In addition to the MEX support of MSL's EDL, MEX is available as a backup relay asset for Curiosity surface operations
  - Four passes were successfully performed over the first 90 sols to validate the MSL-MEX relay capability
  - ESA and NASA continue to exercise the MSL-MEX link every 1-2 mos to verify health of the MEX Melacom relay payload and maintain NASA/ESA relay operations proficiency

Sol	Pass ID	Pass Configuration	Result
13	MEX_MSL_2012_232_02	8k forward link/8k return link	Successful • 7 Mb returned
24	MEX_MSL_2012_244_01	8k forward link/128k return link (Includes MSL command product)	Successful • 55 Mb returned • MSL command product delivered
30	MEX_MSL_2012_250_01	8k forward link/128k return link	Successful • 110 Mb returned
59	MEX_MSL_2012_280_01	8k forward link/128k return link	Successful • 105 Mb returned

Multimission Relay Operations

- The Mars Relay Operations Service (MaROS) provides an integrated, shared resource for multimission relay planning and execution
  - MaROS v3.2 introduced many new features needed to support MSL relay operations
  - All MSL relay activities have been coordinated via MaROS, including long-term strategic planning and short-term tactical changes
  - Post-pass relay performance data are captured and archived for every relay session
  - All operating spacecraft at Mars - including ESA's Mars Express - are utilizing MaROS, and future missions (MAVEN, InSight, and ESA's ExoMars) will also use the service



Example MaROS displays

Key Relay Lessons Learned

- Software Defined Radios
  - Electra/Electra-Lite transceivers on MSL-MRO link are achieving unprecedented levels of data return
  - Adaptive data rate capability implemented on MRO post-launch
- Operational Readiness Testing
  - ORTs were crucial in exercising the full range of multimission relay processes
- Mars Relay Operations Service
  - The MaROS system played a key role in coordinating all of the multimission relay activities among two rovers (MER and MSL) and three orbiters (ODY, MRO, MEX)
- End-to-End Information System
  - UHF Radio-to-radio interoperability is necessary but not sufficient; idiosyncrasies on the interfaces between UHF transceivers and host s/c C&DH resulted in complex operational work-arounds and delays in the V&V test program
- Verification and Validation Test Schedule
  - Several relay issues were discovered late in the MSL test program; while issues were resolved and surface ops has been excellent, an earlier set of V&V test milestones is recommended for future missions
- End-to-End Relay Testbeds
  - The fidelity of the end-to-end relay testbeds plays a significant role in the success of V&V testing
  - For MRO-MSL, we had high-fidelity spacecraft testbeds at JPL
  - For ODY and MEX, only lower-fidelity UHF test racks were available at JPL for testing with MSL; non-flightlike aspects of these testbeds resulted in some late issues in testing
- Electromagnetic Interference
  - Uncertainty in the MRO EMI environment resulted in significant concern prior to MSL arrival as to whether Curiosity would be able to achieve the desired 250 Mb/sol data return via the MRO relay path
  - Drove a large amount of ground and flight testing to characterize EMI impacts
  - Electra frequency-agility was a key tool in dealing with MRO EMI
  - Future missions should give increased attention to EMI issues during flight implementation

Summary

- An international network of Mars relay orbiters is now providing relay support to the Curiosity rover
- MRO, ODY, and MEX provided complementary coverage of MSL's entry, descent, and landing
- MRO and ODY are meeting and exceeding Curiosity's data return requirements on the surface
- New capabilities of the Electra radios onboard MRO and Curiosity (higher data rates, power-efficient modulation, and Adaptive Data Rate functionality) have enabled greatly increased per-pass data return
- A number of important lessons-learned will be applied to future Mars relay orbiters (2013 MAVEN, 2016 ESA ExoMars Trace Gas Orbiter) and landers (2016 ESA EDL Demonstrator Module, 2016 NASA InSight Lander, 2018 ESA ExoMars Rover, 2020 NASA Mars Rover)