Entry, Descent, and Landing Communications for the 2011 Mars Science Laboratory

Fernando Abilleira

Jet Propulsion Laboratory

California Institute of Technology

Jeremy Shidner

NASA Langley Research Center

23rd International Symposium on Space Flight Dynamics

October 29 – November 2, 2012

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MSL Project Overview

- **Main scientific goal**
  - To assess whether Gale Crater ever had conditions capable of supporting microbial life
- **Mission highlights**
  - 3,883 kg (actual) at launch carrying an 899 kg rover
  - Launched on November 26, 2011 at 7:02 AM PST
  - Landing inside Gale Crater on August 5, 2012 at 10:17 PM SCET PDT only ~2.4 km from its target!
  - First mission with guided entry
  - Latitude accessibility: 25° N to 27° S
  - Altitude capability: -1.0 km elevation
  - Landing ellipse ~ 19.7-km x 6.9-km
    - MPF ~ 100-km x 300-km
    - MER-A / MER-B ~ 10-km x 70-km
  - Minimum range of 20-km
    - First Mars mission to enable landing/rove to a specific site

EDL Communication Requirements

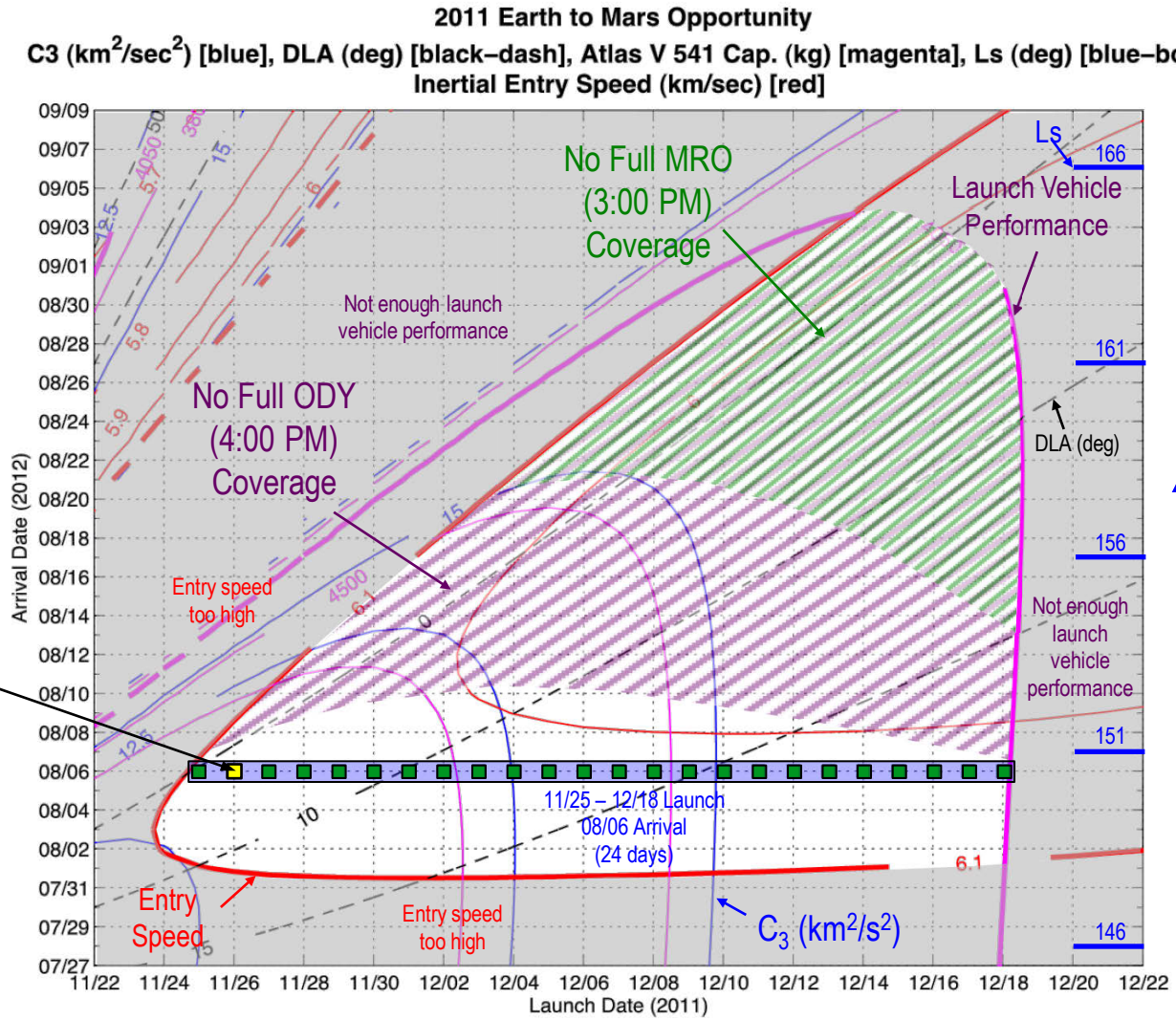
- **EDL Comm for activities**
  - The Project System shall provide for communications throughout EDL sufficient to determine the ongoing activity at any point in time during the EDL timeline, up to positive indication of rover release on the surface of Mars of the descent stage (this requirement could be met by either DTE tones or UHF telemetry)
- **EDL Comm for states**
  - The Project System shall provide return of telemetry to any geometrically available relay asset provided by the Mars Exploration Program, adequate to determine the state of the spacecraft (including the presence of faults) at all times during the EDL timeline up to positive indication of rover release on the surface of Mars of the descent stage (this requirement could only be met only by UHF telemetry)

EDL Coverage Constraints and Assumptions

- **Constraints**
  - Provide EDL visibility from atmospheric entry to landing plus one minute for latitudes from 25° N to 27° S
    - Covers the range of latitudes of current candidate landing sites
    - Drop outs are possible between landing – 60 s and landing – 20 s due to parachute and powered descent dynamics
  - Orbiter UHF relay antenna angle* at entry ≤ 135 deg
  - DTE antenna angle* at entry ≤ 75 deg
  - Mars-Probe-Earth angle at entry > 74.7 deg (Earth must be visible)
  - Orbiter or Earth elevation at landing plus 1 min > 10 deg
- **Assumptions**
  - Only prograde entries considered
  - EDL trajectory profile for nominal EFPA
    - Baseline EFPA = -15.5 deg
    - Central descent angle = 12.01 deg (used for determining launch/arrival strategy)
    - Central descent time = 372.75 s (used for determining launch/arrival strategy)
  - Entry interface radius = 3522.2 km
- **Other mission design constraints**
  - Injected mass = 4,050 kg ⇒ maximum C_3 = ~ 20.1 km^2/s^2 (Atlas V 541, NLS I)
  - Atmosphere-relative entry speed < 5.9 km/s
    - Original 5.6 km/s constraint was relaxed to allow for solutions in the Type 1 region

* Measured with respect to atmosphere-relative anti-velocity direction.

Launch/Arrival Trade Space



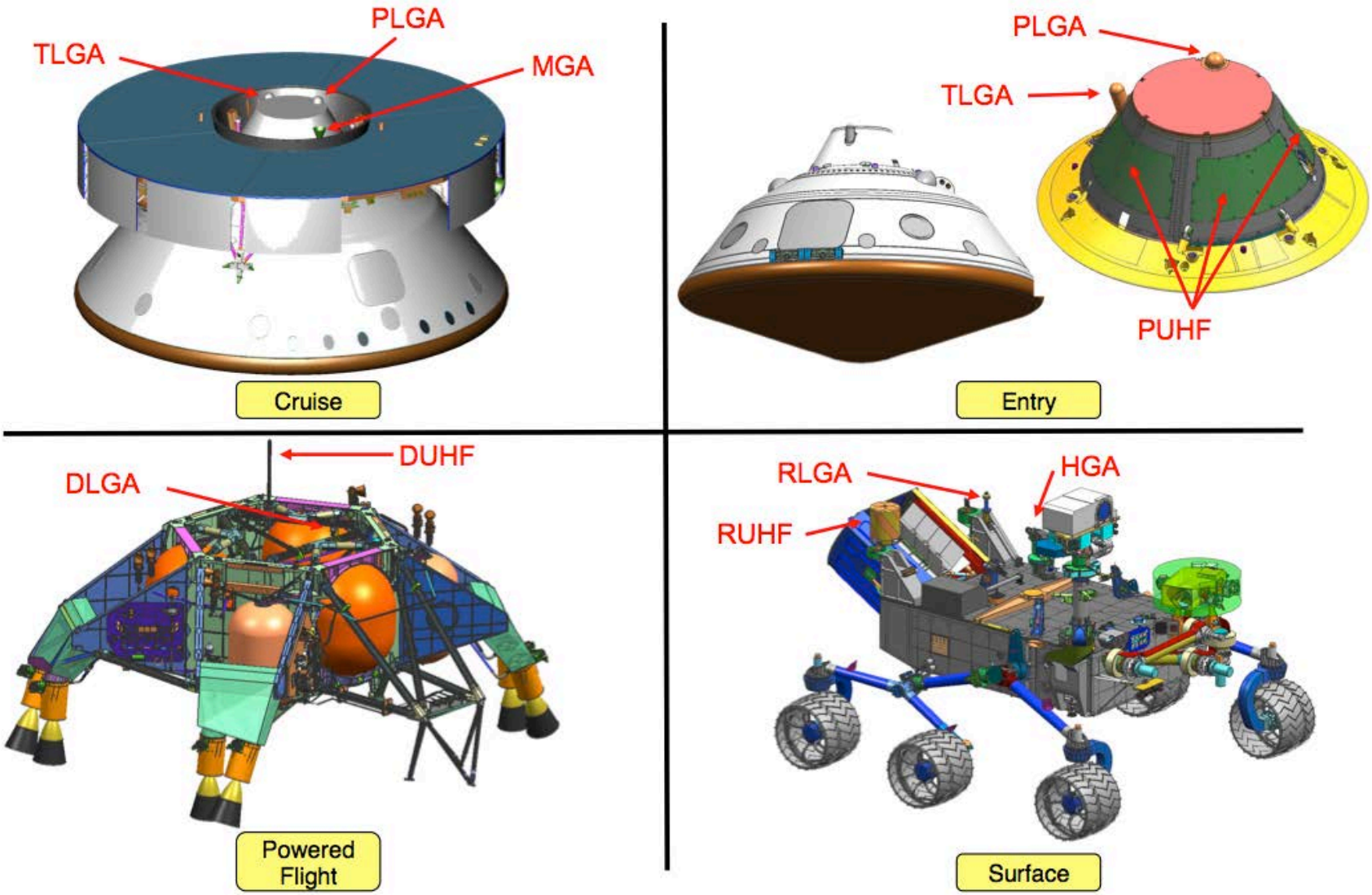
Actual launch day Nov 26, 2012 7:02 PST

Better DTE

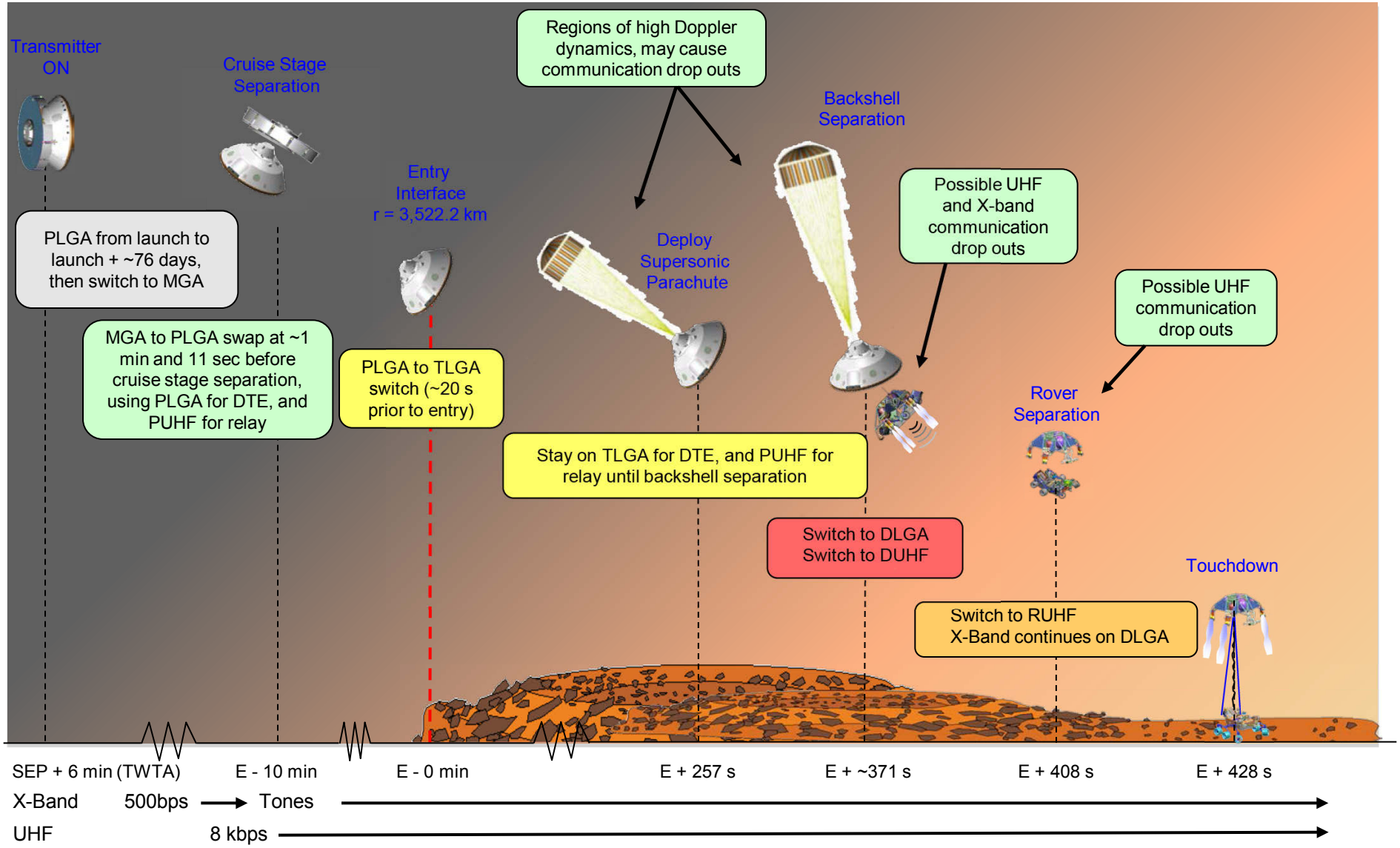
Better MRO/ODY

Inertial Entry Speed ~ 6.1 km/s ≈ Atmosphere-Relative Entry Speed ~ 5.9 km/s

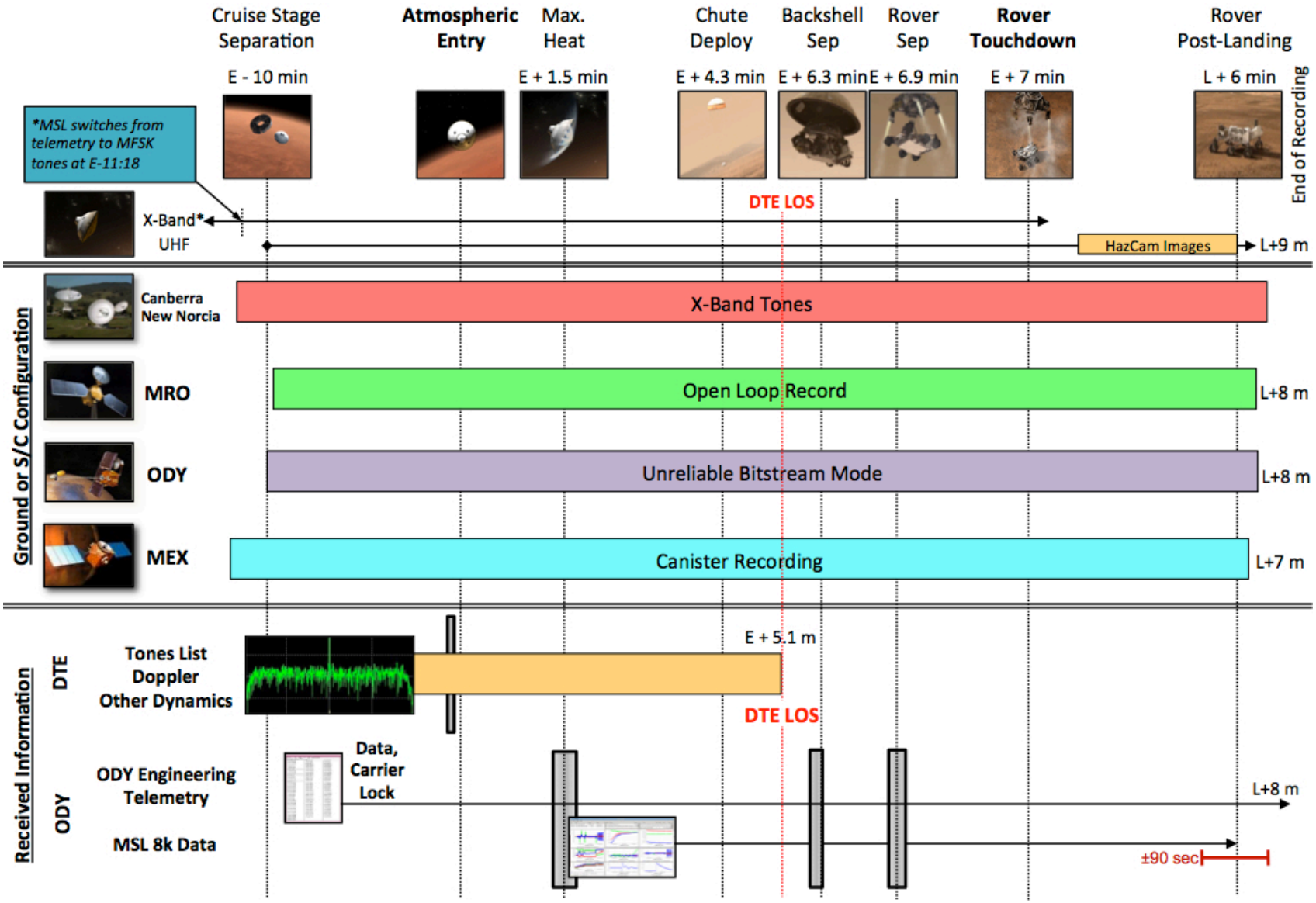
Antenna Locations



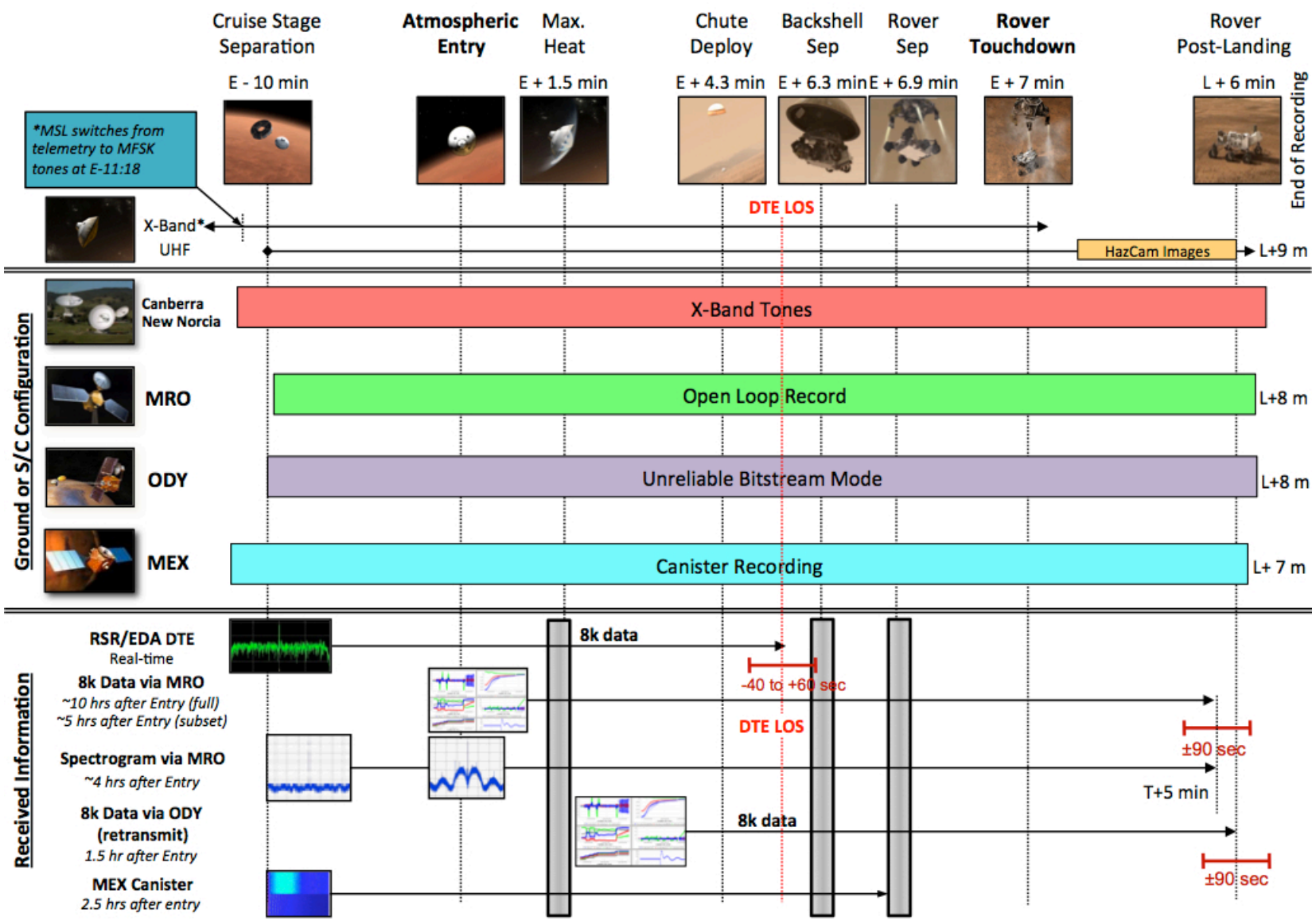
EDL Event Timeline



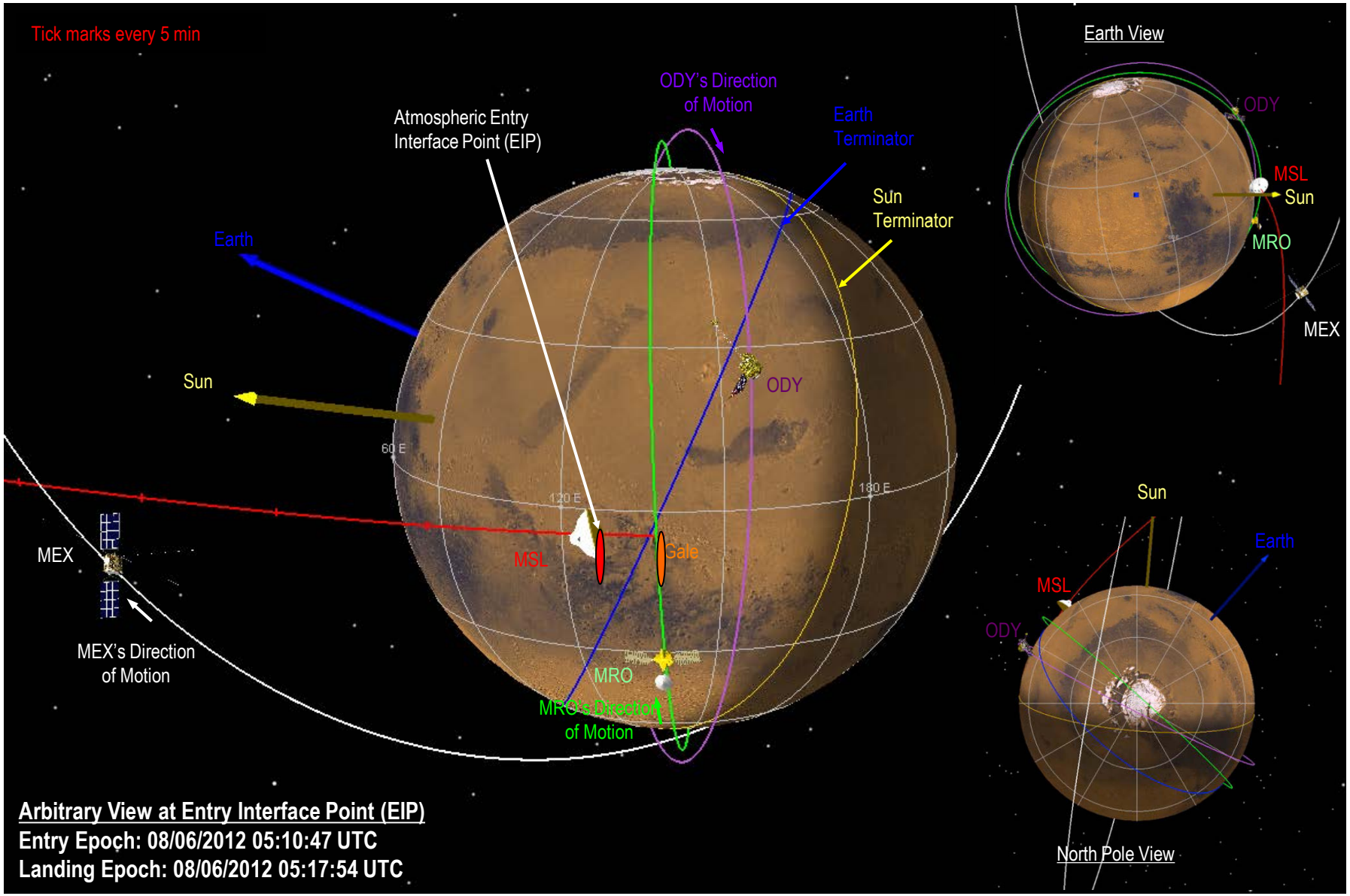
MSL Information Available in Near-Real Time



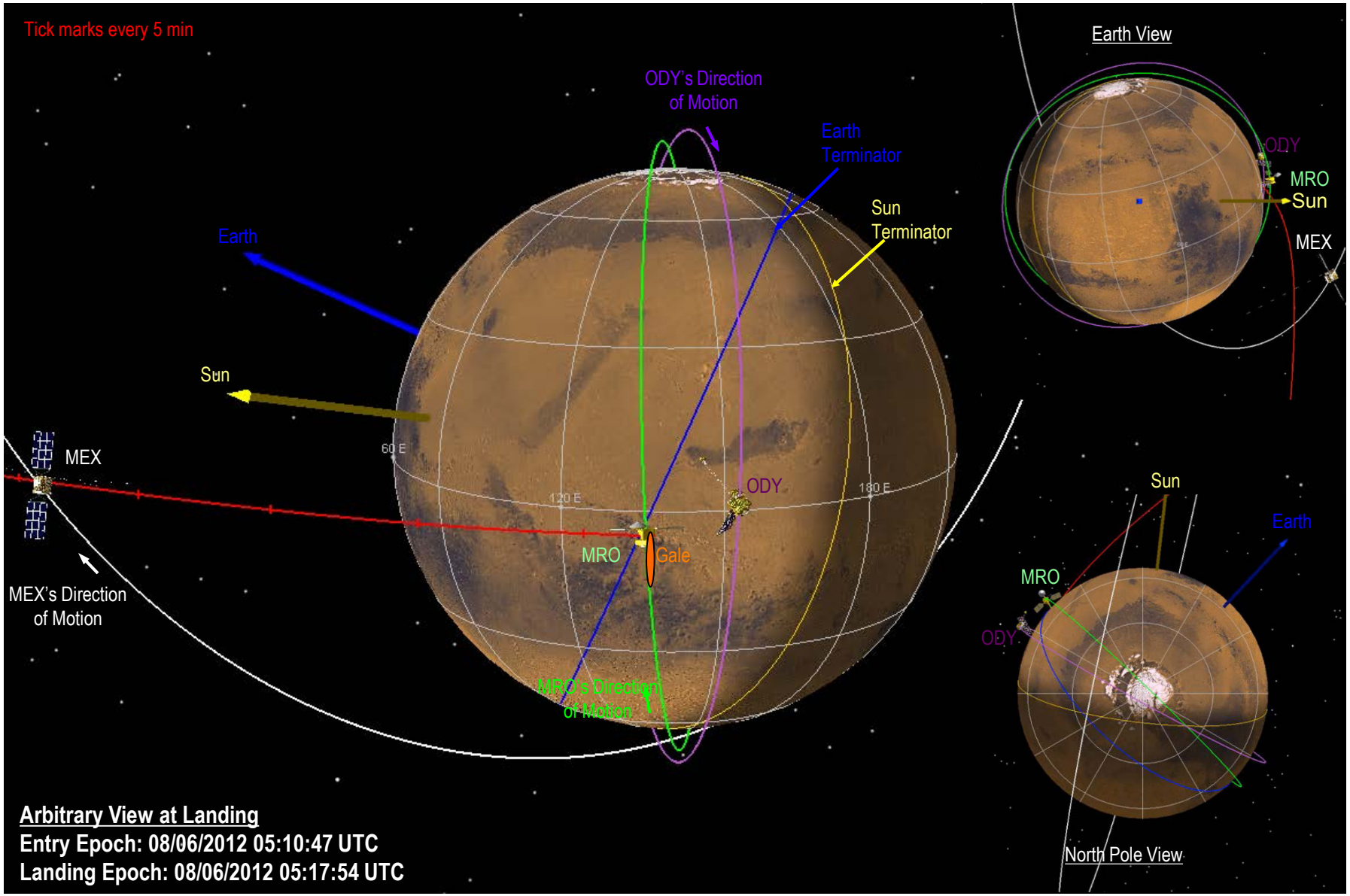
MSL Data Recorded During EDL



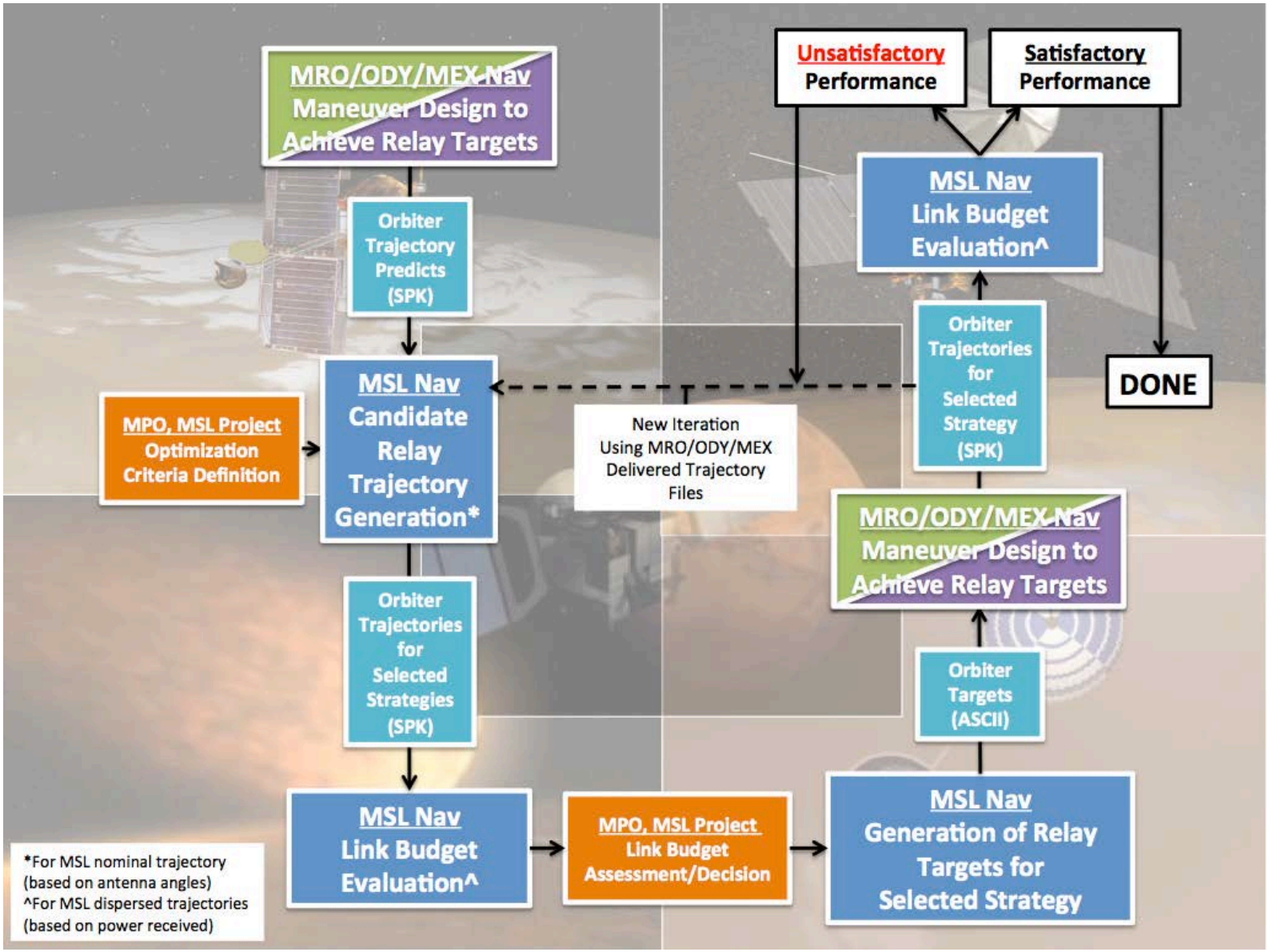
Geometry at Entry Interface Point



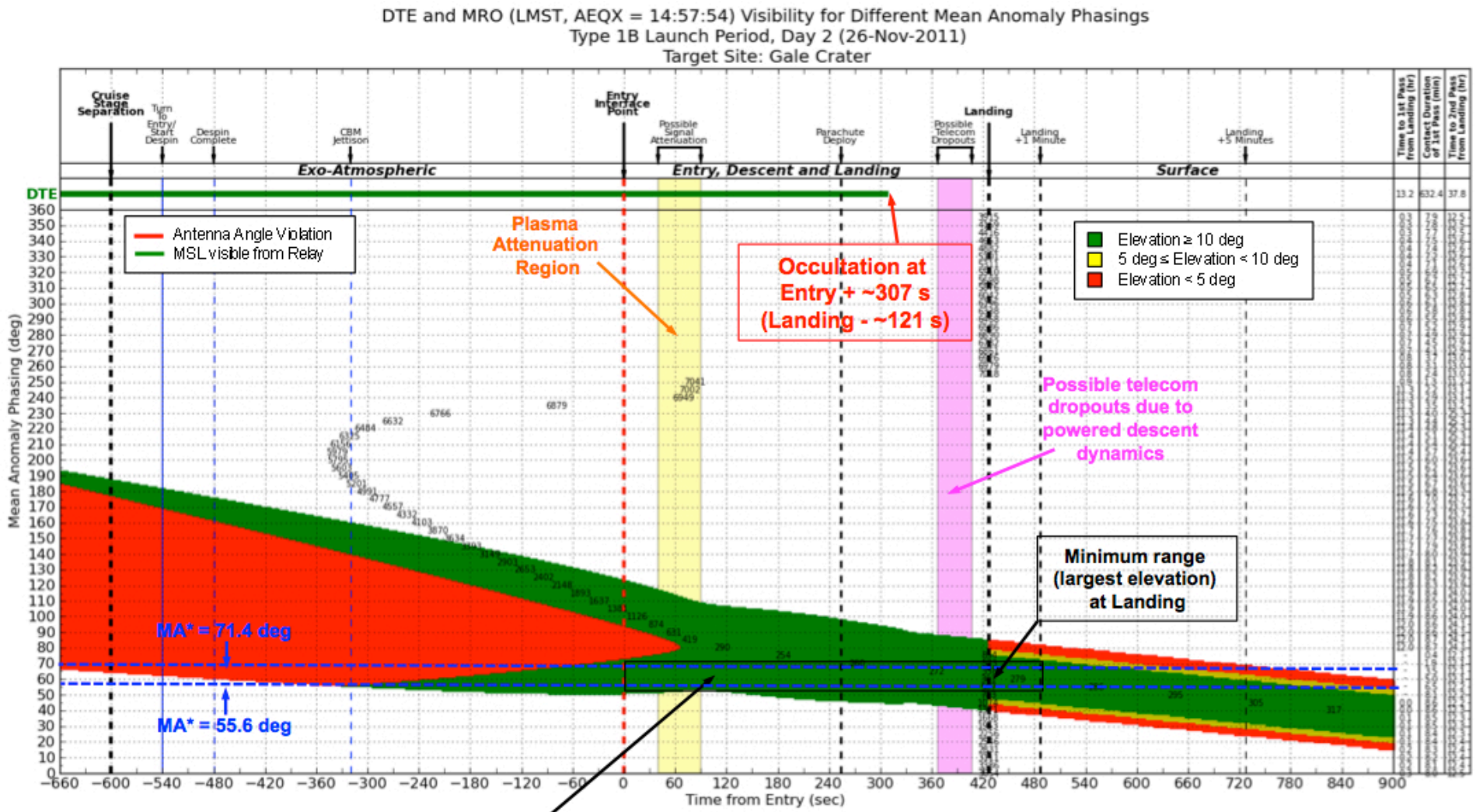
Landing Geometry



EDL Relay Target Generation Cycle



MRO Visibility for Different Orbit Phasings



MA region with EDL coverage from Entry to Landing plus 1 minute (does not include on-orbit phasing control)

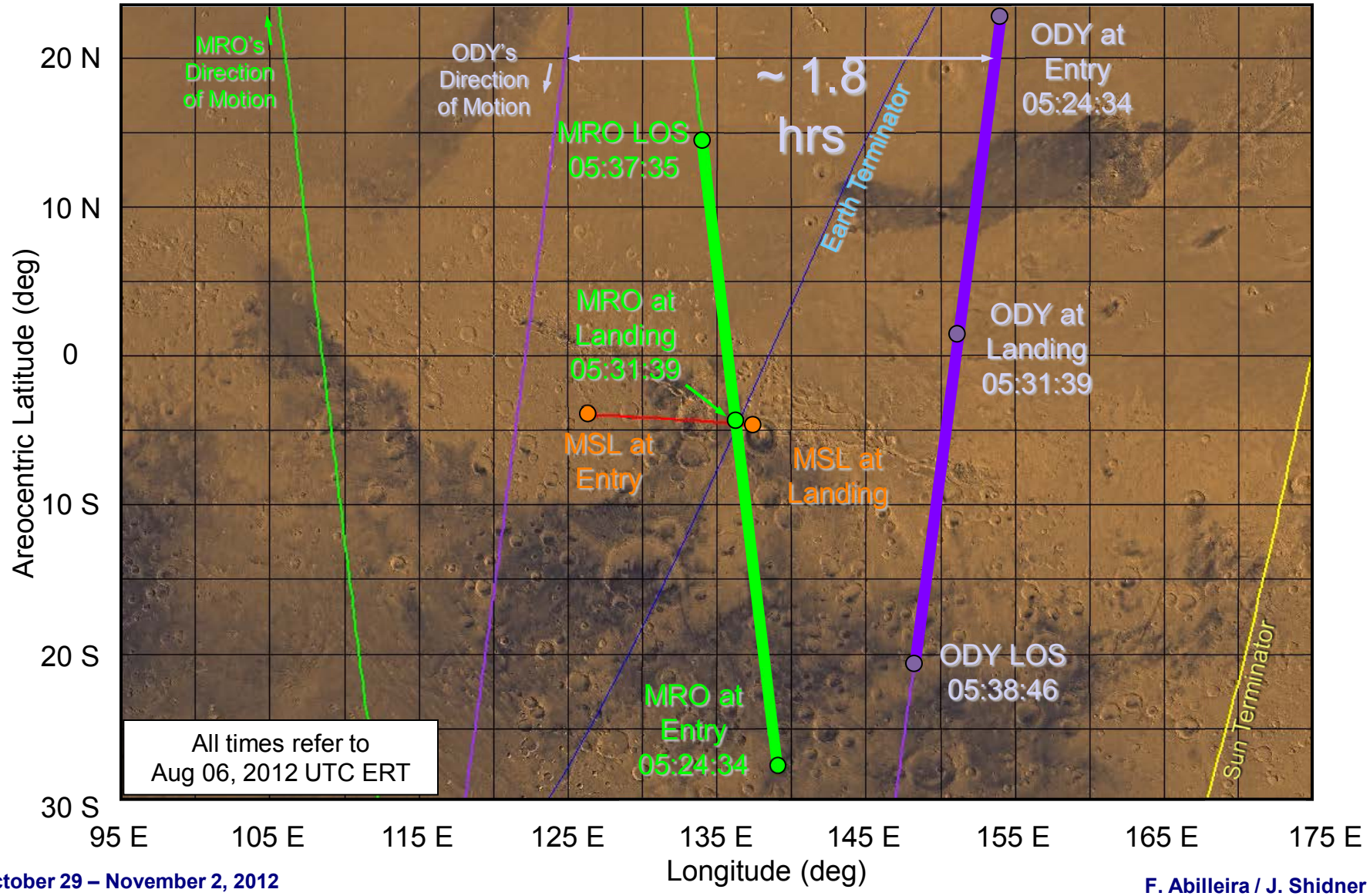
* Includes orbiter phasing control = ± 1.6 deg (± 30 s)

Time to Target Latitude Crossing

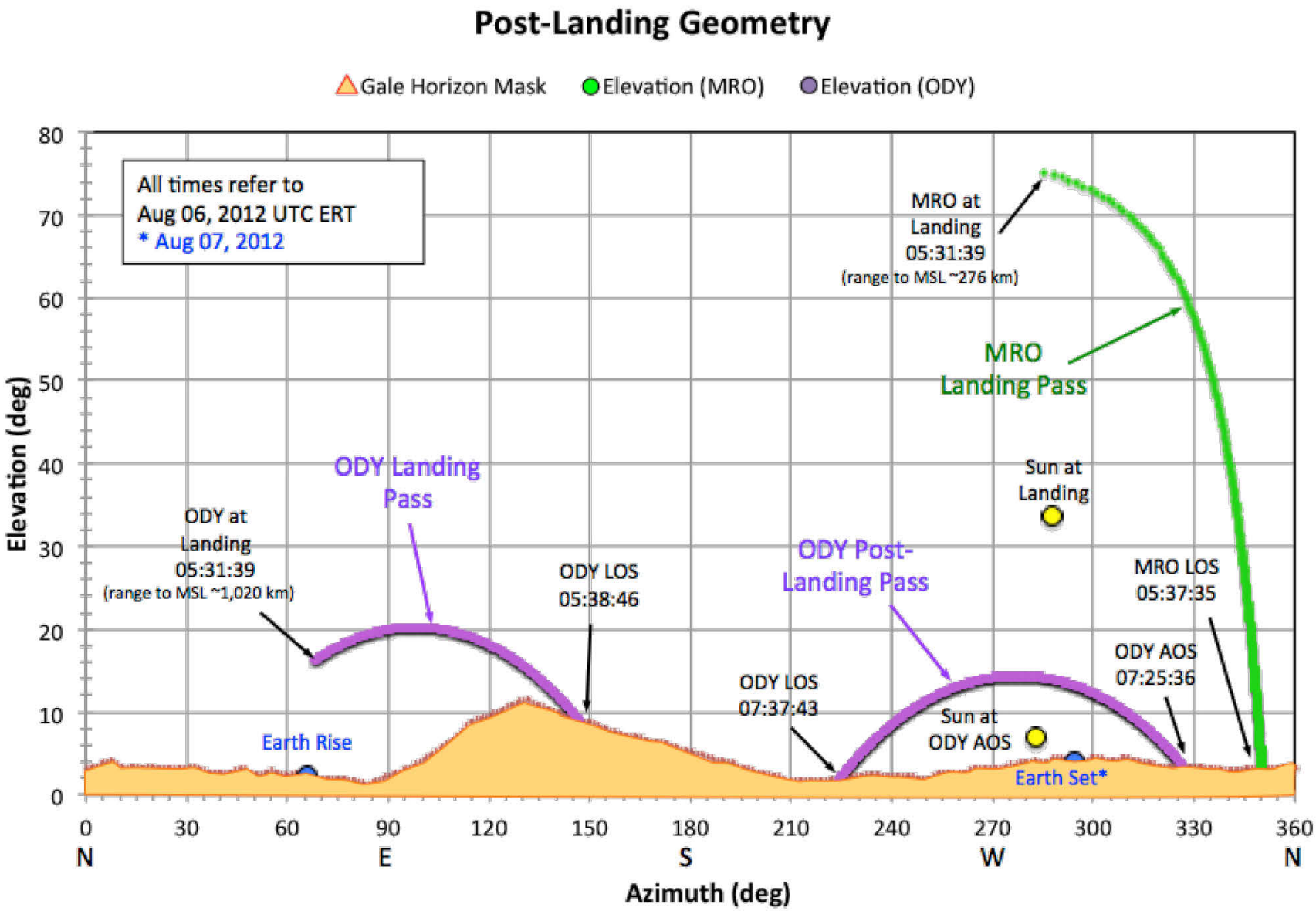
	Time to Target Latitude Crossing (s)																	
	ERTF Response																	
	ERTF 8A (06/11)			ERTF 9 (07/06)			ERTF 10 (07/29)			ERTF 11 (08/03)			ERTF 12 (08/04)			ERTF 13 (08/04)		
ERTF Request	MRO	ODY	MEX	MRO	ODY	MEX	MRO	ODY	MEX	MRO	ODY	MEX	MRO	ODY	MEX	MRO	ODY	MEX
ERTF 8A	0.0	-124.5	34.7	0.0	-124.5	34.7	9.8	-25.1	39.8	9.0	-25.0	41.5	9.0	-25.0	41.5	9.0	-25.0	41.5
ERTF 9	-	-	-	-5.2	-124.4	34.8	-	-	-	-	-	-	-	-	-	-	-	-
ERTF 10	-	-	-	-	-	-	19.0	-24.3	41.4	-	-	-	-	-	-	-	-	-
ERTF 11	-	-	-	-	-	-	-	-	-	18.7	-24.4	43.1	-	-	-	-	-	-
ERTF 12	-	-	-	-	-	-	-	-	-	-	-	-	18.9	-24.3	43.1	-	-	-
ERTF 13	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	18.9	-24.3	43.0

Notes:
- Time to target latitude crossing allowable tolerance - MRO: ± 30 s, ODY: ± 60 s).

Landing Pass Geometry



Landing and Post-Landing Geometry



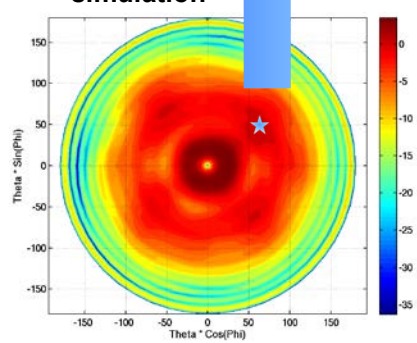
UHF and DTE Link Analysis

- **Telecom link budget process similar to Phoenix approach**
  - Identify key parameters and apply conservative assumptions
    - MSL transmitter power and line losses
    - MSL antenna gain
    - Path parameters
    - Orbiter/DSN antenna gain and line losses
  - Use trajectory information provided by EDL trajectory simulations
    - Range, Doppler, antenna view angles
  - Calculate received power
- **Link budget dominated by antenna gain patterns and geometry**
- **Model, based on link budget, integrated into EDL trajectory simulation, POST2**
  - Allows interrogation of trajectory envelopes
  - Providing best guess (leaning conservative) values for principal drivers: antenna patterns
  - EDL model certification processes applied
    - Compared provided inputs vs. simulation implementations
    - Comparison of trajectory simulation outputs to standalone telecom link analysis results
  - Included in EDL simulation configuration control
- **Used to verify requirement of 90% successful link closure rate during EDL**

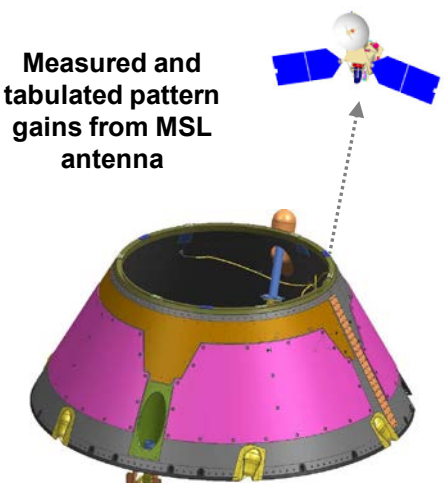
MRO Example t=800 sec after CSS

Link Parameter		Unit	Design Value	Fav Tol	Adv Tol	Mean Value	Var
MSL TRANSMITTER PARAMETERS							
Total Xmitter Pwr		dBm	39.29	0.00	0.00	39.29	0.0000
Xmitter Circuit Loss		dB	-1.15	0.10	-0.20	-1.18	0.0039
MSL Antenna Gain		dBi	-4.84	0.00	0.00	-4.84	0.0000
EIRP (1+2+3+4)		dBm	33.31			33.28	0.0039
PATH PARAMETERS							
Space Loss		dB	-141.82			-141.82	
Atmospheric Attn		dB	0.00	0.00	0.00	0.00	
Polarization Mismatch		dB	-1.00	1.00	-0.50	-0.75	0.1875
MRO Receive Parameters							
MRO Antenna Gain		dBi	2.98	0.00	0.00	2.98	0.0000
Lumped Ckt/Ant Loss		dB	-2.98	0.10	-0.20	-3.03	0.0075
TOTAL POWER SUMMARY							
Total Rcvd Pwr (Pt)	(5+6+7+8+9+10+11)	dBm	**-109.51**			**-109.35**	0.20

MRO location in MSL antenna pattern during trajectory simulation

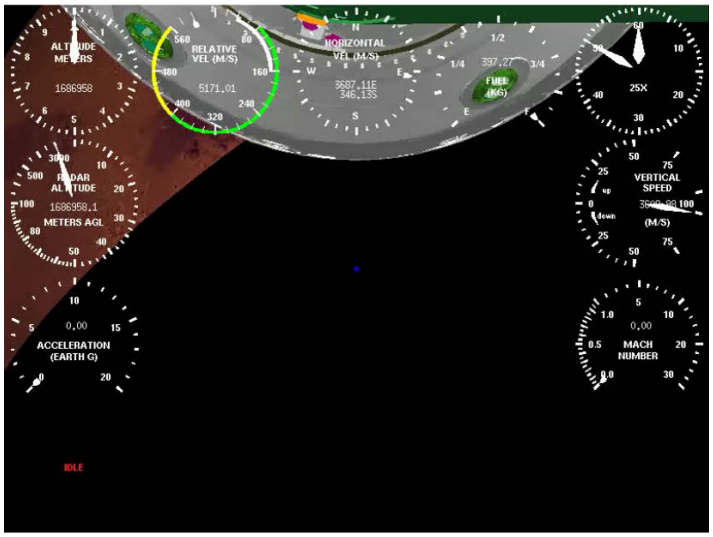


Measured and tabulated pattern gains from MSL antenna

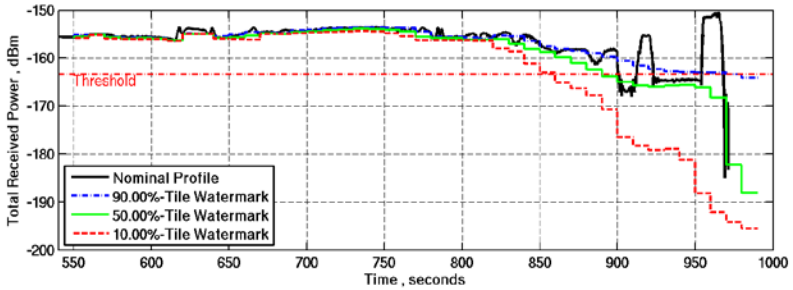


X-Band DTE Link Analysis

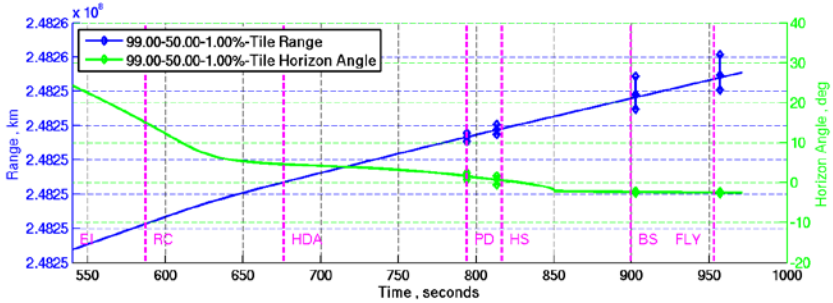
- **DTE coverage was good until Earth set**
  - Excellent for exoatmospheric flight and entry: well above detection thresholds except near Earth set
    - Signal expected to get variable near Earth set due to diffraction off the planet
  - Earth set after heatshield separation



- **Received power drop occurs after parachute deploy**
  - Due to flight path angle turnover indicating unfavorable antenna angles

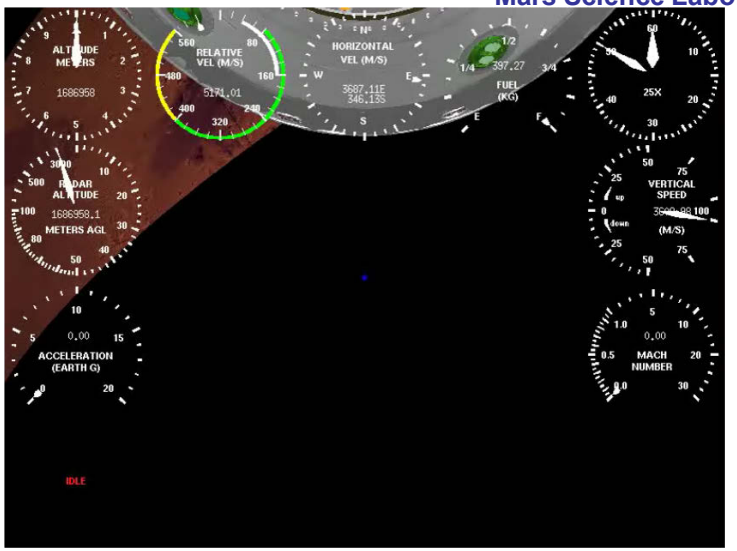


- **Earth loss of signal occurred 21 seconds after heatshield separation in-flight**
  - No unexpected dropouts

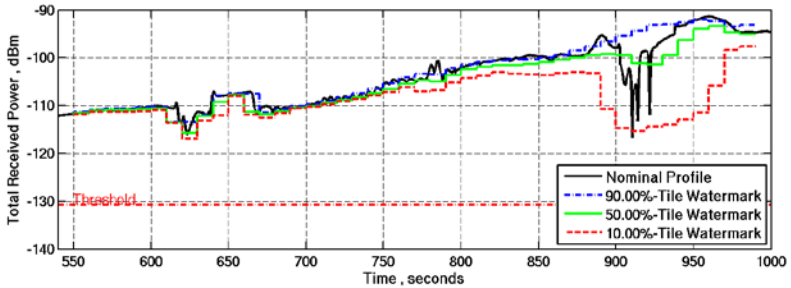


MRO Link Analysis

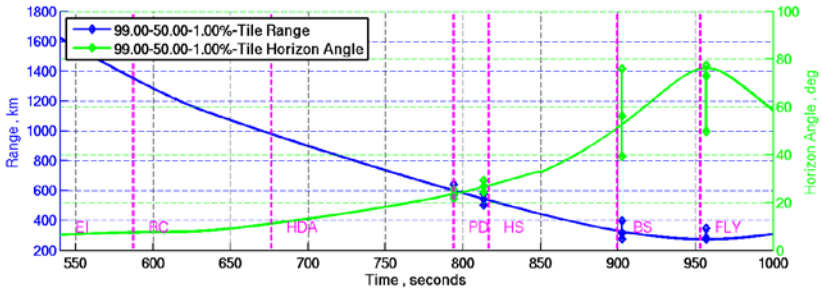
- **Link to MRO began at 8 minutes 7 seconds prior to entry interface and continued well past landing**
  - Selection of crosstrack bias favors MRO over Odyssey
  - Well above received power threshold for all of EDL
  - MRO threshold for link closure was -130.8 dBm
  - MRO was considered prime relay asset for any fault reconstruction analysis



- **Monte Carlo results showed 10%-Tile watermark of received power exceeding threshold throughout EDL**



- **MRO was directly overhead at the start of flyaway, with ~4 minutes of post touchdown contact duration**
  - HiRISE image acquisition occurred between heatshield and backshell separation
  - Predicted HiRISE image acquisition time was 05:16:42 UTC
  - Actual HiRISE image acquisition time was 05:16:43 UTC

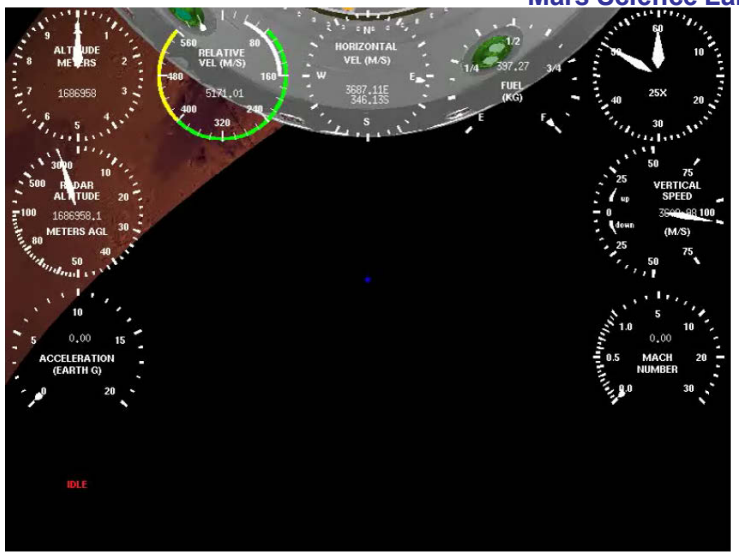


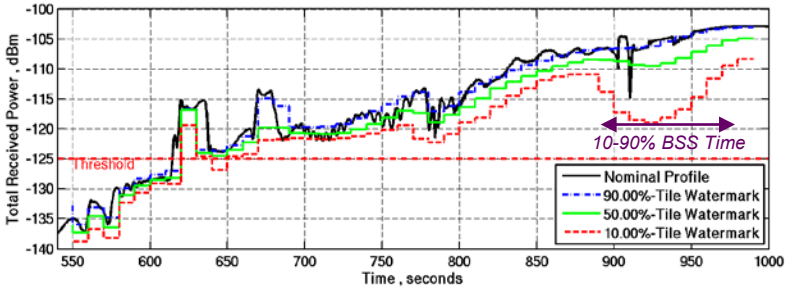
Odyssey Link Analysis

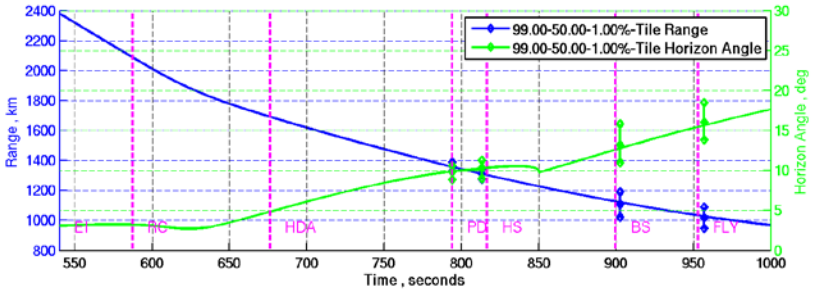
- **Link to Odyssey began at 2 min 18 sec after entry and continued well past landing**
  - Selection of crosstrack bias favored MRO over Odyssey
  - Antenna angles, high range, doppler and plasma limit performance in early entry
  - Odyssey threshold for link closure assumed to be -125 dBm
  - Odyssey doppler threshold assumed to be 6 kHz, due to CE-505 radio

- **Monte Carlo results showed 10%-Tile watermark of received power exceeding threshold after the start of range control (HDA)**
  - Odyssey exited plasma blackout around this time

- **Odyssey still rising above horizon at the start of flyaway, yielding ~4 minutes of post touchdown contact duration**

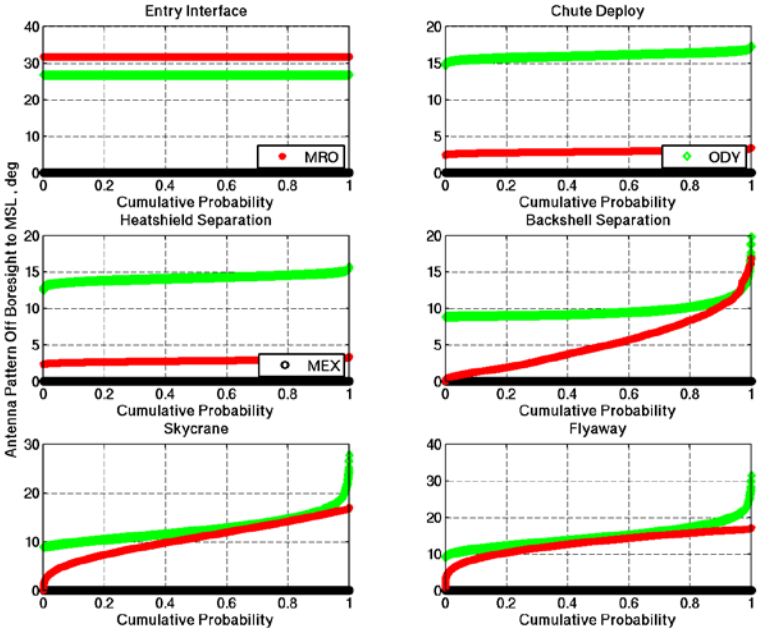






Pointing Accuracy

- **Orbiter teams designed maneuvers that would best capture MSL inside antenna patterns**
  - Maneuvers provided to EDL trajectory simulation for evaluation
- **Monte Carlo analysis performed to ensure that trajectory envelopes did not exceed pattern width**
  - Was useful for evaluating off-nominal maneuvers, i.e. ODY nadir-pointing
- **Analysis performed for HiRISE image acquisition indicated a 74.28% probability of capturing MSL**
  - Image acquisition was successful!



Summary

- **MSL fulfilled all EDL communication requirements**
  - EDL comm activities were determined via DTE tones through heat shield separation and via the UHF telemetry data stream through landing
  - State of the spacecraft was determined at all times during EDL via UHF telemetry in both near real-time (Mars Odyssey), open-loop record (Mars Reconnaissance Orbiter), unreliable bitstream mode retransmit (Mars Odyssey), and canister mode (Mars Express)
- **Mars Reconnaissance Orbiter, Mars Odyssey, and Mars Express fulfilled EDL relay target requirements**
  - Excellent coordination between MSL and the orbiter Navigation teams proved to be key to a perfectly orchestrated EDL communications event on landing day.
- **Monte Carlo runs folded into the EDL relay target generation process were fundamental in ensuring communication coverage throughout EDL**