ENTRY, DESCENT, AND LANDING COMMUNICATIONS FOR THE 2011 MARS SCIENCE LABORATORY

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Abstract: The Mars Science Laboratory (MSL), established as the most advanced rover to land on the surface of Mars to date, launched on November 26th, 2011 and arrived to the Martian Gale Crater during the night of August 5th, 2012 (PDT). MSL will investigate whether the landing region was ever suitable to support carbon-based life, and examine rocks, soil, and the atmosphere with a sophisticated suite of tools. This paper addresses the flight system requirement by which the vehicle transmitted indications of the following events using both X-band tones and UHF telemetry to allow identification of probable root causes should a mission anomaly have occurred: Heat-Rejection System (HRS) venting, completion of the cruise stage separation, turn to entry attitude, atmospheric deceleration, bank angle reversal commanded, parachute deployment, heatshield separation, radar ground acquisition, powered descent initiation, rover separation from the descent stage, and rover release. During Entry, Descent, and Landing (EDL), the flight system transmitted a UHF telemetry stream adequate to determine the state of the spacecraft (including the presence of faults) at 8 kbps initiating from cruise stage separation through at least one minute after positive indication of rover release on the surface of Mars. The flight system also transmitted X-band semaphore tones from Entry to Landing plus one minute although since MSL was occulted, as predicted, by Mars as seen from the Earth, Direct-To-Earth (DTE) communications were interrupted at approximately ~5 min after Entry (~130 prior to Landing). The primary data return paths were through the Deep Space Network (DSN) for DTE and the existing Mars network of orbiting assets for UHF, which included the Mars Reconnaissance Orbiter (MRO), Mars Odyssey (ODY), and Mars Express (MEX) elements. These orbiters recorded the telemetry data stream and returned it back to Earth via the DSN. The paper also discusses the total power received during EDL and the robustness of the telecom design strategy used to ensure EDL communications coverage.

Keywords: *Mars, Mission Design, EDL Communications, Trajectory Design, Relay Operations*

1. Introduction

After having successfully launched on November 26th, 2011, and having traveled more than 500 million km, MSL faced the biggest challenge of every landed Mars mission, Entry, Descent, and Landing (EDL). MSL arrived to Mars at ~5.9 km/s and in approximately seven minutes, decelerated to less than 1 m/s. During the descent, MSL experienced temperatures greater than 1,000 C°, and accelerations up to 12 g's. The success of EDL depended on performing multiple separations, deployments, and the firings of the Mars Landing Engines (MLEs), which were used for the first time during the mission. Due to the large distance between Earth and Mars on landing day, about 250 million km, which translated into a one-way light time delay of roughly 14 min, the vehicle needed to execute all the spacecraft sequences autonomously using onboard sequences previously uplinked and event-based triggers. Engineers in the Mission Support Area (MSA) monitored the vehicle in real time (minus the one-way light time delay) using telemetry data transmitted by MSL to Mars Odyssey and downlinked via the Deep Space Network antennas. The MSL signal was also captured by the Mars Reconnaissance Orbiter (open loop recording) and Mars Express (canister mode). Direct-to-Earth X-band transmissions through Entry plus ~5 min were captured by both Canberra (DSN) and European Space Agency's ground station New Norcia. In addition to these ground assets, Parkes Observatory located in Australia also captured the DTE UHF signal. Figure 1 shows the expected MSL information available in near real-time during MSL EDL. Figure 2 shows the MSL data recorded during EDL.

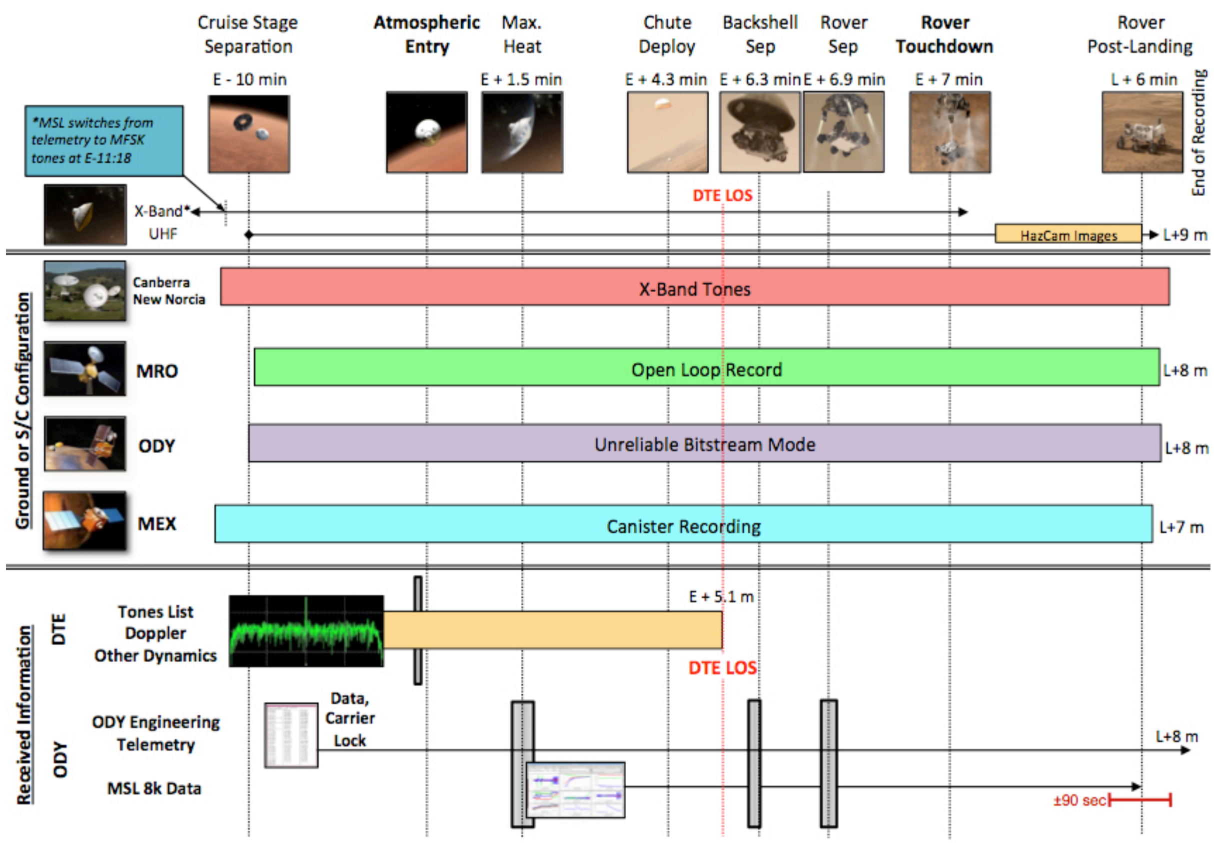

Figure 1. Expected MSL Information Available in Near Real-Time During EDL

Due to the complexity of EDL, and following the Mars Polar Lander (MPL) failure, NASA imposed a requirement on all future NASA missions to provide spacecraft communications during critical events (in particular, during EDL). Designing a robust telecommunications strategy during EDL is a challenge that requires coordination of multiple aspects, including trajectory design, telecom system design, orbital assets maneuvering and pointing design, command and data handling, and ground systems. Due to the high entry speeds and rapid attitude changes that result in potentially large Doppler shifts, it is difficult to initially lock with the entry vehicle. Also, shortly after Entry, the vehicle will go through a signal attenuation period due to plasma. Plasma levels are not typically expected to affect X-band DTE communications but may impact telemetry capabilities for some duration and intermittently lose carrier. Brief loss of signal periods may also occur due to antenna switches or blockage of signal by jettisoned components.

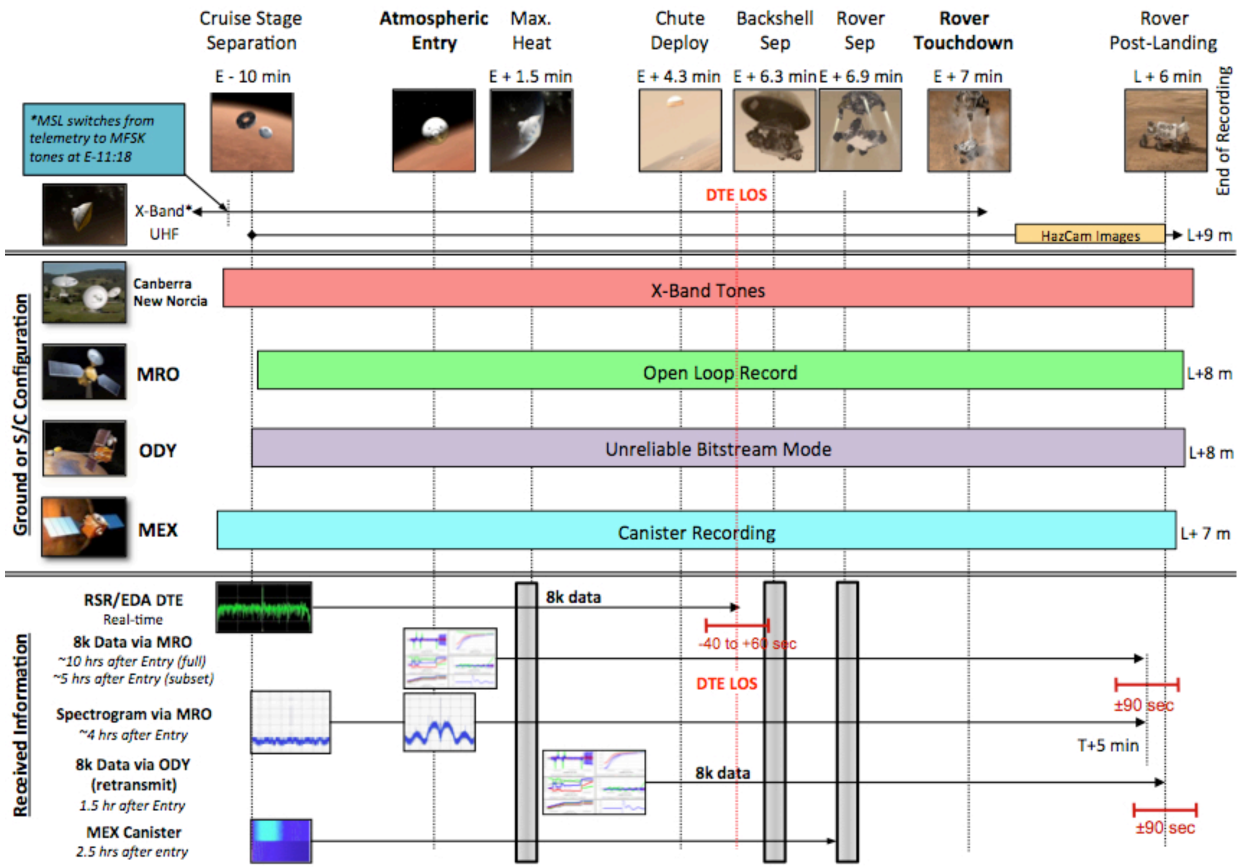

Figure 2. MSL Data Recorded During EDL

1.1 EDL Communications for Past Mars Missions

Since the first Mars missions in the 1970s, past missions have established architectures that provided communications during EDL.

The *Viking 1 and 2* missions (1976) consisted of an orbiter and a lander spacecraft attached to each other. The attached spacecraft inserted into a ~1,500 x ~33,000 km orbit and then the lander was deployed from orbit. During EDL, the lander communicated with the orbiter via a one-way 4 kbps UHF link transmitting altitude and velocity information. The orbiter bent piped the received signal via its S-band link. A blackout of a few seconds occurred during EDL [1].

The *Mars Pathfinder* mission (1997) used a direct entry to land on the Ares Vallis site. During EDL, the spacecraft used X-band Direct-To-Earth communications. The signal included both carrier and semaphore tones, which indicated the execution/completion of EDL events. The vehicle experienced a 30 s communication blackout during the peak deceleration segment of the EDL phase.

The *Mars Polar Lander* (1999) also communicated via X-band; however, the X-band radio was part of the cruise stage; hence, after spacecraft separation a few minutes before entry, X-band communications were disabled. Due to cost constraints, no communications were planned during EDL. Once the vehicle would have landed on the surface, the lander would have communicated using both the UHF link via the Mars Global Surveyor (MGS) and DTE via its X-band radio. Unfortunately, the Mars Polar lander spacecraft failed during EDL. Since no communications were available during the descent, ground teams had little direct information to understand the root cause of the failure. After this failure, NASA imposed a requirement on all future NASA missions to provide communications during critical events such as Mars Orbit Insertion or EDL for forensic purposes should a mission anomaly occur.

The *Mars Exploration Rovers* (2003) mission was the first mission to be subjected to the critical event coverage requirement. This mission transmitted a DTE X-band carrier and semaphores. It counted with 256 different semaphores, whereas Mars Polar Lander had just a few them, which provided general spacecraft state and health information. Each semaphore was transmitted for 10 s in order for the ground stations to detect and monitor EDL events as they took place. Once the rover separated from the backshell, the 8 kbps UHF link to the Mars Global Surveyor obiter was established for the remainder of EDL. The data sent to Mars Global Surveyor was bent piped back to Earth. No signal blackout was observed during EDL probably due to the lower entry speed of the Mars Exploration Rovers when compared to Mars Pathfinder.

The *European Mars Express orbiter* (2003) deployed the *Beagle 2* lander. No communications were planned for Beagle until after the probe successfully landed on the surface. After landing, Beagle would have communicated with Mars Express using its UHF transceiver. Unfortunately, Beagle never communicated with the orbiter providing little direct information to the ground team to understand the nature of the failure. As it happened after the Mars Polar Lander failure, the European Space Agency also recommended providing coverage of critical events such as EDL in future planetary missions.

The *Mars Phoenix lander* (2007) also used a direct entry approach to arrive to the Northern plains of Mars. X-band DTE communications were not available following Cruise Stage separation; however, Phoenix relayed its telemetry via its UHF radio to Mars Reconnaissance Orbiter, Mars Odyssey, and Mars Express for coverage during critical events. Mars Odyssey bent piped the data back to Earth.

2. Launch/Arrival Strategy

The MSL launch/arrival strategy was driven by multiple key requirements that included launch vehicle capability, atmosphere-relative entry speeds, dust storm season avoidance, and communications coverage during Entry, Descent and landing. Based on these requirements, four candidate launch/arrival strategies, one in the type 2 region and three in the type 1 region, were developed.

2.1 EDL Coverage Requirements and Constraints

The four 2011 MSL launch periods satisfied all launch and arrival mission requirements and constraints mostly differing in their EDL coverage characteristics [1]. The EDL coverage requirements and constraints were the following:

- Full Entry, Descent and Landing (EDL) communications coverage (from atmospheric entry, defined to occur at a radius of 3522.2 km, through landing plus 1 min) via at least two of the following assets: Direct-To-Earth (DTE) using an X-band link, Mars Reconnaissance Orbiter (MRO) and Mars Odyssey (ODY) using an UHF link. MRO coverage always has priority over ODY coverage.
- MRO/ODY antenna angles (defined as the angle between the MSL anti-velocity vector and the direction to MRO/ODY) ≤ 135 deg during the EDL phase.
- DTE antenna angles (defined as the angle between the MSL anti-velocity vector and the direction to Earth) ≤ 75 deg during the EDL phase.
- Elevation of MRO/ODY/DTE at Landing and at Landing plus one min ≥ 10 deg.
- DTE EDL coverage from cruise stage separation to entry.
- Maintain the orbiters LMST nodes as close as possible to their nominal values, ~2:58 PM (MRO) and ~3:58 PM (ODY).
- Mars Express visibility is desired but not required.

The type 2 strategy had multiple target sets, which were necessary to cover the span of latitudes (from 25° N to 27° S) that encompassed the final four candidate landing sites. The main advantage of the type 2 launch period was that it provided DTE communications from Entry to landing plus 1 minute across all landing sites; nevertheless, both MRO and ODY would have had to move their orbital node significantly, requiring MRO and ODY to be moved as early as ~1:45 PM, and ~3:00 PM respectively, dramatically impacting the orbiters' science return and orbital lifetime (the required node was a function of actual launch day and landing site selected). The type 2 launch period was also contingent on Juno's launch since both MSL and Juno used the same Atlas V launch pad. ULA initially estimated that a 78-day separation between launches would be required to refurbish the launch pad and complete launch activities (this number was later extended to a minimum of 83 days). Hence, October 22, 2011 would have been the first possible MSL launch day if Juno were to launch on the first day of its launch period (August 5, 2011).

Due to MSL launch being contingent on Juno's launch and the very significant impact to the orbiters should MSL launched in the type 2 region, the type 1 region was investigated and became available once it was determined by the MSL EDL team that atmosphere-relative entry speeds as high as 5.9 km/s were acceptable (the original entry speed requirement was 5.6 km/s).

All three launch periods in the type 1 region were bounded by atmosphere-relative entry speeds at the beginning of the launch period and by launch vehicle performance at the end of the launch period. The arrival dates of these launch periods were selected based on different EDL coverage criteria. The type 1A launch period was optimized to extend EDL communications as much as possible with no regards to how much the orbiters would need to move their nodes. The type 1B launch period was designed to keep the orbiters as close as possible to their nominal LMST node at the expense of degrading DTE communications. The type 1C launch period was optimized to extend DTE communications through at least the end of the signal attenuation region (plasma brownout) while keeping the orbiters' LMST nodes as close as possible to their nominal values, which reduced how much the orbiters needed to move their orbital LMST node when compared to the type 1A launch period.

Ultimately, the type 1B launch period that extended from November 25 through December 18, 2011 was selected. For the final landing site, Gale Crater, DTE communications were available through Entry plus ~300 s for all launch days and both MRO and ODY were not required to move their LMST nodes, saving valuable onboard propellant and extending their orbital lifetime. Another advantage of the type 1B launch period was that it had a constant arrival date of August 6, 2012 (UTC), which simplified planning of surface operations. The Mars Science Laboratory successfully launched on an Atlas V 541 from Launch Complex 41 at the Cape Canaveral Air Force Station on November 26, 2011. The MSL launch/arrival strategy along with the constrains that drove the design of the launch period are shown in Figure 3. The entry speed contour represents the atmosphere-relative entry speed of MSL at the Entry Interface Point (EIP). The maximum entry speed of 5.9 km/s (or 6.1 km/s in inertial space) is contoured in red. C3 curves that represent the required energy for the trans-Mars injection are shown in blue. A maximum C3 of 20.1 km^2/s^2 throws a maximum launch mass of 4,050 kg, which is illustrated in magenta. The purple shaded lines show the region within the entry speed and launch vehicle performance constraints in which no full EDL coverage via ODY at 4:00 PM is available. The green shaded lines show the region with no full EDL coverage via MRO at 3:00 PM [3].

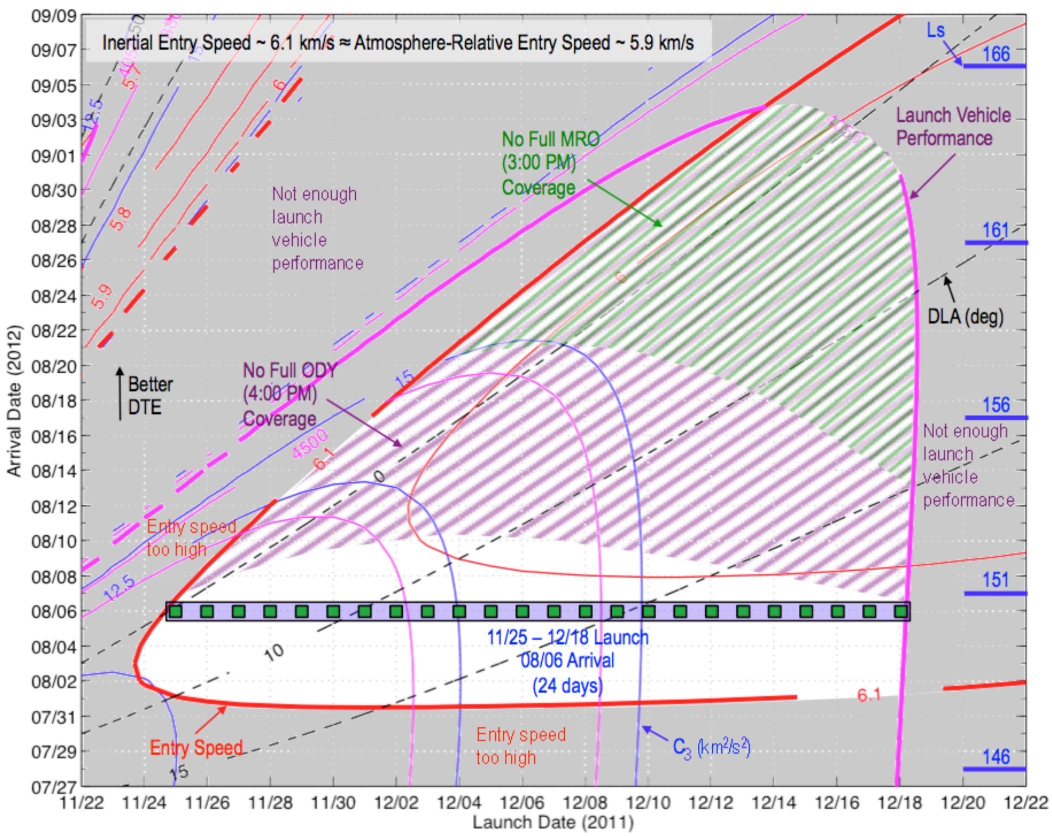

Figure 3. MSL Launch/Arrival Strategy

Both MRO and Odyssey orbiters are in semi-circular, frozen, Sun-Synchronous orbits with an orbital period of approximately two hours. Odyssey arrived to Mars in October 2001 and is currently in a ~350 x ~420 km orbit with a ~3:58 PM descending node. MRO arrived to Mars in March 2006 and is in a ~250 x ~300 km orbit with a ~2:58 PM ascending node. Mars Express which arrived to Mars in December 2003 is in a ~350 x ~10,050 km elliptical orbit with an orbital period of ~6.7 hours. Figures 4 and 5 show the communications geometry at Entry and Landing.

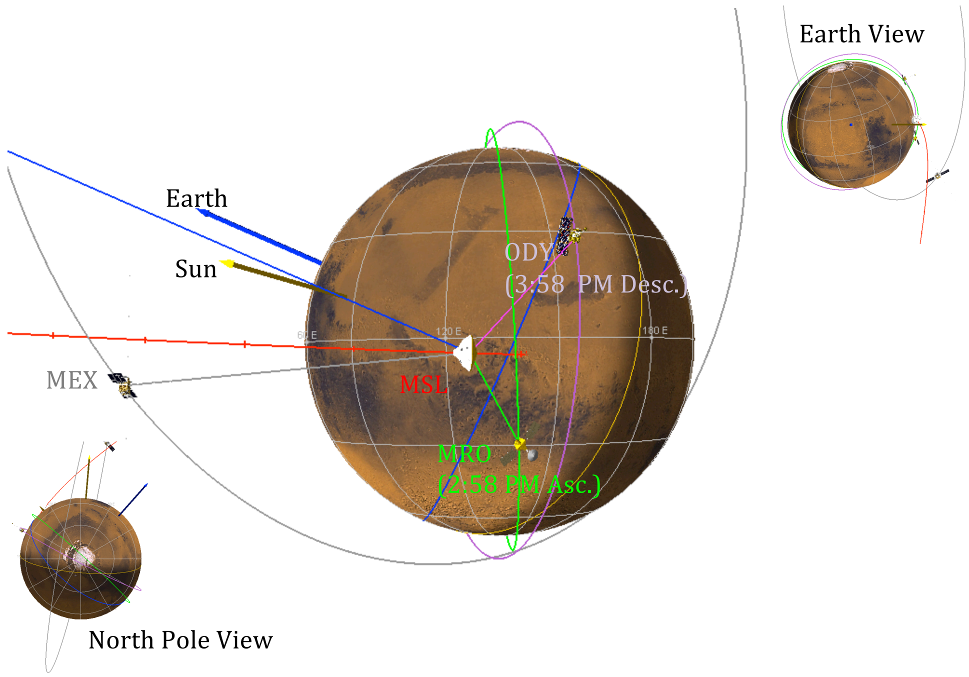

Figure 4. MSL Arrival Geometry at Entry Interface Point

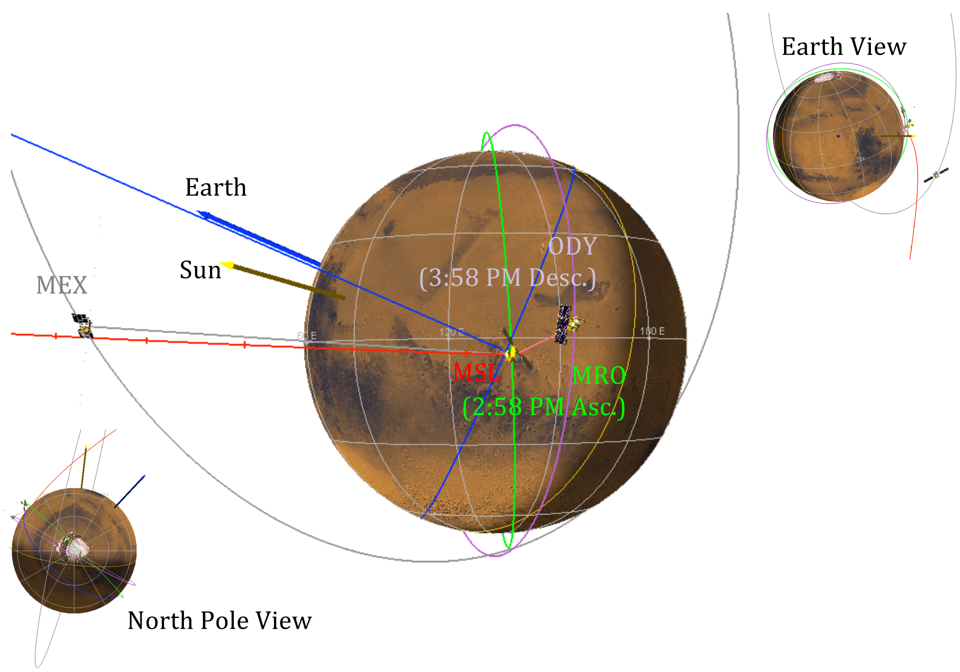

Figure 5. MSL Arrival Geometry at Landing

3. EDL Events Timeline

EDL consisted of six major segments: Exo-Atmospheric, Entry, Parachute Descent, Powered Descent, Sky Crane, and Fly Away [4]. Figure 6 shows a timeline of the different EDL events. Note that the event times correspond to the nominal trajectory. Actual times differed from the nominal event times due to dispersions in the entry time and atmospheric uncertainties. The Exo-Atmospheric segment began once the cruise stage separation command was sent. Once the cruise stage separated, Guidance, Navigation, and Control (GNC) was enabled. Once enabled, the entry body was despun and turned to its entry attitude. Then, the two ~75-kg Cruise Balance Masses (CBMs) were jettisoned to enable aerodynamic lift.

The Entry segment started with the vehicle at the Entry Interface Point (EIP) defined at 3522.2 km from the center of Mars. During the Entry segment, the vehicle went through peak heating and peak deceleration, the Reaction Control System (RCS) controlled the lift vector to achieve the desired down-range and cross-range target. Just prior to parachute deploy, six ~25-kg Entry Balance Masses (EBMs) were jettisoned to eliminate lift and the vehicle rolled to point the Terminal Descent Sensor (TDS) to the ground. This maneuver is called the Straighten Up and Fly Right maneuver (SUFR) or "Victory" roll.

The Parachute descent segment starts with the parachute deployment triggered once the vehicle reached Mach 1.7. RCS wrist mode damping was active 10 s after parachute deploy to reduce wrist mode oscillations. Once the vehicle achieved a speed of Mach 0.7, the heat shield was jettisoned and the TDS started acquiring the ground. The command to jettison the backshell and the parachute was issued at an altitude of 1.6 km and at a velocity of approximately 79 m/s. Just before backshell separation, the Mars Landing Engines (MLEs) were primed in preparation for the start of the powered descent segment.

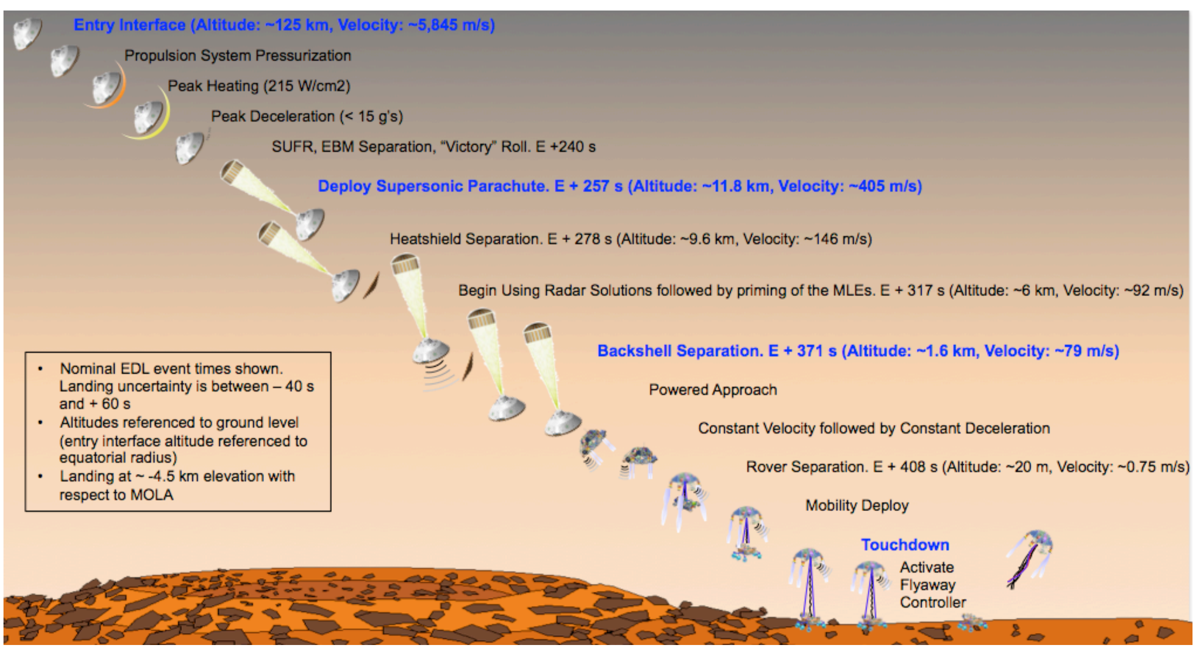

Figure 6. MSL EDL Timeline

The Powered Descent segment began at backshell separation. During powered descent, eight independently throttleable MLEs were actuated, initially to execute a divert maneuver for backshell avoidance which brought the vehicle to vertical flight at a descent rate of 32 m/s. Once vertical flight was achieved, a descent at constant velocity to adjust for altitude error at backshell separation started. This constant velocity phase was followed by a constant deceleration phase, which reduced the vehicle's speed to 0.75 m/s in preparation for the sky crane segment. At this time, the four inboard MLEs were throttled down to near shutdown (1%) while the four remaining MLEs were throttled at 50%.

The Sky Crane segment started following issuance of the rover separation command, which occurred at an altitude of approximately 18.6 m. The rover was lowered to ~7.5 m below the descent stage. Then, the descent stage continued to descend until post-touchdown was detected.

The Fly Away segment started after touchdown was sensed. Once the descent stage stopped its vertical motion, the bridle and electrical umbilical devices were cut and two of the MLE engines were throttled up to 100% while the other two engines were at slightly less than 100%. This caused the descent stage to pitch to ~45°. Once the turn maneuver was completed, all four engines were throttled up to 100%. Constant thrust was applied to ensure the descent stage impacted the surface at least 300 m from the landing point.

4. MSL Telecom System Description

MSL carried a powerful set of antennas to support both X-band for DTE communications, and UHF for communications via the relay orbiters. The Medium Gain Antenna (MGA) was the only antenna located on the cruise stage. Three antennas were attached to the backshell, the Parachute Low Gain Antenna (PLGA), the Tilted Low Gain Antenna (TLGA), and the Parachute UHF (PUHF) antenna. The descent stage utilized the Descent stage Low Gain Antenna (DLGA) for X-band communications, and the Descent stage UHF (DUHF) antenna. The rover has three different antennas for communications during the surface mission. The Rover Low Gain Antenna (RLGA), the High Gain Antenna (HGA), and the Rover UHF (RUHF) antenna [5]. The antenna locations are illustrated in Figure 7.

At Entry – 11 min, 11 s (1 min, 11 s prior to Cruise stage separation) MSL switched from the MGA, which had been used for deep space communications during the majority of the Cruise phase, to the PLGA antenna. At approximately 20 s prior to Entry, X-band communications switched from the PLGA to the TLGA, while the PUHF antenna continued to be used for UHF communications via the relay orbiters. During powered descent and once the vehicle had been separated from the backshell, the DLGA and DUHF antennas located on the Powered Descent Vehicle (PDV) were used. UHF communications were then switched to the RUHF once the sky crane phase started. X-band communications continued via the DLGA. Figure 8 shows the planned X-band and UHF antenna utilization during MSL Cruise, Approach, and EDL.

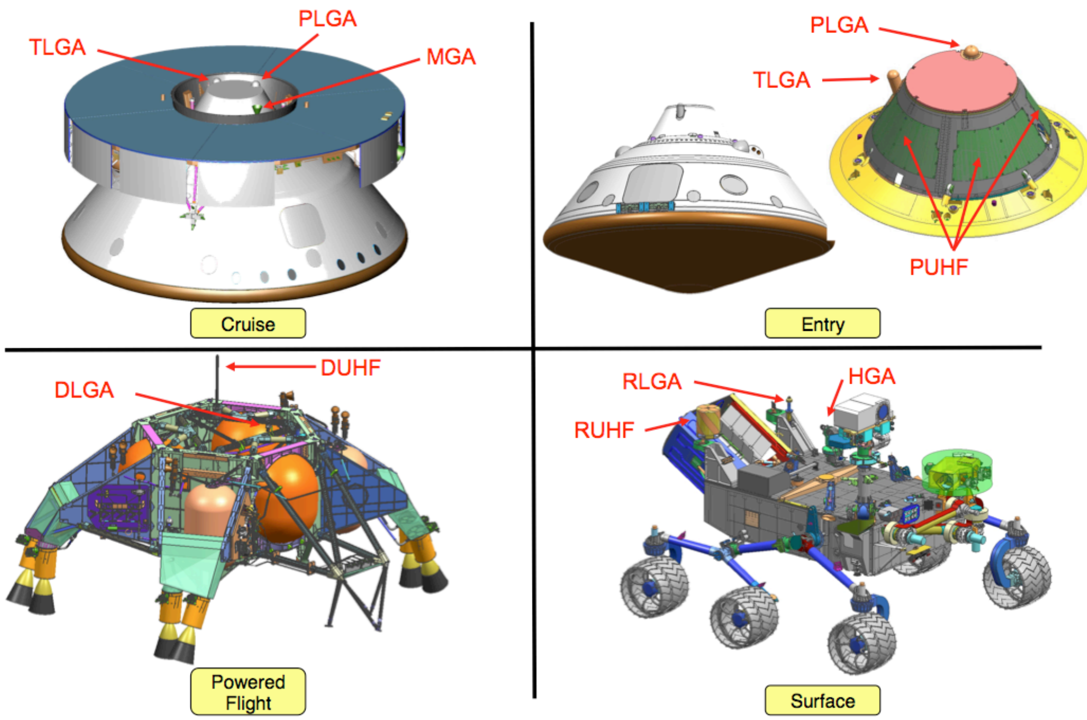

Figure 7. MSL Antenna Locations

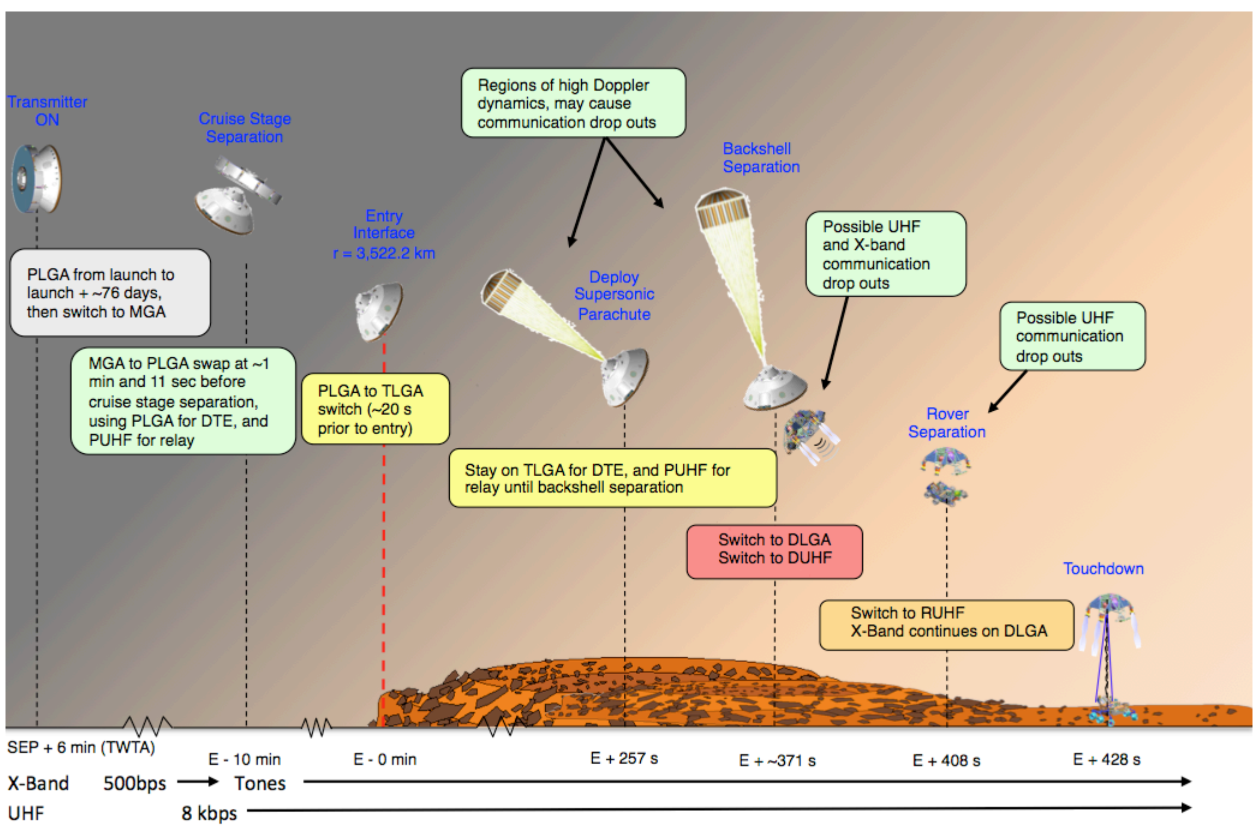

Figure 8. X-band and UHF Antenna Utilization during MSL Cruise, Approach, and EDL

4.1 UHF vs. X-band Coverage of Events

Different events during entry (peak heating, peak deceleration, bank reversals, etc.) are temporally spaced out so long duration X-band tones can keep up with the telemetry flow. UHF signal attenuation was observed 25 s after Entry and extended for ~50 s; however, X-band communications were not impacted. X-band would have been likely sufficient to determine what caused a possible failure but not necessarily the precise conditions of the fault for which telemetry was needed. UHF options existed in order to mitigate possible lack of DTE during plasma blackout by using higher-power UHF tones or carrier only but were not exercised. The downside would have been that if tones/carrier were used, the ability to get telemetry would have been lost if communications would have not been blacked out. During the powered descent and sky crane phases, a rapid succession of events existed which overwhelmed the tone communications capability. At this point, X-band could have established when a failure occurred but it would have not been likely to discover a fault. On the other hand, UHF telemetry would have been likely to be able to provide fault conditions. Brief loss of signal periods also occurred due to antenna switches.

4.2 UHF Antenna Characteristics

Results based on actual hardware testing indicated that performance using the PUHF antenna had acceptable performance for antenna angles up to 135 deg (aside from being null along -Z); therefore, it was assumed that the UHF antenna constraint was 135 deg. Figure 10 shows the PUHF antenna pattern. DUHF performance was acceptable up to 120 deg off boresight. Given the fact that UHF antenna angles decreased from entry to landing, DUHF performance was not threatened by the lower antenna angle constraint. Figure 11 shows the DUHF antenna pattern.

4.3 X-band Antenna Characteristics

Results based on actual hardware testing indicated that performance using the PLGA/TLGA/DLGA antennas had acceptable performance for antenna angles up to 85 deg; although, it was decided to take a conservative approach and assume that the DTE antenna constraint should be 75 deg. Figures 12 through 14 show the antenna pattern for the PLGA, TLGA, and DLGA antennas respectively.

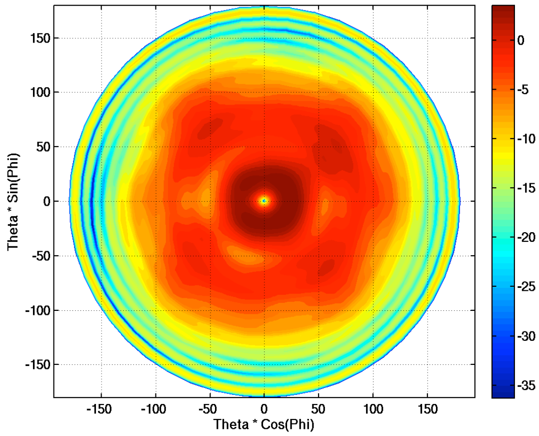

Figure 10. PUHF Antenna Pattern

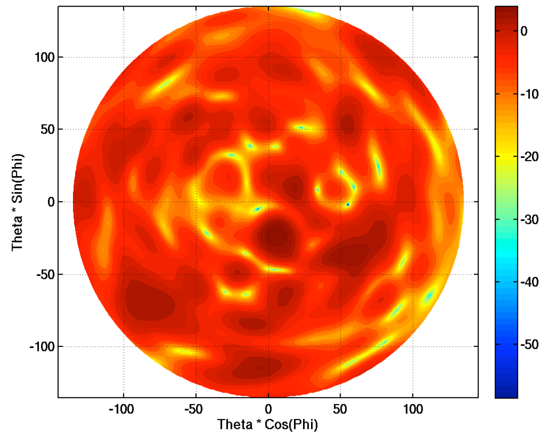

Figure 11. DUHF Antenna Pattern

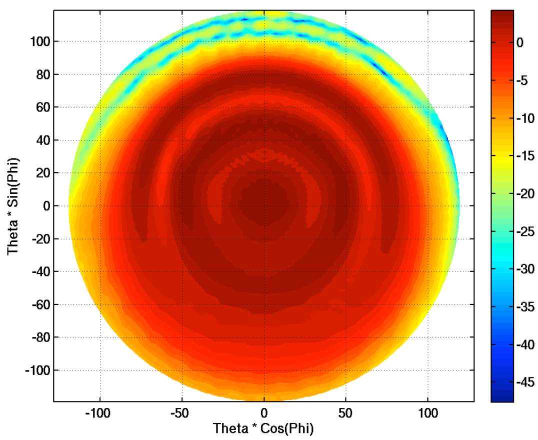

Figure 12. PLGA Antenna Pattern on Parachute Cone (Lid in Place)

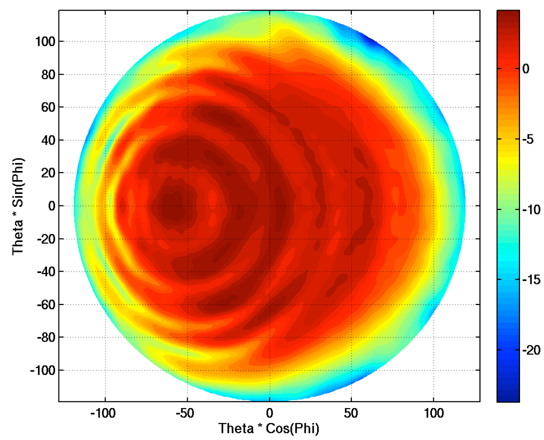

Figure 13. TLGA Antenna Pattern (Parachute Canister Lid Ejected)

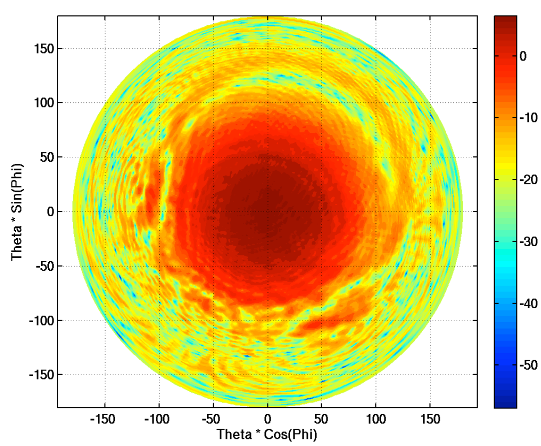

Figure 14. DLGA Antenna Pattern

5. EDL Relay Target Generation Process

In order to ensure EDL communications, the MSL Navigation team worked very closely with the Mars Reconnaissance Orbiter, Mars Odyssey, and Mars Express Navigation teams. A scheduled exchange of trajectory predicts for all the spacecraft was put in place in order to evaluate EDL communications performance and adjust the EDL targets to be achieved by the relay orbiters as necessary. The MRO/ODY/MEX targets along with additional reference trajectory data were specified in the EDL Relay Target Files (ERTF). For MRO and ODY, ERTFs specified the latitude and LMST to be achieved by the orbiters at the MSL Entry epoch. For MEX, the ERTF targets specified the latitude and longitude at the MSL Entry Epoch. ERTF #1 delivered to the orbiter teams at Launch plus 5 days specified the preliminary LMST targets, i.e., the LMST value that both MRO and ODY had to achieve at the MSL Entry Epoch. ERTF #2 delivered at Launch plus 45 days specified the final LMST target. In subsequent ERTF deliveries, the LMST specified by MSL to be achieved by the orbiters matched the LMST value predicted by the orbiter Navigation teams, i.e., the LMST target was "frozen" from that point on. The ERTF development cycle served as a robust method to fulfill EDL communication requirements since it continuously tracked the evolution of the spacecraft trajectory uncertainties. The ERTF generation process started by evaluating EDL communications based on antenna angles using the latest orbiter predicts. Figure 15 shows the expected DTE and MRO visibility for different Mean Anomaly phasings as a function of time from atmospheric Entry. For a particular on-orbit phasing, a red line indicates that visibility between MSL and MRO exists but the antenna angle constraint is violated. A green line indicates that visibility between MSL and MRO exists and the antenna angle constraint is satisfied. No line for a particular on-orbit value indicates no visibility (MSL is occulted by Mars as seen from the orbiter).

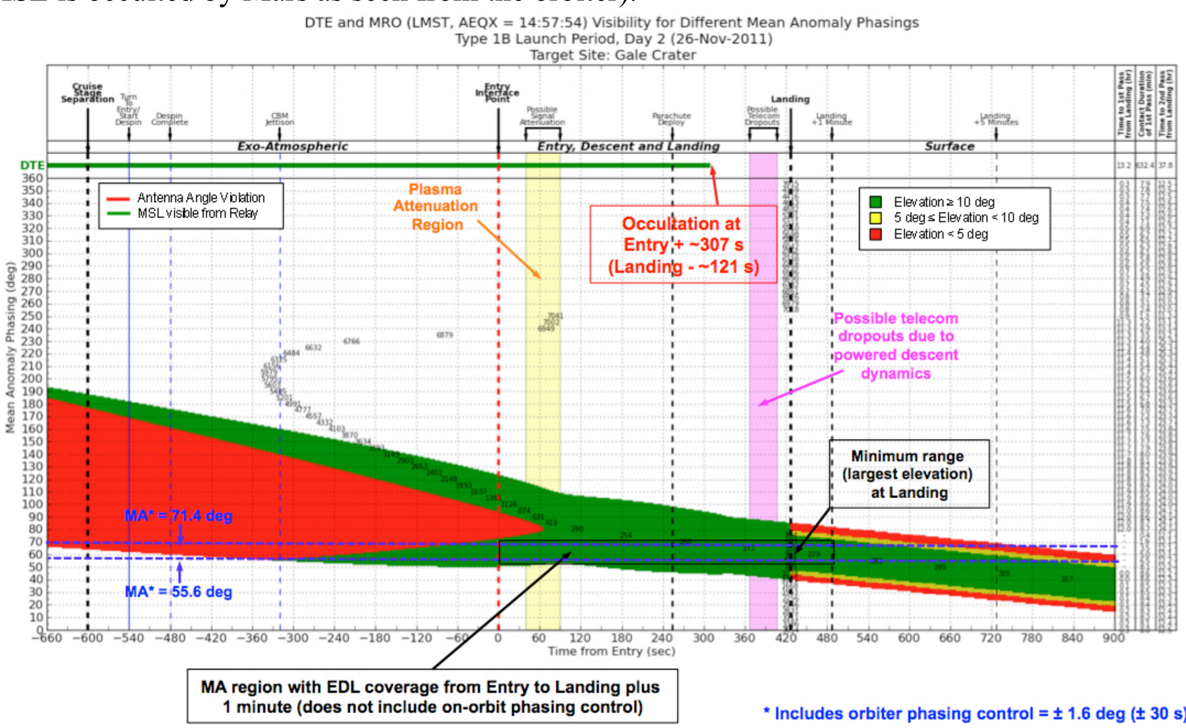

Figure 15. DTE and MRO Visibility for Different Mean Anomaly Phasings

The region limited by the two blue dashed lines, the Entry Interface Point annotated by the red dashed line, and the Landing plus 1 min line annotated by the black dashed line indicate the range of Mean Anomaly values that meet the EDL communications requirement from a geometric standpoint. Using optimization criteria provided by MSL Project Management and the Mars Program Office, a set of on-orbit phasing candidates was further evaluated. Typically, three phased orbit candidates were selected. An “open” Mean Anomaly phasing that provided the longest post-landing contact duration, a “middle” Mean Anomaly phasing with the shortest range (largest elevation angle) between MSL and the orbiter at Landing, and a “close” Mean Anomaly phasing that enveloped the set of solutions but ultimately yielded the worst telecom performance at Landing. Other on-orbit phasing candidates were evaluated early on during the initial ERTF cycles but ultimately disregarded since they provided marginal performance benefit if any.

The selected relay phasing strategies were then analyzed using MSL dispersed trajectories, the latest orbiter predicts, and attitude profiles for all the spacecraft and estimates of power received using the actual antenna angles (instead of antenna angles based on the anti-velocity vector). This link budget evaluation was then presented to the MSL Project and the Mars Program Office, and a final relay orbiter phasing for a given ERTF cycle was selected and delivered to the orbiter teams. The orbiter teams responded to each ERTF with a phased orbiter trajectory that included maneuvers (if necessary) to achieve the requested targets. These trajectories delivered by the orbiter teams were then re-evaluated to ensure that power received by the orbiters satisfied EDL communication requirements. Figure 16 shows a flow chart that illustrates the EDL relay target generation process.

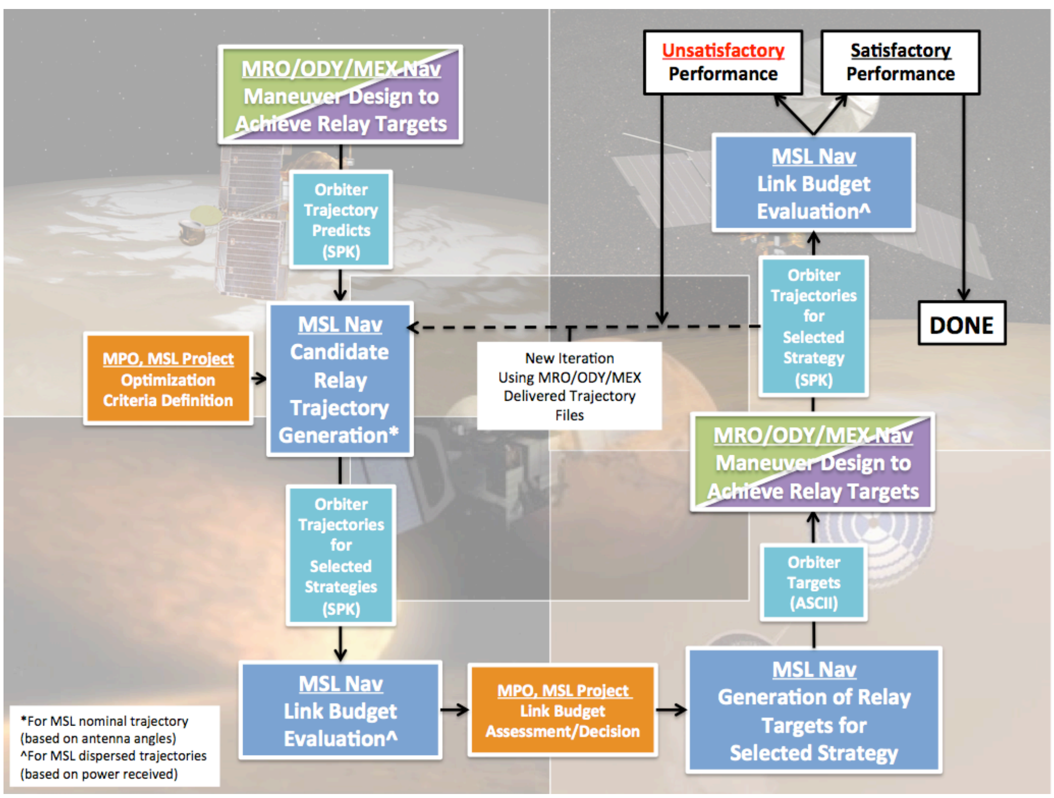

Figure 16. EDL Relay Target Generation Cycle

For both MRO and ODY, the “middle” Mean Anomaly was ultimately selected as the final EDL relay phasing. In the case of MRO, a middle Mean Anomaly phasing provided the shortest range from MSL to MRO at Landing and satisfactory post-landing contact duration. For ODY, the difference in telecom performance between the “open”, “middle”, and “close” Mean Anomaly phasings was not significant; therefore, the “middle” Mean Anomaly phasing was selected since it provided the largest on-orbit phasing error margin. For MEX, there were no on-orbit phasings that provided EDL communications from Entry to Landing due to the orbit plane orientation at the time of Entry. The “open” Mean Anomaly phasing was selected since it extended EDL coverage of MSL via MEX the longest (from Entry through ~1 min before landing) and provided the shortest range between the two spacecraft.

The final phasing targets were specified at Entry minus 56 days in ERTF #8A. ERTF #8 also delivered the final phasing targets but these targets were optimized for a previous landing ellipse target different than the final landing ellipse; hence, an update to ERTF #8 was required. Subsequent ERTF deliveries did not levy any requirements and were used for reference purposes only in order to track the evolution of targets and predicts. They also served three additional purposes: (1) Provided an opportunity to update EDL relay targets should an anomaly occur, (2) served as a method to compare the EDL communications performance based on the final phasing targets specified in ERTF #8A with the optimal EDL relay targets that would be specified with updated trajectory predicts, and (3) tracked how well the orbiters met the requirements using the final phasing targets specified in ERTF #8A. Orbiter teams were expected to achieve their EDL relay targets within ± 30 s (MRO) and ± 60 s (ODY) from the specified on-orbit phasing target (which was consistent with their spacecraft on-orbit phasing control) [6]. Both MRO and ODY satisfied the EDL requirement. MEX EDL communication support was on best effort basis only; therefore, no specific requirement was identified. Table 1 provides a summary of the targeting error in terms of time to achieve the target latitude for the three orbiters.

	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**

Table 1. Time to Target Latitude Crossing for final ERTF Cycles

Figures 17 and 18 show the expected landing pass geometry on a cartographic map and in an azimuth / elevation plot respectively based on last predicts available before Entry Interface.

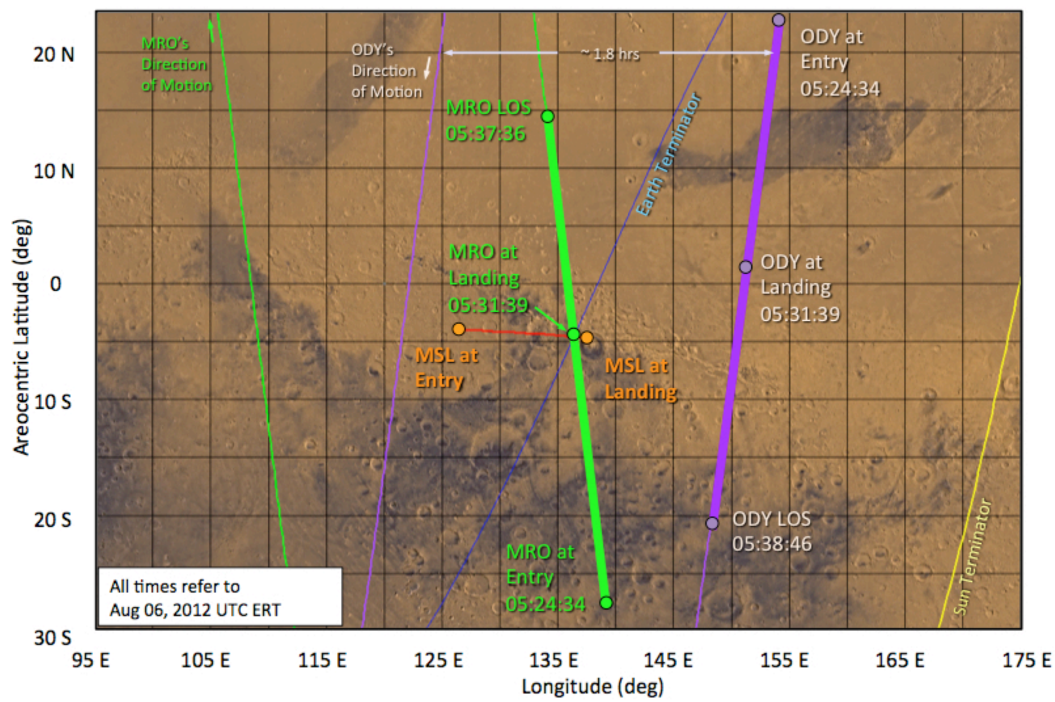

Figure 17. Landing Pass Geometry

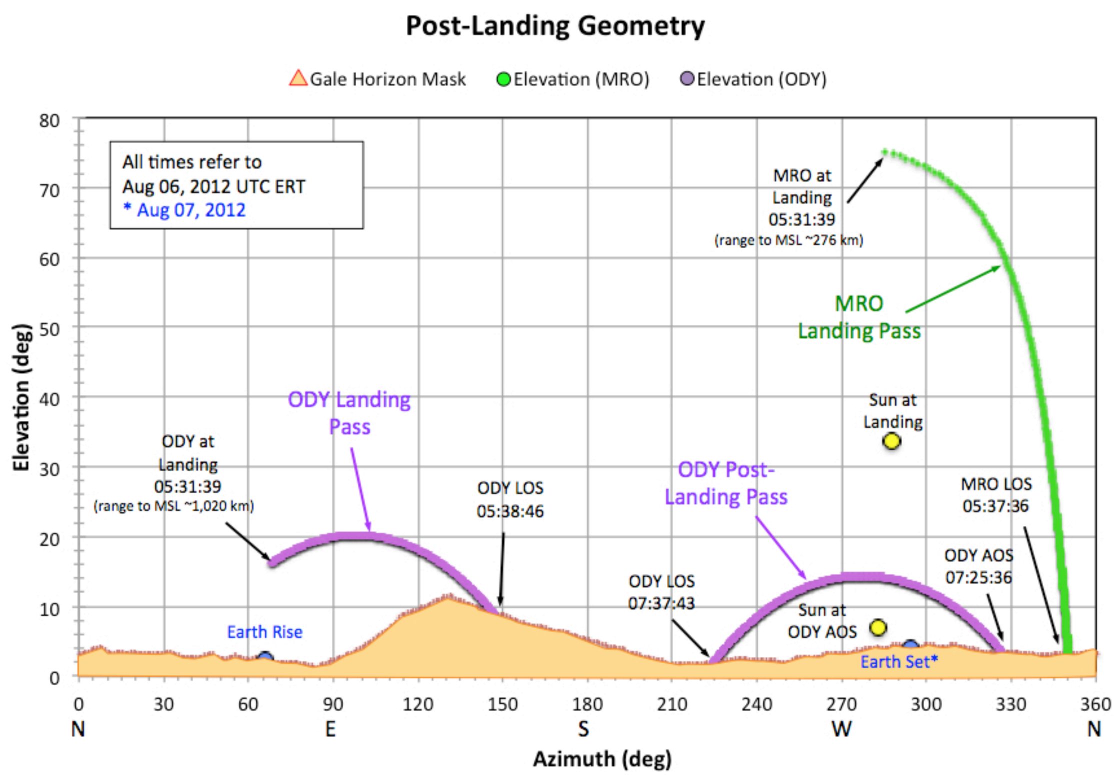

Figure 18. Landing and Post-Landing Geometry

6. Verification of EDL Requirements

Telecom constraints placed on the EDL system require each UHF antenna to meet or exceed specified Effective Isotropic Radiated Power (EIRP) requirements [8]. However, a parent requirement states that a 90% successful link closure rate is required from entry interface to rover release plus 1 minute. The first requirement of pattern EIRP is inconsequential if the geometry during EDL does not favor specific regions of the UHF pattern while closing the link. Therefore, an accurate flight dynamics simulation of the MSL EDL, coupled with the design control table used for link budget analysis, is needed to verify the 90% rate of link closure requirement that ensures EDL communication coverage. This section describes the simulation, link budget and pointing accuracy used to verify EIRP requirements.

6.1 Telecom Flight Dynamics Simulation (POST2)

The flight dynamics simulation used by the MSL project for validating and verifying performance requirements is the Program to Optimize Simulated Trajectories II (POST2). The simulation is used to incorporate various EDL related models into a single end-to-end, Multi-DOF simulation that begins at cruise stage separation and ends at descent stage impact [9]. The simulation utilizes Monte Carlo analysis which disperses models according to developer instruction. Monte Carlos are sets of 8,000 to 100,000 simulations, where parameters can be evaluated at any time in the trajectory. Statistics of specific parameters are considered according to project requirements. The simulation represents dispersed knowledge of MSL state and flight dynamics predicted at Mars, providing a useful testbed for telecom link performance analysis.

6.2 Link Budget

The Design Control Table (DCT) is the primary link budget calculation tool used by JPL which dates back to the Cassini mission. The MSL EDL link budget utilizes the most up-to-date DSN parameters for the DTE calculations, while the UHF calculations have heritage from both MER and Phoenix [10]. Two link budgets are used, one for DTE (X-Band) and one for Relay (UHF). Each is a function of the MSL antenna pattern gains and the associated receive pattern gains (MRO, ODY, MEX and DSN). Gains are evaluated as a function of cone and clock angle within the pattern. The DCT is implemented in POST2 and evaluated at every time step in the simulation for all Monte Carlo cases.

The Earth link budget analysis assumed that the link is closed when the received power to noise spectral density ratio at the DSN Radio Science Receiver is greater than 21 dB-Hz. This translates to a total received power threshold of -163.35 dBm. The nominal total received power during EDL (entry interface to touchdown) is plotted in the top plot in Figure 19 as the black line. The dashed red, green and blue lines represent the 10, 50, and 90 percentile low values measured along 10 s intervals from the Monte Carlo results. The threshold line is plotted for reference as the horizontal red line, labeled “Threshold”. The bottom plot represents the horizon angle (green) and range to Earth (blue) during EDL with dashed vertical magenta lines indicating key events in the nominal EDL event sequence, *EI* (entry interface), *RC* (Start of Range Control), *HDA* (Start of Heading Alignment), *PD* (Parachute Deploy), *HS* (Heatshield Separation), *BS* (Backshell Separation), and *FLY* (Start of Fly-Away). The diamond-vertical lines represent the Monte Carlo 1-99 percentile spread at that event.

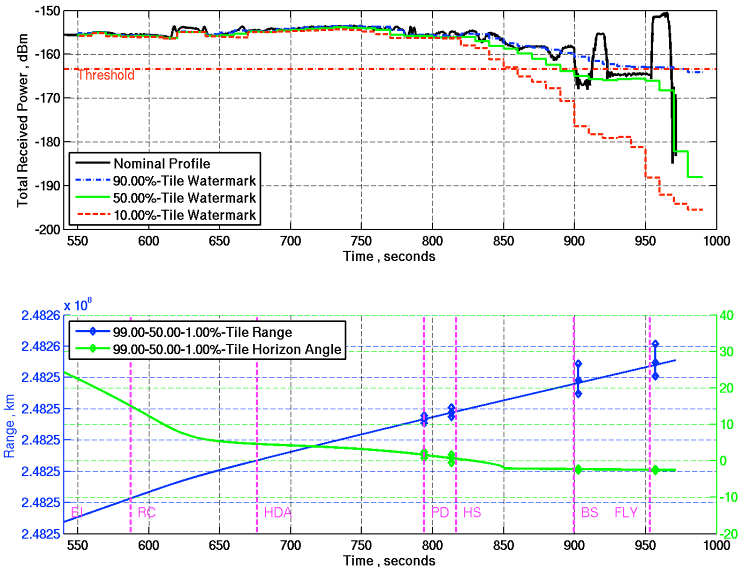

Figure 19. Earth Link Budget

Items to note include the drop in received power after parachute deploy due to the on-chute dynamics and associated flight path angle turnover, indicating unfavorable antenna angles. Earth loss of sight below the horizon occurs around heatshield separation. In flight, Earth loss of signal occurred approximately 21 seconds after heatshield separation. Had Earth remained in view of MSL throughout the rest of EDL, the signal would have deteriorated even further around Backshell separation due to lower transmitter gain on the DLGA and the associated angles that are a result of the powered descent trajectory. The steep decrease in the 10 percentile low watermark line at ~900 s is due to the variability in the Monte Carlo powered descent start time results.

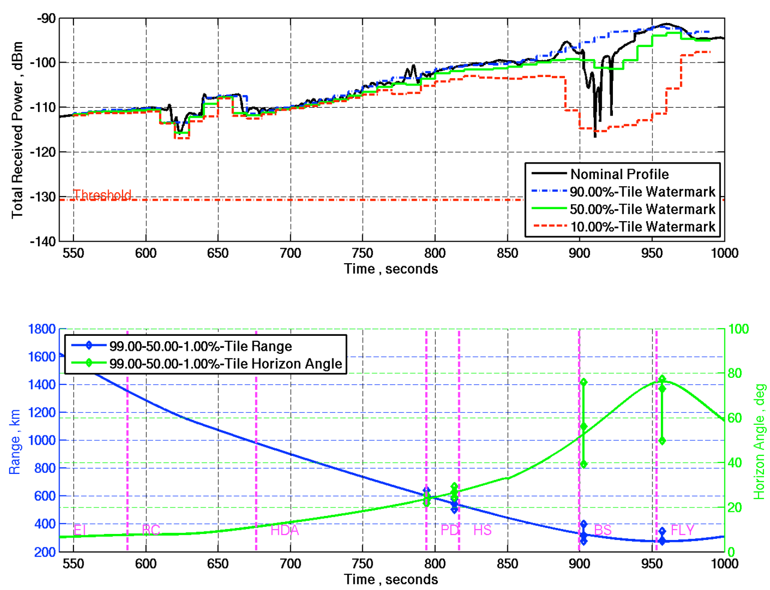

Figure 20. MRO Link Budget

The MRO link budget analysis is shown in Figure 20 using the same format as the Earth link budget. The MRO threshold for link closure is -130.8 dBm [7]. The received power results demonstrate full link closure throughout EDL. Initial closure of the link is not shown in Figure 19, but Monte Carlo results indicated that the 1 to 99 percentile times of acquisition occurred between 7 min, 36 s and 8 min, 20 s prior to entry interface. In flight, the MRO link was established at 8 min, 7 s prior to entry interface. MRO was expected to be closest to MSL at flyaway, flying nearly overhead, with the HiRISE image acquisition occurring between heatshield separation and backshell separation.

The ODY link budget analysis is shown in Figure 21. The ODY threshold assumed for link closure is -125 dBm for an 8 kbps data rate. The received power results demonstrate link closure after the start of range control. The received power increase above threshold at 620 s (1 min, 20 s past entry interface) is due to the first bank reversal, which better aligns the MSL PUHF antenna towards ODY. In flight, the ODY link was established at 2 min, 18 s past entry interface. The reason for the discrepancy in link closure times is due to the plasma blackout experienced during entry. At the start of flyaway, ODY was still rising on the horizon. Horizon set occurred roughly 5 min, 56 s after touchdown. ODY link closure requirements were met for all phases past entry interface.

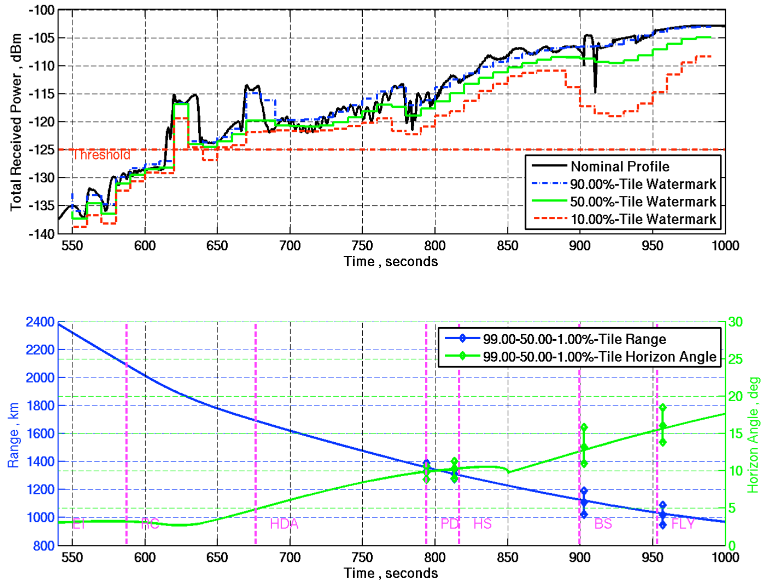

Figure 21. ODY Link Budget

The MEX link budget analysis is shown in Figure 22. The MEX threshold assumed for link closure is -125 dBm for an 8 kbps data rate. The received power results demonstrate link closure up to backshell separation. MEX horizon set was expected to occur between heatshield separation and backshell separation.

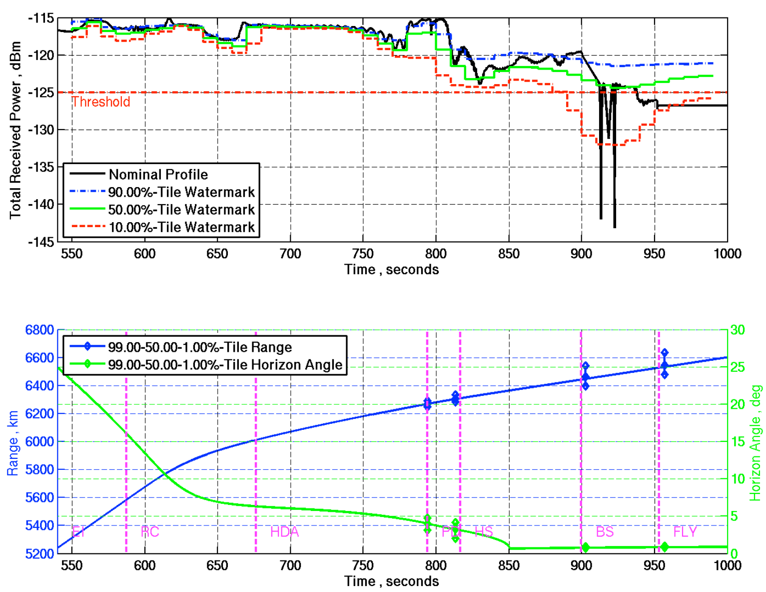

Figure 22. MEX Link Budget

The cumulative probability of link closure is shown in Figure 23 for the link analyses. The figure is broken into six subplots that represent important phases during EDL. *Approach* represents GN&C t0 to entry interface, *Entry* represents entry interface to parachute deploy, *Chute Deploy* represents parachute deploy to heatshield separation, *Post HSS* represents heatshield separation to backshell separation, *Powered Approach* represents backshell separation to start of skycrane, and *Skycrane* represents start of skycrane to touchdown. The y-axis on each plot is the percent time the received power exceeded the link closure threshold for that EDL phase, and the x-axis represents the cumulative probability of that time above threshold for the Monte Carlo. The dashed vertical magenta line is the 90% link closure requirement. Earth is represented by the blue data, MRO by the red data, ODY by the green data, and MEX by the black data.

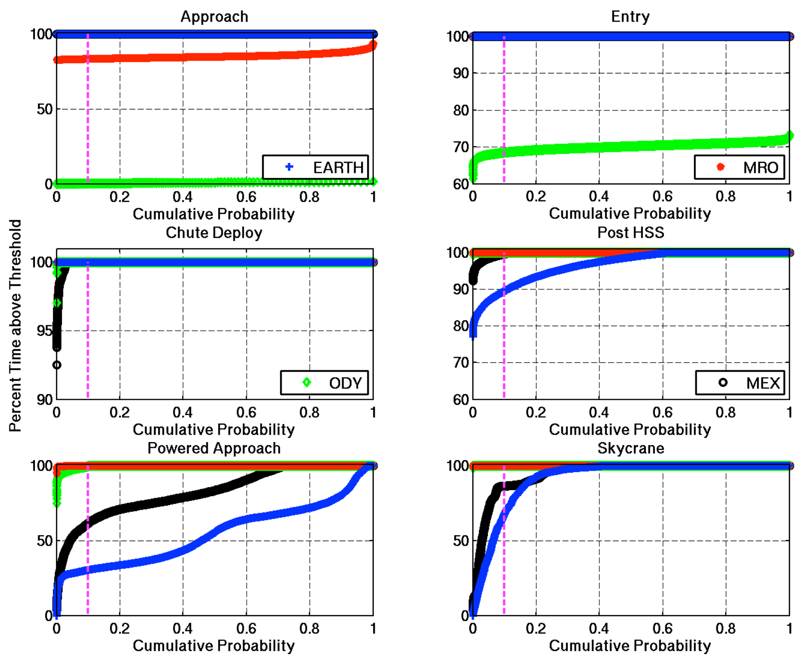

Figure 23. Cumulative Probability of Lock

The Earth link requirement is met for the phases prior to heatshield separation. After heatshield separation, it was known that Earth would set on the horizon; therefore, the link closure requirement was not necessary to be met. The MRO link requirement is met for all phases past entry interface. As mentioned above, MRO acquired MSL's signal at 8 min, 7 s prior to entry interface in flight, which is consistent with the results shown here, since the Approach phase is roughly 9 min from GN&C t0 to entry interface. ODY did not acquire MSL's signal until after the blackout period, which the analysis used here did not take into account, therefore the percent time above threshold of the Entry phase is optimistic. However, for all other phases after Entry, ODY met the link closure requirement. The geometry to MEX was very similar to the Earth geometry, in that both links were lost due to setting on the horizon after parachute deploy. MEX was expected to retain the link a little longer remaining until the start of powered approach. For all phases prior to powered approach, MEX met the link closure requirement.

6.3 Pointing Accuracy

The received power to the various link assets has been shown to meet the requirements for the MSL EDL phase. Additionally, analysis was performed to verify the pointing accuracy and line of sight viewing from MSL to the various relays. Each orbiter provided predicted states and orientations, via SPICE SPK and C-Kernels, to the MSL team. The MSL team then verified the accuracy of the orbiter predicts by determining the pointing accuracy in all Monte Carlo cases. The Monte Carlo results informed the orbiter teams determination of an optimal relay orientation. Figure 24 shows the cumulative probability of the off-boresight angle of MSL from the orbiter UHF boresights at various events during EDL. ODY was the most constrained in achieving pointing accuracy due to the bent-pipe requirement which imposed a secondary constraint to sufficiently point ODY's high gain antenna towards Earth. MEX had very good pointing accuracy due to the distance from MSL during EDL.

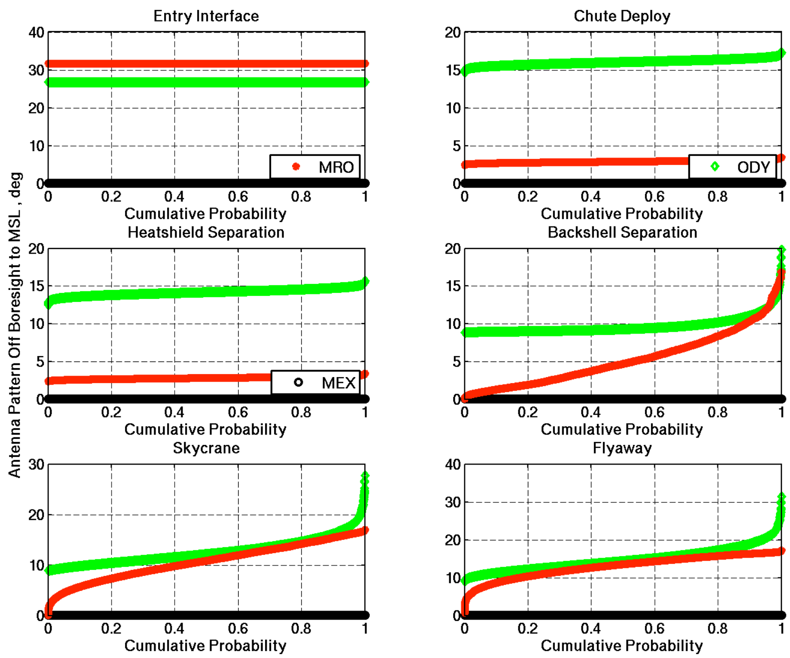

Figure 24. Orbiter Off-Boresight to MSL at Specific EDL Events

MRO's pointing objectives were two-fold for MSL communications. The first objective was to accurately point the UHF boresight for link closure requirements. The second was to utilize the HiRISE camera to attempt acquisition of the MSL spacecraft during EDL. Since the HiRISE boresight is co-aligned with the UHF boresight, the communication pointing accuracy provided an excellent proxy for HiRISE image acquisition as well. The UHF off-boresight angles for MRO in Figure 23 show very good pointing accuracy at the parachute deploy and heatshield separation events, verifying the pointing strategy MRO used.

The second objective of capturing MSL in the HiRISE image required knowledge of the camera field of view and location of MSL relative to MRO. The HiRISE camera has a 1.14-degree field of view that operates in a pushbroom fashion over a specified amount of time. So long as MSL was within the 1.14-degree field of view during the image acquisition, it would be assumed that the MRO pointing profile would capture MSL in the image. Using the Monte Carlo results of MSL location for all cases, it was determined that the HiRISE image had a 74.28% probability of acquiring MSL. Furthermore, there was a 54.69% chance of MSL being on chute, 19.45% chance of MSL being in powered approach, and a 0.137% chance of MSL being in skycrane. The HiRISE camera succeeded in capturing MSL while on chute. The actual acquisition time on Aug 6, 2012 of 05:16:42 UTC was very close to the nominal expected time of acquisition of 05:16:43 UTC.

6.4 Horizon Masking

The descent of MSL into Gale Crater created a different problem than encountered on previous Mars missions, where the landing was typically in a flat terrain. As MSL parachuted into the crater, the crater walls would rise up, occulting views of Earth and MEX, while also occulting the view to MRO and ODY earlier than expected post landing assuming flat-plane analysis. To analyze the time of occultation, the local terrain had to be accurately known in order to estimate when line of sight to the relay asset was lost. For this task, the Mars Orbiting Laser Altimeter (MOLA) digital elevation model at 1/128 degree resolution (~450-m spacing between data points) was used. The analysis tracked the line of sight vector between the UHF and X-Band antenna's to the relay asset, and determined if the terrain occulted the view by tracing the vector along the digital elevation model, evaluating for terrain intercepts. If a terrain intercept was realized, the line of sight to the relay asset would be assumed to be masked by the horizon. The expected loss of signal times are shown in Table 2, along with the loss of signal times encountered in flight. Note that the effects of the plasma blackout were not included in these loss of sight times.

Table 2. Expected vs. In-Flight Loss of Sight Time to Relay

Loss of Sight Time Relative to Entry	1-Percentile	Mean	99-Percentile	In-Flight
Earth	N/A	N/A	N/A	4:59
MRO	12:50	12:57	13:30	13:08
ODY	12:29	14:20	15:10	13:07
MEX	5:29	6:10	6:59	N/A

7. Conclusion

The robust strategy established to ensure communications during MSL EDL provided both near real time telemetry via the Mars Odyssey, and recorded telemetry via the Mars Reconnaissance Orbiter and Mars Express available just a few hours after the successful landing of the vehicle. DTE tones and UHF DTE were also available in near real time until the spacecraft was occulted by Mars as seen from Earth ~5 min after Entry. The existing orbiting assets and the Deep Space Network played a critical role in maintaining a direct communications link from the Earth to the spacecraft, which was more than 248 million km away at the time of Entry. The constant interaction between the MSL Navigation teams and the relay orbiter Navigation teams coupled with the Monte Carlo analysis that evaluated telecom performance using dispersed trajectories were crucial in determining on orbit phasing adjustments that achieve excellent MSL EDL communication performance and set a new standard for EDL communication analysis.

8. Acknowledgements

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9. References

[1] Kornfeld, R, Garcia, M., Craig, L., Butman, S, and Sinori G., “Entry, Descent, and Landing Communications for the 2007 Phoenix Lander”, Journal of Spacecraft and Rockets, vol. 45, no. 3, p. 534-547, May–June 2008.

[2] Abilleira, F., “Mars Science Laboratory Mission Design Overview”, 2010 Earth and Space Conference, March 14-17, 2010, Honolulu, Hawaii

[3] Abilleira, F. “Mars Science Laboratory Launch Period Design”, 2011 AAS/AIAA Astrodynamics Specialist Conference, Girdwood, Alaska, July 2011

[4] Prakash R., Burkhart P., Chen A., Komeaux K., Guernsey C., Kipp D., Lorenzoni L., Mendeck, Powell R., Rivellini T., San Martin A., Sell S., Steltzner A., Way D., "Mars Science Laboratory Entry, Descent, and Landing System Overview", IEEE 1531, IEEE Aerospace Conference, Big Sky, MT, 2008.

[5] Abilleira, F., “Mars Science Laboratory, Entry, Descent, and Landing Coverage Handbook”, Initial Release (Preliminary Version), Volume 2: Type 1B Launch Period”, JPL D-65986, MSL-387-3012

[6] Chen, A. “Mars Science Laboratory, Detailed EDL Relay Orbiter Support Agreement”, Draft, JPL-D-65276, MSL-217-2939, 2011.

[7] Taylor, J., Lee, D., and Shambayati, S. “Mars Reconnaissance Orbiter Telecommunications”, DESCANSO Design and Performance Summary Series, Article 12, September 2006.

[8] Ilott, P., “Mars Science Laboratory Telecommunications: EDL Telecom Requirements Summary and Analysis”, JPL D-69266, March 2, 2012.

[9] Prakash, R., et al. “Mars Science Laboratory Entry, Descent, and Landing System Overview”, IEEE Big Sky Conference, May 20, 2008.

[10] Arnold, B., et al. “Mars UHF Relay Telecom: Engineering Tools and Analysis”, IEEE Big Sky Conference, March 3, 2012.