# Mars Science Laboratory Entry, Descent, and Landing System

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*Abstract*—In 2010, the Mars Science Laboratory (MSL) mission will pioneer the next generation of robotic Entry, Descent, and Landing (EDL) systems by delivering the largest and most capable rover to date to the surface of Mars. In addition to landing more mass than prior missions to Mars, MSL will offer access to regions of Mars that have been previously unreachable. By providing an EDL system capable of landing at altitudes as high as 2 km above the reference areoid, as defined by the Mars Orbiting Laser Altimeter (MOLA) program, MSL will demonstrate sufficient performance to land on a large fraction of the Martian surface. By contrast, the highest altitude landing to date on Mars has been the Mars Exploration Rover (MER) MER-B at 1.44 km below the areoid. The coupling of this improved altitude performance with latitude limits as large as 60 degrees off of the equator and a precise delivery to within 10 km of a surface target will allow the science community to select the MSL landing site from thousands of scientifically interesting possibilities.

In meeting these requirements, MSL is extending the limits of the EDL technologies qualified by the Mars Viking, Mars Pathfinder, and MER missions. This paper discusses the MSL EDL architecture, system, and subsystem design and discusses some of the challenges faced in delivering such an unprecedented rover payload to the surface of Mars.[1,2]

### Table of Contents



## 1. Introduction

The Entry, Descent, and Landing (EDL) architecture for the Mars Science Laboratory (MSL) has been constructed from a blend of heritage and innovation. Many elements are derived directly from the successful Viking, Pathfinder (MPF) and Mars Exploration Rover (MER) missions. Several new elements enter into the architecture as well; most notably a novel new touchdown method. Mission requirements dictate delivery of a 750 kg rover to an altitude of 2 km MOLA within an error ellipse of only 10 km. As a point of comparison, MER delivered a 173 kg rover to an altitude of -1.44 km MOLA within an error ellipse of approximately 60 km. Consistent with these requirements, and relative to previous missions, the EDL architecture will deliver a significantly larger mass to a significantly higher altitude, while maintaining a significantly tighter delivery ellipse.

One focus of the EDL architecture is to create clean interfaces between EDL subsystems and sub-phases to minimize complex system interactions and simplify the verification and validation process for the flight system. The architecture is presented below by interrogating events and associated subsystems in chronological order according to the EDL sequence as shown in Figure 1 below.

1

[1] 0-7803-9546-8/06/$20.00© 2006 IEEE
[2] IEEEAC paper #1497

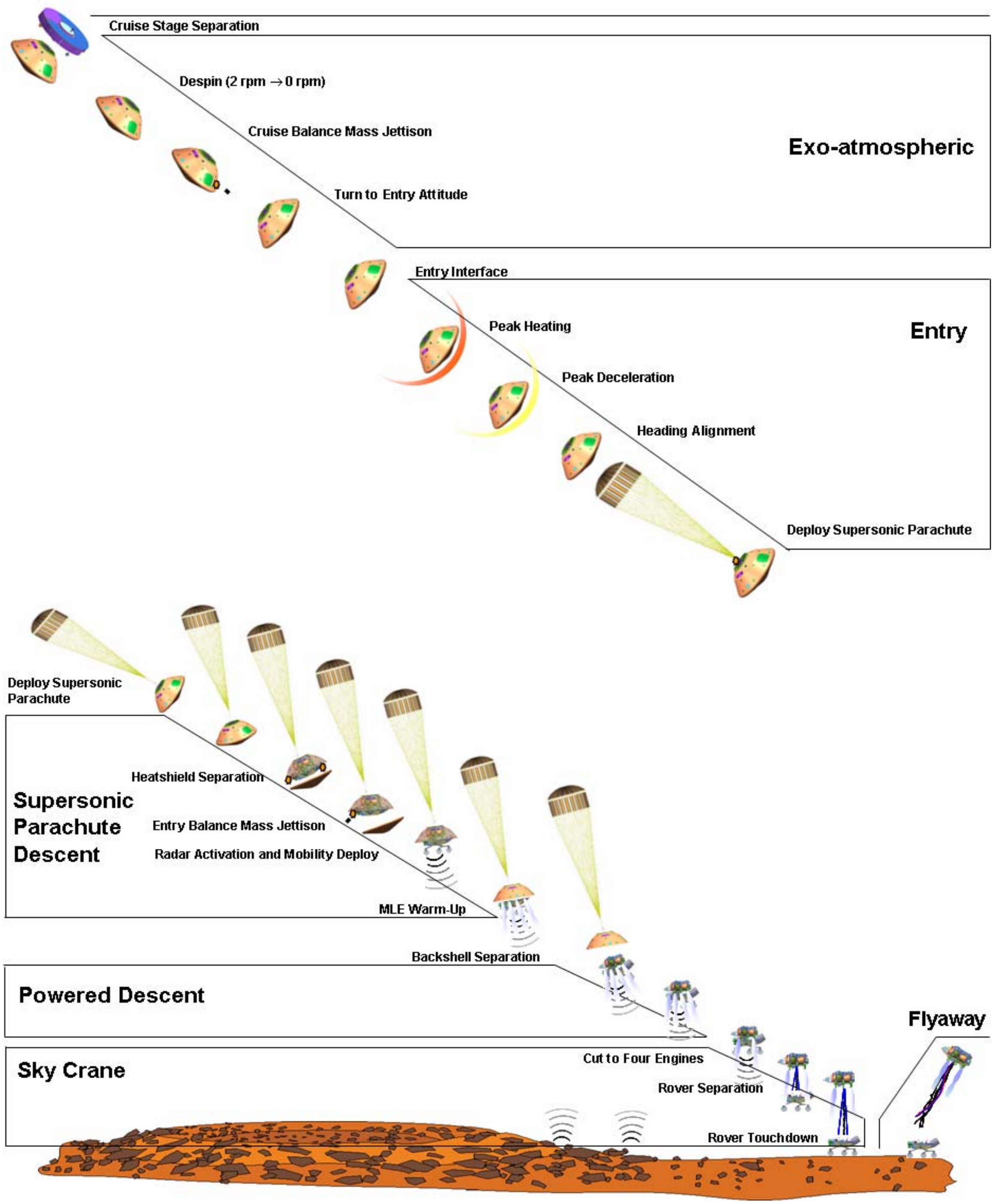


**Figure 1-MSL Entry, Descent and Landing Sequence of Events**

## 2. VEHICLE CONFIGURATION

In this section, we discuss the evolution of the spacecraft configuration from launch to landing. This section may be referred to throughout the paper as we discuss the chronology of events.

MSL is a significantly larger vehicle than its MER and MPF predecessors. The entry aeroshell, measuring 4.5 meters in diameter, is 25% wider than a MINI Cooper automobile, at 3.6 meters, is long. The size necessitates use of a 5 m launch fairing with a 4.572 m internal envelope. The launch configuration is shown in Figure 2. Note the access panels to allow RTG integration, HRS loading, and emergency off-loading of propulsion.

Spacecraft cruise configuration is shown in Figure 3. Note the stowed configuration of the lander mobility system and descent stage internal to the aeroshell. An external balance mass is used to maintain zero cg-offset during spinning cruise.

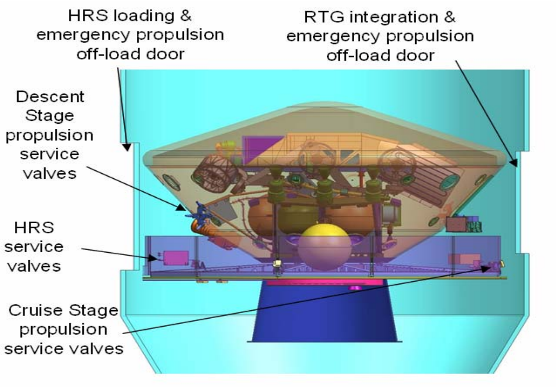


**Figure 2-MSL Launch Configuration**

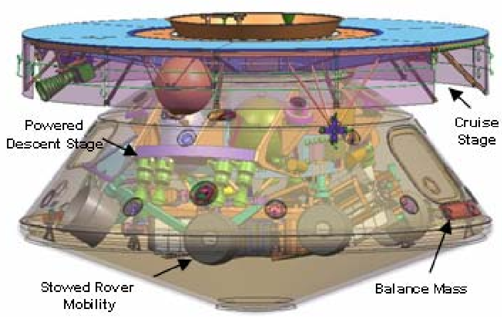


**Figure 3-Cruise Configuration**

The cruise balance mass is jettisoned prior to entry in order to enable a guided lifting entry by offsetting the vehicle center of mass from the aeroshell axis of symmetry. Entry configuration, including active EDL communication antennae and active RCS thrusters, is shown in Figure 4.

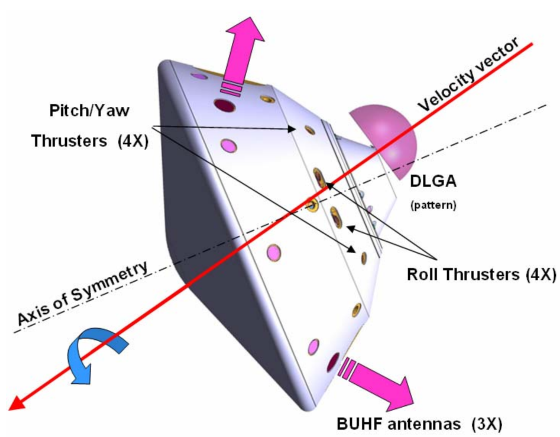


**Figure 4- Entry Configuration**

During parachute descent, the heatshield is jettisoned and rover mobility is deployed from its stowed configuration. After reconfiguration, the descent stage is released from the backshell at the appropriate altitude and velocity to begin powered descent. This process is illustrated in Figure 5.

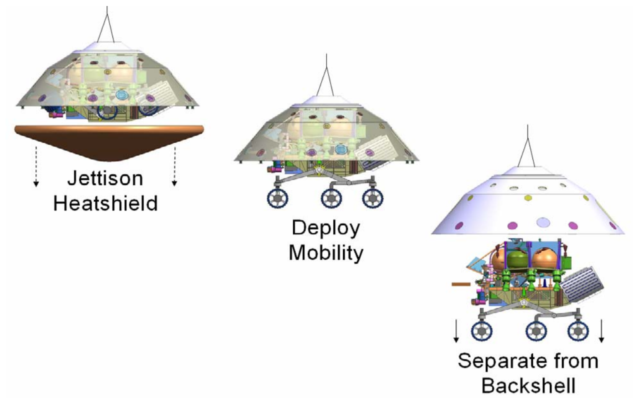


**Figure 5- On-Chute Configurations**

Finally, just prior to landing, the rover is mechanically separated from the descent stage and lowered in preparation for touchdown. Three load bearing bridles and a non-load bearing electrical umbilical maintain a physical connection between the rover and the descent stage. This configuration, referred to as the Sky Crane, is shown in Figure 6 just after separation. Figure 7 diagrams the descent stage, highlighting the position of the eight Mars Lander Engines as well as the radar based Terminal Descent Sensor.

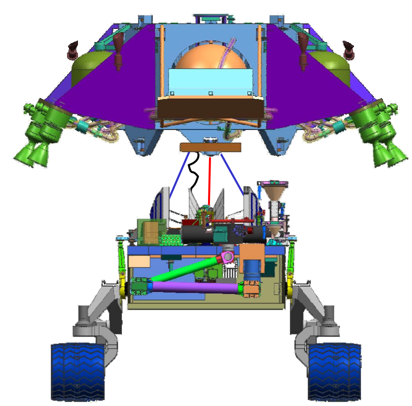

**Figure 6- Rover Separation Configuration**

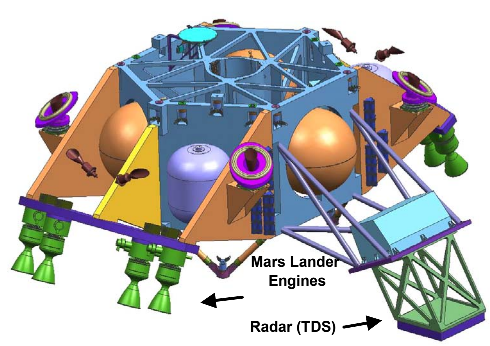


**Figure 7-Descent Stage Configuration**

## 3. FINAL APPROACH AND EXO-ATMOSPHERIC FLIGHT

*Approach Navigation*

The fundamental objective of approach navigation for MSL is to ensure the spacecraft will arrive at the specified entry conditions at the correct time. An entry target is chosen that combines a viable Earth-Mars transfer trajectory and an EDL trajectory that ends with a safe landing at the desired surface target. Requirements are defined at atmospheric entry that capture the allowable contribution to landed position error from approach navigation. For MSL, these include a targeting uncertainty that is limited by control authority of the guided entry phase coupled with a position and velocity metric that defines the initial knowledge uncertainties in these components. It is important to note that the largest contributors to surface position error are the uncertainties in the initial position and attitude, as the targeting requirement is defined to be within the control authority of the vehicle. The result is that targeting errors can be flown out by entry guidance.

The tool used to assess the impact of the various error sources (including spacecraft dynamics, Mars ephemeris errors and signal path effects that degrade the DSN radiometric data used for orbit determination) during development is covariance analysis. Specifically, the influence of selected error sources and assumed error levels on the resulting target uncertainties are evaluated in order to define a robust navigation strategy that meets the imposed requirements. The data that are used for navigation analysis are two-way Doppler, 2-way range and Delta Differential One-Way Range (DeltaDOR). The tracking schedule, parameters and values used in developing the filter setup are based on past lander flight experience and the assumed baseline for the MER mission. Performance results for several selected cases are shown in Table 1.

| | | Entry State Update | |
|---|---|---|---|
| **Scenario** | **TCM-5 Delivery EFPA error (deg, 3sig)** | **Knowledge RSS position error (km, 3sig), Map to Entry** | **Knowledge RSS velocity error (m/s, 3sig), Map to Entry** |
| **05-17a** | 0.17 | 3.656 | 2.645 |
| **05-18a1** | 0.12 | 2.859 | 2.074 |
| **05-21** | 0.10 | 2.900 | 2.106 |
| **REQUIREMENT** | **0.20** | **5.000** | **5.000** |

**Table 1- Delivery and Knowledge Requirements and Performance for Three Selected Cases**

*Transition to Entry*

The transition from cruise to entry utilizes MER heritage where applicable, with incremental improvements. EDL execution will be performed by parameterized flight software behaviors encompassing entry minus 5 days, to the completion of descent stage flyaway. Additional flight software behaviors are running in parallel to EDL behaviors, and work is underway to minimize interactions between the parallel behaviors. Prior to cruise stage separation, EDL behavior is initialized, the heat rejection system (HRS) is vented, the entry propellant and engine and thruster catalyst beds are preheated, a final trajectory correction maneuver is performed if necessary, and vehicle attitude knowledge is initialized using an on-board star scanner. Cruise stage separation occurs 10 minutes prior to entry, after which the entry vehicle will despin from its nominal cruise rate of 2 RPM to a zero spin, 3-axis stabilized state. In this state, any maneuvering is performed using the entry RCS thrusters. After despinning, an external balance mass is jettisoned to create an offset center of gravity that provides a nominal lift-to-drag ratio of 0.21 during atmospheric flight. Turn to entry attitude is performed 7 minutes prior to entry. Atmospheric entry is defined at a nominal interface radius of 3522.2 km from the center of Mars.

## 4. ENTRY

*Guided Entry*

In contrast to the spin stabilized entries of MER and MPF, MSL utilizes an offset center of mass to create a nominal 14 degree angle of attack through peak dynamic pressure and a 17 degree angle of attack at parachute deployment. This angle of attack generates lift which is used to reduce the landing error ellipse size and increase the parachute deploy altitude. Entry guidance provides bank angle commands throughout entry that orient the vehicle lift vector to compensate for dispersions in initial delivery state, atmospheric conditions, and aerodynamic performance. This enables the vehicle to arrive at the supersonic parachute deployment velocity close to the desired downrange and crossrange position while maintaining a safe deployment altitude. Based on navigated attitude and the commanded bank angle, the entry controller generates roll, pitch, and yaw torque commands that are mapped into individual on/off commands for each of the 8 entry thrusters - four roll and four pitch/yaw thrusters configured about the aeroshell as shown in Figure 4.

The MSL entry guidance algorithm is broken into four phases. Entry minus 4 minutes marks the start of guided entry; guidance is initialized in the pre-bank phase and the controller commands bank attitude hold until the sensed acceleration exceeds 0.1 Earth g's, at which point the range control phase begins. During the range control phase, the bank angle is commanded to minimize predicted downrange error at parachute deployment. Throughout this phase crossrange error is maintained within a manageable deadband limit by executing bank reversals. Peak heating and peak deceleration occur during this guidance phase. Once the navigated relative velocity drops below 900 m/s guidance transitions to a heading alignment phase to minimize residual crossrange error before parachute deployment is triggered at a navigated velocity of 442 m/s.

*Ellipse Size*

The dispersed ellipse size at parachute deploy is driven by three factors. One is the navigated position knowledge error as the guidance cannot reduce the ellipse size any smaller. Another factor is the residual downrange error that results from a velocity-based parachute deploy trigger, although in MSL this contribution is secondary to the knowledge error magnitude. Third, the guidance accuracy is sensitive to the attitude initialization error prior to cruise stage separation. This error results in errors in the integrated altitude rate during entry, a quantity used by the guidance to predict the range flown. Greater attitude initialization errors result in greater range deploy errors as shown in Figure 8. Sufficiently large attitude initialization errors will dominate over other factors in the ellipse size.

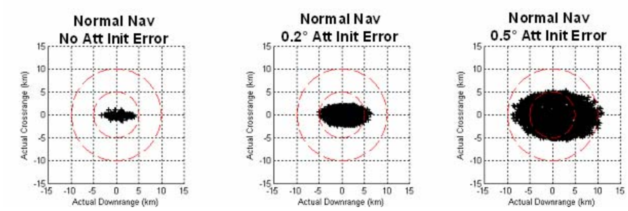


**Figure 8- Attitude Initialization Error Propagation**

*Aerodynamic*

Given the use of a heritage forebody geometry, the 70° sphere-cone, aerodynamic analysis for MSL will utilize an aerodynamic database that draws upon databases generated and used by the successful Viking, MER, and Pathfinder missions. Through additional CFD analysis, wind tunnel testing, and ballistic range testing, the database will be augmented and refined to address MSL-specific risks. One such risk being addressed is the potential coupling of the entry RCS thrusters to the entry flow field aerodynamics, which may introduce unexpected control forces and augment backshell heating.

*Aerothermal*

An analysis of the entry aeroheating environment leads the team to expect smooth body transition to turbulence prior to peak heating, an occurrence which has not been predicted or observed in prior missions and will result in significantly higher heating rates. A combination of high ballistic coefficient, large aeroshell diameter, high atmosphere relative entry velocity, and a non-zero angle of attack promotes this transition. Figure 9 shows the impact of the predicted turbulent augmentation on the peak heating rates seen on the leeside of the MSL forebody. Studies and additional testing are underway to properly bound the heating environment and estimate associated uncertainties.

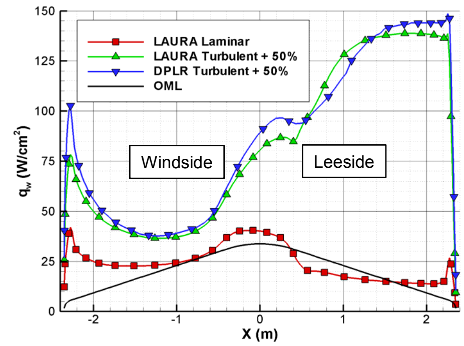


**Figure 9-MSL Turbulent vs. Laminar Heating**

The augmented heating environment pushes the previously established qualification limits for high Mars heritage TPS materials like SLA-561V. As a result, the project is investigating the performance of SLA-561, as well as other candidate materials such as SRAM-17 and SRAM-20, at and above the heating rates predicted for MSL. Additionally, testing at a range of heating conditions is allowing the development of high fidelity TPS material response models for the candidate materials.

*EDL Communications*

A suite of X-Band and UHF antennas are utilized to maintain communications both directly to Earth and to Mars orbiting assets during the entire EDL mission phase. Direct to Earth (DTE) communications, the primary mode of communications throughout cruise and during the exo-atmospheric segment of EDL, will be through X-band low gain antennas. Due to signal strength constraints, DTE communications are limited to one-way semaphores from the spacecraft, as demonstrated by the MER mission. From the entry interface point through landing, UHF relay to the Mars Reconnaissance Orbiter is the primary communications path and has an expected bandwidth of 2 kbps. X-band and UHF antennas are mounted on the backshell, descent stage, and rover and will transmit data and semaphores sufficient for fault reconstruction.

*Parachute Deployment*

Parachute deployment is triggered when the system reaches a navigated velocity of 442 m/s as determined by integration of the inertial measurement unit data in a navigation filter. The parachute deployment conditions are constrained by the heritage qualification of the 19.7 m Viking parachute configuration to Mach less than 2.15 and a dynamic pressure less than 850 Pascals with a capsule angle of attack not more than 20 degrees. Figure 10 illustrates how the dispersed MSL deployment conditions align with prior testing and mission experience.

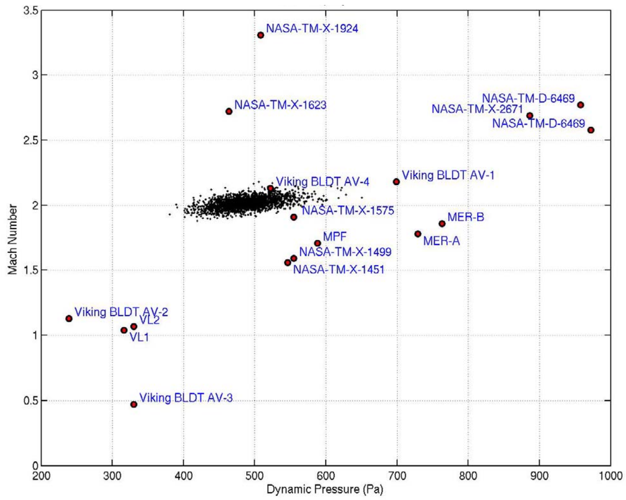


**Figure 10-Parachute Deployment Conditions**

## 5. PARACHUTE DESCENT

MSL design utilizes a disk-gap-band parachute decelerator scaled geometrically from Viking heritage and constructed using MER techniques and materials. The system is mortar deployed with a mortar design similar to MER and MPF. Approximately 20 seconds after parachute deployment, when the spacecraft has reached a navigated velocity corresponding to Mach 0.8, the heatshield is jettisoned and the stowed rover and descent stage are exposed. Shortly after heatshield separation, an internal balance mass is also jettisoned to null the cg-offset used during guided entry. The rover mobility system is reconfigured from its stowed configuration to prepare for surface interaction, and a radar based terminal descent sensor is activated.

*Parachute Design*

The high landed mass requirement couples with the high landed altitude requirement to create demand for a very high performance parachute decelerator system. Design trades, including multiple parachute options, resulted in the baseline of a single 19.7 meter diameter supersonic parachute. This parachute, which is scaled geometrically from the Viking disk-gap-band design, will be larger than any chute ever flown on Mars. The size of this parachute was chosen to maintain Viking heritage scaling with the increased MSL vehicle size. Further, this parachute size protects against the asymptotic sensitivity discussed in [Ref 1]. Clearly this prompts close consideration of the parachute qualification and expected Mars flight characteristics.

An issue of some concern, based on historical data, is the phenomenon of parachute area oscillations, where the parachutes projected area oscillates notably during flight. This phenomenon creates a dynamic environment involving high parachute loading and high aeroshell attitudes and attitude rates. Such behavior is difficult to model. Shown in Figure 11 are loading histories for three Viking era test flights that exhibit area oscillations. Load oscillations correlate well with observed area oscillations and it is clear from the figure that oscillations become more dramatic as inflation Mach number increases. Further study shows that area oscillations die down once the flight Mach number drops below ~1.4.

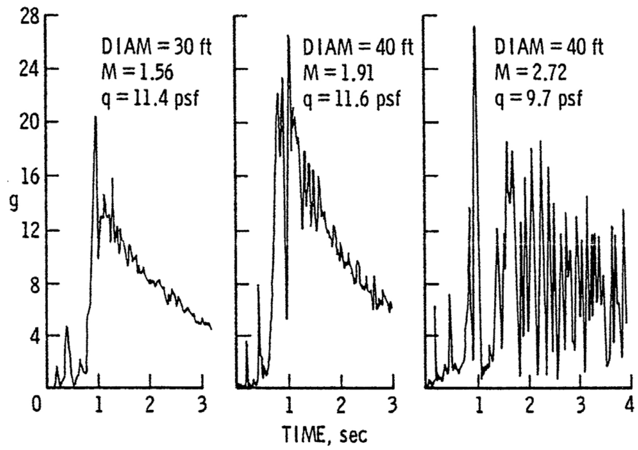


**Figure 11-Pre-Viking Development Parachute Test Data**

The selection of a 19.7 m chute reduces the MSL flight exposure to the Mach>1.4 regime, where area oscillations have been observed, while enabling landed altitude capabilities consistent with the 2.0 km MOLA requirement.

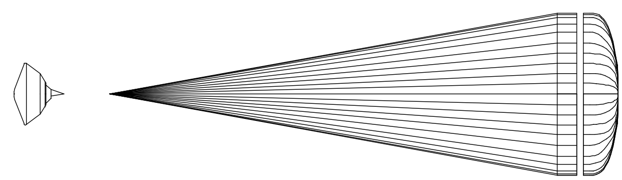

**Figure 12-Parachute Configuration**

*Terminal Descent Sensor*

The terminal descent sensor (TDS) will directly measure vehicle altitude and velocity relative to the Martian surface using a 3-axis Doppler velocimeter and a slant range altimeter. This system is tasked with providing robust, but not highly accurate, measurements prior to start of powered descent as well as providing highly accurate measurements closer to the touchdown event. Of concern when addressing the robustness of these measurements are the on-chute capsule dynamics. Historical data from MER shows a highly dynamic environment with on chute attitude rates exceeding 80 deg/s well after parachute inflation. Additionally, robust TDS design allows for the potential that the ground is obscured from one of its radar beams by the previously jettisoned heatshield.

*Heatshield Separation Requirements*

Heatshield separation must satisfy two requirements for all conditions at Mach numbers between 0.5 and 0.8, and under attitudes and attitude rates of up to 20 degrees and 60 degrees per second: positive separation from the flight system with no recontact and satisfactory separation to ensure no more than one beam of the TDS is obscured after the TDS is activated.

Positive separation is analyzed by breaking the problem into near term recontact and long term recontact. Near term recontact occurs when the attitude rates of the heatshield immediately following separation from the backshell are sufficiently high, relative to the separation rate, such that the heatshield rotates into the flight system during the initial moments following separation. This half of the problem is solved via mechanical push off springs sized to impart a sufficient delta-V to the heatshield.

Long term recontact occurs when the difference in ballistics is insufficient to assure that the elements will not recontact after successful near term separation. In kind with this second issue is the requirement that no more than one beam of the TDS is obscured during operation. That requirement, along with timeline and simple geometry, dictates that separation of 17 meters must occur during the first 8 seconds after jettison. Again, this is a function of ballistic difference under the influence of interference dynamics. These issues are currently not a concern and will be continually monitored throughout the evolution of the flight system.

## 6. POWERED DESCENT

The beginning of powered descent is triggered based on TDS velocimetry and altimetry measurements. The phase begins with the warm-up of the 8 MLEs 2 seconds prior to backshell separation at approximately 800 m above ground level. A low throttle setting persists for 5 seconds to allow the descent stage to fall a safe distance away from the backshell and parachute before the descent stage is throttled up. Powered descent concludes once the system is delivered to Sky Crane start conditions of 19.5 m altitude with zero horizontal velocity and a vertical velocity of 0.75 m/s.

*Mars Lander Engines and Descent Propulsion*

The MSL descent propulsion system is a throttled, pressure regulated, mono-propellant propulsion system. The design of this system is shown schematically in Figure 13.

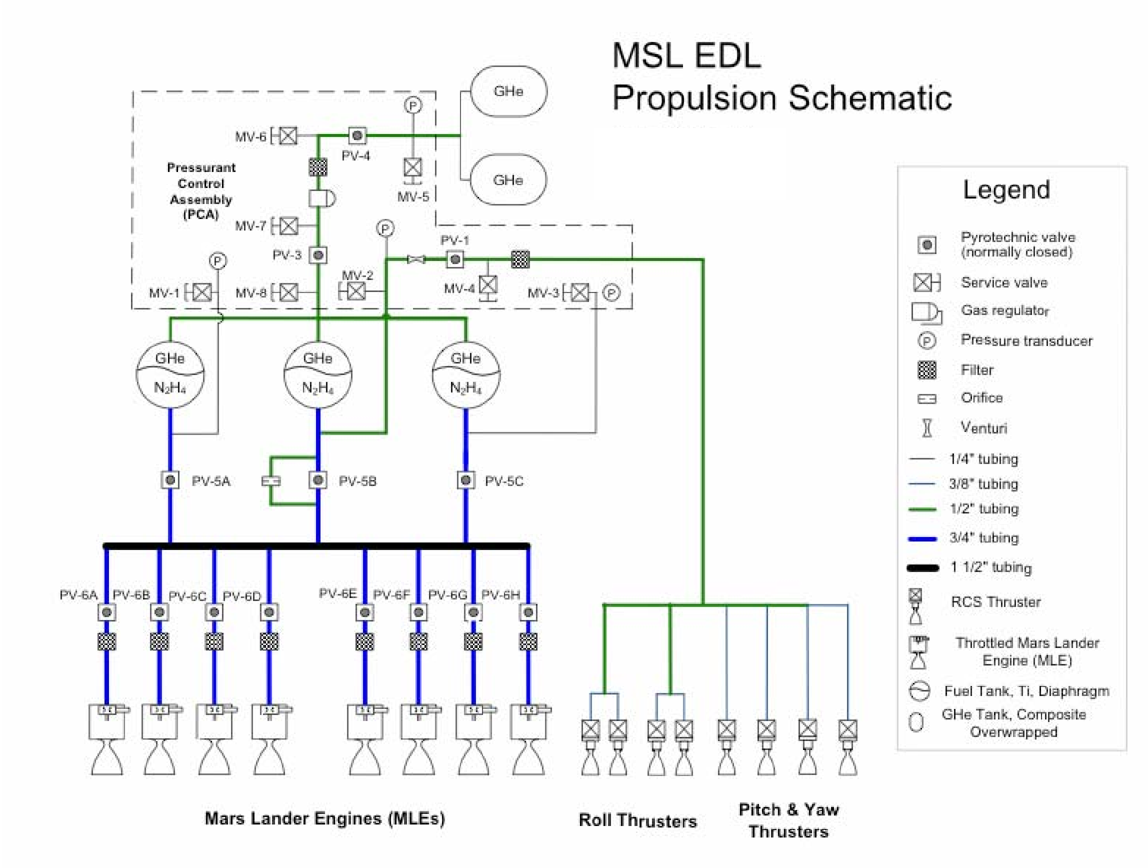


**Figure 13-MSL EDL Propulsion Schematic**

The propulsion system uses eight throttled Mars Lander Engines (MLE's), which are canted to avoid plume impingement on the rover, to provide braking and three-axis attitude control during powered descent. As mentioned above, eight RCS thrusters are used to provide three axis control following separation from the cruise stage and during atmospheric entry. Three propellant tanks are used to provide a usable propellant load of up to 285 kg of high purity hydrazine monopropellant. The propellant tanks are pressurized via a mechanical pressure regulator from two helium pressurant tanks. The descent stage engine configuration is shown in Figure 7.

MLE development leans heavily on Viking heritage, especially for the injector and catalyst bed design, but has also incorporated a number of improvements and EDL architecture specific changes. Since trenching concerns have been alleviated by the Sky Crane touchdown system, the thrust chamber has been altered to a single nozzle design rather than the Viking "showerhead" design, providing additional thrust and efficiency. Additionally, the MLE's incorporate a new cavitating throttle valve assembly design that provides superior control of flowrate and thrust when compared to the Viking design. A pintle and converging-diverging inlet section are used to provide a continuously variable flow area and a velocity profile similar to that found in simple cavitating venturis. As long as it is operated in the cavitating regime, this effectively uncouples the flow rate from downstream pressure drop changes in the injector or catalyst bed. It also virtually eliminates propagation of pressure fluctuations in the combustion chamber to the system upstream of the valve.

Each MLE will provide a throttle range from 400 to 3000 N of thrust. In addition, the MLE's are required to provide a reduced thrust level of less than 1% at start up and when four of the eight engines are "shut down" for the final constant velocity terminal descent. To date, two flight-weight development MLE's have been subjected to hot fire testing. MLE hardware is pictured in Figure 14.

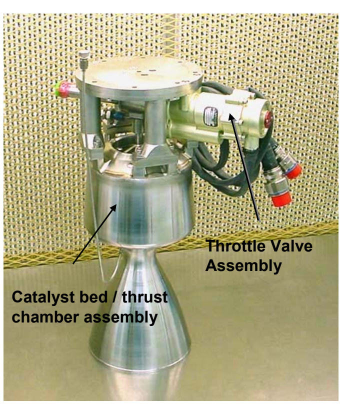


**Figure 14-Mars Lander Engine Hardware**

The descent propulsion system is pressure regulated to minimize propellant tank mass and volume. In addition, a pressure regulated system eliminates the variation of MLE thrust which would occur as propellant is consumed if a blow-down system similar to Viking were used. A highly accurate, pilot operated pressure regulator designed to MSL flow requirements is under development.

The propellant tanks are of conventional titanium construction and incorporate elastomeric diaphragms to provide positive propellant expulsion. This reduces concern over differential draining of the tanks to one of minimizing center-of-mass migration during terminal descent, rather than reducing usable propellant. In addition, the relatively stiff elastomeric diaphragms provide some damping of propellant slosh modes.

The helium pressurant tanks are conventional composite over wrapped pressure vessels. Helium pressurant is stored at an initial pressure of up to 310 bar and is then used to maintain the propellant tanks at an operating pressure of 41 bar during powered descent.

A number of pyrotechnically actuated valves are used to provide isolation of the propellant and pressurant prior to system actuation. In particular, pyro valves are used to provide isolation of the propellant tanks from the MLE's and from each other until shortly before powered descent. This prevents migration of propellant between the tanks during cruise or aero-maneuvering during entry, which can produce significant lateral accelerations. To avoid having the tanks interconnected during entry, the propellant for the RCS thrusters is drawn from a single tank. The quantity of propellant used during this phase is small enough that this produces negligible motion of the entry vehicle center-of-mass.

*Backshell Recontact*

Throughout the maturing design of the EDL system, the relative motion the backshell/chute and the descent stage will be tracked to ensuring that no long term re-contact occurs. This is a significant issue that is exacerbated for MSL, relative to MER/MPF, because the use of propulsive descent allows the backshell to catch up with the descent stage. Viking faced a similar challenge, but MSL faces a more difficult version due to a higher ratio of backshell mass to descent stage mass. Fuel margin for possible lateral divert maneuvers exists and relevant studies are ongoing.

*Guidance*

Due to terrain variation and radar altimetry errors under high attitude rates at altitude, the guidance algorithm must be robust to altitude errors on the order of 100 m. Traditional guidance strategies have been to reserve control authority for cases where the ground is closer than estimated, and to reserve fuel allocation for cases where the ground is further than estimated. Several different guidance strategies are currently under evaluation.

## 7. Sky Crane And Fly Away

The touchdown technique employed by the MSL design is the most innovative portion of the EDL architecture. The technique, referred to as the Sky Crane maneuver, involves lowering the lander on three bridles from the slowly descending descent stage until the bridles are fully extended to a length of 7.5 m. A 0.75 m/s constant velocity vertical descent is maintained until rover touchdown is detected via persistence of bridle offloading as inferred from descent stage throttle commands.

Implementation of the Sky Crane architecture presents many advantages over historical touchdown methods, namely airbags and legged landers. The two body architecture keeps the engines and thrusters away from the surface, mitigating surface interactions like dust excavation and trenching, while enabling closed looped control during the touchdown event. The bridle decouples the touchdown event and associated disturbances from the descent stage controller. Additionally, unlike many traditional touchdown sensors, a persistent touchdown signature appears after bridle offloading occurs.

Thanks to the persistence of tethering during touchdown and low touchdown velocities, the system has greater touchdown stability and experiences lower impact loads than other landing systems. High stability and low loading, on par with rover driving loads, means that a separate touchdown system is not required and the egress phase can be eliminated. Rather, the rover's rocker-bogey suspension, which is specifically designed for surface interaction, is the touchdown system and it is properly positioned to begin operations immediately after touchdown. A summary of this mission phase is shown in Figure 15.

*Sky Crane Guidance*

The Sky Crane maneuver is broken into several sub-phases; beginning with a one-body phase marking the transition from fully powered descent. During this transition, which occurs at an altitude of 19.5 m AGL as measured by the TDS, four of the eight MLE's are throttled down to 1% and are essentially shut down. Beginning with the transition to one-body phase and until touchdown is detected, the descent stage is commanded to follow a vertical reference trajectory with a constant descent velocity of 0.75 m/s.

The one-body phase lasts 2 seconds to allow for damping of the throttle-down transients that mark the transition. At this point, the TDS is commanded to stop altimetry measurements and we rely on velocimetry measurements and the navigation filter to maintain the constant vertical descent rate until touchdown. Rover deployment pyros are fired to separate the lander from the descent stage. The lander's descent is controlled by the Bridle, Umbilical, and Descent Rate Limiter (BUD) device. Deployment to full bridle extension takes 6 seconds. At this point there is a 2 second post-deployment phase, to allow the system to damp out any separation transients, after which the system is prepared for touchdown and touchdown logic is enabled.

*Touchdown Logic*

While the descent stage is following a constant velocity reference trajectory the commanded vertical thrust is equal to the weight of the system. Prior to touchdown the commanded vertical thrust will be equal to the gravitational acceleration times the combined mass of the descent stage and rover. After touchdown, the rover weight is supported by the surface, the bridle is offloaded, and the commanded vertical thrust is reduced by about a factor of two. This reduction in commanded thrust will persist after touchdown because the constant vertical descent reference trajectory ensures persistent offloading of the bride.

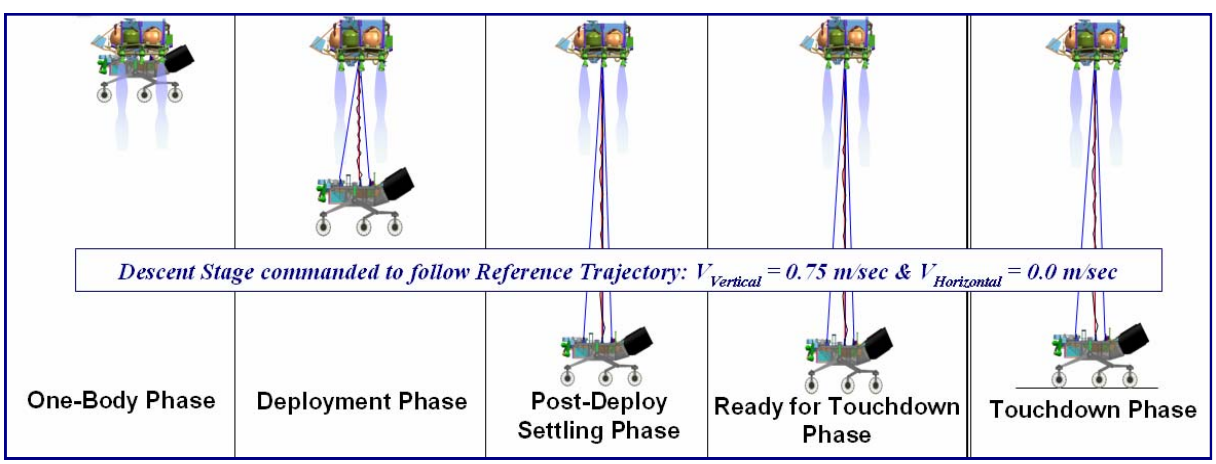


**Figure 15-Sky Crane Phase Description**

The touchdown algorithm takes advantage of this inherent off-loading by relying on the commanded vertical thrust to sense the touchdown event. Once enabled, touchdown logic monitors the commanded vertical thrust for a persistent value that is consistent with the weight of the descent stage. In reality, this logic does not sense touchdown, but rather the persistence of the post-touchdown state.

*Landing Stability and Loads*

Understanding surface interactions is crucial to validation of Sky Crane performance. In particular, an understanding of rover stability and loading relative to landing site terrain is key. The terrain is characterized by surface slope on varying length scales and rock abundances for different sized rocks. Initial analysis demonstrates the ability to land on rover length scale slopes of up to 20 degrees with vertical and horizontal velocities up to 1 m/s and 0.5 m/s respectively, which are well within anticipated dispersions. Similarly bounded analysis of worst case touchdown loads, including specific wheel impact cases, shows anticipated torques, loads, and accelerations what are in family with the traverse design loads for the rocker-bogey system. At worst case these touchdown analyses are a factor of 1.5 worse than the traverse design loads.

*Bridle, Umbilical, and Descent Rate Limiter (BUD)*

The BUD device is the mechanism for lowering the rover from descent stage during the Sky Crane maneuver. Currently, the BUD length is set at 7.5 m and the duration of the deployment is capped at 5 seconds following rover separation. The BUD, as shown in Figure 16, is a rotating spool with braking and retraction elements that pays out the triple bridle, responsible for bearing the load of the rover, and a single electrical umbilical, responsible for the signal connections between the rover and descent stage. Operations during the Sky Crane phase are managed entirely by the rover's onboard flight computer. IMU data and throttle commands are sent via the electrical umbilical. To minimize coupling between the rover and descent stage, the bridles pass through an exit guide at the descent stage center of mass, as shown in Figure 17.

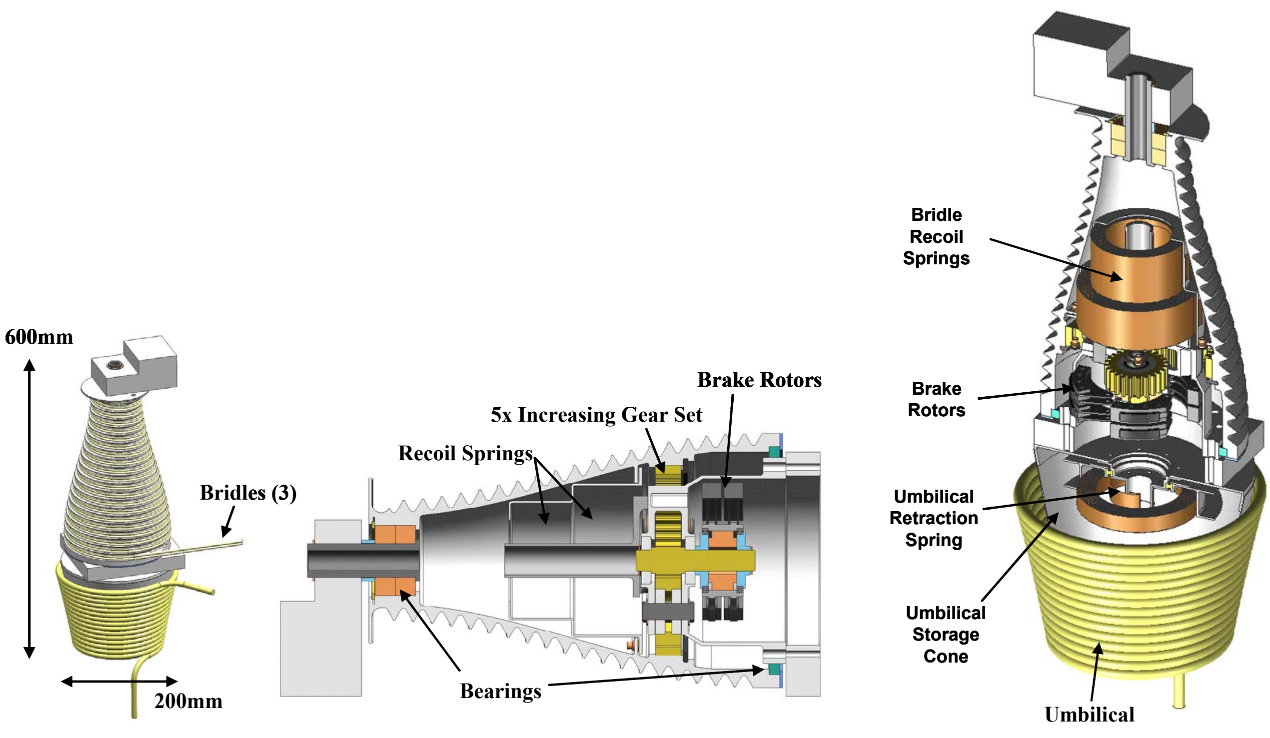


**Figure 16-Bridle, Umbilical, and Descent Rate Limiter Device (BUD)**

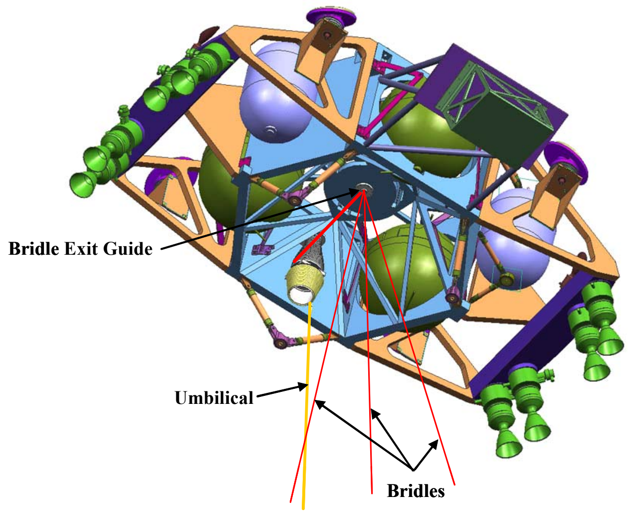


**Figure 17-BUD Interface to the Descent Stage**

*Flyaway*

After persistent touchdown is detected, the BUD will be cut by the rover and the descent stage will fly away, taking the bridles and umbilical with it, to a safe distance before itself coming to rest on the surface. The flyaway segment objectives are to keep the rover safe, both from the descent stage itself and from plume effects, and to allay site contamination concerns by removing propellant and propellant products from the vicinity of the landing site.

Post BUD cut, the descent stage will throttle up and execute a pre-planned thrust profile to leave the vicinity of the landing site without any direct plume impingement on the rover.

*Plume Effects*

The unique "sky-crane" landing concept introduces concerns over rocket plume interactions not present in "Viking-Style" landers. These concerns include the potential for damage to the rover due to direct plume impingement or contamination from combustion products. Plume effects may also introduce disturbances to the Sky Crane guidance, navigation, and control in the form of unexpected dynamics. Finally, the effects of the plume on the surface must be understood.

The plume structure has two zones of interest: an inner zone containing shock patterns and high-enthalpy exhaust, and an outer zone of entrained gas as shown in Figure 18. The inner zone could present heating concerns if impingement on the rover occurs. Fortunately, this zone will be very narrow, as the descent engine is nearly perfectly expanded to the Mars ambient pressure. The inner plume can be modeled, over the distances of interest here, as a cylinder with diameter twice the nozzle diameter. Since the engines are canted 25 degrees off vertical, it would require a descent stage attitude excursion much larger than the current estimates of a few degrees to result in direct impingement. The outer zone, formed by turbulent mixing with ambient atmosphere, can lead to extraneous forces on the rover. Beyond the first few exit diameters, the outer plume can be approximated as an axisymetric turbulent jet, The forces, therefore, are limited to less than 50 $N/m^2$ on the 750 kg rover.

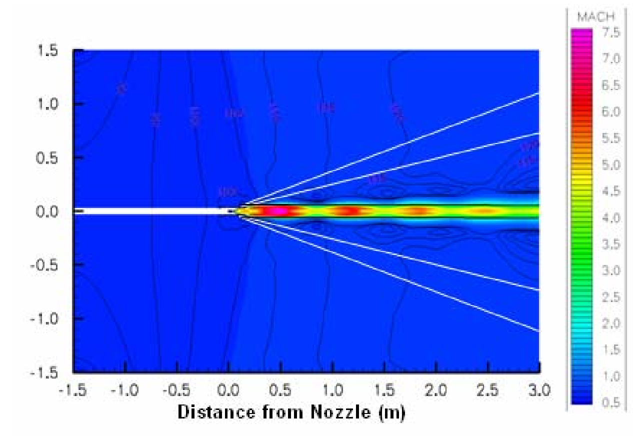


**Figure 18-Computational Prediction of Plume Structure**

The nominal Sky Crane maneuver consumes ~70 kg of hydrazine fuel. "Some" exhaust products and entrained dust will circulate into the region under the lander. The most condensable plume product is water (less than 0.5% by weight). The second most condensable plume product is ammonia. Hydrogen and Nitrogen are not a contamination issue. It appears unlikely that plume products will be a contamination issue unless some of the science instruments are sensitive to ammonia. If this becomes the case, covers or guards may be required. At an altitude of 7 m above the surface, the plume impingement pressure on the surface can be expected to be from 0.1 psia to 0.5 psia, depending on throttle position. Based on soil analysis of the existing landing sites and the Viking experience, these pressures do not indicate significant surface interactions.

## 8. LANDING SITE SELECTION

The landing site selection process is a process open to public participation. Starting in the summer of 2006, a set of meetings will be conducted which are open to public participation and are anticipated to involve scientists from around the country and perhaps the world. The planned process follows closely the process used for selecting the sites for the Mars Exploration Rovers mission in 2003, which selected two sites for the two identical rovers.

The landing site selection process will use a set of engineering constraints that will enforce acceptable landing success probabilities. These constraints will include, terrain properties, such as rock densities and size distribution, slope distributions, radar reflectivity, wind and atmosphere conditions. The aim of these constraints is to

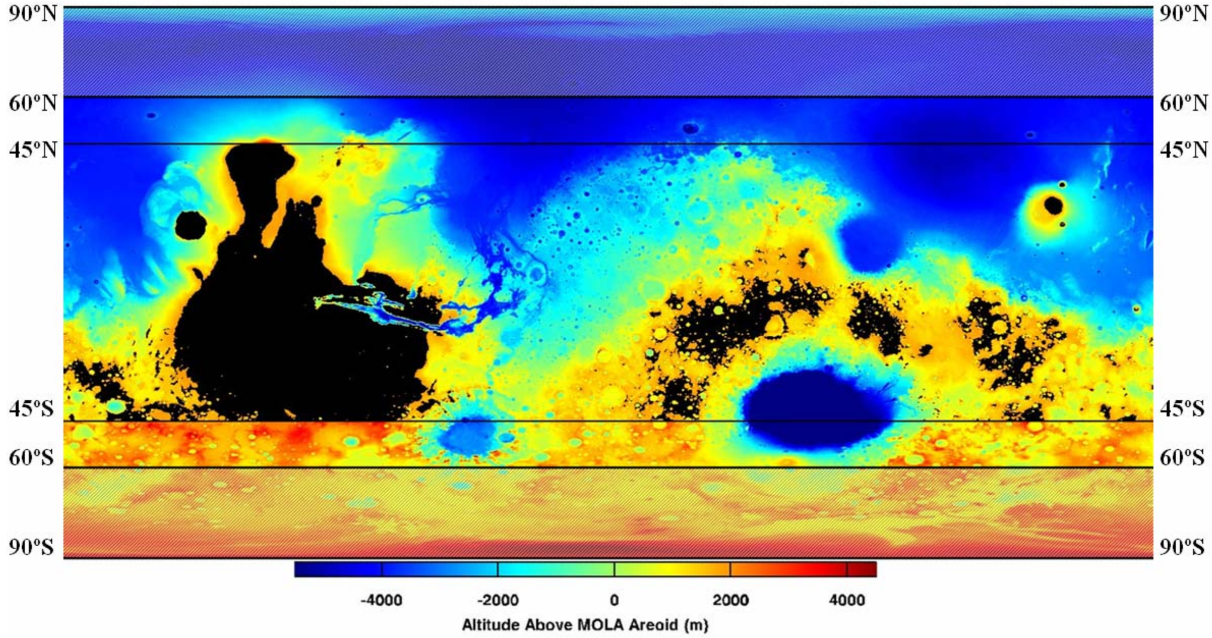


**Figure 19-MSL Surface Accessibility**

Generate guidance for the site selection process. A small set of final selected sites will be evaluated in more detail. This final evaluation will include a landing success probability assessment which will be used, in conjunction with the intrinsic scientific interest of the site, to help form a final recommendation.

The capabilities of the MSL EDL system mean that a large fraction of the Martian surface is accessible. Figure 19 illustrates the regions of Mars that will be accessible to scientists. The shaded zones of the topographic map correspond to inaccessible latitudes greater then 60 degrees from the equator. Within 45 degrees of the equator, altitudes exceeding MSL's 2.0 km MOLA landing capability are shaded black.

## 9. System Performance Simulation

*POST2 Simulation*

The POST2 [Ref 2] end-to-end Mars Science Laboratory Entry, Descent, and Landing performance simulation leverages the versatility and heritage of POST2 and adds specialized user routines specific to the MSL mission. This simulation begins with Cruise Stage Separation, ten minutes prior to the nominal atmospheric entry interface, and ends with Descent Stage impact, following rover touchdown and execution of the flyaway maneuver. Major EDL events modeled in the simulation include hypersonic guided entry, supersonic parachute deploy and inflation, subsonic heatshield jettison, terminal descent sensor start, descent engine warm-up and powered descent initiation, powered approach, rover separation and BUD deployment, sky crane terminal descent, rover touchdown detection, and descent stage flyaway. EDL system performance is assessed in a Monte Carlo approach through simulating thousands of entries with random perturbations, generating statistics, and evaluating trends and outlying cases. These random perturbations (Monte Carlo input variables) represent uncertainties in the atmospheric models, aerodynamic characteristics, mass properties, vehicle control authority, initial states, sensor performance, etc.

As the mission design life cycle progresses from conceptual design to operations, the fidelity of the various simulation models are increased to reflect the maturity of the overall system design. Early in the design process, performance Monte Carlo runs are typically conducted in Three Degrees of Freedom (3-DoF) with simplified models, allowing quick assessments of design trades. Later, as day of entry approaches, the performance simulation will be conducted in Six Degree of Freedom (6-DoF) or Multi-body with the most detailed models of the system to evaluate the control system performance, sensor interaction, parachute dynamics impact, detailed "Sky Crane" dynamics, etc. In addition, the simulation allows the degrees of freedom to be adjusted within a single run to tailor the fidelity to the specific problem being analyzed. For example, if the "Sky Crane" dynamics are the subject of the investigation, the portions of the simulation prior to terminal descent can be run in a 3-DoF mode to provide realistic starting conditions with minimal CPU usage and then the fidelity of the simulation can be increased to Multi-body and 6-DoF for the remainder of descent. The choice of the fidelity distribution within different events is a simple modification to the POST2 input, thus allowing the same master input to support multiple degrees of fidelity during the EDL simulation.

MSL performance Monte Carlo runs are given an alphanumeric designation (i.e. MSL 05-21d) and tracked in a configuration control spreadsheet. This document is source controlled and contains pertinent simulation inputs and outputs. The use of this spreadsheet facilitates the passing of data among team members and ensures that everyone is utilizing consistent assumptions. The use of such configuration control is especially important because the design team is spread over multiple NASA centers.

### *Initial Conditions*

*Initial State (EI-10min)*

The initial vehicle position and velocity states are supplied in the Mars-Centered Inertial (MCI) Cartesian coordinates at 10 minutes prior to the nominal entry interface time. The Mars Mean Equator plane and the Mars Prime Meridian vector of date define the particular choice of MCI coordinate frame in use. A detailed approach navigation analysis is performed to assess the expected delivery and knowledge covariances, based on the navigation strategy employed. This analysis is similar to that performed for the Mars Odyssey, Mars Exploration Rover (MER), and Mars Reconnaissance Orbiter (MRO) missions.

*Flight Path Angle*

Because MSL is utilizing a guided hypersonic entry, the choice of entry flight path angle is an important design parameter that affects the overall system performance. The nominal flight path angle is chosen when constructing the entry guidance reference trajectory to maximize the parachute deploy altitude while reserving sufficient performance margin to remove the expected delivery errors and respecting maximum heat rate, heat load, deceleration, and lofting limits [Ref 3]. Once the nominal flight path angle has been chosen, the nominal initial state is adjusted to target the desired landing site.

*Initial Attitude Error*

With sufficient hypersonic Lift-to-Drag ratio (L/D) to fly-out the expected delivery dispersions, the parachute deploy footprint is dominated by the residual knowledge error. The initial attitude error (IMU misalignment at the last navigation upload prior to entry) contributes to guidance range error through integrating errors in the estimated altitude rate. Because of the EDL system sensitivity to this parameter, a conservative assumption is modeled in the simulation. The attitude error is assumed to be at a fixed, "worst-case" magnitude in a nearly uniform random direction. Sweeps of Monte Carlo runs are performed at different levels of attitude error to quantify the EDL system sensitivity to this parameter.

*Atmosphere*

The MSL project is currently using the Mars Global Reference Atmospheric Model (MarsGRAM) [Ref 4] atmosphere models. These models, developed by Jere Justus, are engineering estimates of the atmosphere, and account for altitude, season, location, and time of day. As the MSL mission design matures, a lading site-specific model will replace this atmospheric model, such as was done for MER.

### *Monte Carlo Products*

*Outputs*

Any parameter contained in the list of POST output variables can be captured at critical events during a Monte Carlo run. Currently in the MSL simulation, 669 output variables are captured at 22 events for each of the Monte Carlo cases. These outputs are used to generate statistics and plots that facilitate the evaluation of the vehicle design and EDL system performance. Statistics for particular parameters of interest are reported in the configuration control spreadsheet. Some examples of typical Monte Carlo products are discussed next.

*Statistics*

Typically, Monte Carlo runs are conducted with 2000 randomly perturbed cases in addition to the nominal. Experience has shown this number to be a reasonable balance between statistical accuracy and computer run time. However, runs with as many as 100,000 cases are periodically performed to ensure that the statistics generated with 2000 cases are representative of the larger data sets.

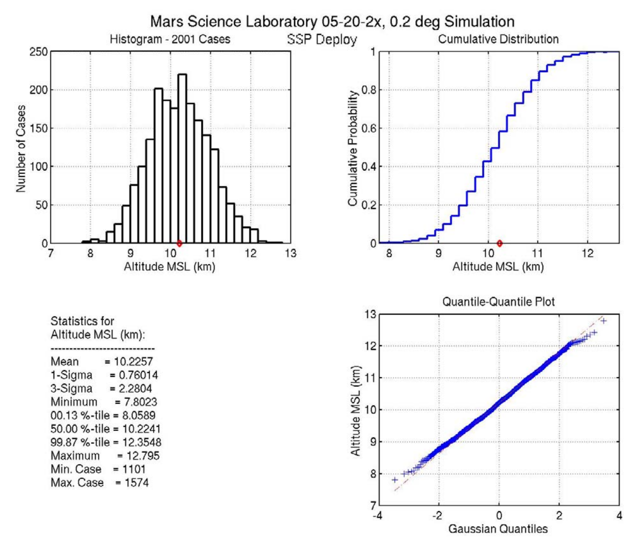


**Figure 20-Statistical Quad Chart**

Figure 20 is an example of a statistical quad-chart reported on a Monte Carlo output variable (e.g. altitude at supersonic parachute deploy). A histogram of the data is plotted in the upper-left quadrant. In the upper-right quadrant, a cumulative distribution function is shown. The quantile-quantile plot (or q-q plot) in the lower-right quadrant is used to assess whether or not the given sample is drawn from a Gaussian distribution. If the distribution is Gaussian, the points plotted in the quantile-quantile plot will fall along a linear line with an intercept equal to the mean and a slope equal to the standard deviation. The text in the lower-left quadrant reveals the minimum, maximum, mean, and various percentiles of the data. By convention, most performance metrics are tracked by a 0.13 percentile or 99.87 percentile statistics. This convention is used to provide requirements with a high probability (3-sigma under the assumption of a Gaussian distribution) of success that is insensitive to the underlying distribution or the number of cases run.

### *Scatter Plots*

*Parachute Deploy Conditions*

Figure 10 is an example of a scatter plot reported for a Monte Carlo performance run. This figure shows the supersonic parachute deploy conditions in Mach and dynamic pressure. Figures such as this are used by the design team to track system requirements, such as those for safe deployment of the parachute. This figure superimposes the conditions of high-altitude Earth tests and previous Mars flights to compare the current design with test and flight heritage. Another utility of scatter plots such as this is the ease of identifying outlying cases. Any outliers are subjected to more detailed forensic analysis, and if a fundamental design flaw is uncovered, the design is modified.

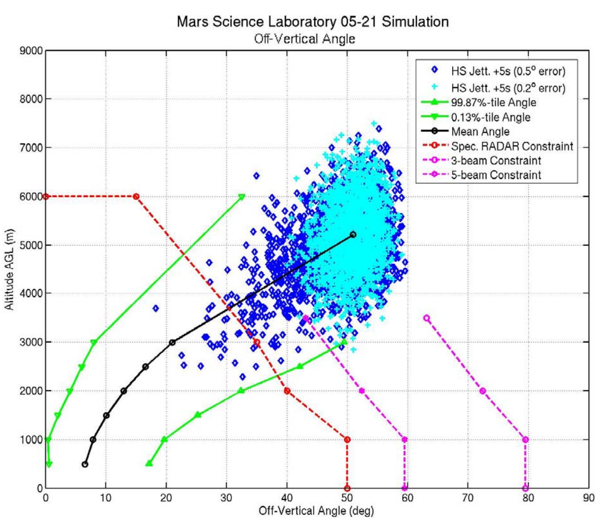


**Figure 21-Heatshield Jettison Conditions**

*RADAR Constraints*

Figure 21 is another example of a scatter plot, showing altitude and off-vertical angle at 5 seconds post-heatshield-jettison, along with radar constraints. In this figure, three additional curves indicate the mean, 0.13-perctile, and 99.87-percentile off-vertical angle statistics at different altitudes. These additional curves help the design team understand how the parameters that effect RADAR performance change with proposed design modifications.

*Profile Plots*

For most Monte Carlo runs, the stored data is limited to a relatively small (several hundred) number of variables at specific critical events. However, it is often of interest to see how particular parameters vary between the discrete events. To facilitate this, individual cases from a Monte Carlo run can be rerun and saved. As many as 300 variables can be stored in a profile at each simulation time step. This capability allows that individual runs can be subjected to detailed forensic analysis, but also groups can be systematically investigated to better understand sensitivities. For example, Figure 22 shows 25 profiles of bank angle as a function of velocity during the guided entry. Plots such as this are used to evaluate guidance and control performance (e.g. is the guidance saturating, are the bank reversals consistent, is the control system able to provide the guidance commands, etc.).

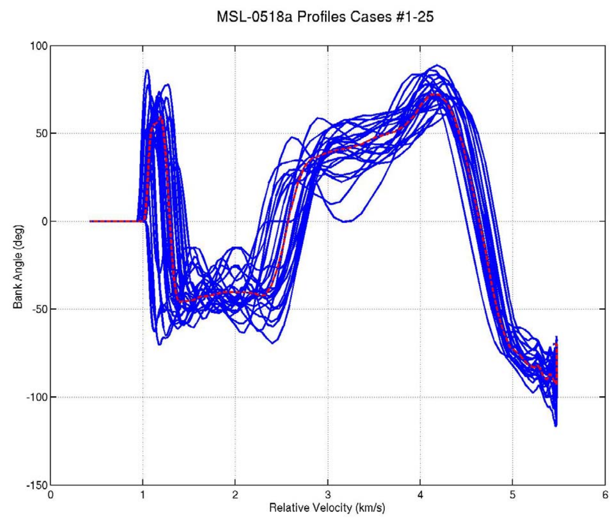


**Figure 22-Bank Angle Profile**

## 10. SUMMARY

As Mars exploration advances there are pressures to deliver increasingly larger payloads to the surface. The EDL system discussed in this paper is a new architecture designed to meet such a challenge. Work to date suggests that this system design can deliver a rover of over 750 kg in mass to the surface at an altitude of up to 2.0 km MOLA.

Several key challenges have been faced thus far in the development of this EDL system. The architecture had to extend the Apollo guidance scheme from earth application to Mars to provide altitude performance and accuracy superior to previous ballistic or lift-only trajectories. The system development has highlighted the issues of asymptotic sensitivity for aerodynamic decelerator systems. To deal with this asymptotic sensitivity, a large heritage based supersonic parachute had to be employed to keep scale with the large delivery mass. A new terminal descent radar has had to be developed to meet the needs of this EDL system while containing development costs. Finally, a novel touchdown system, the Sky Crane, had to be developed to mass efficiently deliver a 750 kg class of rover to the surface.

Such increased EDL performance under budgets constraints similar to previous mission such as MER has in itself presented organizational and programmatic challenge. One feature of the development effort is the team structure. The development of such a high performance EDL system requires careful coordinated team effort over a broad range of disciplines and centers of excellence. NASA/JPL has constructed a small agile team of experts and systems engineers, drawing on the experience and expertise of several NASA centers and including flight project experience spanning several decades of robotic and manned space exploration.

The development of the MSL EDL system will continue over the next four years. The MSL EDL system described herein extends current delivery capabilities in terms of mass delivered, altitude attained and landing accuracy. This system will enable a notable extension in the advancement of Mars surface science by delivering more science capability than ever before to the surface of Mars.

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## BIOGRAPHY

***Adam Steltzner*** *joined JPL in 1991 and has worked on flight projects including Galileo, Cassini, Mars Pathfinder, and the Mars Exploration Rovers. Adam holds a BS from University of California, Davis, and MS from the California Institute of Technology and a PhD from the University of Wisconsin, Madison. Adam was the mechanical systems lead for EDL on MER and is currently the Chief Engineer for EDL on MSL.*

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