Mars Science Laboratory Entry Descent and Landing System Verification and Validation Program

Robert Mitcheltree, Adam Steltzner, Allen Chen, Miguel SanMartin, Tomasso Rivellini
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91109
818-393-6713
Robert.A.Mitcheltree@jpl.nasa.gov

Abstract—The Mars Science Laboratory (MSL)[1] mission will land the next generation of robotic Entry, Descent, and Landing (EDL) systems on Mars in 2010. Relative to previous missions, the MSL EDL architecture will deliver a significantly larger mass to a significantly higher altitude while maintaining a significantly tighter delivery ellipse. MSL is pushing the limits of EDL technologies qualified previously by the Mars Viking, Mars Pathfinder, and Mars Exploration Rover missions as well as introducing new elements into the architecture. Given the difficulties of conducting a meaningful end-to-end flight test on Earth, this combination introduces numerous challenges for the EDL Verification and Validation program. This paper discusses how system Validation challenges influenced the design of the EDL architecture and highlights how some of the remaining challenges will be addressed to assure a successful landing of this unprecedented rover on Mars.

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1. INTRODUCTION

The Entry, Descent, and Landing (EDL) architecture for the Mars Science Laboratory (MSL) Mission 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, however, are required to achieve the unprecedented performance requirements: most notably a novel new touchdown method. Preliminary mission requirements dictate delivery of a 725 kg lander to an altitude of 2 km MOLA within an error ellipse of only 10 km.

System validation for an EDL system differs from traditional spacecraft system validation. Environmental effects cannot be recreated on a vibration table or in a thermal-vacuum chamber. Validation is not simply the matter of assuring the system functions in the associated environments. The function of this system *is* its interaction with the atmospheric and surface environments. Thus, in addition to traditional test-bed, hardware-in-the-loop, testing of the on-board electrical systems, a validation program that confirms the performance during atmospheric and surface interaction is required.

Unfortunately, it is not possible to conduct an end-to-end flight test of a Mars landing system on Earth due to gravity and atmosphere differences. The performance validation plan has to make use of a complex combination of analysis, simulation, and numerous Earth based flight and facility tests. The logic of how these activities combine into system validation is an explicit part of the Validation plan [1]. This logic should be stated, reviewed, and tracked by a validation approach which differs from the traditional requirements verification process.

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Limitations of Earth-based testing were recognized early in, and affected the design of, the MSL EDL architecture. One focus of the design was to simplify interfaces among EDL systems and phases to minimize complex system interactions. Removing these interactions is an essential step towards removing the need for an end-to-end system flight test. It permits a validation and verification process comprised of focused tests and/or analysis woven together through end-to-end simulation. Unfortunately, simplification of interfaces typically decreases performance. Systems optimized for performance often include the possibility of highly complex subsystem interactions necessitating extensive testing. The central challenge in the design of the MSL EDL system was to identify a architecture with vast improvements in performance while simultaneously decreasing intra-subsystem dependencies. Performance gains had to be achieved by dramatic improvements in individual subsystems performance not by increased system-level interdependencies.

A second, V&V driven, focus in the definition of the EDL architecture was to minimize dependencies on events which are not amenable to analysis or simulation. The past 50 years of flight and research in entry systems has produced an impressive set of analytical capabilities. This set, however, is not uniformly distributed across all the physics of EDL. Computational fluid dynamics can now predict the complex high temperature molecular interactions within the forebody shock layer at Mach 20, while detailed description of the seemingly less exotic dynamics of a parachute in terminal descent continues to elude analysts. An architecture is desired which avoids critical dependence on understanding those events which remain difficult to simulate.

The MSL EDL concept is described in reference 2. It includes hypersonic guidance of a lifting blunt capsule, a supersonic parachute, and a powered descent to a novel "Sky-crane" touchdown. The remaining sections of this paper describe the Verification and Validation program for this EDL concept by phase.

2. Exo-Atmospheric Flight

Numerous events must occur on the spacecraft just prior to atmospheric entry to establish the desired initial state at entry. These events include initialization of the EDL software behavior, venting of the internal heat rejection system (HRS), pre-heating the entry propellant catalyst, and , if necessary, performance of a final trajectory correction maneuver. Also at this point, the vehicle attitude knowledge is initialized using an on-board star scanner. Cruise stage separation occurs minutes prior to entry, after which the entry vehicle will de-spin 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 Reaction Control System (RCS) thrusters. After de-spinning, an external balance mass is jettisoned to create an offset center of gravity that provides a nominal lift-to-drag ratio 0.21-0.24 during atmospheric flight. Turn to entry attitude is performed minutes prior to entry. Atmospheric entry occurs at a nominal interface radius of 3522.2 km.

The events associated with exo-atmospheric flight do not include interactions with the Mars atmosphere. Their validation is a challenge but is similar to that of most spacecraft so is not discussed in this paper.

3. Entry

. Two areas of the entry phase are highlighted for their validation challenges: hypersonic guidance and Thermal Protection System (TPS).

In contrast to the spin stabilized, ballistic entries of MER and MPF, MSL utilizes an offset center of mass to create a nominal 16 degree angle of attack through peak dynamic pressure and a 19 degree angle of attack at parachute deployment. This angle of attack creates lift. Bank angle modulation commands 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 deploy conditions with a desired downrange and cross-range 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 which are mapped into individual on/off commands for each of the 8 entry thrusters configured about the aeroshell as shown in Figure 1.

Validation of the entry systems ability to perform this aero-maneuvering is accomplished in six degree-of-freedom (6-dof) Monte-Carlo simulation. The simulation contains models of the aerodynamics and thruster performance from dedicated analysis and facility tests. Models are also required for the vehicles mass properties (including fuel slosh), Mars gravity and atmosphere. These models must include a statistical description of uncertainties. The simulation also mimics the behavior of the on-board computational element with the guidance algorithm running. Such models and simulation have been validated from previous Mars entries and other flight vehicles. One key is to assure the entry capsule structure is sufficiently stiff such that the capsule can be modeled as a rigid body. Two areas of concern from a validation standpoint are the ever-present challenge of modeling the atmosphere and the more MSL specific challenge of modeling the RCS interaction with capsule wake. The latter interaction can introduce undesired controller axis coupling, and augmented heating on the backshell. Fortunately in both of these cases, the primary focus is bounding the behavior to assure the design can handle the worst case situation.

The hypersonic portion of the entry phase is also characterized by aerodynamic heating. MSL's 4.5 m diameter capsule is a larger vehicle than its Viking, MER and MPF predecessors. This size is the largest which can be packaged within the existing 5 m launch vehicles fairings and represents an example of where the MSL EDL architecture strives to extract the greatest amount of performance from an individual subsystem.

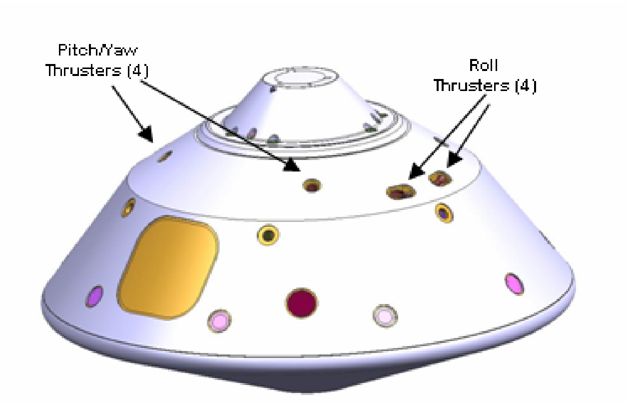

Figure 1 –Entry Configuration

Despite a velocity vs. altitude trajectory which is similar to previous missions, this large capsule with its associated long running lengths will permit boundary layer transition to turbulence during the high heating portion of the trajectory. A turbulent boundary layer is comprised of mixing eddys which bring the super-heated post-shock gases closer to the surface. The net result is a dramatic increase in aerodynamic heating. This increase places greater demands on the thermal protection system (i.e. heatshield). The two validation challenges associated with this increased heating are 1) accurately predicting the environment and 2) demonstrating the TPS material's ability to survive that environment. This augmented heating environment pushes the qualification limits for high heritage TPS material SLA-561V. Studies are underway to bound the heating environment and associated thermal response. Alternate TPS materials are available if deemed necessary.

The qualification of TPS materials in Earth-based arc-jet facilities, even for the higher heating expected, is a demonstrated technology. The primary validation challenge for the MSL entry phase is properly bounding the turbulent heating environment. Facility tests and computational aerothermodynamics are both employed to accomplish this task.

4. PARACHUTE DESCENT

MSL will use 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/MPF. deployment. Deployment is triggered when the system reaches a fixed planet-relative velocity as determined by integration of the inertial measurement unit. After parachute deployment, the heatshield is jettisoned and the stowed rover and descent stage are exposed. At the same time, an internal balance mass is 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.

Qualification of the MSL parachute must establish 1) that it will deploy correctly, 2) that it will inflate successfully, and 3) that it will provide the expected drag and stability once inflated.

Deployment qualification will be accomplished by Earth based mortar-firing tests. These tests do not require special environments or facilities. Measurement of the parachute pack speed during deployment is sufficient to demonstrate the performance. 4

The qualification of the parachute inflation and the supersonic transients in inflation are the most challenging aspect and is detailed below. The drag and stability of the fully inflated parachute can be established from heritage flight and windtunnel data.

As with the entry capsule, the high landed mass requirement couples with the high landed altitude requirement to create demand for a larger parachute decelerator system. Design trades, including multiple parachute options, resulted in the baseline of a single large diameter (19.7 m D_0) supersonic parachute. This size parachute is the largest DGB that has been tested in high altitude Earth testing but is larger than has previously flown on Mars. Selecting a single large parachute is another example of where the MSL EDL architecture has opted to maximize performance of individual subsystems while minimizing complex interdependencies such as those associated with multi-stage parachute systems. In addition, the deployment conditions up to Mach 2.15 have been tested in smaller 16.1 m parachutes on Earth but will be the highest Mach deployment on Mars (Next highest is MER B at Mach 1.9). These two areas of potential concern are balanced by two other areas where heritage is preserved by selecting the larger parachute for this mission. The first is the ratio of capsule size to parachute size. This ratio dictates the capsule wake effects on the parachute – an area of complex fluid dynamics and structures interaction important during inflation and inflated performance. The second area where heritage is preserved is the ballistic coefficient of the system under parachute. The larger parachute decelerates the larger mass is a manner similar to previous Mars entries and assures the exposure of the system to supersonic conditions is limited. Exposure to supersonic flow is of concern, based on historical data, since Disk-Gap-Band parachute appear to undergo area-oscillations when operating above mach 1.4. This phenomenon creates a dynamic environment involving high parachute loading and perturbed aeroshell attitudes and attitude rates.

The detailed dynamics of parachute inflation remains elusive to predictive analysis. Qualification of a parachute system, therefore, requires full-scale testing and empirical models derived from full scale testing. The only means on Earth to approximate Mars inflations is via high altitude, full-scale, supersonic testing. Recent estimates of the cost to recreate these high-altitude-balloon, rocket-powered, tests indicate they are outside the budget of a Mars robotic mission. Therefore, all NASA Mars landers have made use of this same Viking DGB parachute, or its derivative, and have relied upon heritage arguments for aspects of inflation qualification.

In the absence of a high altitude supersonic inflation test, the MSL parachute qualification must follow the MER path which divided inflation qualification into two separate questions, “Will the deployed parachute open in the expected conditions?” and “Will it survive inflation loads?” Initial inflation is “qualified” by similarity to a combination of previous Mars flights and high altitude Earth testing. Qualification for the latter is a structural strength issue. It requires predictive knowledge of the Mars loads in conjunction with some form of Earth test that subjects the parachute to the loads.

Predictive capabilities for opening loads make use of data collected from the Viking BLDT tests as well as the Viking and Mars Pathfinder flight data.

The only remaining element which requires ground testing is one of strength. As with MER, this strength testing will be conducted in the 80 by 120 ft. full scale windtunnel at NASA ARC. This strength testing will include cyclic loading to demonstrate the system’s ability to handle area-oscillations.

Heatshield separation follows parachute deployment and inflation. Heatshield separation must satisfy two requirements: (1) no recontact with the flight system, either short or long term, and (2) satisfactory separation to ensure no more than one beam of the Terminal Descent Sensor (TDS) is obscured after the TDS is activated. The central challenge to validation of these separation requirements is to understand the interference aerodynamics between the separating heatshield and the backshell. Fortunately, the MSL case is a scaled version of the Viking separation. The Viking program conducted extensive wind-tunnel tests which are applicable to MSL.

5. TERMINAL DESCENT SENSOR

The terminal descent sensor (TDS) will directly measure vehicle altitude and velocity relative to the Mars surface using a 3-axis Doppler velocimeter and a slant range altimeter. This system, which can sense the ground only after heatshield separation, is tasked with providing robust, but not highly accurate, measurements prior to 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.

Validation of the terminal descent sensor will include a series of Earth based field tests. These tests establish the accuracy and performance of the sensor under a range of descent velocities, attitude dynamics, and terrain. Since the required tests focus only on the TDS they can use any means available to achieve the desired velocities and dynamics and hence circumvent the limitations of Earth based testing. The results from the tests are also used to construct a detailed computer model of the TDS performance which can then be used in end-to-end simulations and avionics test beds.

6. POWERED DESCENT

The beginning of powered descent is triggered based on TDS velocimetry and altimetry measurements. The phase begins while still descending under parachute with the warm-up of the 8 Mars Lander Engines (MLEs) for 1.5 seconds prior to backshell separation. The actual separation occurs approximately 1100 m above ground level. The first challenge of powered descent is to assure a clean separation without recontact. Initially the higher ballistic coefficient descent stage falls free of the backshell and parachute, but when the MLE engines are throttled up, the vertical velocity of the descent stage is decreased to less than the terminal velocity of the backshell and parachute and the situation reverses introducing the possibility of re-contact.

This separation is similar to Viking except the larger relative mass of the MSL backshell left under the parachute means the initial ballistic separation is slower. Viking was able to delay throttle-up of the MLEs for >10 seconds after separation allowing significant initial separation. MSL can not tolerate the altitude loss associated with that delay and is looking to begin throttle up 1-2 seconds after separation. Viking did not do any explicit maneuver to avoid recontact, MSL is examining introducing a divert maneuver interlaced into the powered descent profile to mitigate the risk of recontact with the discarded backshell plus parachute system. Since the bodies in question can be treated as rigid and the forces from the propulsion system can be characterized via test-stand firing, qualification of this separation and the ensuing flight can be accomplished via multi-body dynamic simulation. The central validation challenge is constructing a model of the parachute's behavior in the presence of the MLE engine plumes. Viking faced this same challenge and conducted scaled tests to establish the degradation in parachute performance. The applicability of these tests to MSL is under review. Either they will be used or new scaled tests will be conducted to establish the interference aerodynamics.

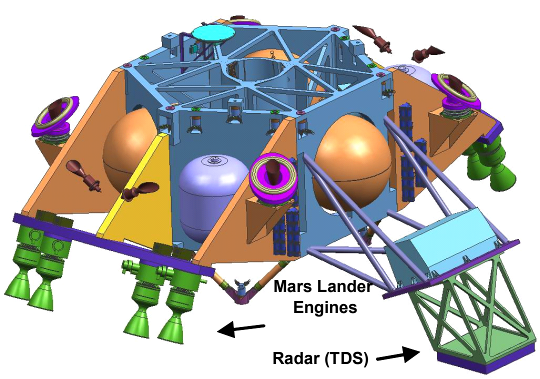

Figure 2 –Descent Stage Configuration

Control authority during powered descent is provided by the 8 MLE's which are canted to avoid plume impingement on the rover during descent and touchdown. Mixing logic is employed to provide 3-axis control during powered descent using only the Mars Lander Engines. Thruster configuration is shown in Figure 2. Each MLE will provide 3000N of thrust at full throttle. MLE development has relied on Viking heritage for injector and catalyst bed design as well as incorporating new developments – most notable the throttle valve assembly. Validation and characterization of the engines will be accomplished via test stand firing. Powered descent is complete when the Sky Crane start conditions of 19.5 m with zero horizontal velocity and a vertical velocity of [0.75] m/s are attained.

7. SKY CRANE AND TOUCHDOWN

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. A 0.75 m/s constant velocity vertical descent is maintained by the descent stage until rover touchdown is detected via bridle offloading. The two body architecture enables closed looped control during the touchdown event. From a validation standpoint, the key feature of the maneuver is that the touchdown event, which includes all of the uncertainty of the terrain, is decoupled from descent stage control. In fact all of the events during this phase – rover release, rover descent down the bridle, rover snatch at the bottom of the bridle, and touchdown – represent only small disturbances to the actively controlled descent stage. By minimizing the magnitude of these disturbances and employing a high bandwidth control system with exceptional disturbance rejection ability, the validation of the system is dissociated into two decoupled problems. The first is determining the bounds of each disturbance. The second is demonstrating the capability of the control system to continue its constant descent despite those disturbances. Since, the magnitude of each disturbance can be measured by focused testing (e.g. rover separation testing, rover bridle deployment testing, and rover touchdown testing, and the performance of the descent stage in the presence of these disturbances is amenable to analysis, a full-scale "hot-fire" test of the entire system is not required.

In the end, the goal of the Sky Crane maneuver is to set the rover down on the Mars surface upright and within specified touchdown velocities to avoid rover damage. The system has greater stability for rover attitude, thanks to the persistence of tethering during touchdown, and experiences lower loads which, thanks to the low landing velocity, are similar the rover driving loads. High stability and low loading means that a separate touchdown system is not required and there is no egress phase. Rather, the rover rocker-bogey suspension is the touchdown system and it is properly positioned to begin operations immediately after touchdown.

Operations during the Sky Crane phase are managed entirely by the rover's onboard flight computer. IMU data and throttle commands are sent via a non-load-bearing electrical umbilical that runs parallel to the bridle system. After persistent touchdown is detected, the umbilical and bridles will be cut just above the rover surface 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.

8. SUMMARY

A high performance entry, descent and landing architecture design has been developed for the Mars Science Laboratory mission. It is a blend of existing EDL technologies with a new touchdown scenario. Verification and validation of the system played an integral part in definition of the architecture. Complex subsystem interactions are avoided in favor of more capable individual subsystems. Critical dependencies on interactions which are difficult to simulate are avoided. Key developments and validation challenges, however, remain. These include the use of bank modulated entry guidance, the largest supersonic parachute ever flown on Mars, and the advent of the Sky Crane landing maneuver.

9. REFERENCES

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10. BIOGRAPHY

Dr. Robert Mitcheltree is the Verification and Validation Lead for the Mars Science Laboratory Mission at NASA's Jet Propulsion Laboratory. He held the same position for the Mars Exploration Rover Mission.

Prior to joining JPL in 2001, he worked for NASA's Langley Research Center for 12 years.