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MARS EXPLORATION ROVER MISSION: ENTRY, DESCENT, AND LANDING SYSTEM VALIDATION

Robert A. Mitcheltree

The Jet Propulsion Laboratory, California Institute of Technology, Pasadena, Ca.
Robert.Mitcheltree@jpl.nasa.gov

Wayne Lee, Adam Steltzner, Alejanhdro SanMartin

The Jet Propulsion Laboratory, California Institute of Technology, Pasadena, Ca.

Abstract

System validation for a Mars entry, descent, and landing system is not simply a demonstration that the electrical system functions in the associated environments. The function of this system *is* its interaction with the atmospheric and surface environment. Thus, in addition to traditional test-bed, hardware-in-the-loop, testing, a validation program that confirms the environmental interaction is required. Unfortunately, it is not possible to conduct a meaningful end-to-end test of a Mars landing system on Earth. The validation plan must be constructed from an interconnected combination of simulation, analysis and test. For the Mars Exploration Rover mission, this combination of activities and the logic of how they combined to the system's validation was explicitly stated, reviewed, and tracked as part of the development plan.

Introduction

The Mars Exploration Rover Mission (MER) successfully landed two rovers on Mars January 4th and January 24th, 2004. The Entry Descent and Landing system (EDL) selected for this mission was to be identical to that used by the successful Mars Pathfinder mission[1] of 1996. Initially, this repetition promised decreased design and validation costs as well as increased mission success probabilities. Cost reduction for the flight system would allow larger portions of the project's resources to be directed towards development of a sophisticated mobile science package. However, as this package's development progressed, its associated mass and size increased beyond that which the Mars Pathfinder EDL system could safely deliver to the surface.

The MER Rover, when finally completed, weighted 175 kg. This was more massive than the 25 kg Sojourner Rover from Mars Pathfinder. The MER rovers, however, carried all landed mission assets on the mobile platform while Mars Pathfinder distributed them between the rover and the lander. Despite this, the MER system still weighted 539 kg at touchdown, which is larger than the 370 kg Mars Pathfinder value. The increase in landed mass increased the entire entry systems mass from 583 kg for Mars Pathfinder to ~830 kg for MER (827 kg for Spirit, 832 for Opportunity).

The MER mission also hoped to land this mobile payload at sites with significant scientific potential. The two sites selected: Gusev Crator for Spirit at –1.6 km altitude and Meridianni Planum for Opportunity at –1.3 km altitude, were higher than the –3.5 km altitude of the Ares Vallis site for Mars Pathfinder. Higher altitude landings reduce the amount of thin Mars atmosphere available for an EDL system to decelerate its payload. Decreased atmosphere for deceleration decreases the timeline necessary to accomplish the landing sequence and ultimately pushes the requirements for parachute deployment to higher altitudes and loads. In addition, remote sensing of the Gusev Crator site indicated the potential for high winds and a rough surface. Both winds and surface characteristics directly affect the design of the EDL system.

Historical events also affected the design and validation plan for MER. The double failure of the Mars Climate Orbiter Mission and the Mars Polar Lander Missions in 1999 removed NASA's appetite for the Better-Faster-Cheaper

flavor of risk in Mars missions. The Young report[2] on these failures introduced two recommendations that affected MER EDL. First, more comprehensive system validation activities were to be conducted and these activities were to be reviewed by increased number of independent panels. Second, a requirement for real-time communication during critical events such as EDL was introduced. Real time communication required landing during Mars daylight hours at the selected landing sites. These landing times have lower atmospheric density and higher winds – both stress the design for EDL.

MER was able to make use of the successful landing architecture pioneered by Mars Pathfinder, but the combination of these four factors – larger landing mass, higher altitude landing sites, daytime density and winds, and decreased risk posture - necessitated significant redesign, analysis, and system validation of the Entry, Descent, and Landing system.

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, system testing of the on-board electrical systems, a validation program that confirms the performance during atmospheric and surface interaction is required. This paper focuses on this environmental interaction validation.

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 had 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. This logic was stated, reviewed and tracked by a validation approach which differed from the traditional requirements verification process.

This paper will summarize the major changes to the EDL system from its Mars Pathfinder predecessor and focus on the new challenges these changes placed on EDL system performance validation. A subset of the major subsystem qualifications are highlighted to reveal how this combination led to the successful landing of the Spirit and Opportunity landers.

Entry, Descent, and Landing Architecture

Entry, Descent, and Landing of a spacecraft on Mars is a problem of energy removal. The spacecraft, upon arrival at the edge of the planet's atmosphere, possesses giga-Joules of combined kinetic and potential energy relative to the surface. This energy must be dissipated while managing the mechanical and thermal loads delivered to the rover payload. Optimal EDL design is then the challenge of minimizing the mass required to accomplish this energy removal while maximizing reliability within project cost and schedule constraints.

The architecture of the Entry Descent and Landing system for MER, like Mars Pathfinder, relied on four stages of deceleration. Each stage is designed to dissipate a portion of the immense kinetic and potential energy possessed by the capsule as it enters the Mars atmosphere from a hyperbolic approach trajectory.

The initial deceleration is accomplished aerodynamically by a blunted 70 degree half-angle cone capsule. The forebody heatshield of this cone is covered with the SLA-561 ablator developed for Mars Viking and also used on Mars Pathfinder. This initial passive stage accomplishes a 99.6 % reduction in energy relative to the surface as the capsule is decelerated from over 5.7 km/s at atmospheric interface to 420 m/s at 10 km altitude.

The associated deceleration pulse peaks at near 6 Earth G's. Accelerations sensed during this entry are monitored by a parachute deploy algorithm which determines what moment to mortar deploy the 14.1 m diameter Disk-Gap-Band parachute. A back-up timer in conjunction with a series of algorithm sensor checks mitigates the potential for sensor error leading to incorrect deployment.

The parachute supplies the second stage of deceleration. It removes 98% of the remaining energy as it takes the system from its Mach 1.7 and 9 km altitude deployment condition down to approximately 70 m/s near the surface.

After parachute deployment, the heatshield is released and the lander deployed on a combination bridle and descent-rate-limiter. The resulting descent train is a three-body system comprised of parachute, backshell, and lander shown in Figure 1.

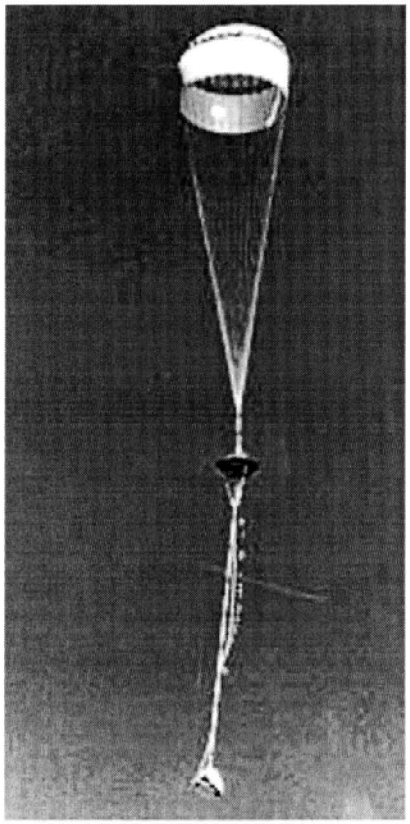

Figure 1. Terminal Descent Configuration (MPF Earth Test image)

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The third stage of deceleration is a set of solid rockets in the backshell which decelerate the three body system from 70 m/s at ~120 m height to a near zero velocity at 10-15 m off the surface. This additional 98% reduction in energy is triggered autonomously by algorithms monitoring a radar during descent.

The final stage of deceleration is then accomplished by an airbag system. A series of bounces on these airbags brings the system to rest on the surface.

Successful EDL requires the on-board electrical system to command 5 events: Parachute deploy, heatshield separation, lander deployment, airbag inflation, and the firing of the RAD and, if necessary, the TIRS rockets.
The heatshield separation and lander deployment events are timed events following parachute deploy. Airbag inflation is a timed event just prior to rocket firing. Thus, the onboard autonomy must establish only two events: parachute deploy and the rocket firings.

Modifications to EDL From Mars Pathfinder

There are numerous changes between the Mars Pathfinder EDL system and that of MER. Many changes followed the increased mechanical loads on individual subsystems to handle the increased system mass, and lower atmospheric density (from daytime landing at higher landing site altitudes). Two changes of particular note resulting from increased loads are the increased strength of the parachute and the airbags.

The parachute was required to open at higher altitudes – and thus higher dynamic pressure and loads. Qualification of the parachute for these increased loads presented a challenge and is discussed in the *Parachute Qualification* section. The airbag testing was approached in a manner similar to that used in Mars pathfinder but performance assessment included additional analysis. Both are summarized in the *Airbag Qualification* Section

The major change in the landing system architecture was the introduction of the Transverse Impulse Rocket System or TIRS subsystem. The TIRS rockets in conjunction with the MPF-heritage Rocket Assisted Deceleration or RAD system are the third stage of deceleration during EDL. The RAD rockets decelerate essentially in the vertical axis, the TIRS system fires horizontal thrusters if necessary to decrease the horizontal velocity at airbag impact. The 3 TIRS rockets are spaced 120 degrees apart around the backshell. A single TIRS engine can be fired or any combination of two making a total of seven options (including no fire). In addition the rockets can be fired early in the RAD burn or late in the RAD burn to give two different degrees of effectiveness, making a total of 13 discrete options for control. An autonomous TIRS algorithm selects which option to fire. The TIRS algorithm monitors the motion of the backshell via the Inertial Measurement Unit (IMU) and predicts the relative attitude state of the three body system 0.2 seconds in the future. At the moment the RAD algorithm determines the RAD rockets must fire, this prediction is used to estimate the horizontal velocity vector that would be induced by the RAD firing, This induced horizontal velocity prediction is then vectorally combined with the horizontal drift velocity being propogated by the IMU from an initial value determined by the Descent Image Motion Estimation camera (DIMES) during descent. The appropriate TIRS motor or combination is selected to best counter the estimated direction. Qualification of the TIRS algorithm was particular challenging and is discussed in the *TIRS Qualification* section.

Finally, despite the unqualified success of the Mars Pathfinder landing - which represents the best possible system test of a Mars EDL system - these changes and additions to the EDL subsystems increased the need for a thorough system-level validation. Formulation of the system level plan is discussed in the *Validation Approach* section. The system validation activities are discussed in the *System Validation* Section.

Validation Approach

The changes in the EDL system introduced a need to repeat all subsystem level tests, create new tests for the new subsystems, and revalidate at the system level.

Since an end-to-end test of the EDL system could not be conducted on Earth, the system validation was accomplished via a combination of analysis, simulation, facility, and field tests. An integral part of the validation plan is the logic of how these activities combine into system validation.

Formulation of the MER EDL system validation plan utilized an event-tree based approach. The event trees are a logical model of the system constructed in a manner similar to that used in Probabilistic Risk Assessment. This approach offers several advantages to the traditional requirements matrix verification approach. The key feature is that it embeds verification activities in a logical model of the system. Combining the verification activities with the system's logic is effective in exposing validation issues that may have been omitted from the system requirements definition. This logic can then be tracked and if needed, adjusted to reflect descopes or failures of related verification activities. The logical structure of the trees also illustrates the flow of verification tasks at the subsystem and system level to over-all system validation, so it is effective in communicating within the project team, and to outside review panels, the completeness of the plan. Simultaneously, it helps define objectives of specific tests or analysis.

The event-trees broke the EDL Phase into 6 segments: Final Approach, Entry, Initial Descent, Terminal Descent, Landing, and Egress Preparation. Each of these segments were further decomposed into events, and the events divided into sub-events down to a level where subsystem level verification activities were conducted. Unlike a fault tree analysis where only the bottom-most branches of the tree must be addressed., each branch linking subsystem branches together in the event-tree must have some specification of what was done to verify these two subsystems worked together. In this manner, the system level validation was defined and its strength's and weaknesses revealed.

The following sections describe a few of the major subsystem-level qualification efforts followed by a description of the System-level activities.

Parachute Qualification

Qualification of the MER parachute had to 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 was 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.

The qualification of the parachute inflation was the most challenging aspect and is detailed below. The drag and stability of the inflated parachute was established from heritage data as well as MER-dedicated subscale windtunnel testing[3] in facilities that could approximate Mars conditions.

The increased payload mass and landing site altitudes required the MER parachute to inflate at higher dynamic pressures than previously demonstrated. The challenge in parachute qualification for MER centered on demonstrating the parachute would inflate successfully at these higher dynamic pressure conditions.

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 supersonic testing.

The Mars Viking mission conducted the Balloon Launched Decelerator Tests (BLDT)[4] to qualify the supersonic Viking Disk-Gap-Band Parachute. 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 MER parachute qualification divided inflation qualification into two questions, "Will the deployed parachute open in the expected conditions?" and "Will it survive inflation loads?" Qualification for the latter was a structural strength issue, it required predictive knowledge of the Mars loads in conjunction with some form of Earth test that subjected the parachute to those loads.

Predictive capabilities for opening loads made use of data collected from the Viking BLDT tests as well as the Viking and Mars Pathfinder flight data. Fortunately, the Mars inflation is an infinite mass inflation with peak load occurring at full inflation. This simplifies the prediction of peak loads for Mars but exacerbates the ability to conduct an adequate low altitude Earth drop test. Earth's density at low altitude is approximately 100 times greater than Mars. To match dynamic pressure, the velocity must then be limited to about one tenth of the Mars conditions. In addition, the amount of gas mass captured by the parachute during low altitude Earth inflation is about 100 times greater than on Mars. Almost half of the total load experienced by the parachute in low altitude inflation is due to accelerating this massive quantity of gas.

This is much different than Mars where the inertia of the gas contributes only about 15 percent of the load. This inertial effect requires further reduction in the velocity at inflation for low altitude Earth testing to avoid overloading the parachute. Helicopter drop tests of the canopy strength initially began with a 3000 lbm drop article, but after realization that inflation times in low altitude were longer than expected, that mass was increased to 8000 lbm. However, since the contribution to load from apparent mass inertia is sensitive to inflation times, and the low speeds are changing rapidly during the initial free-fall of the test article, obtaining the desired loads in these tests required an expensive iterative approach. Ultimately, the helicopter drop tests were abandoned in favor of the more controlled situation offered by the NASA Ames Research Center full scale windtunnel.

The windtunnel tests demonstrated that the parachute would open and survive opening loads in low altitude Earth conditions. However, since the conditions were so different from the expected Mars conditions only the latter strength aspect was valid for qualification. The question remained, ''Will the parachute open in the high dynamic pressure Mars conditions?'' Although MER was to inflate the parachute within the Mach number range previously demonstrated in BLDT and MPF, the dynamic pressure was larger and neither BLDT nor MPF would suffice as a heritage qualification argument. Fortunately, the predecessor to BLDT – the Planetary Exploration Parachute Program (PEPP)[5] - did inflate disk-gap-band parachutes at higher dynamic pressures including ones higher than MER expected. Unfortunately, the PEPP canopies possessed shorter band lengths than MER. So in the strictest sense of validation, the MER mission ultimately flew without this inflation validation demonstrated. Comparison of inflation data from the PEPP DGB design and the MER DGB design revealed that the band length and dynamic pressure did not appear to affect inflation. Thus, this heritage data suggested there was an acceptable risk in proceeding.

TIRS Algorithm Qualification

The addition of the TIRS subsystem and its associated sensors (the Inertial Measurement Unit (IMU) and the DIMES imager) represented the greatest change to MER's EDL system from that of Mars Pathfinder. The TIRS system is simple and robust, but validating aspects of the associated control algorithms posed a challenge. These algorithms must successfully complete four tasks:

1) Predict the relative attitude state of the three body system 0.2 seconds in the future from the Backshell IMU data alone
2) Predict the induced horizontal velocity from firing the RAD motors at that attitude state.
3) Predict the effect of firing each of the 13 TIRS options during RAD firing (To allow selection of the optimal option)
4) Know the correct directionality for late TIRS firing options.

Items two and three in the above list are amenable to dynamic simulation and could be handled by combining measured rocket performance with measured mass and geometries of the elements. Tests were conducted to establish the validity of the simulations for two aspects of this event. First, the contribution of the parachute during its rapid offloading was examined in a dynamically scaled parachute offloading test. Second, the propulsion structural interactions of the Motors and the backshell structure were examined in a Backshell/RAD interactions test.

The remaining tasks (1 and 4) are not easily validated in dynamic simulations. The difficult aspect of the dynamic state estimator and predictor (task 1) is the complex interaction between parachute dynamic stability and the three-body pendulum dynamics of the terminal descent system. While three-body pendulum dynamics are routinely modeled in dynamic simulations, the forcing function on these dynamics for MER comes from parachute dynamic stability and the parachute's response to winds. Neither this form of parachute stability or Mars winds are well characterized.

A test was desired that included a real parachute and encountered real wind shears. As stated previously, the gravitational and atmospheric differences between Earth and Mars compromise flight-testing of Mars terminal descent dynamics on Earth. Full-scale Earth tests of the Mars flight hardware - even at high altitudes - will not recreate the Mars dynamics and would not represent a validation of the TIRS system. Fortunately, dynamic scaling laws can be utilized to design an Earth flight test - even a low altitude Earth flight test - that recreates the important interplay between aerodynamics and gravity as a means of validating these simulations. These scaling laws are described in reference 6. A dynamically scaled ``Multi-Body Dynamics Test" was conducted which demonstrated the robustness of this aspect of the TIRS algorithm.

Algorithm task 4 in the above list was also difficult to rely on simulations for validation. When the RAD motors fire, they produce a slight deformation in the backshell that leads to a the application of a spin torque to the backshell. Since the dynamic simulations did not include these structural deformations, this aspect could not be qualified in the simulations. The "spin-up" algorithm could handle a large range of spin torques. Its simple predictive nature, however, could produce large errors if the spin included dynamic signals in the lwoer frequency ranges. A dynamic test was required which allowed the backshell to spin freely. A live fire test was conducted which positioned the backshell in a

test stand in an arrangement that allowed it to spin up during the RAD firing. Data was collected from an onboard IMU in the flight location. The algorithm was then exercised on this data to makes its prediction that could then be compared with the truth data recorded. The test demonstrated there were no lower frequencies associated with the spin-up. One interesting outcome of the test was a realization that the structural mounting of the IMU sensor was the greatest source of low frequency "noise" to the system.

Airbag Qualification.

No single test could qualify the airbag system for MER. Airbag qualification for the selected landing sites required demonstrating that an acceptable probability of success was assured. This effort required a combination of four activities.

The trajectory state of the lander at first ground impact was predicted using multi-degree-of-freedom computer simulations that combined the autonomous behavior of the algorithms with models for all of the associated forces. These forces included gravity, aerodynamics, winds, and RAD+ TIRS motor thrusts. Uncertainties in these forces required a statistical Monte-Carlo simulation to determine typically 2000 different first impact cases for each landing site.

The second activity was estimation of the terrain characteristics of the landing sites. Mars Global Surveyor imagery and radar data were utilized to determine surface inclinations on several length scales. These were combined with impact-crater ejecta models to estimate rock density, and rock characteristics. Digital Elevation Maps of the sites were populated with the rock information to give statistical description of the surface characteristics.

The third activity was the airbag drop testing. The pressure rise during impact can only be recreated in the appropriate absolute pressure. Recreating Mars surface pressures requires use of a vacuum chamber. MER, like MPF before it, utilized the Plumbrook vacuum chamber at NASA's Glen Research Center. A total of 54 drop tests were conducted in the combined development plus characterization testing. This testing not only demonstrated airbag robustness to the most expected impact conditions but was used to construct an airbag capabilities map. The dimensions of this map included velocity normal and tangent to the surface, as well as rock size and characteristics, as well as relative spin orientation of the lander to the surface. The map defined a conservative boundary between demonstrated success and real (or assumed) failure of the airbags and specified the mode of failure for cases outside the boundary

Finally an additional trajectory simulation was utilized to follow the airbag bounces across the terrain. Ultimately it was this simulation that provided the probabilities of success for the airbags. The "bounce" simulation took the Flight trajectory simulations' 2000 predictions of state at first impact as its initial states. It utilized the terrain model to define the surface and rock characteristics for each impact. It utilized the airbag capabilities map for determination of success or failure for an impact, and then it utilized a empirical model of the forces associated with bounce to propagate the airbag lander from that first impact to each subsequent impact to roll-out.

System Qualification

In the absence of an end-to-end flight test on Earth, EDL system validation was accomplished in an electronic test bed containing flight-like versions of all electronic aspects of the system. The test bed was exercised with the IMU, radar, and DIMES sensors in the loop to assure each was electrically compatible with the system, then they were removed and replaced with numerical models. These models had to provide realistic simulations of the sensor's expected outputs to the system's dynamics. For example, extensive field testing of the radar altimeter and DIMES imager were conducted which established not only their functional performance but characterized their output to sufficient detail to permit the construction of numerical models of their performance. The same was done for the IMU. The multi-degree of freedom EDL trajectory simulation was then run producing the time history of the spacecraft elements for nine different cases that were thought to span the range of conditions that stressed the system. These trajectory histories were then used to drive the sensor models to produce a time-synchronized, consistent set of sensor outputs for use in the test bed. This decoupled approach required two iterations to synchronize the algotithm controlled events with the initial trajectory simulations, but produced a reasonable representation of sensor inputs to the test bed.

Summary

System validation for a Mars entry, descent, and landing system is not simply a demonstration that the electrical system functions in the associated environments. The function of this system *is* its interaction with the atmospheric and surface environment. Unfortunately, it is not possible to conduct a meaningful end-to-end test of a Mars landing system on Earth. For the Mars Exploration Rover mission, System Validation of the Entry, Descent, and Landing System utilized a combination of analysis, simulation, facility tests, and field tests. This combination of activities and the logic of how they combined to the system's validation was explicitly stated, reviewed, and tracked as part of the development plan. This approach should be considered for validation of any system when no valid system-level test is available.

Acknowledgements

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