Terrain Safety Assessment in Support of the Mars Science Laboratory Mission

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Abstract— **In August 2012, 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. The process to select the MSL landing site took over five years and began with over 50 initial candidate sites from which four finalist sites were chosen. The four finalist sites were examined in detail to assess overall science merit, EDL safety, and rover traversability on the surface. Ultimately, the engineering assessments demonstrated a high level of safety and robustness at all four finalist sites and differences in the assessment across those sites were small enough that neither EDL safety nor rover traversability considerations could significantly discriminate among the final four sites. Thus the MSL landing site at Gale Crater was selected from among the four finalists primarily on the basis of science considerations.**

TABLE OF CONTENTS

1. INTRODUCTION

Assessment of Entry, Descent, and Landing (EDL) success probabilities at candidate landing sites is a critical element of any landing site selection process. For previous landed Mars missions (Viking, MPF, MER, PHX) variation in EDL success probabilities across candidate sites yielded a significant discriminator in the site selection process and, for those missions, EDL safety was the primary arbiter which selected the landing site from a short list of finalist candidate sites. The MSL EDL system was architected specifically to enable access to a greater portion of the Martian surface and to allow a more science-driven site selection process in which site-to-site variation in EDL safety would be minimized. The benefit of this architectural design stratagem was borne out during final site selection: the safety differences between the four finalists sites were determined to be negligible despite notable site-to-site differences in surface altitude, regional atmosphere, and surface topography. Ultimately, Gale Crater was selected from among the group of finalists primarily on the merits of the science that could be performed at that site.

There are two EDL innovations on MSL which proved particularly beneficial in increasing EDL success probabilities across a wide range of potential landing sites.

Firstly, the adoption of the Sky Crane landing architecture allows for safe landings on surface slopes up to 30 degrees and rocks up to 55 cm tall. Capability to accommodate such extreme terrain, terrain that would have posed unacceptable landing risk for prior missions, results from the combination of low touchdown velocity and from employing the rover's surface mobility system, which readily articulates to adapt to the local surface topography, as the landing gear. The tolerance to steep slopes and large rocks allows for the landing ellipse to be placed in regions previously inaccessible from an EDL safety perspective.

Secondly, inclusion of entry guidance in the architecture allows the spacecraft to actively control range flown via the use of bank angle modulation during hypersonic flight. The major benefit of entry guidance for the site selection process is a dramatically smaller landing ellipse than for previous Mars missions, nominally less than 20 km by 25 km. Among other benefits, this smaller ellipse allows for the ellipse to be placed inside smaller features (e.g. canyons, craters) that may be circumscribed by hazardous terrain. A secondary consideration of the smaller ellipse is a significant reduction in the amount of orbital data required to characterize the entirety of the ellipse.

This brings us to another key advancement that has been critical to advancing the state-of the art in EDL safety assessment for MSL. The availability of hi-resolution orbital imagery from MRO, and specifically from the HiRISE camera, allows characterization of local surface topography at length scales smaller than the Curiosity rover. The availability of this high-resolution imaging data, combined

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with the reduced landing ellipse, allowed an essentially complete characterization of an entire landing ellipse for the first time in the history of planetary exploration. This paper contains an overview of the data, analysis tools, and methodologies used to assess terrain safety at each of the candidate landing sites.

2. SUMMARY OF TERRAIN DATA SETS

Site specific safety assessments require a wealth of site-specific terrain data describing surface topography, rock distributions, and mechanical properties of the surface over the entire landing ellipse. Detailed datasets were acquired for each of the four finalist sites; Eberswalde Crater, Gale Crater, Holden Crater, and Mawrth Vallis (Figure 1). A summary of the two most critical datasets (surface topography, and rock distribution maps) is covered here. For more detailed discussion of the complete suite of terrain data see reference [1].

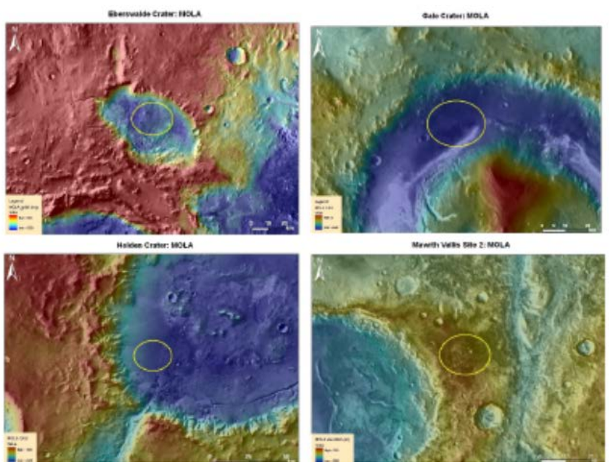

Figure 1 – MOLA Topography and Location of Landing Ellipses for Finalist MSL Candidate Landing Sites

Digital Elevation Maps

Digital Elevation Maps (DEMs) produced from HiRISE stereo pairs for the MSL site selection process represent the highest fidelity, and highest volume, Martian planetary data set ever produced. Over 30 stereo pairs were processed, covering over 4000 square kilometers, providing 90-98% areal coverage at each of the finalist landing sites. Individual pairs were controlled to MOLA and mosaicked to create a single DEM product. These DEMs are produced at a resolution of 1m and are co-registered to sub-meter accuracy both horizontally and vertically. In order to provide complete and seamless coverage for the entire region of each ellipse, the mosaicked HiRISE DEMs were supplemented with lower resolution digital elevation data derived from the High Resolution Stereo Camera (HRSC) (Figures 2-5). Elevation data products were validated by detailed comparisons against MOLA, MOC, THEMIS, and MER ground truth.

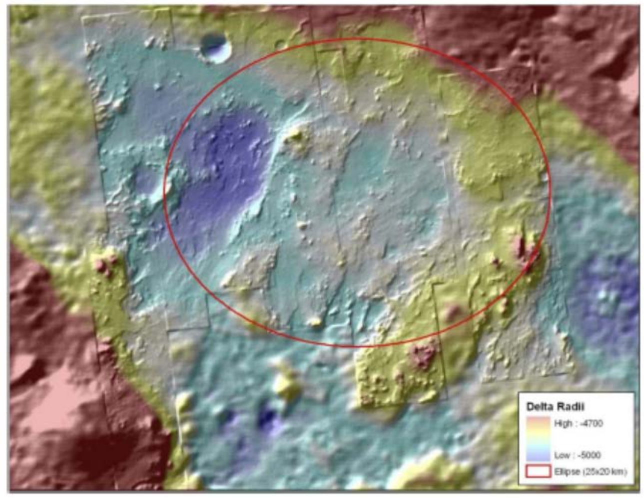

Figure 2 – HiRISE/HRSC Digital Elevation Mosaic at Eberswalde Crater

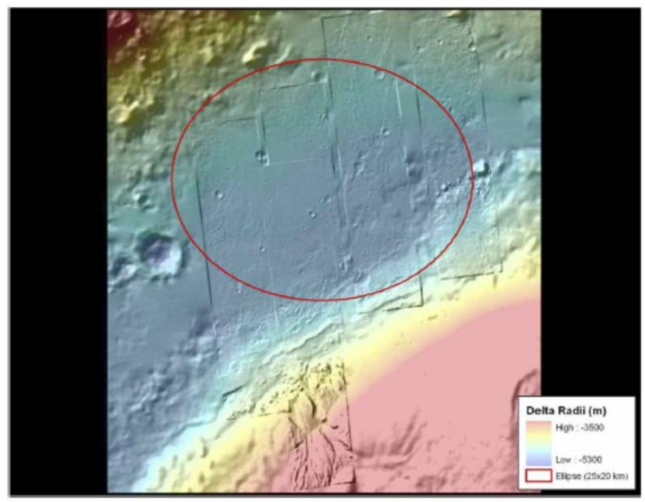

Figure 3 – HiRISE/HRSC Digital Elevation Mosaic at Gale Crater

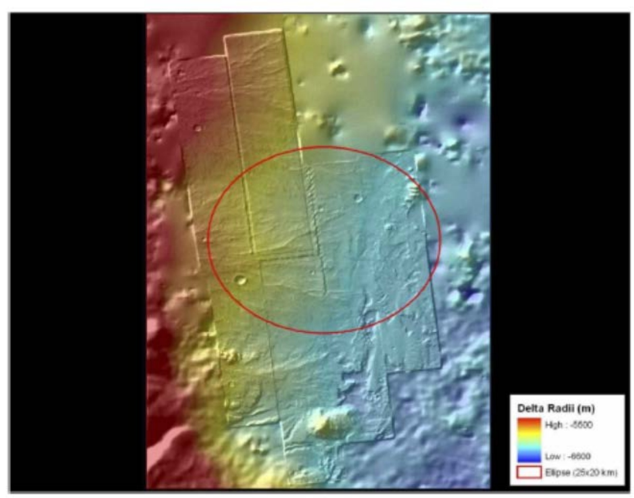

Figure 4 – HiRISE/HRSC Digital Elevation Mosaic at Holden Crater

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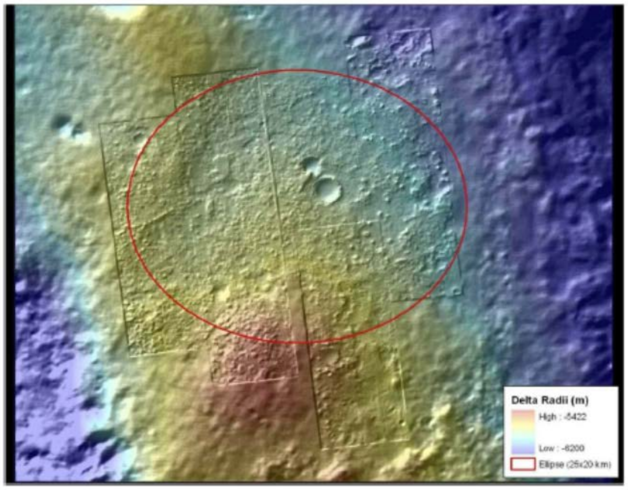

Figure 5 – HiRISE/HRSC Digital Elevation Mosaic at Mawrth Vallis

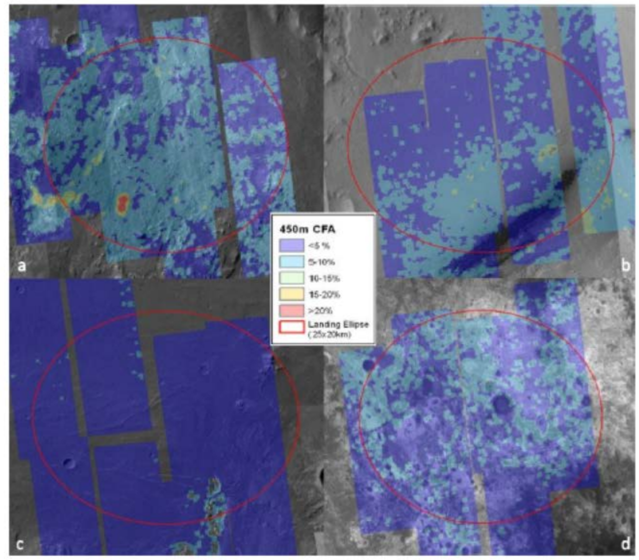

Figure 6 –Rock Abundance Maps Showing Cumulative Fractional Area Covered by Rocks at Eberswalde (a), Gale (b), and Holden (c) Craters, and Mawrth Vallis (d)

Rock Maps

Rock maps developed in support of MSL have leveraged the same image processing software used in support of PHX site selection [2]. The process involves automated identification of shadows in HiRISE images, and then uses sun angle and viewing angle information to determine the size of the object casting each shadow.

Improvements to the image processing algorithm leverage sharpened images to resolve shadows as small as 3 pixels in size. These improvements allow for reliable detections of all rocks larger than 1.5 meters in diameter. Model fits to the Golombek-Rapp model are used locally to extrapolate populations of rocks smaller than this detection limit and then estimate the local cumulative fractional area (CFA) covered by rocks of all sizes (Figure 6). CFA maps can then be used directly for estimating the risks posed by a localized rock population

Over 100 HiRISE images have been processed into rock maps, representing over 7200 square kilometers of area. Rock maps provide full coverage coincident with the HiRISE DEMs and are co-registered to the DEMs with sub-meter accuracy This co-registration allows for simultaneous knowledge of local rocks and slopes at the same precise location on the surface. This rock mapping approach has been validated, in support of both PHX and MSL, but comparison against ground truth data at VL1, VL2, MPF, PHX, and MER surface locations. Automated extrapolation of rock observations and goodness of model fit was verified via extensive manual counting efforts across a variety of terrain.

3. Entry Descent and Landing Overview

The MSL EDL sequence of events is shown in Figure 7. Entry interface (shown as ‘E+0 min’ in the timeline) is defined as occurring when the vehicle reaches a radius of 3522.2 km from the center of Mars. Prior to entry interface the entry vehicle separates from the cruise stage and jettisons two cruise balance masses. These cruise balance masses allow for a centrally balanced spacecraft during spinning cruise and are jettisoned to create on offset center-of-gravity that enables guided entry through the use of bank-angle modulated lift vector control.

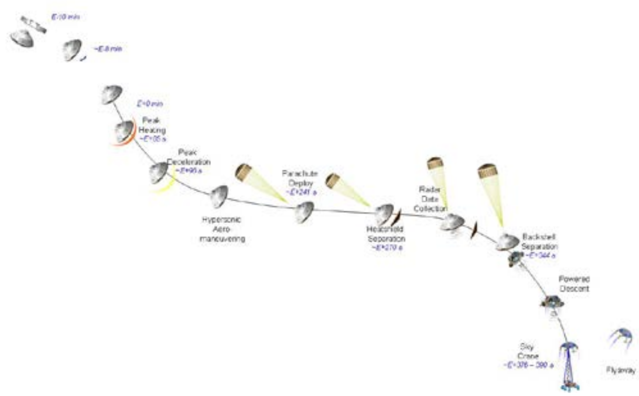

Figure 7 – MSL EDL Sequence of Events

After entry interface the entry vehicle experiences peak heating and peak deceleration while performing hypersonic aero-maneuvering to control the range flown prior to parachute deployment. Parachute deployment is triggered after the vehicle has slowed to approximately Mach 1.7 and heat shield separation is triggered after the vehicle has slowed to approximately Mach 0.8. Following heat shield jettison the Terminal Descent Sensor (TDS) begins acquiring radar measurements of the surface that enable on-board determination of ground-relative altitude and velocity. TDS measurements continue during parachute deployment until the vehicle reaches its backshell separation altitude; just less than two kilometers above ground level. After backshell separation the spacecraft flies a closed-loop powered descent profile which ends at the SkyCrane start conditions. SkyCrane starts approximately 20 meters above the surface with nominally zero horizontal velocity and 0.75 m/s vertical velocity. During skycrane the rover is separated from the descent stage and lowered on three nylon bridles while the rover's mobility system is simultaneously deployed to its ready-for-touchdown configuration. Once the bridles are fully extended the rover is suspended approximately 10 meters below the descent stage; which continues to descend at the rate of 0.75 m/s until the rover is placed gently on the surface. After touchdown is sensed, the bridles are cut via pyrotechnically actuated line cutters and the descent stage flies away to a safe distance before impacting the Martian surface.

Finally, during Skycrane and Flyaway, high velocity exhaust plumes emanating from the descent stage engines are impinging on the Martian surface in close proximity to the rover. Direct and indirect plume risks must be considered as a function of local surface terrain. Additionally, the viability of the post-touchdown state as an initial condition for the surface mission phase must be assessed, along with the suitability of the mobility to traverse local terrain en route to the primary science targets.

4. EDL SITE SAFETY CONSIDERATIONS

Site-specific safety considerations for EDL can be divided into three distinct categories. (1) Vehicle interactions with the local atmosphere during entry and parachute descent, (2) radar-terrain interactions during parachute descent and powered flight, and (3) rover mechanical interactions with the terrain during touchdown. Due to both functional and temporal separation, EDL safety for each of these interactions can be considered in a largely independent fashion. A good discussion of atmospheric sensitivities, including landing site altitude dependencies, can be found in [3].

Radar Terrain Interactions

Successful EDL is dependent on the performance of the on-board radar altimeter/velocimeter over in situ terrain at lateral distances up to several kilometers removed from the ultimate touchdown location. Features with significant vertical relief across this length scale can induce mission failure, even in the case of perfectly functioning radar, due the variation between the measured "truth" altitude and the altitude at the location where the vehicle finally touches down.

The MSL Terminal Descent Sensor (TDS) begins operating shortly after Heat shield Separation and generates measurements of surface relative altitude and velocity for the remainder of EDL. The TDS is comprised of six individual radar transmit/receive modules which are body-fixed at different orientations (aligned 0, 20, and 50 degrees from the vehicle axis of symmetry) in order to acquire distributed measurements across the local terrain. Since the encountered Martian surface will almost certainly be non-planar, each consecutive measurement will yield a slightly different measurement of the local surface altitude and an on-board navigation filter is needed to combine measurements and produce a single estimate of the landing site altitude.

The navigation filter has no information regarding where the vehicle will ultimately land, and is reliant upon a distributed set of terrain measurements taken at locations some distance removed from the touchdown location, so altitude solutions produced at high altitudes will invariably be 'wrong' to some degree. The degree of 'wrongness' is a function of local terrain relief and will decrease gradually as the vehicle approaches the surface. MSL's powered descent profile is designed to accommodate certain altimetry errors through the use of altitude "accordions" which are flown at a constant velocity for variable duration until a target altitude is reached. These accordions are sized appropriately for each landing site, depending on the amount of vertical relief seen in the local terrain and the amount of fuel available on the spacecraft to allocate to each accordion.

The first accordion, designed to "fly-out" altimetry errors from backshell separation (at approximately 2km AGL), can consume anywhere from 0m to 200m of altitude in order to fly out altimetry errors of up to 100m in either direction. If the altitude solution at backshell separation is over 100 m too low – then the vehicle is at risk of impacting the surface before it reaches SkyCrane start conditions due to insufficient control authority. If the altitude solution is over 100m too high –then the vehicle is at risk of running out of fuel due to exceeding the amount of fuel allocated for the first accordion.

Additional safeguards are present in the design to allow re-planning of constant deceleration and skycrane profiles in order to further adjust for altitude updates that come after the first accordion. However, because these safeguards are off-nominal scenarios, they are not part of the terrain safety assessment.

The second accordion, designed to "fly-out" altimetry errors from SkyCrane start, can consume anywhere from 0m to 6m of altitude after the vehicle has achieved a ready-for-touchdown state. If the altitude solution at SkyCrane start is over 3m too low, then the vehicle will encounter the surface before it is mechanically configured for safe touchdown. If the altitude solution at SkyCrane start is over 3m too high – then, as with the first accordion, the vehicle is at risking of running out of fuel. A schematic of these segments of the powered flight profile illustrating the utility of these "accordions" is shown in Figure 8.

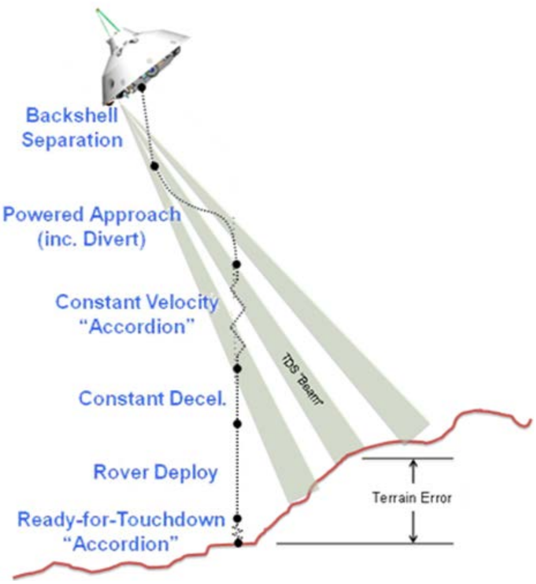

Figure 8 – Segments of the MSL Powered Flight Profile

Terrain relief at the 0 – 1000 m scale was assessed by interrogation of the mosaicked DEM's at each site. A calculation was performed at each DEM posting that considered all other postings within 1km range to determine the maximum altitude difference between the center posting and any other. Sampling the DEM in this way approximates the worst case scenario where only a single radar measurement is taken prior to backshell separation and then EDL proceeds and the rover ultimately touches down at the location where the difference between that single measurement and local ground altitude is greatest. This scenario provides an upper bound on the local terrain relief as seen by the flight system during EDL. This upper bound, however, is inconsistent with the way EDL is flown. In truth, many dozens of TDS measurements are taken and the altitude estimate at backshell separation will likely be closer to the local mean ground altitude within a 1km radius. Assuming perfect knowledge of the local mean ground altitude allows for a more reasonable estimate of the terrain relief as seen by the spacecraft during EDL. Using insight derived from simulation, a probability curve was developed which spans the gap from the idealized estimate to the worst case estimate and determines the local probability of exceeding the terrain relief allocation. This allocation varies by landing site; set at 130m for Eberswalde and 100 m for Holden, Mawrth and Gale.

This analysis yields an initial assessment into whether 0 - 1000 m terrain relief may present hazards to EDL, as well as providing a tool to size the terrain relief allocation. Results are shown in Figure 9 below which includes nominal 20km x 25km landing ellipses for reference. Note that the colorbar saturates at 10% local probability of exceeding the allocation.

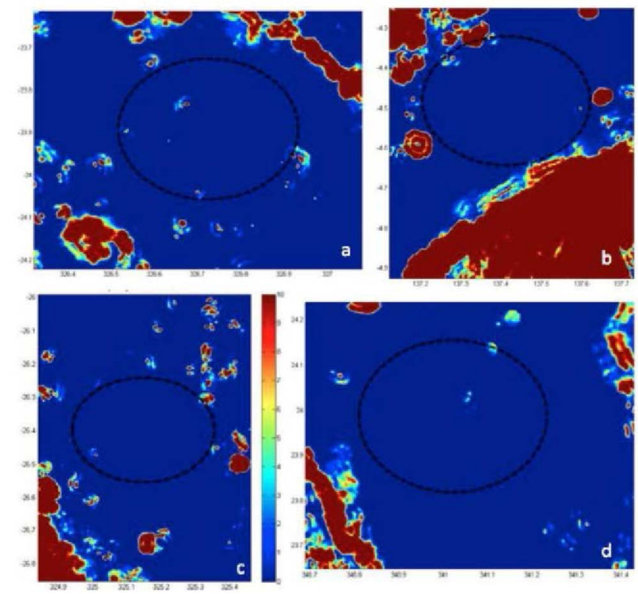

Figure 9 – Estimated Local Probability of Exceeding First Accordion Allocation at Eberswalde (a), Gale (b), and Holden (c) Craters, and Mawrth Vallis (d)

Rover Terrain Interactions

Because EDL is architected to begin SkyCrane at carefully controlled conditions (altitude and velocity), the landing event is effectively decoupled from atmospheric dispersions (winds, temperatures, density, etc.) and the safety of touchdown is driven entirely by the local terrain.

Curiosity, the MSL rover, will be placed on the surface in its ready-for-touchdown configuration. In this configuration the rover's six wheeled surface-mobility system is deployed and will encounter the surface at a gentle 0.75 m/s. Because the mobility system was designed to handle large rocks and slopes during the surface mission – it is an inherently capable landing system and can safely tolerate slopes (up to 30deg) and rocks (up to 55cm) much higher and larger than previous landed missions.

Touchdown failures can occur when the combination of local rocks and slopes exceeds the stability limit of the rover or when a rock is encountered which exceeds Curiosity's ground clearance and impinges on the rover's belly pan. Belly pan strikes can result in a high-centered rover that is unable to traverse, internal damage to the rover, or both.

5. Assessment of EDL Success

Overall EDL success probabilities are determined by a two-step process. The first step is to assess Entry and Descent success via Monte Carlo simulation, and the second is to assess Touchdown success via the use of hazard maps that define the probability of successful touchdown at each location within a landing region.

Entry and Descent Assessment Approach

Entry and descent success is assessed via Monte Carlo simulation of several thousand EDL scenarios, referred to as 'cases', using the primary MSL EDL performance verification simulation, built within the Program to Optimize Simulated Trajectories (POST) [Way et al]. This simulation is the highest fidelity environment used to simulate end-to-end EDL trajectories. The simulation incorporates the MSL EDL flight software and includes detailed, and generously dispersed, models of the vehicle's initial state prior to entry, the vehicle's mass properties, the vehicle's aerodynamic properties, and all of the vehicle's critical sensors and actuators (DIMU, TDS, RCS, MLE, etc.). In addition to these detailed system models, the landing sites environments are modeled in the simulation as well. The simulation incorporates dispersed atmospheric conditions derived from site-specific mesoscale atmosphere modeling and simulates the surface using the highest resolution digital elevation maps available. For each simulated EDL scenario, over 5000 individual variables are stored to represent the state of the vehicle at key times during the EDL sequence of events. These stored variables are post-processed to determine system margins and identify any out-of-spec cases which violate predetermined EDL flight rules. Any EDL scenario which includes even a single out-of-spec parameter is flagged and identified as a potential failed case. Taking the number of flagged cases and dividing by the total number of simulated cases provides the first input for determining an overall EDL success rate at each landing site.

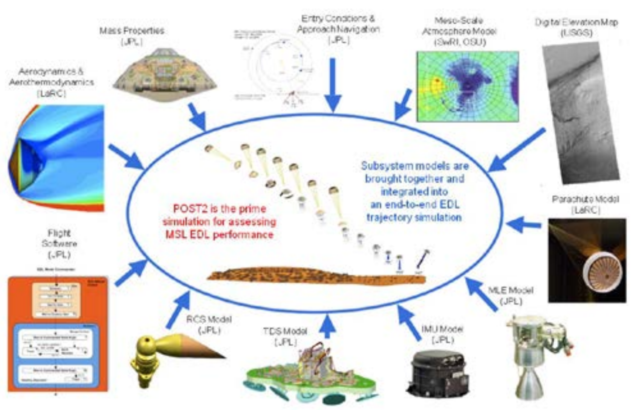

Figure 10 – Summary of Models Included in End-to-End EDL Flight Performance Simulation Environment

Touchdown Success Assessment Approach

Because the end-to-end simulation does not model the touchdown event in high fidelity, a second step is necessary to determine the probability of successful touchdown. Touchdown hazard maps, which define the local probability of successful touchdown at any location on the surface, were generated as the tool by which touchdown success is determined.

Touchdown hazard maps were generated by considering the local terrain and the capability of the rover to handle terrain during touchdown. Touchdown capabilities on rocks and slopes were determined via a series of tests and test validated analyses [4] and are summarized Table 1.

Table 1. Touchdown Capability of the MSL Rover

Touchdown Capability	Failure Rate	
Slope Tolerance	0% 1% 12%	slopes < 24° slopes 24° to 30° slopes 30° to 35°
Rock Tolerance	0.03% 0.31% 0.82% 1.43% 2.09% 2.78% Assume 100%	CFA=5% CFA=10% CFA=15% CFA=20% CFA=25% CFA=30% CFA>30%
Inescapable Hazards	Assume 100%	Areas within identified features

Many potential failure modes were considered in the construction this table including Mars Lander Engine plume interactions with the local terrain, terrain-induced touchdown trigger spoofing, and the potential for bridles to damage hardware on the rover's top deck. Additionally, the post-touchdown state of the rover was considered inasmuch as the rover is to be left in a safe orientation and location for surface operations to commence. After assessing each of these failure modes, it was determined that slope tolerance at capability was primarily limited by stability and structural loading of the rover during touchdown.

During touchdown the vehicle is tolerant of all rocks which safely fit under the rover's belly pan at 60 cm height. The combined effect of encountering slopes with rocks less than 60 cm is considered in the analysis and included in the given slope tolerance numbers. Assuming hemispherical rocks, rocks larger than 1.2 meters in diameter will pose a hazard to the belly-pan at touchdown. Additionally, rocks larger than 2.25 meters in diameter will pose a threat to the mobility system. Failure rates due to local rock abundance, as given in the table, are calculated based on these tolerances.

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Armed with this knowledge of the EDL system's slope and rock tolerance during touchdown, as well as with carefully co-registered DTM's and rock maps, it is straightforward to calculate the local probability of a successful touchdown. For the purposes of MSL, the Martian surface was discretized into a uniform grid with 150 meter x 150 meter cells. Rover-scale slope statistics were derived from DTM's for each cell and local rock abundances (CFA) were also determined for each cell. Each cell is then assigned an overall touchdown failure rate according to the combination of local CFA, local slope statistics, and the capability of the system.

Touchdown hazard maps are shown below for the finalist candidate sites.

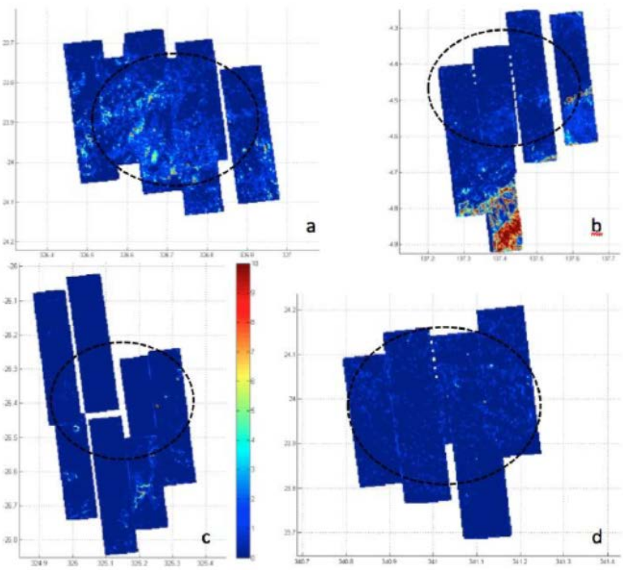

Figure 11 – Touchdown Hazard Maps at Eberswalde (a), Gale (b), and Holden (c) Craters, and Mawrth Vallis (d)

Once armed with these touchdown hazard maps, there is one step remaining to determine the probability of a successful touchdown. This final step incorporates knowledge from the end-to-end EDL simulation regarding the probability of landing at a given location in the hazard map. Thousands of individual simulation cases yield thousands of landing points which are combined to produce a landing probability map which gives the probability of landing at each location within the prescribed landing region. By convolving this landing probability map with the local hazard map, the overall probability of successful touchdown can be determined.

Site-by-Site Assessment Results

The following section outlines EDL safety assessment results generated in May 2011 in support of the final down-selection. An 8001 case Monte Carlo simulation was run at each of the final four candidates to enable a direct comparison of entry and descent performance across sites. These Monte Carlos were run assuming no internal spacecraft faults in order to isolate site-specific risks from those risks that are internal to the system and may be present regardless of the selected site. As such these results are not intended to represent the overall probability of EDL success, but rather to illuminate site-to-site differences in the level of EDL risk.

Because each site presents different challenges for EDL, certain parameters (e.g. parachute deploy trigger) must be tuned differently at each site. Monte Carlo's run in support of site selection were set up to approximate how EDL would be individually tuned for each site with the understanding that a detailed final tuning would only be performed at the selected site. Hence these results represent an upper bound on the number of "out-of-spec", or off-nominal, cases at each site. Each "out-of-spec" case does not necessarily represent a failure scenario, but represents a scenario that may lead to failure. "Out-of-spec" cases during entry and descent were tracked and are summarized in Table 2. Less than 0.3% of cases were flagged as "out-of-spec" at any site. Conversely, over 99.7% of simulated cases performed a successful entry and descent at all sites.

Landing point distributions were also generated from each Monte Carlo and were convolved with terrain hazard maps to determine touchdown failure rates due to terrain. These results are shown in Table 3. As with entry and descent, the percent of cases subject to hazards at touchdown are less than one percent at all sites. As one familiar with these landing sites may expect, touchdown hazards are more prevalent at Eberswalde than at the other three sites. However, the overall entry, descent, and landing success rate is assessed to be greater than 99% at all sites.

Table 2. Summary of "Out-of-Spec" Cases at Each Site

Parameter	In-Spec Limit	EBW (Number of Cases)	GAL (Number of Cases)	HOL (Number of Cases)	MAW (Number of Cases)
Descent stage Flyaway Distance	Range < 150 m	0	0	0	0
Backshell recontact (long term)	Range < 60 m	15	0	7	4
Backshell recontact (short term)	CPA < 40 m	2	0	1	1
Touchdown Before Diff Release (TD too Early)	TD in mode 34	1	0	0	1
Peak heating rate exceeded (aerothermal)	>225.7 W/cm2	0	19	0	2
Touchdown Rover Vertical Velocity exceeded	> 0.85 m/s	0	0	1	1
Parachute inflation loads exceeded	> 65,000 lbf	0	2	1	1
Peak shear exceeded (aerothermal)	> 538 Pa	0	1	0	0
Mortar cover recontact	CPA < 20 m	0	0	2	1
TOTAL		18 / 8001 (0.22%)	22 / 8001 (0.27%)	12 / 8001 (0.15%)	11 / 8001 (0.14%)

Table 3. Overall Touchdown Hazard Rates at Each Site

Parameter	EBW (Percent of Cases)	GAL (Percent of Cases)	HOL (Percent of Cases)	MAW (Percent of Cases)
Touchdown Hazard	0.64%	0.21%	0.21%	0.14%

In addition to looking at "out-of-spec" cases, critical EDL margins were tracked in each Monte Carlo to verify adequate timeline margin, fuel margin, and acceptable time exposure to supersonic parachute descent. These metrics are indicators of EDL robustness and margins were determined to be healthy and acceptable at all of the finalist sites.

The combined entry, descent, and landing success rates across finalist landing sites ranged from 99.14% to 99.72%. The engineering judgment of the EDL systems team ascribed a ±0.5% uncertainty on these results. Thus, the difference in overall assessed success rates is comparable with the level of uncertainty of the result. There is, nonetheless, an unambiguous conclusion that certain sites are safer than others. However, the success rates at all sites are very high compared to historical precedent and the project concluded that the differences in EDL safety did not represent a significant discriminator to be used in selecting the final site.

6. CONCLUSIONS

The process to select the MSL landing site took over five years and narrowed over 50 initial candidate sites to four finalist sites. The four finalist sites were examined in detail to assess overall science merit, EDL safety, and rover traversability. Differences in EDL safety and rover traversability were determined to be negligible for the purposes of selecting a landing site from among the four finalists and, ultimately, Gale crater was selected as the MSL landing site primarily on the basis of science considerations. This result is a testament to the robustness of the EDL system developed for MSL and to the contributions of MRO to provide the extensive terrain data needed in order to undertake such a detailed assessment.

However, in focusing this paper on the four finalist sites, it is also important not to lose sight of the limitations of the MSL EDL system. Several initial candidate sites had to be removed from consideration explicitly for risks associated with EDL safety. There is a fundamental limitation of the MSL EDL architecture when it comes to higher elevation landing sites (above -1.0 km MOLA) in that the vehicle is unable to reach safe parachute deployment conditions in time to enable safe altitude and timeline margins for parachute descent and powered flight. Additionally, certain regions of Mars exhibit surface topography too extreme to be safely accessed by the MSL architecture regardless of site elevation. Continued technology developments are necessary to further expand Martian surface accessibility for continued scientific exploration.

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BIOGRAPHIES

Devin Kipp *received his B.S. in Engineering from the University of Washington in 2003 and his M.S. in Space Systems Engineering from the Georgia Institute of Technology in 2005. Devin has been employed by the California Institute of Technology working at the Jet Propulsion Laboratory since 2005 working almost exclusively as a member of the MSL EDL Team for the entirety. From 2007 to 2011 Devin served as the MSL EDL Terrain Interaction lead.*

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