MSL Landing Site Selection
User's Guide to Engineering Constraints

The Mars Science Laboratory Project

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Change Log	
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1 Engineering Constraints for MSL Landing Sites

1.1 EDL Engineering Constraints: Introduction

The Mars Science Laboratory mission will land a long-range rover equipped with a sophisticated suite of scientific instruments on Mars. The entry, descent, and landing (EDL) system is designed to land the rover within a 10-km radius circle at elevations as high as +1 km with respect to the Mars Orbiter Laser Altimeter (MOLA) defined geoid.

The current design calls for the entry vehicle to separate from the cruise stage, de-spin, turn to the proper attitude, and encounter the Martian atmosphere at a hypersonic velocity of approximately 6 km/s (Figure 1). The entry vehicle's heat shield slows the spacecraft. Peak heating occurs after atmospheric entry, and within about four minutes the vehicle decelerates to a supersonic velocity of approximately Mach 2. The vehicle then deploys a parachute at an altitude of ~10 km (MOLA) for further deceleration. The heatshield is then released, the radar activated, and separation from the parachute and backshell occurs, allowing the start of the powered descent phase. During powered descent, the vehicle uses radar and its propulsion system to control position and velocity. At approximately 20 m above the surface (as measured by the radar), the rover is lowered on a tether from the propulsion system (known as the descent stage) in a "sky crane" configuration and placed directly on the martian surface with its mobility system (i.e., wheels and suspension) fully deployed. The descent stage then flies away from the rover. It should be noted that the design and specifications of the landing system are still being worked, so all performance characteristics identified below should be considered working assumptions subject to future review and revision.

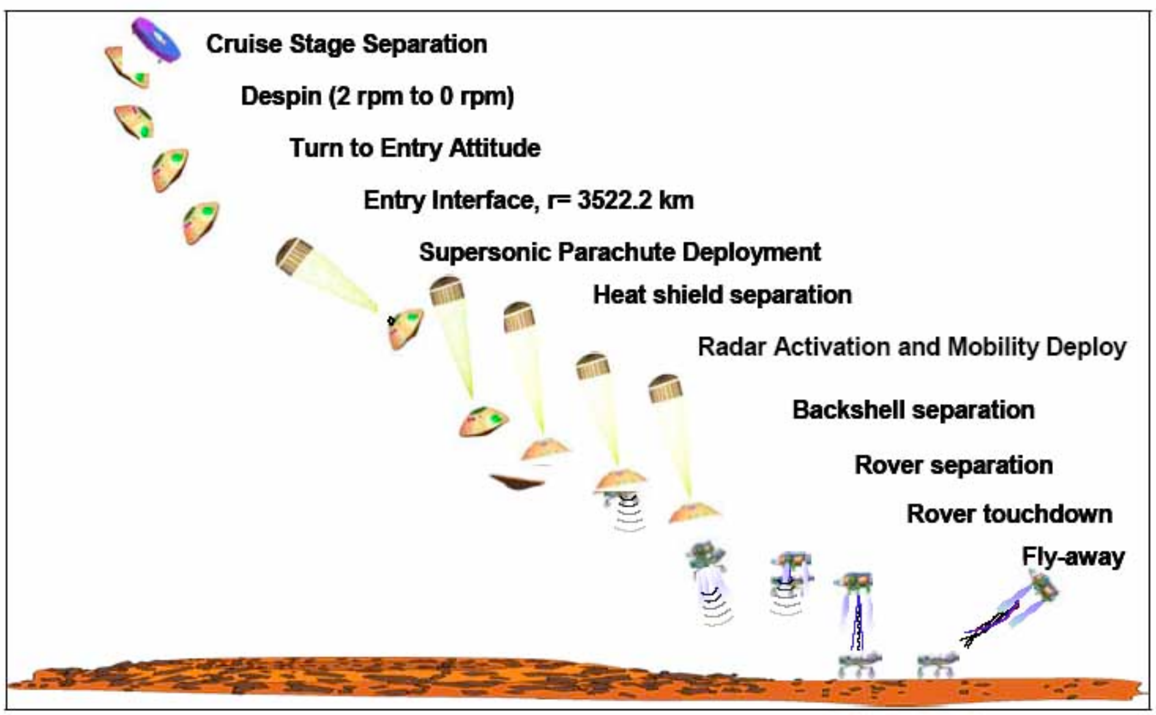

Figure 1.1 Illustration of EDL events.

1.2 Latitude and Elevation

MSL EDL is designed to land at any latitude between 45°N and 45°S.

Previous landing sites have generally been at low elevation for an adequate atmospheric density column to provide enough drag and consequently enough time to allow completion of all the events needed for a safe landing. For MSL, the EDL system is designed to provide lift and guidance during descent, thereby allowing the landing site elevation to be as high as +1 km with respect to the MOLA-defined geoid.

1.3 Local Time and Season

For the nominal mission, the local time of landing ranges from approximately 14:00 to 17:30 Local True Solar Time, depending somewhat on site latitude. However, all latitudes have a multi-hour landing window within that range. The landing L_s would be between 116º and 128º (July and August, 2010), depending on site latitude.

In the unlikely event that orbital assets are not available and EDL must be monitored directly from Earth, landing would occur between 12:00 and 14:30 LTST, and at L_s = 148º (mid-September, 2010).

1.4 Landing Ellipse

MSL EDL is designed to allow precision landing with errors no greater than 10 km radially. It is likely that additional analysis will slightly change the size and shape of the landing ellipse (more ellipsoidal, slightly shorter in the cross-track direction).

1.5 Slopes

As designed, a Doppler velocimeter/altimeter, known as the terminal descent sensor, on the descent stage uses multiple radar antennas to measure the distance to the surface and the descent velocity (both vertical and horizontal components). The first measurement is taken while still on the parachute before backshell separation, with continuous measurements up to rover release. Over the range of the vehicle's trajectory during this time, slopes at various length scales may alter the measured altitude of the spacecraft above ground level, with potential adverse effects on fuel consumption, control authority, and vehicle safety. These considerations result in the following slope constraints within the landing ellipse: three degrees or less over a 2 to 5 km length scale to avoid altimetry errors in preparation for powered descent; five degrees or less over a 200 to 500 m length scale to ensure proper control authority and fuel consumption during powered descent; fifteen degrees or less over a 20 to 40 m length scale to ensure proper control authority and fuel consumption during the sky crane maneuver; and fifteen degrees or less over a 2 to 5 m length scale to ensure landing stability and trafficability of the rover. Slopes at the kilometer length scale can be addressed with MOLA point-to-point elevation data. Slopes at the 200-500 m length scale can be addressed by extrapolation from MOLA point-to-point elevation and pulse-spread data as well as via stereo image data and photoclinometry. Slopes at the 20 to 40 m and 2 to 5 m length scale will require high-resolution stereo images or photoclinometry. Intermediate and small length scale slopes are expected to be determined for only the highest priority sites.

Although not all of the landing ellipse must meet all of these slope requirements, the more area that exceeds them, the less likely the site would meet all the safety criteria thereby increasing the chances for failure and selection of a different landing site.

1.6 Rocks

The area below the rover must be free of rocks capable of damaging the rover's lower structure, or "belly pan," which, as designed, is 0.6 m above the ground. The rover mobility system (section 2.1.4) would accommodate rocks that are 0.55 m high. The probability of damaging the rover via landing on high rocks must be a small fraction of the allowable failure probability being book-kept for EDL. This allocation implies the probability that a rock taller than 0.55 m occurs in a random sampled area of 4 m^2 (the area of the belly pan) should be less than 0.25%. If the rock size-frequency distribution is assumed similar to models based on measured distributions at the existing landing sites, this translates to a rock abundance (cumulative area covered by rocks) of around 10%. However, given the expected acquisition of very high-resolution images of high-priority landing sites during the selection process, potentially damaging rocks may be characterized more directly to estimate this hazard more accurately.

1.7 Atmospheric Parameters

The MSL EDL system is designed to maintain control, landing accuracy, and timing of critical events over a range of potential profiles of atmospheric density, horizontal and vertical wind, and speed of sound. However, there are thresholds in the absolute value or uncertainty envelope of these parameters that must not be exceeded over candidate landing sites in order to maintain expected landing performance. These thresholds are functions of height, since they correspond to specific, sensitive events in the EDL timeline (e.g., deceleration, parachute deployment, initiation of powered descent). A table of these thresholds is given in Section 3.3.

A minimum atmospheric temperature of 160K from the surface to 10 km altitude (MOLA) is being used in the design of the MSL EDL system. It is not expected that any potential landing sites would violate this minimum threshold. However it is listed here for completeness.

1.8 Radar Reflectivity and Thermophysical Properties

The surface material at the landing site must: i) be radar reflective (sufficient radar backscatter cross-section) to enable measurement of altitude and velocity during descent, ii) bear the load of the rover at landing, iii) be trafficable by the rover (next section), and iv) experience a range of temperatures within the limits of the rover design. These requirements constrain the radar and thermophysical properties of the surface materials, including albedo, thermal inertia (and bulk density, through the latter), radar backscatter cross-section and reflectivity (and inferred bulk density).

The Doppler velocimeter/altimeter requires Ka band radar echoes from the martian surface to properly measure altitude and velocity of the descent vehicle. This requires that the landing site have an appropriate radar backscatter cross-section (> -20 dB and < 10 dB at Ka band) and a radar reflective surface. The requirement will be addressed via Xband, S-band, and UHF radar returns and models that relate their backscatter and reflectivity to Ka band.

Broad tracts of Mars have very low thermal inertia and high albedo and have been interpreted to be surfaces dominated by loose dust that could be meters thick. Experience and extrapolation from the existing landing sites argues that loose dusty material is not load bearing. In addition, at least one such dusty surface is not radar reflective. Global thermal inertia and albedo data show a mode with thermal inertias less than 100 J m^{-2} $s^{-0.5}$ K^{-1} and albedo higher than 0.25 that corresponds with very dusty surfaces. Further, the rover is designed for temperatures between approximately 145-310K, with a maximum diurnal range of 145K. Although thick, dusty surfaces are unlikely to violate these temperature constraints, they will fail to meet the other requirements listed above.

Surfaces with these characteristics (thermal inertias less than 100 J m^{-2} $s^{-0.5}$ K^{-1} and albedo higher than 0.25) are not suitable for landing spacecraft or driving rovers (next section) and the dust would curtail science operations. Large temperature extremes at low thermal inertia, high albedo sites would also reduce surface operations through the diversion of available energy to rover thermal maintenance and reduced hazard avoidance (from CO_2 frost coverage).

2 MSL Trafficability Considerations

2.1 Vehicle Performance Characteristics

The following sections outline the intended mobile capabilities of the MSL surface system. Constraints derived from the mobility system are separate from those derived from EDL, but are levied on the entire landing ellipse and any traverse planned outside the ellipse as might occur for a “go to” site. It should be noted that the design of this vehicle is still in its preliminary stages, so all performance characteristics identified below should be considered working assumptions subject to future review and revision.

2.1.1 Traverse Rate and Distance

Rover traverse speed is affected by several variables, both operational and environmental. The vehicle’s mechanical speed is determined by the rotational rate of its drive and steering actuators, while the system speed is a combination of mechanical speed and required computational time for navigation and hazard avoidance. Finally, vehicle speed is greatly affected by the terrain in which it traverses, both in slope incline and slip rate.

Currently, the rover is being designed for a mechanical ground speed of 4.2 cm/s (approximately 2.5 m/min) on hard, flat terrain. When the vehicle is using hazard avoidance and onboard path planning, the effective traverse rate would be 50% of the mechanical speed, or 2.1 cm/s (approximately 1.25 m/min). When visual odometry, a technique using engineering cameras to determine actual vehicle traverse progress, is utilized, the resultant traverse rate would be 25% of the mechanical speed, or around 1 cm/s (approximately 0.6 m/min).

As part of its primary mission, the MSL rover would include the capability for traversing long distances. Currently, the system is being designed for a total actual traverse distance capability of no less than 20 km. For purposes of hardware life and cycle evaluation, it is assumed that this traverse occurs over a terrain with an average rock abundance of 15%, an average slope of 5 degrees, and an average slip rate of 10%. Under these conditions the rover would travel on average about 100-150 m/sol.

2.1.2 Vehicle Maneuverability

As conceived, the vehicle's mobility system is a 6 wheel drive, 4 wheel steer rocker-bogie configuration, similar in architecture to MER. Given this configuration, the vehicle has the capability to perform three types of traverses: 1) straight line motion, forward or reverse; 2) turn-in-place motion, pivoting the vehicle about a position in the center of the vehicle at the midpoint between the two center wheels; and 3) arc turn motion, with a minimum arc turn radius capability of 1.5 m.

2.1.3 Static Stability / Slope Access

Vehicle stability is a key characteristic of both a successful sky crane touchdown and surface accessibility. The MSL rover is being designed to a static stability of no less than 45 degrees tilt in any direction. Of course, vehicle slope access would also likely be affected by the composition of the local terrain itself, so the static stability limit should only be seen as an upper bound for vehicle safety. Nominal vehicle operations would usually be kept at vehicle tilt angles below 30 degrees. For testing the slope of the surface is grouped into three types: Low slope ($\leq$5 degrees); Moderate slope (5 < slope $\leq$ 15 degrees); and High slope ($\geq$15 degrees).

2.1.4 Hazards and Rock Field Trafficability

One key feature of the rocker-bogie suspension system is its ability to traverse obstacles larger than the vehicle's wheel diameter. Coupled with a high ground clearance, this would give the rover a significant capability to traffic areas of the surface populated by dense rock fields. Currently, the MSL rover is being designed to successfully traverse a protrusion or hole obstacle of less than 0.5 m in height / depth. This compares to a 0.2-m allowable obstacle height / depth on MER.

One measure of the effect of increased obstacle-climbing capability is in a parameter called vehicle mean free path. Specifically, mean free path is a measure of the total straight line distance the rover could traverse without encountering a hazard that would have to be avoided. As designed, the MSL vehicle's mean free paths in a terrain covered by a 20% rock distribution is 48 m.

While the above information highlights the MSL rover's increased trafficability in rocky terrain, it should also be noted that other types of protrusion / hole hazards, particularly sand ripples, may affect the overall climbing capability. This, of course, can and will vary as a function of the size and shape of the feature. Ripples of a size similar to the vehicle's own wheelbase or track width may more be appropriately be categorized as sandy slopes, and therefore performance would be dictated by the limitations outlined in the next section. Surface roughness that could limit trafficability can be assessed from radar backscatter data and derived root-mean-squared slope.

2.1.5 Slope Traversability – Granular Material

The vehicle's planned capability to access science targets at high terrain angles will be driven by the soil's own material properties as much as the vehicle's own performance criteria. One important characteristic of vehicle design that affects traversability in granular media is ground pressure, which is a function of vehicle weight and wheel size. MSL is currently designing to an average ground pressure that is less than or equal to that of MER. Given this design requirement, it is a reasonable assumption that MSL would have similar traversability in granular material to the twin MER rovers.

The ground pressure of the rover requires the surface to be load bearing. Very low density, very fined grained materials may not be load bearing. Dusty material did not support a footpad of Viking Lander 1 and experience with Mars Pathfinder and the Mars Exploration Rovers indicates that deposits of dust are not load bearing. As a result as for landing, surfaces dominated by fine-grained dust are not suitable for rover traversing. Thermal inertia, albedo and radar reflectivity will be used to assess dusty and non-load-bearing surfaces.

Increased terrain angle in granular or aggregate materials would predominately affect the rover's slip rate performance. In general, slow speed vehicle traverse in sandy / granular terrain can be separated in three distinct categories:

- Low / Moderate slope angle (< 10 degrees tilt) = 0 – 25% upslope slip
- Transitionary slope angle (10 – 17 degrees tilt) = 25 – 80% upslope slip
- High slope angle (> 17 degrees tilt) = > 80% upslope slip

In granular terrains of low to moderate slope, wheel traction and local tread / terrain interaction determines the degree of vehicle slip. As slope angle increases through the transitionary regime, slip rate will increase dramatically as the slope material begins to fail out from under the rover wheels, limited by the material's own bearing and shear strength. This transition can be quite abrupt, occurring over as little as 2-3 degrees tilt, and is obviously a function of the slope material's own mechanical properties. In high slope angles, granular material failure dominates the slip regime, and vehicle forward motion is as much an exercise in material transport as it is in rolling motion. In terrain with slope angles over 20 degrees, vehicle upslope motion can effectively be arrested, with slip rates well over 90% quite common.

2.1.6 Slope Traversability – Solid Surface

While access to high terrain angles in granular material can be quite limited, this is not necessarily the case when faced with planning a route through sloped terrain consisting of predominately solid surfaces. The most relevant example of this type of terrain is the wall material of Endurance crater, where favorable surface interaction allowed vehicle access up to and exceeding the system's own operational limit of 30 degrees. In this type of surface interaction, access to high angles is limited by the frictional holding limit between the surface material and the wheel and the rover's own static stability limit. It is expected that the MSL rover would meet or exceed the capabilities of MER in terrain of this type. However, while this capability may exist, it is very likely that a traverse including terrain in this category would be approached with caution, requiring special operational restrictions and / or testbed evaluation.

2.2 Nominal Terrain "Design-To" Cases

This section provides the nominal "design-to" terrain cases. The following small set of terrain examples represent the type of surface compositions the MSL vehicle is being designed to successfully traverse (Table 1).

Rather than specify terrains based solely on assignment of characteristics defined in the above subsections, selected terrains from the MER missions are utilized. This not only provides reference imagery to better understand terrain, but also actual in-flight experience/performance with the MER rovers.

Table 2.2: "Design-To" Mobility Terrain Cases

Case	Material Analog	Slope	Structure	Rock Abundance
Rim of Bonneville crater	Beach Sand	5-10 degrees	N/A	20%
Columbia hills	Beach sand with embedded rocks	10-15 degrees	N/A	10%
Meridiani Ripples	Beach sand	N/A	z = 0.3sin(4x/pi) in meters	N/A

2.2.1 Vehicle Capabilities in Extreme Conditions

The above sections outline vehicle performance under nominal and, sometimes, fringe environmental conditions. It is expected that the rover would have reduced capabilities in other, more extreme environments. In these cases, nominal vehicle operations may be hindered or restricted, but overall vehicle safety is still maintained. These terrains should be avoided within landing ellipses and reduced operations expected in traverses with these terrains. The best example of this type of vehicle condition is MER Opportunity's experience at Purgatory drift. In this case, vehicle operations were hampered for several weeks, but overall vehicle safety and eventual functionality were not compromised. Examples of such conditions include, but are not limited to, the following:

- Partial or complete burial of one or more wheels
- Access to terrain in excess of 30 degrees
- Obstacle climbing in excess of 0.5 meters height / depth
- Belly pan contact with terrain

2.2.2 Trafficability "Go To" Requirements

The small landing ellipse and long traverse capability of the rover allow the possibility of considering "go to" sites. The MSL rover is being designed to traverse at least 20 km over a terrain with an average rock distribution of 15%, an average slope of 5 degrees, and an average slip rate of 10%, and so would be capable of driving out of the landing ellipse in any direction. "Go to" sites have a safe landing site adjacent to the target of science interest and require traversing outside of the landing ellipse to sample the materials of highest interest. In this case, the area that must be traversed to get into the region of highest science interest (required to accomplish the science objectives of the mission) must be trafficable from anywhere within the ellipse. This requires that the trafficability requirements be satisfied in the area being roved through that is outside the landing ellipse.

Traversing out of the ellipse would take time out of the beginning of the nominal mission. For terrain with the characteristics described above, the rover could travel on average about 100-150 m/sol. At these rates, traversing 10 km would take 65-100 sols, which is roughly 10-15% of the nominal mission. This suggests that "go to" sites should be especially compelling scientifically.

3 MSL Operational Considerations

3.1 Vehicle Performance Characteristics – Higher Latitudes

MSL is being designed to operate over a broad range of latitudes. However, the design is optimized for "average surface conditions" over the accessible latitude range, as opposed to optimized for higher-latitude performance. As the latitude increases (north or south), several conditions begin to develop that will naturally reduce rover operational efficiency. When the latitude approaches 45°N or S, these can in some cases be significant. For example, reduced illumination and the presence of CO_2 frost may degrade the quality and interpretability of images used for science or rover operations, such as arm motions or driving. Persistent cold temperatures may reduce the energy available to operate the science instruments.

For these reasons, the science value of a high latitude site must therefore be great enough to outweigh possible operational efficiency reduction. For higher northern latitude cases, this case is even stronger, since MSL is arriving as northern Fall heads into northern Winter. Thus, far northerly landing sites would be heading into a reduced capability phase shortly after landing, which is less favorable from an engineering and operations viewpoint.

3.2 Vehicle Performance – Surface Winds

The rover system, including payload elements, is being designed to maintain operational capability over a wide range of temperatures. Strong, steady surface winds may impede the ability of the system to maintain operational temperatures. The system is currently designed to operate with steady winds of 0-15 m/s, with gusts up to 30 m/s at 1 m above the surface. In addition, steady winds must never exceed 40 m/s, even when the rover and payload are in non-operating modes. Note that the surface wind constraint presently is tighter than the constraint from EDL. However, we consider each separately since they may change as our design matures.

3.3 Tables of Engineering Requirements

Engineering Parameter		Requirement	Notes
Latitude		45°N to 45°S	
Elevation		≤ +1 km	MOLA-derived elevation
Landing ellipse radius		≤ 10 km	Excluding uncontrolled wind effects during parachute descent
Slopes	2 to 5 km length scale	≤ 3 degrees	Radar altimetry errors to start powered descent
	200 to 500 m length scale	≤ 5 degrees	Control authority and fuel consumption during powered descent
	20 to 40 m length scale	≤ 15 degrees	Control authority and fuel consumption during sky crane
	2 to 5 m length scale	≤ 15 degrees	Rover landing stability and trafficability in loose granular material
Rock height		≤ 0.55 m	Probability that a rock higher than 0.55 m occurs in a random sampled area of 4 m^2 should be less than 0.25%. Suggests low to moderate rock abundance
Radar reflectivity		Ka band reflective	Adequate Ka band radar backscatter cross-section (> -20 dB and < 10 dB)
Load bearing surface		Not dominated by dust	Thermal inertia >100 J m^{-2} $s^{-0.5}$ K^{-1} and albedo <0.25; radar reflectivity >0.01 for load bearing bulk density
Surface winds		< 15 m/s (steady) < 30 m/s (gusts)	Constraints apply over all seasons and times of day, at 1 m above the surface. Steady winds never exceed 40 m/s.

Table 3.3-1: Summary of surface engineering requirements.

Altitude	Density	Horizontal Wind	Vertical Wind	Speed of Sound
20 to 30 km above MOLA geoid	≤ 15% uncertainty			
8 to 20 km above MOLA geoid	≤ 10% uncertainty	≤ 25 m/s uncertainty		≤ 7% uncertainty (8 to 15 km)
4 to 8 km above MOLA geoid		≤ 20 m/s uncertainty	≤ 20 m/s uncertainty	≤ 7 % uncertainty (3 to 8 km)
1 to 5 km above ground level			maximum ≤ 20 m/s	

Table 3.3-2: Summary of atmospheric engineering thresholds. The thresholds for altitudes above 8 km must not be exceeded within at least 100 km of the candidate landing site (to account for the horizontal component of the trajectory). The thresholds for uncertainty are 3-sigma (99.87%) values. These uncertainties are especially critical for landing sites with elevations above -1 km with respect to the MOLA-defined geoid. The threshold for maximum vertical wind speed near the surface (bottom row) applies to all landing site elevations. Also see a constraint on atmospheric temperature in Section 1.7.