

# **MSL Landing Site Selection User's Guide to Engineering Constraints**

## **The Mars Science Laboratory Project**

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<b>Change Log</b>	
April 2006	Modified EDL slope constraint (1.5) Modified EDL wind constraint (1.7) Added surface wind constraint (3.2)
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# 1 Engineering Constraints for MSL Landing Sites

## 1.1 EDL Engineering Constraints: Introduction

The Mars Science Laboratory Mission would 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 2 km with respect to the Mars Orbiter Laser Altimeter (MOLA) defined areoid. Landing would occur in the afternoon, and between  $L_s$  120 and 150.

The current design calls for the rover, inside the entry vehicle, to separate from the de-spun cruise stage and within approximately 10 minutes, after turning to a proper attitude, encounter the martian atmosphere at 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 a few (3-4) minutes the vehicle decelerates to a supersonic velocity of approximately Mach 2. The vehicle then deploys the parachute for further deceleration at an altitude of  $\sim 10$  km. The heatshield is then released, the radar activated and separation from the parachute occurs allowing the start of the powered descent phase. During powered descent, the vehicle uses the radar and its propulsion system to control position and velocity. At approximately 35 m above the surface (as measured by the radar), the rover is lowered on a tether from the propulsion system in a "sky crane" configuration and placed directly on the martian surface with its mobility system (i.e., wheels) fully deployed. The propulsion system (known as 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.

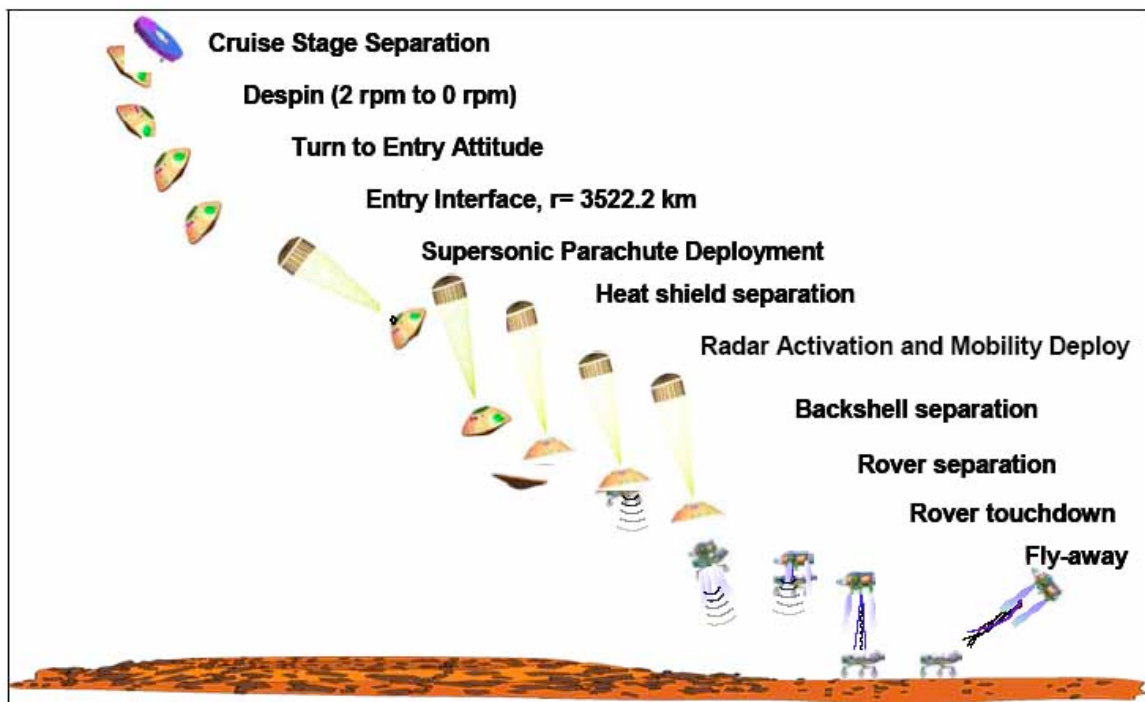


Figure 1. Illustration of EDL events.

## **1.2 Latitude**

MSL EDL is designed to land at any latitude between 60°N and 60°S.

## **1.3 Altitude**

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 guidance during descent, thereby allowing the landing site altitude to be as high as +2 km with respect to the MOLA-defined areoid.

In order to achieve this performance, the design calls for MSL to deploy a large 19.7-m diameter supersonic parachute at approximately Mach 2. Since there are some potential risk issues with this deployment that are currently being evaluated, a possible contingency plan (which is not currently baselined) of deployment at lower Mach number could reduce the landing site altitude from +2.0 km to -2.0 km. The Mars Exploration Program is therefore also interested in identifying potential landing sites that meet this "contingency" requirement and specifically request additional submissions of candidate sites for this -2.0 km landing site altitude scenario.

## **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 with a slightly shorter 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 in the landing site are important for accurate altitude estimation, fuel consumption, 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 the start of powered descent; five degrees or less over a 200 to 500 m length scale to avoid altimetry errors in preparation for the sky-crane landing maneuver; fifteen degrees or less over a 20 to 40 m length scale to avoid altimetry errors in preparation for rover release; and fifteen degrees or less over a 5 m length scale to ensure landing stability and trafficability of the rover. Slopes at the 100s of m to kilometer length scale can be addressed with MOLA point-to-point elevation data. Slopes at the 20-40 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 photogrammetry. Slopes at the 5 m length scale require high-resolution stereo images or photogrammetry. 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 0.5 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 0.6 m occurs in a random sampled area of 4 m<sup>2</sup> (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 directly to estimate this hazard more accurately.

## **1.7 Winds**

Steady horizontal and vertical winds over the last few kilometers of the descent result in the landing system's velocity potentially matching the wind speed and can increase the total velocity of the landing system, limiting control over the landing error ellipse and rover velocity at touchdown. The entry system presently constrains steady horizontal and vertical wind speed to be less than 30 m/s and 10 m/s, respectively, at altitudes between 0 and 5 km above ground level. At altitudes between 5 and 10 km above ground level the system is less sensitive, but winds that differ significantly from the above values may present a problem, as may wind fields that contain large spatial (vertical or horizontal) or temporal variations. No particular constraints on wind gusts are presently known or anticipated, although testing and models during development may yield future constraints. Models of the atmosphere at the highest priority sites will be used to compare with tested configurations.

## **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 sufficient radar backscatter cross-section (>-20 db at Ka band) and a radar reflective surface. The requirement will be addressed via X-band, 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  $100 \text{ J m}^{-2} \text{ s}^{-0.5} \text{ K}^{-1}$  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  $100 \text{ J m}^{-2} \text{ s}^{-0.5} \text{ K}^{-1}$  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  $\text{CO}_2$  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 ( $5 < \text{slope} \leq 15$  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 fine 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
- Transitional 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 transitional 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 1: “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	$z = 0.3\sin(4x/\pi)$ 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 – High 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 high 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 50-60°N or S, these can in some cases be significant. For example, reduced illumination and the presence of CO<sub>2</sub> 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. Finally, the short duration or absence of Earth view will impede direct to/from Earth communications.

For these reasons, the science value of a high latitude site must therefore be great enough to outweigh possible operational efficiency reduction. For high northern latitude cases, this case is even stronger, since MSL is arriving at an L<sub>s</sub> between 120 and 150, meaning austral spring heading into austral summer. Thus, far northerly landing sites will

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 Table of Engineering Requirements

<i>Engineering Parameter</i>		<i>Requirement</i>	<i>Notes</i>
Latitude		60°N to 60°S	
Altitude		≤ 2 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	Radar altimetry errors in preparation for sky crane maneuver
	20 to 40 m length scale	≤ 15 degrees	Radar altimetry errors in preparation for rover release
	5 m length scale	≤ 15 degrees	Rover landing stability and trafficability in loose granular material
Rock height		≤ 0.6 m	Probability that a rock higher than 0.6 m occurs in a random sampled area of 4 m <sup>2</sup> should be less than 0.25%. Suggests low to moderate rock abundance
EDL winds	Steady state horizontal	≤ 30 m/s	At altitudes of 0 to 5 km above ground level; not significantly stronger between 5-10 km
	Steady state vertical	≤ 10 m/s	At altitudes of 0 to 5 km above ground level; not significantly stronger between 5-10 km
EDL wind gusts / variability		Evaluate case by case	At altitudes of 0 to 10 km above the surface
Radar reflectivity		Ka band reflective	Adequate Ka band radar backscatter cross-section (>-20 db)
Load bearing surface		Not dominated by dust	Thermal inertia >100 J m <sup>-2</sup> s <sup>-0.5</sup> K <sup>-1</sup> 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 2: Summary of engineering requirements.