7 MPL DISCIPLINE AREA ASSESSMENTS

The major thrust of this investigation was centered on Review Teams of the Board conducting detailed reviews and interviews in specific technical discipline areas. Each Review Team focused on a list of postulated failure modes and attempted to ascertain whether or not the failure was plausible, based on precautions taken during the design phase, tests, or verifications conducted during system validation, and/or in-flight performance that validated that the functionality in question was available at the last time telemetry was available from the lander.

7.1 MPL Environment and Landing Site

INTRODUCTION

As part of the JPL Special Review Board MPL/DS2 failure investigation, a multidisciplinary Review Team was formed to examine environmental effects that might have led to the loss of MPL or DS2. Two groups were formed: one focused on the surface properties and interactions with any of the three spacecraft; the second addressed issues relating to aerodynamic entry and descent.

The first group reviewed the information that had been obtained prior to landing regarding the nature of the terrain in the targeted landing site. In addition, the MGS science teams provided new observations of the landing area and analyses in the following areas:

1. *Large-scale slopes (scale of hundreds of meters)*. The presence of large-scale slopes greater than 10 degrees would introduce Radar–terrain interactions that affect the horizontal–velocity control during terminal descent. The laser altimeter (MOLA) on MGS provided maps of topography and point-to-point slopes. Most of the area is smooth; however, the area does include a large depression marked by slopes, the majority of which are less than 5 degrees. Approximately 1 percent of the area has large-scale slopes greater than 10 degrees.
2. *Medium-scale slopes (scale of tens of meters).* The spread of the returned optical pulse was used to map the roughness of the surface at the scale of the laser footprint. Over the majority of the landing zone, the pulse spread correlates well with the larger scale slopes, which is contrary to the norm for most of Mars. This indicates that the pulse spread is most likely due to the regional slope and that the surface at this scale is smoother than the norm for most of Mars.
3. *Small-scale slopes (scale of meters).* The camera (MOC) on MGS obtained high-resolution images of the landing zone. MOC provided stereophotogrammetric and photoclinometric (shape from shading) analysis for both medium- and small-scale slopes, calibrated by reference to a MOLA profile across the edge of the depression. Most of the landing zone appears to be quite smooth. In the most rugged region (a small portion of the landing zone) along the profile crossing the edge of the depressions, no more than 12 percent of the surface has slopes of more than 10 degrees at scales of 10 to 40 meters per pixel. In addition, approximately 4 percent of the surface has slopes of more than 15 degrees. The percentage of the landing ellipse that could present small-scale hazards is small — only a few percent.
4. *Surface properties.* Thermal emission data from TES and from previous missions indicate that most of the landing zone has a layer of a low thermal inertia/low-density material that is at least a few centimeters thick. Both these data and the accepted geologic model for this terrain indicate that rocks greater than 30 centimeters should not be a problem (that is, within the available lander clearance height).
5. *Subsurface conditions/models.* The presence of a hard subsurface of frozen permafrost is predicted by typical models of this terrain. The depth of this material could be anywhere below a few

centimeters. The presence of low-density, loosely packed material on top of a hard surface might lead to a "lubricating" situation that results in the inability of MPL to come to rest in the required azimuthal orientation or the inability of the DS2 probes to penetrate the surface and remain upright.

The topics that follow were considered by the second group, which focused on aerodynamics and the atmospheric entry conditions:

1. *Heatshield design heritage.* Mars Pathfinder design, manufacturing and test heritage and deviations therefrom (size, ballistic coefficient, thickness, lack of spin). Discussion of worst-case effects of each deviation on landing-site accuracy, integrated heating load, structural g-loads.
2. *Heatshield physical integrity/workmanship.* Deviations from the Mars Pathfinder manufacturing/inspection process (limited). Rework/handling incidents prior to launch (one to the heatshield substructure, none to the TPS). Tooling pinhole issue discussion.
3. *Entry body mass properties*. Center of mass/center of pressure mismatch, mass properties, and effect on landing site or hypersonic entry survivability. Hypersonic entry orientation: specification of propulsion tank axis (30 degrees from vertical; relationship to downtrack and cross-track errors). Natural frequencies of heatshield aerodynamics and propellant tanks fuel slosh/transfer during variable dynamic pressure/deceleration field and potential for coupling.
4. *Small-forces discrepancies between telemetry and radio metric reconstructions.* Magnitude, possible causes (thrusters, mass properties, etc.); implications for entry state and/or hypersonic entry.
5. *Delivery to the entry state*. Cross-track drift from TCM-4 to entry. Discussion of possible causes. TCM-4 execution errors (subsequently shown to be statistically consistent with expected errors for a maneuver of the size encountered), small forces, etc. Rationale for lack of cross-range adjustment capability at TCM-5.
6. *MPL parachute/backshell touchdown separation from the lander*. Addressed the concern that the parachute/backshell may have come down near/on top of MPL.

7.1.1 Delivery Corridor to Landing Site Errors (Due to Entry Flight Path, Cross-Track, or Center of Mass)

FAILURE MODE DESCRIPTION

Errors in the navigation delivery to the atmospheric entry point can cause loss of the spacecraft due to atmospheric "skip-out" under the following conditions:

- If the trajectory is too shallow.
- If there is not sufficient time to complete parachute/propulsive deceleration.
- If the trajectory is too steep or causes the spacecraft to be sent into unacceptably hazardous terrain in the up-, down-, or cross-track directions.

These effects can also be caused by incompatibilities between the spacecraft inertial mass properties and aerodynamic properties. This section discusses the effects of all such failures, as well as potential causes due to navigation delivery errors. Due to the interdisciplinary nature of this failure mode, several other causes of failure are discussed elsewhere (specifically, aerodynamic properties are discussed in 7.1.2, center-of-mass motion due to mechanical shifting is discussed in 7.2.2, and center-of-mass motion due to propellant migration is discussed in sections 7.5.3 through 7.5.5).

INTRODUCTION

The delivery of the spacecraft to the targeted atmospheric entry conditions within the allowable tolerances was to be accomplished by the navigation team after collecting radio metric tracking data, performing a series of orbit-determination solutions, and specifying a series of propulsive maneuvers as required. Ultimately, the parameters of interest were reduced to the control of entry flight-path angle (critical to both hypersonic entry and landing-site accuracy) and the cross-track error (primarily influencing only the landing-site accuracy). These effects can also occur if there is a large misalignment between the aerodynamic center of pressure and the physical center of mass of the entry body, and can cause the lander to follow a trajectory that is either too steep or too shallow. Mass properties primarily contribute to the in-plane (steep/shallow) error and not to the cross-track error. This is because the primary source of uncertainty in spacecraft mass properties is due to potential mass migration between the two propellant tanks. These tanks lie on a line only 30 degrees from the entry plane, as discussed in sections 7.2.2 and 7.5.3 through 7.5.5.

MISSION NAVIGATION OVERVIEW

During project development, a navigation plan was created to confirm that, given certain assumed spacecraft performance characteristics, the flight team could execute a navigation strategy (including periods of orbit determination, followed by planned course corrections) that would result in delivery to a point in space from which the lander could commence a safe entry into the atmosphere and a safe descent to the desired zone on the surface. This pre-launch analysis included assumptions regarding the number of small-force events (thruster firings for attitude control or re-orientation) and the ability of the flight team to measure or model the effects of each of these items on the trajectory. These assumptions were folded into the development of a maneuver strategy intended to ensure that the penultimate maneuver (TCM-4) would be small enough to correct all but the smallest trajectory errors (errors so small that they could only be seen once inside the gravity well at Mars). These final errors (believed to be predominantly in the entry flight-path dimension or along-track) were to have been corrected by the execution of TCM-5, approximately 6 hours prior to entry. Because of the concern of a potential operator error in designing a maneuver from scratch at this critical point, the project made the decision to pre-design a series of along-track maneuvers; at the appropriate time, the project would uplink the maneuver that was closest to the desired solution. This technique was previously employed on Mars Pathfinder, MGS, and Magellan.

For reasons described below, it became more difficult to meet the expected navigation performance after launch while following the plan described above. The first event that caused difficulty was an anomaly encountered immediately after launch affecting the spacecraft’s Star Camera. Stray light from the spacecraft interfered with its ability to use the camera to perform gyro and attitude updates without slewing the spacecraft away from its normal cruise attitude. This would ultimately increase the number of small-force events encountered by the spacecraft throughout cruise, adversely affecting the navigation accuracy.

The second unanticipated event occurred after the navigation team was augmented with additional workforce and expertise following the loss of MCO. At this point, it was discovered that the ability to model the effects of small forces (already more numerous than previously planned because of the daily slews required by the Star Camera anomaly) based on telemetry received from the spacecraft was not as good as was previously assumed. During the final weeks prior to entry, significant progress was made in improving the understanding of these uncertainties, yielding information that could have been put to better use if uncovered earlier in the mission. Finally, given the new environment of more frequent small-force events, and the increased uncertainty associated with each, the size of TCM-4 was recalculated. Predictably, the magnitude of the maneuver had increased in size over the previous plan.

The recalculation of TCM-4 caused the magnitude to cross a boundary within the spacecraft performance space that led to unanticipated, nonlinear increases in the execution errors associated with this burn. The spacecraft performance requirements typically call for side errors between 1 and 2 percent of the commanded velocity for maneuvers that are either short enough to avoid creating off-axis disturbances or long enough to allow the control systems to damp these disturbances out. In between these extremes, there is a region of maneuver magnitudes where larger errors (up to 10 percent) build up before the control system has time to zero these out. As previously noted, the navigation plan did call for an opportunity following TCM-4 to correct the along-track component of these errors, but there was no plan to correct the cross-track errors, which had previously been assumed to be smaller. Eventually, this led to a delivery that was quite close to the expected center of the desired landing-zone along-track, but that was at the western extreme of the cross-track dispersions. A detailed description of these events and the corresponding analysis follows.

DESIGN DESCRIPTION

During the spacecraft development, the planned entry corridor for MPL was ± 0.54 degree at a 3-sigma confidence level. This corresponded to an error in the navigation delivery of 10.7 kilometers, 3 sigma in the B-plane semi-major axis, and a semi-minor axis of 2.6 kilometers, 3-sigma (predominantly contributing to cross-track errors). As previously discussed, these statistics included models and assumptions regarding the following:

- The nature of the small forces that the spacecraft produced in course-maintaining attitude control and performing required slews (including the uncertainties in these forces, as was reported in telemetry).
- The usefulness of new tracking data types to be employed for the first time on MPL (for example, near-simultaneous tracking of the lander on approach, together with an additional spacecraft already at Mars, either MCO or MGS).
- Maneuver-execution errors estimated based on the planned sizes of each trajectory correction.

Additionally, in order to achieve the desired landing ellipse on the surface of Mars, the analysis assumed that the spacecraft center of mass could be controlled to within 2.8 millimeters of the centerline of the entry body. The resulting surface ellipse had dimensions of 85 kilometers semi-major axis (along-track) by 5.4 kilometers semi-minor axis (cross-track), both 2 sigma. Figure 7-1 shows the landing ellipse estimate at the time of the site selection several months before EDL, based on earlier 3DOF/4DOF LMA Monte Carlo simulations, adjusted in orientation to the new landing latitude of –76° S. (*Note*: The landing latitude was –75° at launch.)

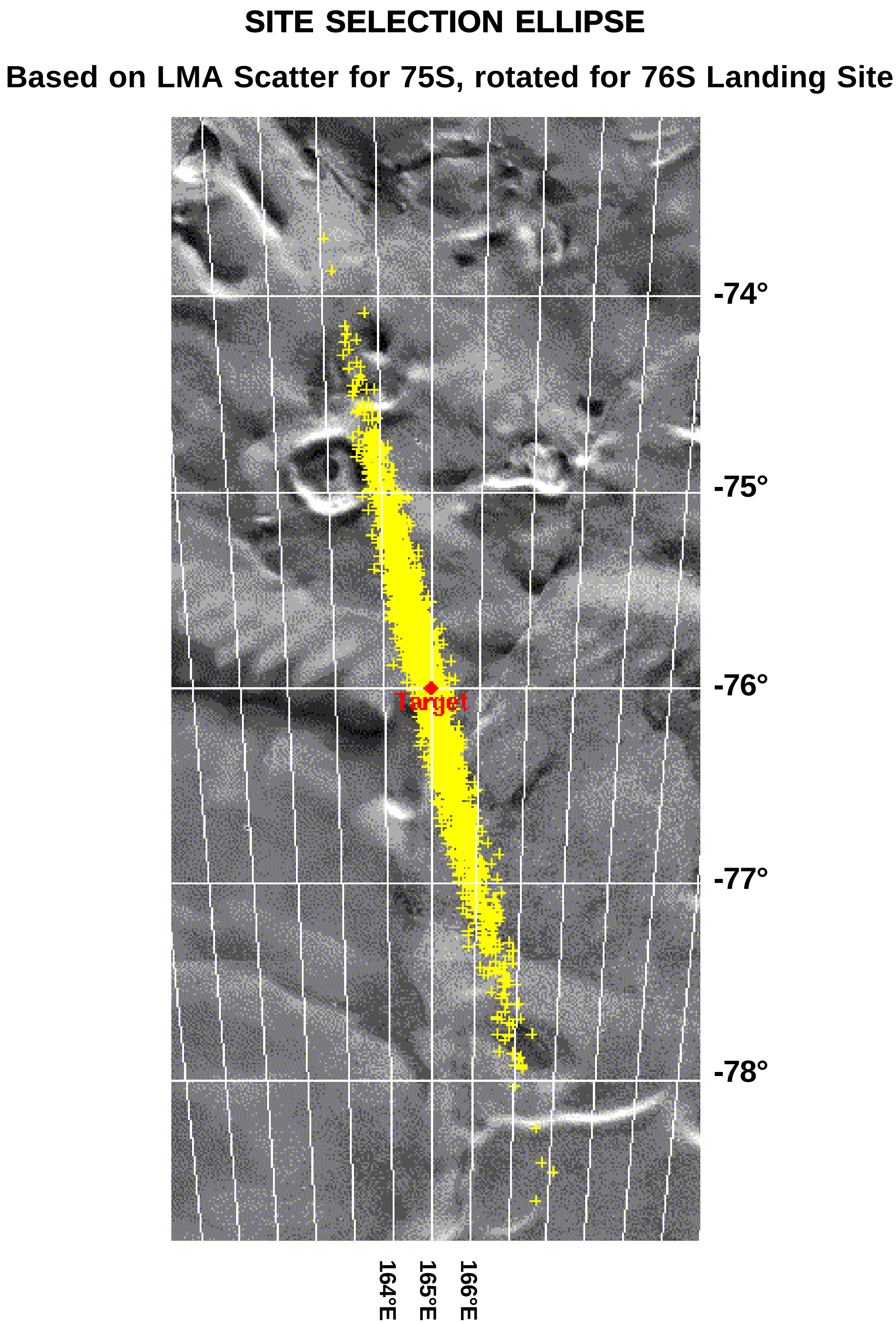

**Figure 7-1. Site Selection Ellipse —
Based on LMA Scatter for 75° S, Rotated for 76° S Landing Site**

As noted above, after the loss of MCO, additional navigation expertise was added to the project to help ensure a successful delivery to atmospheric entry. At this point, the assessment of small-forces assumptions and the improvements to be expected from near-simultaneous tracking were revisited. A new set of entry statistics was calculated on 10 November 1999 that resulted in an expected B-plane error ellipse of dimension 19.3 kilometers × 3.0 kilometers, 3 sigma, including orbit determination and maneuver-execution errors (for the magnitude of TCM-4 assumed in the pre-launch navigation plan). This corresponded to a 3-sigma entry flight-path angle of 0.94 degree, 3 sigma, which was still believed to be within the spacecraft design capabilities, even though this was considerably larger than previously planned for. The resulting surface ellipse, including the effects of an updated atmosphere model, had dimensions of 138 kilometers semi-major axis (along-track) by 5.4 kilometers semi-minor axis (cross-track), both 2 sigma. Figure 7-2 shows the TCM-4 planning ellipse, based on 3DOF LaRC simulations. Both the width and orientation of the landing ellipse are comparable to the estimates developed based on navigation analyses before the MPL launch; however, the length of the ellipse is considerably larger. This graph represents the data set available to the project to make the TCM-4 decision.

Analyses performed after EDL revealed that the effects of maneuver-execution errors were larger than expected. The TCM-4 planning ellipse was based on a maneuver magnitude of 0.35 meter per second, the best estimate available at that time. The final TCM-4 maneuver magnitude was 0.6 meter per second. This maneuver magnitude resulted in considerably larger execution errors than had been previously assumed. For very short burns, execution errors are small because little time is available for pointing errors to develop. For longer burns, errors are also small because the control system will steer back to the desired attitude. The executed burn magnitude fell in between these extremes and, therefore, was subject to a larger set of expected errors. This increased the size of the 3-sigma B-plane error to as high as 20.5 kilometers × 13.8 kilometers, using worst-case requirement estimates of maneuver-execution errors. (Typical or “expected” maneuver-execution errors led to substantially smaller B-plane errors (18.3 kilometers × 6.2 kilometers). This widening effect is illustrated in Figure 7-3, which shows both the narrow TCM-4 planning ellipse, based on the assumed maneuver magnitudes and associated error statistics, and the wider ellipse, based on the actual maneuver magnitude and associated error statistics. This graphic represents the difference between the delivery accuracy that the project assumed was achievable at the time of TCM-4 versus what is now believed to be the best estimate, after the fact. Also shown is the center of the final navigation solution based on tracking data after TCM-5 through the loss of signal.

On the basis of the final pre-entry tracking, the desired in-plane entry conditions appear to have been met. The entry flight-path angle was reconstructed at –13.10 degrees against the target zone of –13.25 ± 0.94 degrees (revised from the original –13.25 ± 0.54 degrees). The cross-track error in the B-plane was within 7.2 kilometers of the planned target, which corresponds to a motion of approximately 8 kilometers at the surface. This distance is marginally consistent (within approximately 2 sigma) with the eventual understanding of the uncertainty surrounding the spacecraft small-forces environment and TCM-4 execution errors, which are discussed above. In Figure 7-4, the yellow (light) data once again reflect the best estimate of the delivery accuracy after TCM-4; these data are based on analysis after the fact. Also in Figure 7-4, the green (dark) data represents the best estimate of where the lander actually did go, eliminating effectively all navigation errors by using the final tracking data arc through loss of signal, but continuing to represent scatter around that final solution due to atmospheric and aerodynamic uncertainties.

TCM4 PLANNING ELLIPSE

LARC 3DOF Scatter 11/23/99

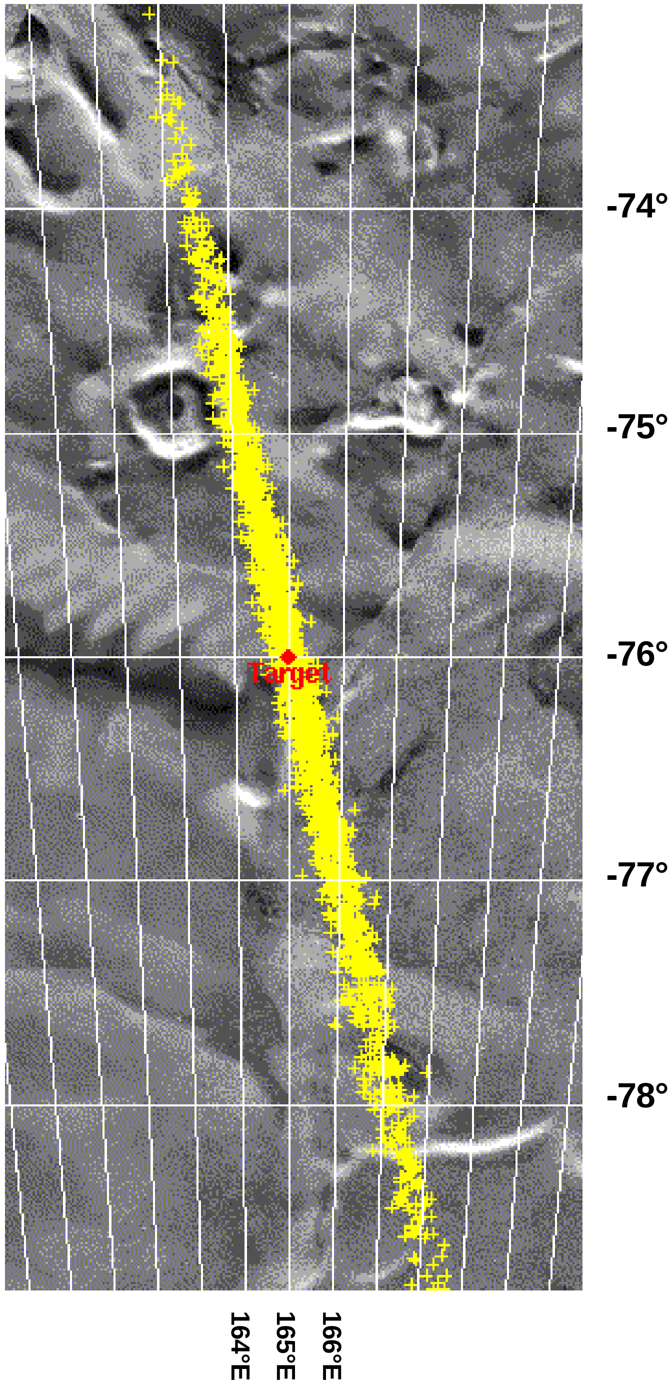

Figure 7-2. TCM-4 Planning Ellipse — LaRC 3DOF Scatter, 11/23/99