Entry, Descent, and Landing Operations Analysis for the Mars Phoenix Lander

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The Mars Phoenix lander was launched August 4, 2007 and remained in cruise for ten months before landing in the northern plains of Mars in May 2008. The one-month Entry, Descent, and Landing (EDL) operations phase prior to entry consisted of daily analyses, meetings, and decisions necessary to determine if trajectory correction maneuvers and environmental parameter updates to the spacecraft were required. An overview of the Phoenix EDL trajectory simulation and analysis that was performed during the EDL approach and operations phase is described in detail. The evolution of the Monte Carlo statistics and footprint ellipse during the final approach phase is also provided. The EDL operations effort accurately delivered the Phoenix lander to the desired landing region on May 25, 2008.

Nomenclature

E	=	atmospheric entry time
EDL	=	entry, descent, and landing
EPU	=	environmental parameter update
L	=	spacecraft landing time
MOLA	=	Mars Orbiter Laser Altimeter
OD	=	orbit determination
r	=	radial distance to the center of Mars
TCM	=	trajectory correction maneuver
V_h	=	horizontal velocity
V_v	=	vertical velocity
γ	=	inertial flight path angle

I. Introduction

Mars Phoenix was the first NASA Scout mission – selected in 2003 for launch in 2007. It was originally built as the 2001 Mars Surveyor lander, but after the failure of the sister spacecraft, Mars Polar Lander, there was insufficient time to address findings from the failure review board prior to launch.[1,2] Instead, the spacecraft was placed in storage until its reincarnation as Phoenix in 2003. Phoenix carries on it a new science payload, enhanced radar, and went through a rigorous test program prior to launch. The objective of the Phoenix mission is to uncover the history of water on Mars and to study the habitability potential in the arctic ice-rich soil region of northern Mars.[3] To com-

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plete a successful mission, however, it is imperative to execute safely the entry, descent, and landing (EDL) portion of the mission. The month prior to EDL was spent analyzing every aspect of the EDL phase and planning for every nominal and contingency plan for targeting and uploading critical data to the spacecraft.

This paper provides an overview of the EDL operations phase of flight and the trajectory analysis performed to support the project in the final months prior to entry. In addition, the evolution of the EDL performance, and in particular, the landing ellipse, from Monte Carlo analysis will be presented. This analysis was required to ensure mission success and to guarantee a safe landing location.

The Phoenix simulation at NASA Langley Research Center (LaRC) was the prime simulation used for Monte Carlo analysis during the operations phase of EDL. Many groups, however, supported the design and operations of the EDL phase: the spacecraft team at Lockheed Martin Space Systems (LMSS), the EDL team at Jet Propulsion Laboratory (JPL), and the LaRC team. Reference 4 provides an in-depth description of the simulation developed and utilized during the design and operations phases. In addition, much of the post-processing and analysis of the simulation was performed by the entire EDL simulation team consisting of engineers and analysts at LaRC, JPL, and LMSS. This critical analysis of the EDL phase led to a safe and successful landing of Phoenix on Mars on May 25, 2008.

II. EDL Overview

The EDL phase of the Phoenix mission begins ten minute prior to entry and continues until touchdown of the lander on the surface of Mars. Seven minutes prior to entry, Phoenix separates from its cruise stage and begins a slew to entry attitude. The hypersonic phase of flight begins from atmospheric interface having a -13.0 deg inertial flight path angle and an inertial entry velocity of 5.6 km/s. The hypersonic phase is an unguided ballistic entry until parachute deployment (expanding the traditional definition of hypersonic flight). The parachute phase continues from parachute deploy until after the heatshield is separated, the lander legs are deployed, and the parachute-backshell system is jettisoned. The remainder of EDL from lander separation until touchdown is considered the terminal descent phase where the propulsion systems allows the three-legged lander to softly touch down on the surface of Mars between 1.4 m/s and 3.4 m/s in vertical velocity.[4] Figure 1 provides an overview of the EDL phases and sequence of events.

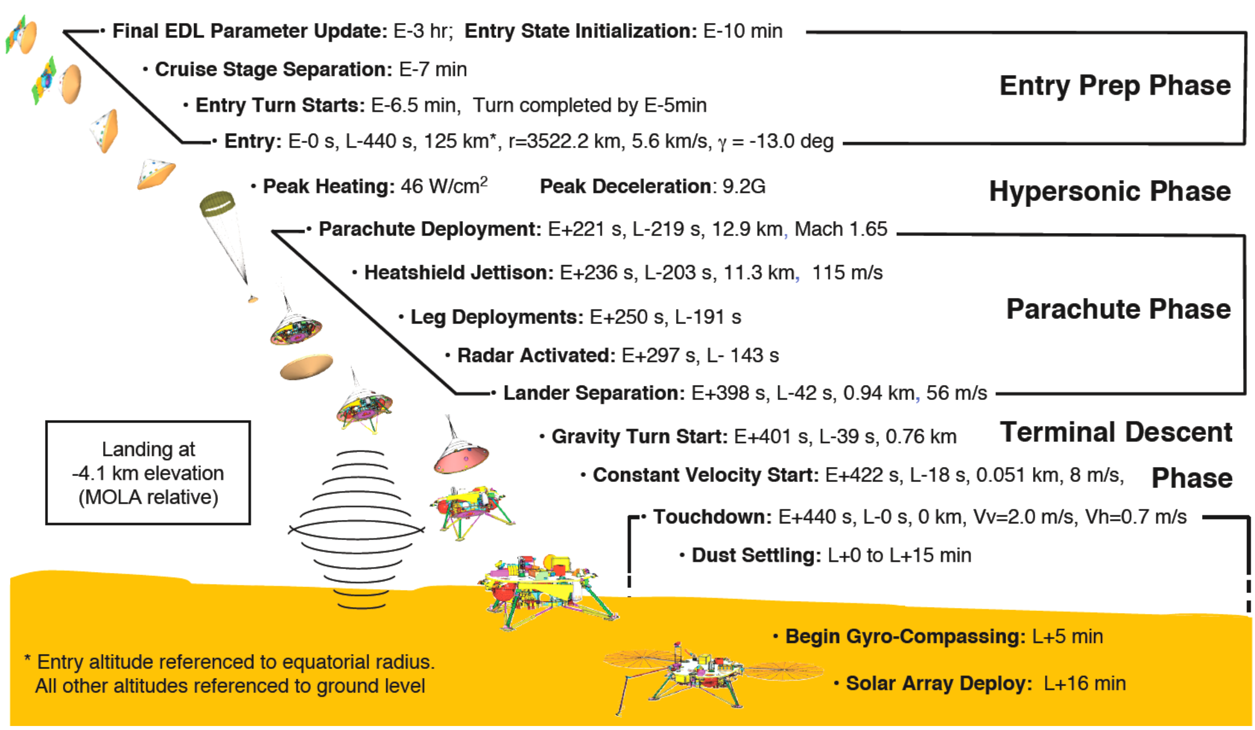

Figure 1. EDL sequence of events for Phoenix.

Prior to EDL, the operations phase was primarily focused on making decisions for two events: i) trajectory correction maneuvers (TCM), and ii) onboard spacecraft entry parameter updates (EPU) consisting of navigated spacecraft state and time as well as parachute trigger parameters. These decisions were based largely on the effectiveness of each TCM or EPU option on the EDL phase. Simulations were run with every viable TCM and EPU option to ensure that the risk of these options to EDL was low. This simulation effort is the focus of the operations phase of EDL and will be discussed in subsequent sections.

III. Planned Operations Timeline

The operations phase of EDL began the week prior to the planned TCM-4, on May 5. Collaboratively, the EDL team provided analysis and decision support for all TCM options and spacecraft parameter updates between TCM-4 that was planned for Saturday, May 10 until four hours prior to entry on May 25. The project followed a detailed timeline during operations that allowed for nominal TCM performance as well as contingency anomaly response. This timeline is outlined in Fig. 2.

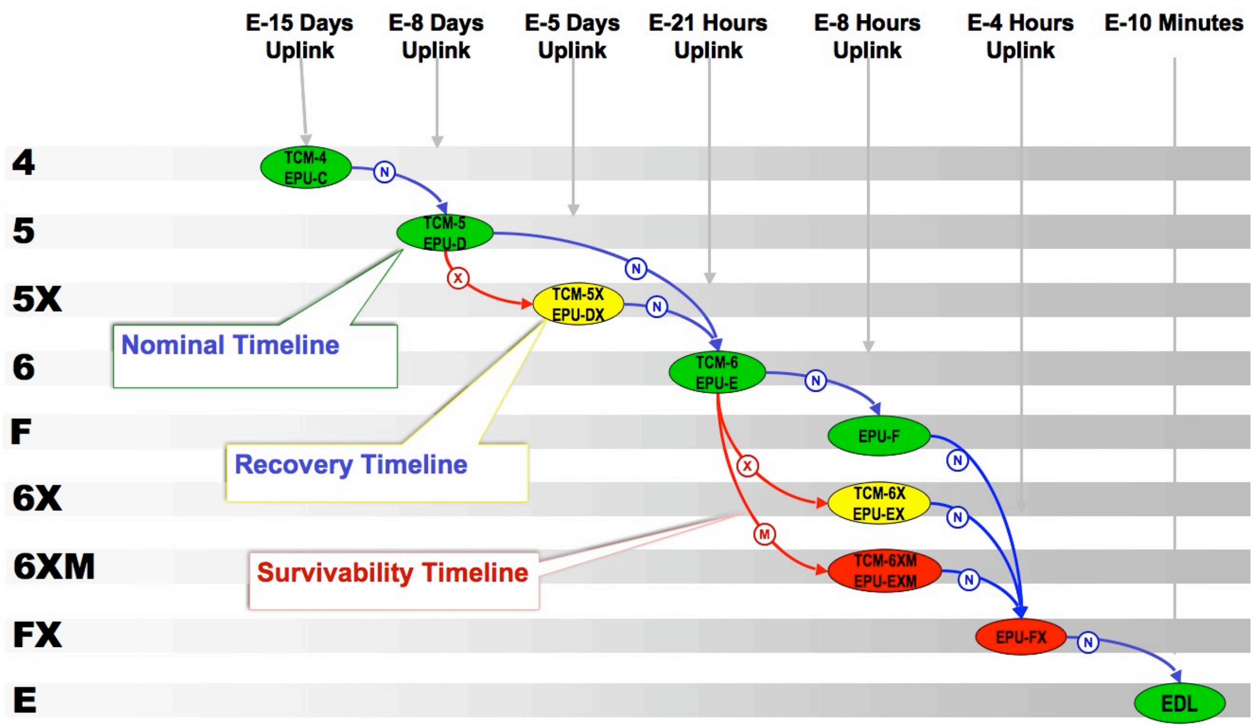

Figure 2. Phoenix approach and EDL endgame strategy: nominal and contingency timeline plan.

In Fig. 2, the green bubbles indicate a nominal timeline. The criteria that must be satisfied for the nominal timeline include nominal TCM performance, landing site selection criteria, and nominal EDL performance. Each of these criteria will be discussed in subsequent sections. In the nominal timeline scenario, TCM-4 is performed at Entry minus 15 days (Saturday, May 10). At Entry minus 8 days (Saturday, May 17), TCM-5 is performed. If TCM-5 is executed as planned, the nominal timeline continues to TCM-6 at Entry minus 21 hours. If an anomaly occurs however, and either the planned TCM-5 is not executed properly, a Recovery Timeline is established during which a TCM-5X may be performed at Entry minus 5 days. The Recovery Timeline can be triggered due to an inadvisable TCM-5 or TCM-6 opportunity: the TCM build process is not completed, there is an anomaly on the spacecraft, or a required DSN station is down. Note, the TCM-5X option is analyzed in parallel with TCM-5 planning in preparation for this potential contingency. If on the Recovery Timeline, once TCM-5X has been executed, the operations path will return to the nominal TCM-6 timeline. After TCM-6 is performed, there is nominally no requirement for an additional TCM. Rather, EPU-F is planned for Entry minus 8 hours. However, if TCM-6 did not execute properly, a Recovery Timeline is established such that a TCM-6X can occur at Entry minus 8 hours. In the event that the spacecraft is unable to receive an uplink with the designed TCM-6X or that there is poor execution of TCM-6 or TCM-6X, there exists an onboard menu of TCM options that have previously been built and tested. One of these menu options can be chosen to be executed as TCM-6XM as part of the Survivability Timeline. After one of these three options occurs (EPU-F, TCM-6X, or TCM-6XM), the path again returns to the nominal timeline with EPU-FX at Entry minus 4 hours followed by EDL at Entry minus 10 minutes.

During the operations phase, the focus was on making decisions for two events: trajectory correction maneuvers (TCM) and onboard spacecraft entry parameter updates (EPU). These decisions were based on two major criteria: landing site selection and EDL performance based on Monte Carlo analysis. Analysis was performed on each option of each timeline for every working day of operations. Nominally, the simulation team would provide analysis of two (a "duo"), four (a "quad"), or six (a "6-pack") Monte Carlo simulations every day for the combination of a TCM or no TCM (Burn or NoBurn) or an EPU or no EPU (Update or NoUpdate). For example, while on the Nominal TCM-4 Timeline, the team ran a quad: NoBurn NoUpdate; NoBurn Update; TCM-4 NoUpdate; TCM-4 Update. While on the Nominal TCM-5 Timeline, the team would analyze a 6-pack: NoBurn, NoUpdate; NoBurn Update; TCM-5 NoUpdate; TCM-5 Update; TCM-5X NoUpdate, and TCM-5X Update. And finally, prior to EPU-F, the team ran a duo: NoBurn NoUpdate and NoBurn Update.

The daily schedule of events was planned months prior to EDL and was exercised through several Operational Readiness Tests (ORT). At the beginning of each nominal working day, the EDL team met for a Daily Plans and Status Meeting. This meeting was designed to keep the entire team updated on EDL progress. This meeting occurred at 9:00 am PDT and was immediately followed by the Simulation Kickoff Meeting. This simulation meeting was geared towards an understanding on what was to be delivered on each particular day, what entry state files (ESF) would be created, what atmosphere model was recommended, and what products were expected. Each Monte Carlo simulation was given approximately one hour for completion allowing for ample time to assess and run any additional analyses as necessary. A 12:00 pm PDT Anomaly Response Placeholder meeting was scheduled in the event of an unplanned circumstance, but was never utilized for this purpose. An EDL Communications meeting was scheduled for 2:00pm PDT and an Atmosphere Delivery meeting occurred at 3:00pm PDT daily. The Navigation Advisory Group (NAG) met daily at 4:00 pm PDT followed by a Landing Site Selection (LSS) Criteria meeting at 5:00 pm PDT and an Approach and EDL assessment meeting at 5:30pm PDT. The final TCM Decision Meeting occurred daily at 6:00 pm PDT. On TCM-planning weekends, additional meetings were held for TCM preparation: Go/No-Go Command Authorization Meeting (CAM) and TCM Assessment meetings. These meetings were scheduled around the execution time of each potential TCM. Shift schedules for each member of the EDL team were designed months in advance to accommodate nominal working days as well as 24-hour operations work during planned TCM weekends. These shift schedules were also planned months in advance and practiced in the ORTs in the months prior to EDL.

IV. EPU Decision Analysis

The flight software onboard the spacecraft required updates to several parameters. Those parameters were limited to onboard propagated time and state as well as the triggers with which to deploy the parachute. The onboard time and state required updates so that the initial error in state or time would not propagate into large errors throughout descent. The parachute triggers required a change based on the current entry flight path angle of the entry capsule. Since the trigger is based on velocity and acceleration, optimized to deploy at 490 Pa dynamic pressure, a change in the flight path angle can change at what accelerations this dynamic pressure is achieved. The trigger is then re-optimized so that the 490 Pa is achieved. Decisions on spacecraft parameter updates were based largely on worksheets designed by the EDL team in comparing Monte Carlo results both without an update and with a potential update. In addition to the EPU worksheets, daily meetings were held to assess the validity of the worksheets, the confidence in the results, and the appropriate recommendation to the larger EDL team.

The EPU worksheets consisted of several sections that allowed proper tracking of all the results generated and also served as a configuration management process to assure that the proper inputs were used in generating the results. Section A included a procedure checklist for processes required to populate the worksheet, necessary for documenting status of worksheet production and to notify the users of the worksheet if data was missing. Section B was an entry state assessment. This provided actual values of the onboard and updated entry state file and the delta of each component of state and time. These deltas were flagged as red or green indicating whether the data triggered an update or no update. Thresholds in determining an update were ±1 second in time, ±0.46 km in each component of Cartesian position, and ±0.1 m/s in Cartesian velocity. Section C was a simulation confidence table. It provided nominal trajectory results from the LaRC POST2, the LMSS POST2, and the JPL DSENDS simulations. This served as a source of independent verification and validation of the results of the LaRC POST2 simulation that was used as the prime EDL simulation. Section D of the EPU worksheet provided performance metrics of each Monte Carlo: with the current ESF or the updated ESF. In addition, the results from each previous EPU were identified for reference in Section D. Included in the performance metrics were 95 percentile values for each EDL parameter to be reviewed and the percent of margin to the requirement that was held. Each performance metric was flagged in green, red, or yellow indicating that it possessed sufficient margin, little margin, or negative margin respectively. The analysis of the EDL parameter criteria of the Update Monte Carlo results was assessed against that of the No Update Monte Carlo and a recommendation was made based on that judgment. Section E of the EPU worksheet contained documentation sources of all data that populated the worksheet. The second page of the worksheet provided additional backup data to the primary page: a list of the individual parameters in the spacecraft configuration file, a verification of the data taken from the configuration file, and the Monte Carlo EDL performance violation criteria. The EDL performance violation criteria table was helpful in identifying the sensitivities in each Monte Carlo set and its comparison to the baseline Monte Carlo set. An example of a violation criteria table from the May 17 TCM/EPU criteria sheet for the TCM-5 case is shown in Table 1.

Table 1. TCM-5 EDL Parameter Violation Criteria Comparison

Performance Metric	Units	Rqmt	Anchor	Onboard	Updated
Peak Heating Rate	W/cm2	>64	0.0%	0.0%	0.0%
Integrated Heat Load	J/cm2	>3320	0.0%	0.0%	0.0%
Angle of Attack at Peak Heating	deg	>10	0.0%	0.0%	0.0%
Peak Deceleration	g's	>13	0.0%	0.0%	0.0%
Dynamic Pressure at Chute Deploy	Pa	>560	0.1%	0.1%	0.1%
Dynamic Pressure at Chute Deploy	Pa	<300	0.0%	0.0%	0.0%
Mach Number at Chute Deploy	Mach	>2.13	0.0%	0.0%	0.0%
Mach Number at Chute Deploy	Mach	<1.1	0.0%	0.0%	0.0%
Angle of Attack at Chute Deploy	deg	>10	0.1%	0.1%	0.3%
Mach Number at HS Separation	Mach	>0.8	0.0%	0.0%	0.0%
Attitude Rate at HS Separation	deg/s	>100	0.0%	0.0%	0.0%
Attitude Rate at Leg Deploy	deg/s	>100	0.0%	0.0%	0.0%
Attitude Rate at Lander Separation	deg/s	>100	1.1%	0.9%	1.1%
Vertical Velocity at Touchdown	m/s	>3.4	0.1%	0.4%	0.1%
Vertical Velocity at Touchdown	m/s	<1.0	0.1%	0.0%	0.1%
Horizontal Velocity at Touchdown	m/s	>1.4	0.2%	13.5%	0.3%
End-to-End Propellant Margin	kg	<5	0.0%	0.0%	0.0%
Total Out of Spec	%	<5%	1.5%	14.6%	1.7%
Total Incomplete	%	—	0.1%	0.0%	0.0%

Table 1 shows that for this analysis without the EPU (Onboard column), the horizontal velocity touchdown requirement was violated in 13.5% of the Monte Carlo cases. The reason for this large violation was due to the large difference from the onboard navigated time and the updated navigated time. This large violation was expected considering that the time difference between the actual entry time and the time stored on the spacecraft was greater than 13 seconds. Because of this large performance metric violation, and considering that an EPU (Updated column) would decrease this violate rate to 1.7%, an update was recommended and executed. This example illustrates the daily process that was conducted during the month long operations phase prior to EDL.

V. TCM Decision Analysis

Decisions on TCMs were based on landing site selection (LSS) criteria as well as EDL performance criteria. The Monte Carlo EDL analysis produced landing locations on the surface. From this data, one-sigma landing ellipses were generated: ellipses on the surface that incorporated one-sigma of the landing locations. The first LSS criterion required that 95% of the one-sigma landing ellipse by area must be within the Lowland Bright Terrain. The second LSS criterion required that 99% of the one-sigma landing ellipse by area lies in the safe MOLA slope mask, defined as areas with less than five degrees in slope. The third LSS criterion required that there must be a 0.80 probability of landing in a Certified Safe Zone. Reference 5 provides an in-depth overview of the LSS criteria.[5] The Certified Safe Zones are regions that are designated as safe by the Mars Reconnaissance Orbiter (MRO) Hi-Rise images provided to the Phoenix Project. These Certified Safe Zone areas are indicated in green in Fig. 3. The two ellipses indicate Monte Carlo results with (smaller ellipse) and without TCM-5 (larger ellipse). Based on the satisfaction of these three landing criteria, a design to perform or not to perform a TCM was recommended.

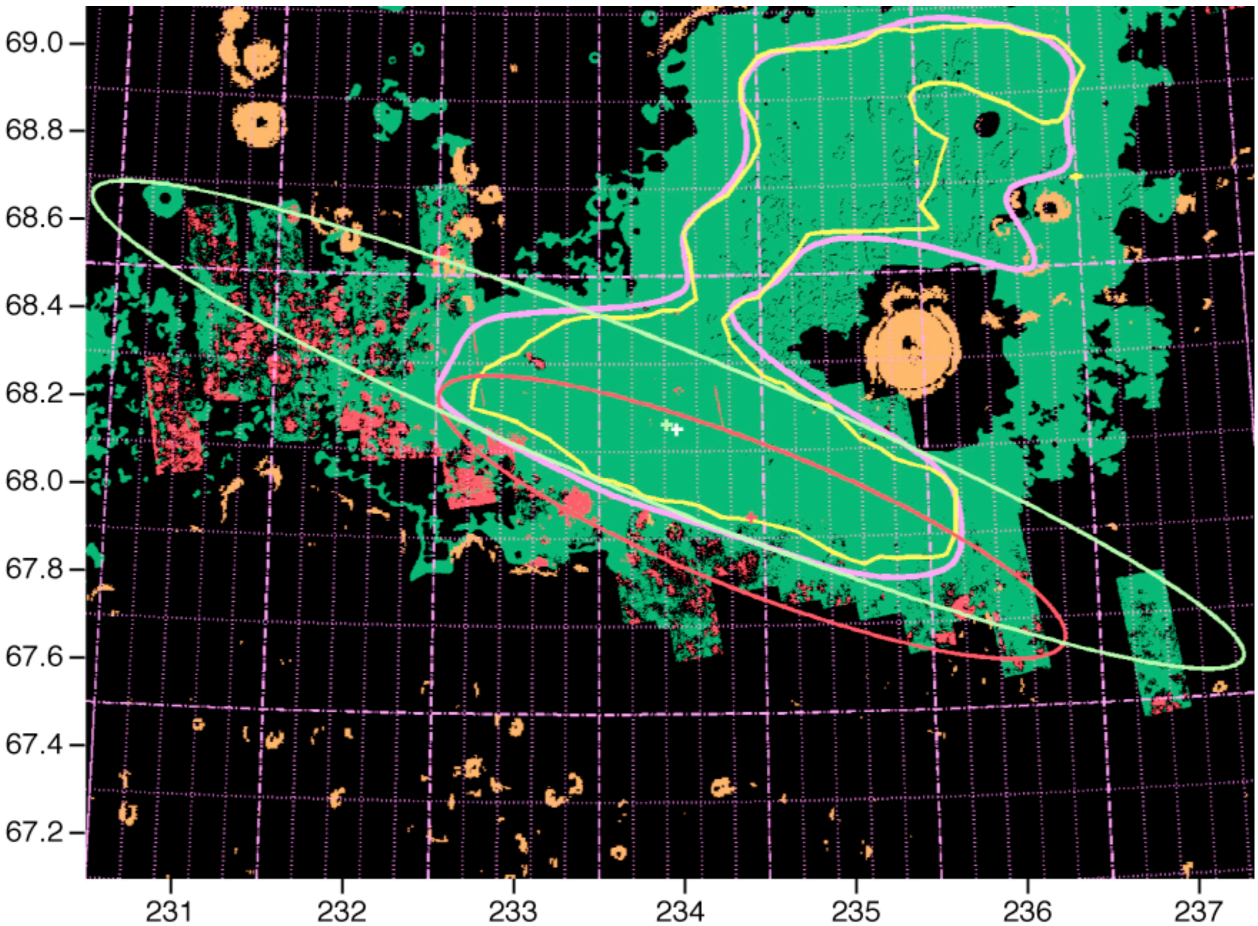

Figure 3. Landing site selection certified safe zone mapping.

VI. Simulation Team Operations Process

During operations, upon delivery of a new ESF, the simulation team began its process of Monte Carlo analysis. The LMSS EDL team provided the essential spacecraft clock input to the flight software based on the new ESF. Once received, the Monte Carlo for the NoUpdate Monte Carlo commenced. Meanwhile, the LMSS EDL created the updated configuration files containing the optimized parachute trigger parameters. Upon receipt of these new files, the Update Monte Carlo simulation began. Once the Monte Carlos completed, they were post-processed and translated into the aforementioned EPU Criteria Worksheet for team analysis. Assuming the first ESF delivery was for a NoBurn scenario, the process would replicate for each maneuver (e.g., for a quad or a 6-pack). Typically, one hour was allotted for the processing of each Monte Carlo. Because of the availability of a large computing network, the actual CPU run-time of any given Monte Carlo was approximately eight minutes. Pre-processing, thorough validation of simulation processes, and post-processing required the remaining allotted hour of analysis.

VII. Operational Updates

Each day of operations, the Navigation team provided a new NoBurn ESF corresponding to a new orbit determination (OD) solution. In previous Monte Carlo analyses, the designed 99% landing ellipse was approximately 110 km by 20 km. On May 14, the Navigation team reduced its conservatism in the orbit determination solution, reducing the margin of error in planet-relative entry flight path angle by 50% (±0.5° uncertainty to a ±0.24° uncertainty), since the actual spacecraft performance was much better at that time compared to the margins assumed. This reduction in navigation error decreased the predicted NoBurn Update landing ellipse from 213 km by 21 km to 115 km by 20 km.[6]

During operations, the Atmosphere team was performing daily weather observations of the Phoenix landing site using MRO. They met daily to determine whether an update to the atmosphere model was recommended for use in the Monte Carlo simulations.[7] There were several updates generated based on MRO observations, but the simulation team used only incorporated three during operations. At the beginning of the operations phase, the simulation team was using the model indicated by ATM004. This model was used in much of the EDL design phase.[4] On May 7, the Atmosphere team recommended the change to ATM008. There was little change between the two models. However, the major difference was that ATM008 was based on MRO data rather than computational models. On May 21, the weather on Mars had changed sufficiently enough to warrant an atmosphere update to ATM012. The comparison of these three models is shown in Fig. 4 as a fractional deviation from the ATM008 profile. The deviations observed were within 1-sigma variations.

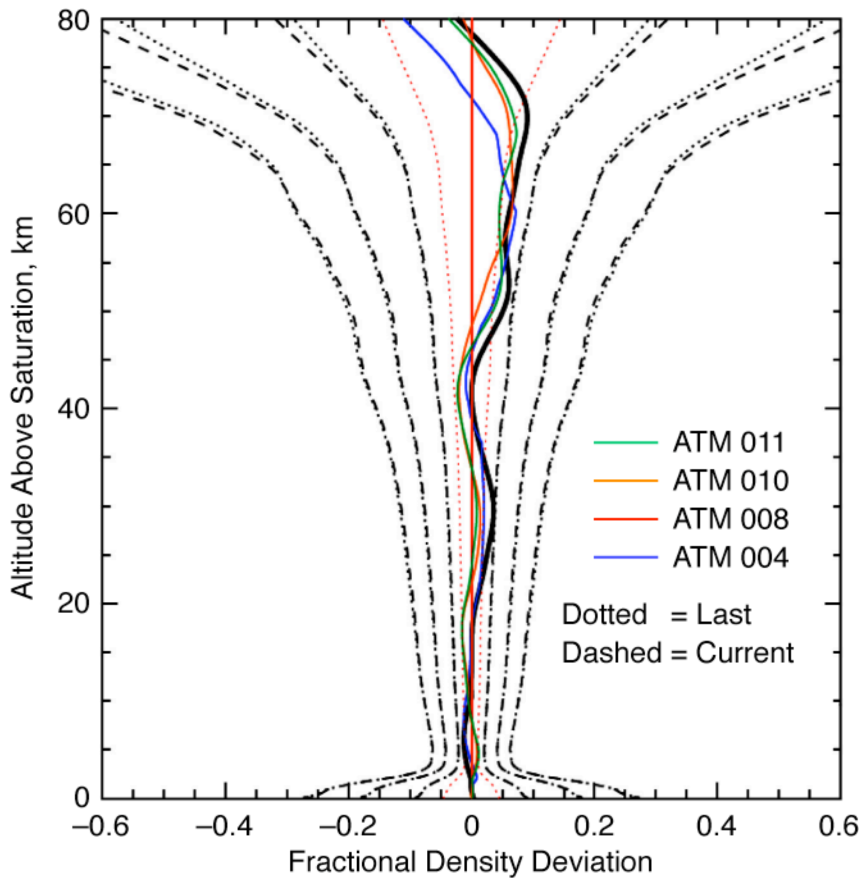

Figure 4. Operational atmosphere model comparison.

VIII. Results

At the TCM decision meeting on May 8, TCM-4 was canceled. The navigation was well enough on target that the risk of a maneuver outweighed the potential gain from the maneuver. However, EPU-C was performed. The corresponding Monte Carlo from OD051 was the NoBurn Update analysis. At the TCM decision meeting on May 17, TCM-5 was recommended. The corresponding Monte Carlo from OD055 was the TCM-5 Update analysis. At the TCM decision meeting on May 24, TCM-6 was canceled, since the landing ellipse and the nominal landing location met all of the LSS requirements. The risk of a potential anomaly occurring during TCM-6 outweighed the potential gain. The corresponding Monte Carlo from OD062 was the NoBurn Update analysis. The landing ellipses from these three analyses are shown in Fig 5. The progression in landing ellipse size and target can be seen during operations. The landing footprint ellipse decreased from 213.56 km by 20.85 km for OD051 to 93.56 km by 19.85 km for OD055 to 61.76 km by 19.21 km for OD062.

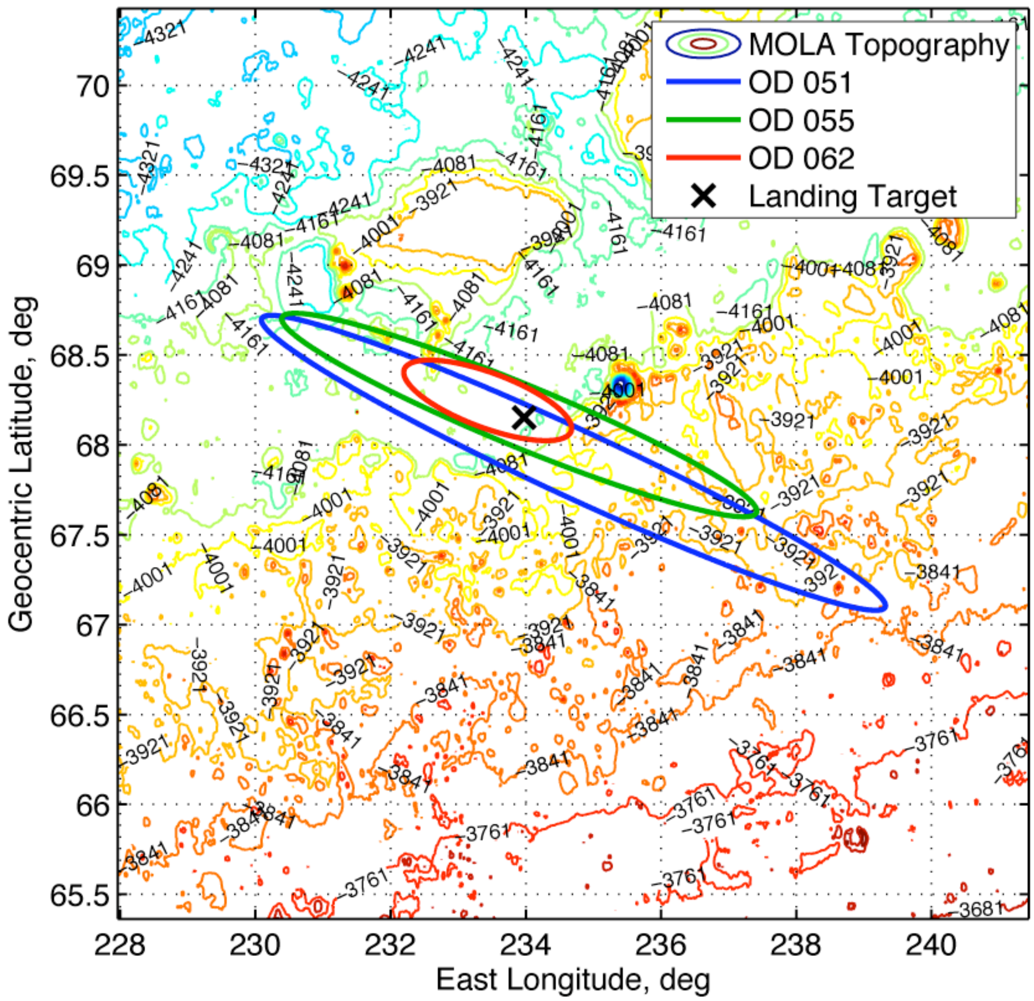

Figure 5. Landing ellipse progression throughout the EDL Operations phase.

The landing ellipse from the final estimated OD077, which was the best known estimate of the navigation state prior to entry on May 25, is shown in Fig 6. Also indicated on Fig 6 is the actual Phoenix landing location at 234.25° E. Longitude, 68.22° N. Latitude. The final landing location was within the 99% final pre-entry predicted landing ellipse, and well within the downrange of the design landing ellipse requirement 110 km by 20 km.[8] More details of the actual performance of Phoenix during its EDL can be found in Ref. 8.

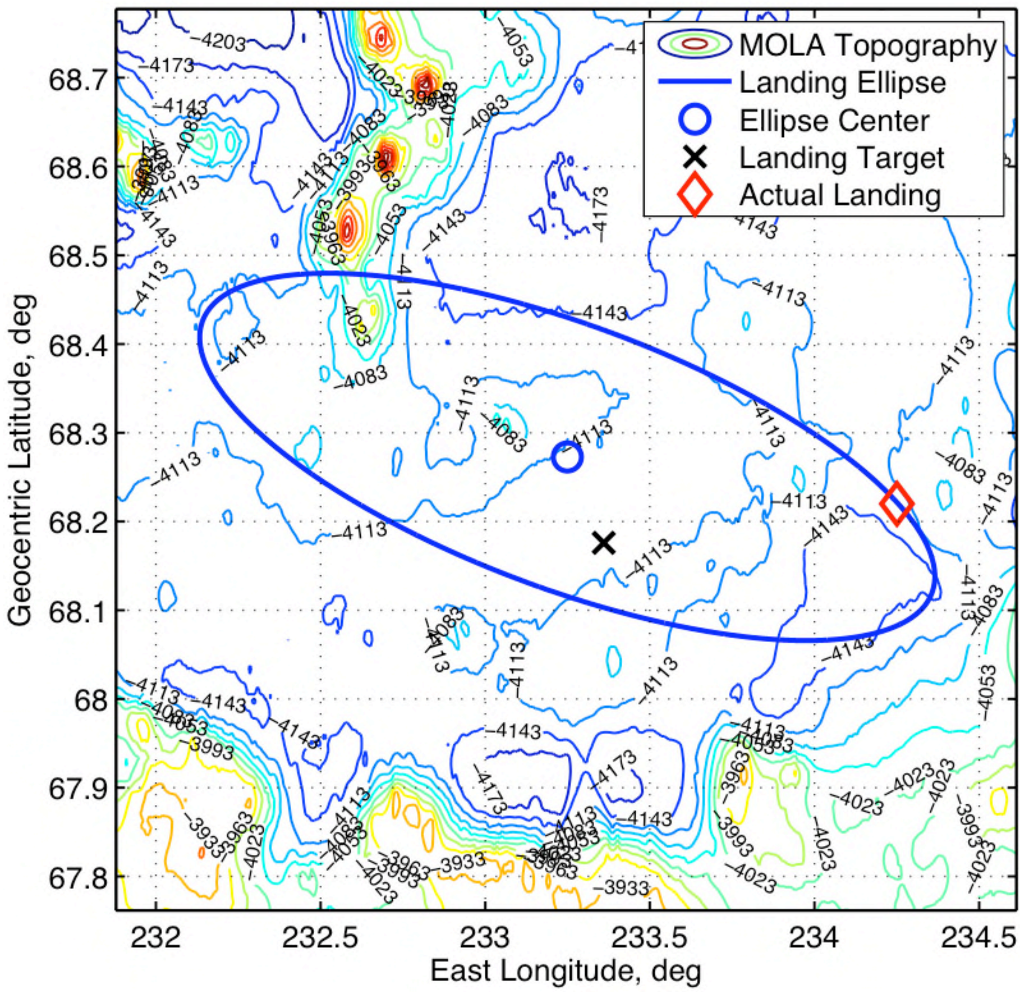

Figure 6. Landing ellipse from OD077.

Summary

The operations phase of the Mars Phoenix entry, descent, and landing began May 5, 2008 and was completed with the successful landing of Phoenix in the northern plains of Mars on May 25, 2008. The operations phase was carefully planned allotting sufficient time for simulation analyses of and decisions regarding the trajectory correction maneuvers and uploading of spacecraft entry parameters. Entry, descent, and landing (EDL) performance metrics and landing ellipses were assessed to ensure satisfaction of all EDL and landing site selection criteria. Throughout the operations phase, the navigation orbit determination estimates were consistently improving. The atmosphere model was updated twice based on weather observations. Using these updates, the EDL performance and the shift in the landing ellipses throughout the operations phase were tracked. Mars Phoenix operations went nominally and according to the well-designed plan. The anticipated TCM-4 and TCM-6 maneuvers were cancelled because of the precise targeting and nominal predicted EDL performance of the spacecraft. Preliminary results indicate that the Phoenix landed within the predicted landing ellipse.

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