Mission Design Overview for the Phoenix Mars Scout Mission

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The Phoenix Mars Scout Lander – the first robotic explorer in NASA's "Scout Program" – is scheduled to launch in August 2007, and will land on the northern plains of Mars in May 2008, prior to the start of the northern, Martian summer.

The Phoenix mission "follows the water" by landing in a region where NASA's Mars Odyssey orbiter has discovered evidence of ice-rich soil very near the Martian surface. For three months after landing, the fixed Lander will perform in-situ and remote sensing investigations that will characterize the chemistry of the materials at the local surface, sub-surface, and atmosphere, and will identify potential provenance of key indicator elements of significance to the biological potential of Mars, including potential organics and any accessible water ice. The Lander will employ a robotic arm to dig to the ice layer, and will analyze the acquired samples using a suite of deck-mounted, science instruments.

The development of the baseline strategy to achieve the objectives of this mission involves the integration of a variety of elements into a coherent mission plan. These elements have been involved in developing plans for the launch phase, interplanetary trajectory and navigation, atmospheric entry, descent, and landing (EDL), landing site selection, and the surface mission. An overview of the integrated mission plan, from launch through surface operations, is described.

INTRODUCTION

The Phoenix project is the first mission in the Mars Scout program, a program designed to augment NASA's systematic, long-term exploration of Mars by quickly responding to compelling scientific discoveries. The discovery, made by Mars Odyssey in 2002, to which Phoenix responds is that of soils in the martian north polar region that are rich in water ice – up to 50% water by weight in the subsurface layer.[1] Scouts can be responsive because their objectives are highly focused, they are cost-capped, and they are led by a Principal Investigator (PI) supported by a Project Manager and personnel at JPL, with other

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partners in academia and industry. The scope of the Phoenix project includes all activities to be undertaken by NASA, the Jet Propulsion Laboratory (JPL), Lockheed Martin, the University of Arizona, and international partners participating in the project (e.g., Canadian Space Agency) to design, develop, test, launch and operate the Phoenix Lander to achieve the above objectives.

Phoenix is able to respond so quickly to Odyssey's discovery because a) it makes use of an existing spacecraft and b) its instrument suite is largely based on instruments that have already flown; which, coincidentally, is also the reason for the name "Phoenix" as the mission is truly reborn out of the embers of previous Mars missions.

In the case of the spacecraft, Phoenix returns to flight the Mars Surveyor Program 2001 (MSP'01) Lander platform which was fully designed and constructed when the program was halted four months into Assembly, Test, and Launch Operations (ATLO). Modifications have been made to the Phoenix spacecraft to address a wide variety of issues, most notably: to replace hardware taken by other projects (especially MRO), to respond to Return to Flight recommendations, and, to accommodate an updated mission design.[2] Major mission design changes from the MSP'01 Lander days to the present are necessary for two main reasons: the Earth/Mars opportunity itself and the change in the latitude of the landing site. For the former reason, a Type II trajectory in 2007/2008 at the open of the launch period leads to Sun and Earth locations at Mars arrival that are roughly 0.2 AU (30 million km) further away than was the case for the 2001/2002 Type II opportunity of MSP'01.[3] The latter reason is a change because MSP'01 Lander was designed to land and operate in the Martian equatorial region, whereas Phoenix will be conducting surface operations in the martian arctic, somewhere in the latitude band 65°N to 72°N.

Almost all of the instruments being flown on Phoenix have a high degree of heritage from either MSP'01 or Mars Polar Lander (MPL). With few modifications, these instruments have been built to explore the icy region in the martian arctic and perform in-situ and remote sensing investigations that seek to answer the following questions: (1) can the Martian arctic support life, (2) what is the history of water at the landing site, and (3) how is the Martian climate affected by polar dynamics?[4] The payload that has been assembled to answer these questions is served by a sophisticated Robotic Arm (RA) that digs through the soil to the underlying ice and delivers samples to the Thermal and Evolved Gas Analyzer (TEGA) and the Microscopy, Electrochemistry, and Conductivity Analyzer (MECA) for analysis. In addition to these two experiments, the lander also contains a Meteorological Station (MET) to take daily weather readings, and a Surface Stereo Imager (SSI) to take high-resolution stereoscopic images of the martian terrain. When factoring in the Mars Descent Imager (MARDI) and an Atomic Force Microscope (AFM) inside MECA, the Phoenix imaging systems provide unprecedented views of Mars across 12 orders of magnitude.

MISSION OVERVIEW

The Phoenix Mission will use the 2007 Earth-to-Mars launch opportunity to safely deliver a spacecraft to a high latitude site on Mars. This opportunity is illustrated at right by the launch/arrival "porkchop" plot that contains contours of C3, arrival V_∞, Local Mean Solar Time (LMST) @ landing, and the maximum latitude achievable for each launch/ arrival pair. Also depicted on the plot are the actual launch/arrival pairs (yellow stars) that comprise Phoenix' 22-day launch period (8/3/2007-8/24/2007). The first 15-day leg of the launch period has arrivals at Mars on 5/25/2008, and the second 7-day launch leg has arrivals on 6/5/2008.

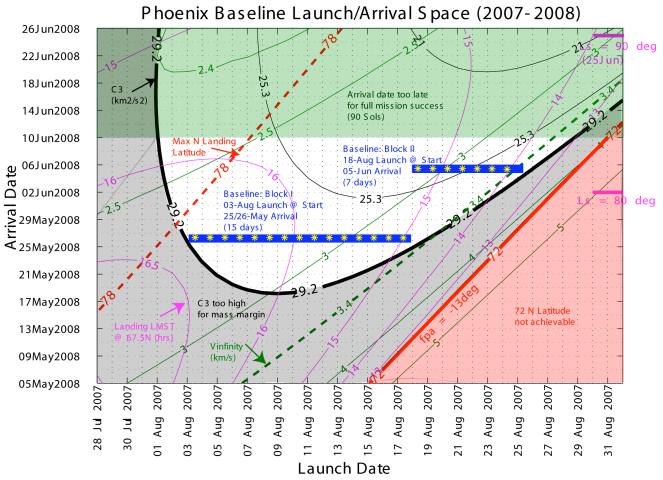

Figure 1 Phoenix Launch/Arrival Design Space

Shaded areas in Figure 1 highlight launch/arrival date combinations that do not meet mission design requirements on injection energy per unit mass (C3), maximum landing site latitude accessibility, V_∞ of arrival, and arrival date. Of these four major constraints, the one that has perhaps the least flexibility is arrival date. This is because the larger the Ls (Mars orbital longitude) at arrival, the worse the energy margin situation becomes over the course of the mission. This is the main reason that the first leg of the launch period (earliest arrivals) is so long because there is a 96% cumulative probability of launching by Day 15 based on Monte Carlo results using historical Delta II launch data (current through August 2004).

Phoenix will be launched using a Delta II 7925 launch vehicle from Space Launch Complex 17A (SLC-17A) at the Cape Canaveral Air Force Station (CCAFS) in Florida. During the 22-day launch period there will be two instantaneous launch opportunities per day, one flying from a launch azimuth of 93°, the other from an azimuth of 99°, exactly like the Mars Exploration Rover missions. Phoenix is capable of flying either a short-coast or a long-coast launch vehicle trajectory, but a long-coast was chosen because it greatly improves the chances of avoiding weather delays due to August thunderstorms, which typically occur in the afternoon hours at the Cape and all of Phoenix' launches occur before 6 am local time.

Key differences between Phoenix' launch and arrival trajectory designs are highlighted in the following table, with a comment describing how the difference impacts the mission design.

Table 1 Key Mission Design Differences between PHX and MSP'01 Lander

Parameter	Phoenix	MSP'01 Lander[6]	Comment
Launch Period Length	22 days	16 days	21 days ensures > 99% probability of initiating launch
Maximum C3 (km^2/s^2)	29.1	8.0	Forces PHX to use 7925 vs. 7425 on MSP'01
Arrival Date Range	2 possible dates	Varies with launch date	Constant arrival minimizes Cruise redesign work
Sun Distance, Open Arrival	1.67 AU	1.45 AU	Power/thermal implications for PHX
Earth Distance, Open Arrival	1.84 AU	1.65 AU	More constrained D/L & U/L rates for PHX
Max Landing Latitude	72N	12S	Only constraining if an extended launch period develops
Max Entry Velocity (km/s)	5.9	6.9	PHX arrival less demanding on thermal protection system
Landing Site Altitude	<-3.5 km	<+2.5 km	PHX significantly lower landing site altitudes vastly improves EDL timeline margin

The Phoenix long coast trajectory will be the longest ever flown on the Delta II; fortunately, analyses performed by Boeing (now United Launch Alliance) have verified that it can be flown with relatively few modifications to the launch vehicle. The sequence of trajectory-related events for the first 24 hours after launch is shown in Figure 2 at right. Note that for this launch (93°/Open), the spacecraft is already in view of the Goldstone Deep Space Network (DSN) complex at the time of separation from the 3rd stage, which is not the case for all launch days.

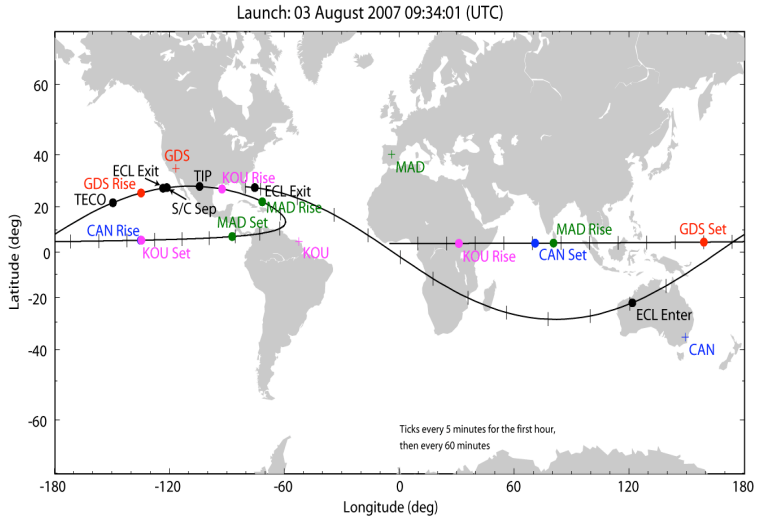

Figure 2 Launch Period Open Groundtrack, 93° Launch Azimuth

When the spacecraft senses separation from the 3rd stage, it commands an entry into Safe Mode. Major actions that occur during this early version of Safe Mode include damping tipoff rates, configuring the telecom system for initial acquisition, deploying the solar array, and acquiring attitude knowledge (using the sun sensors and star tracker). Once attitude knowledge is established, the spacecraft slews to an initial communication attitude for playback of telemetry recorded during the launch phase. This initial communication attitude was designed not only for telecom purposes but also for power and thermal safety for the first several days of the mission.

The day after a successful launch, the spacecraft is commanded out of Safe Mode and setup for transition to nominal Cruise phase operations. During the ensuing 10-month "cruise" to Mars, both the spacecraft and the science instruments will be checked out via a number of planned activities. Also during Cruise, the teams that will be operating the spacecraft during the critical "end game", Entry, Descent, and Landing (EDL), and early surface timeframes will be practicing their roles via a series of Operational Readiness Tests (ORTs). Figure 3 below shows the placement of the checkout activities taking place onboard the spacecraft in relation to the ORTs and other major activities, most notably the 6 Trajectory Correction Maneuvers (TCMs). As with all NASA planetary missions, telecommunications with the spacecraft are enabled by the DSN. Downlink (D/L) bit rates from Phoenix are depicted in Figure 3 as a function of days past launch, with the requirement being that 40 bps must be supportable at all times.

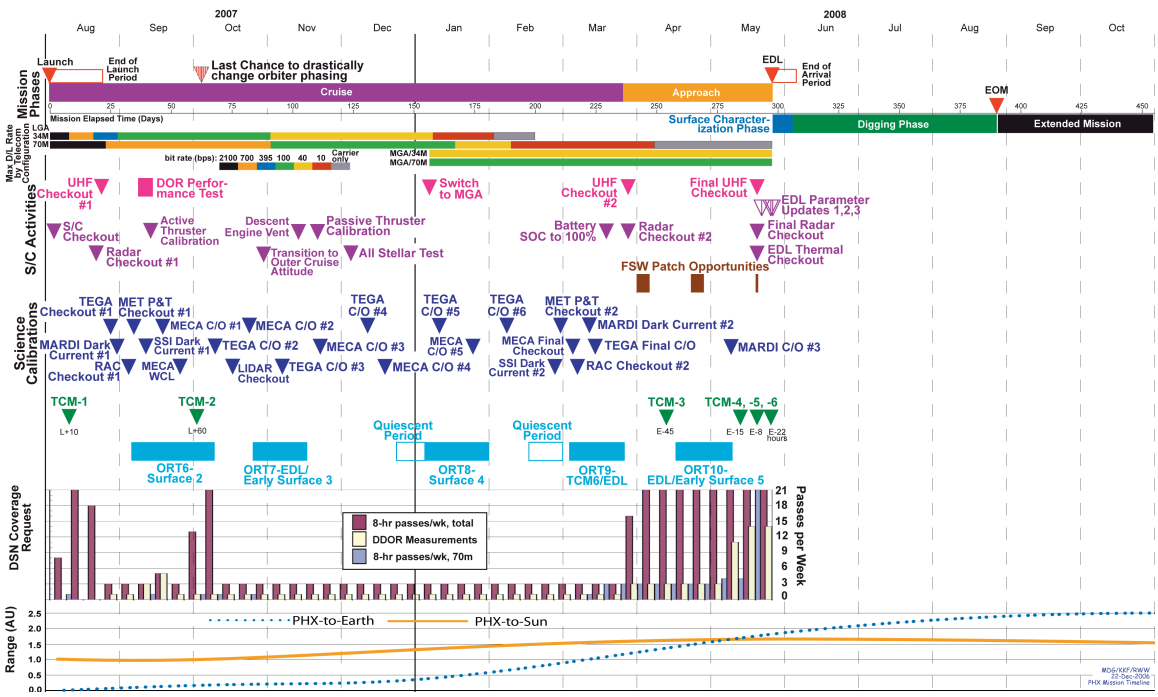

Figure 3 Overview Mission Timeline

From Entry minus 60 days onward, the mission is in a subphase of Cruise known as "Approach", within which the activity level dramatically increases. During this phase there will be continuous DSN coverage (21 passes/week is equivalent to 24/7 coverage) and 4 TCMs as the spacecrafts flight path is fine tuned for delivery into the martian atmosphere. Five minutes prior to atmospheric entry, the spacecraft will have finished slewing to the entry attitude and the Entry Vehicle will separate from the Cruise Stage (Figure 4 shows the Phoenix spacecraft in all of its various configurations). The EDL phase lasts approximately 7 minutes from Entry through Touchdown, and is broken into Hypersonic, Parachute, and Terminal Descent subphases, all of which require that the spacecraft be in a different configuration. Terminal Descent on Phoenix is accomplished using a pulsed propulsion system whose heritage is from MPL. Communications

during EDL – from Cruise Stage Separation (CSS) through Landing plus one minute – will be via UHF relay to Mars Reconnaissance Orbiter (MRO) and Mars Odyssey (ODY) only as all X-band capability is lost once the Cruise Stage is jettisoned.

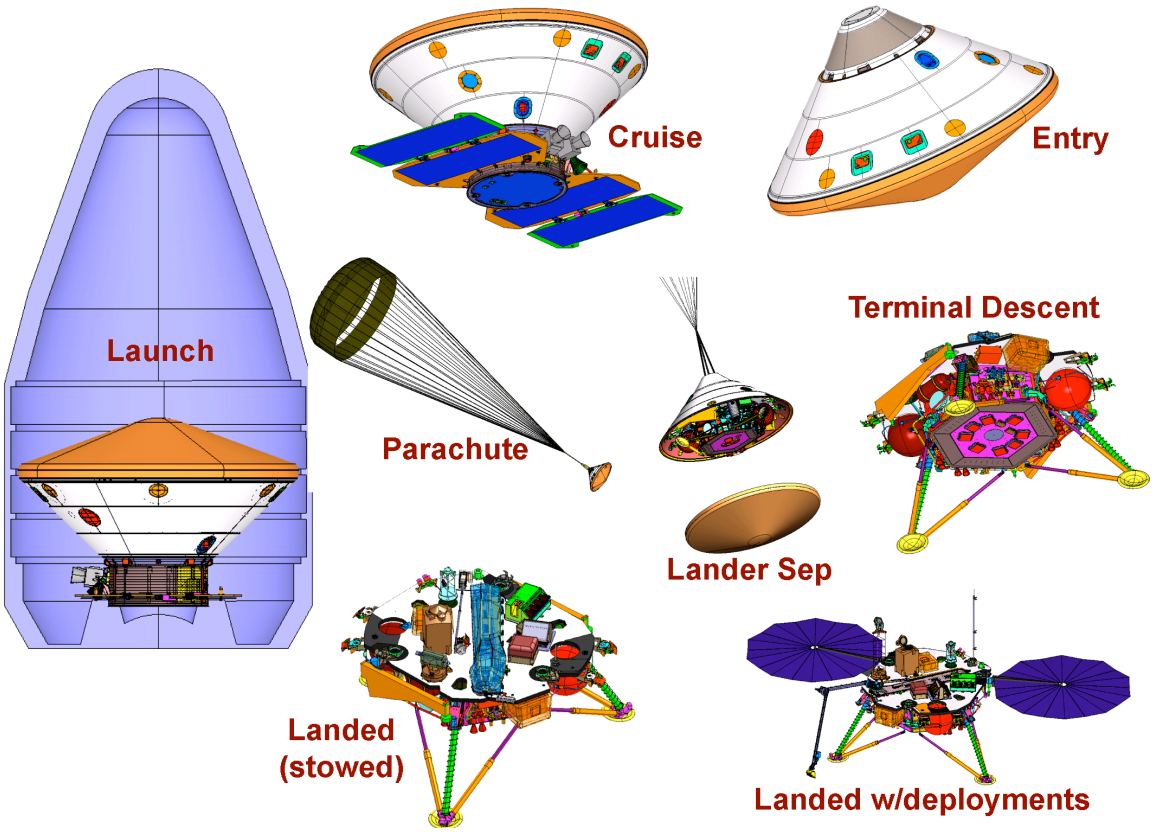

Figure 4 All Possible Configurations of the Phoenix Spacecraft

Following its soft touchdown at an as yet undetermined site between 65°N to 72°N latitude, the Lander will, after waiting 15 minutes for the dust to settle, perform a number of critical activities. These "Sol 0" (a sol is a mars day) activities include deployments of the landed solar arrays, the bio-barrier covering the RA, and the SSI and MET masts. The SSI will be used to take images of the bio-barrier, solar arrays, and part of the footpad and workspace. High priority EDL (including images acquired by MARDI) and Sol 0 data will be saved to Flash memory within the first hour after touchdown, after which the Lander will go to sleep to conserve energy. The Lander will wake up for 10 minutes for the first post-landed UHF communication pass one ODY or MRO orbit period (approximately 2 hours) after landing. After relaying some eagerly anticipated data to the orbiter(s) during that first pass, the Lander will go to sleep again. Payload heaters are on continuously from touchdown, with Lander heaters kicking in around midnight for 4-5 hours of keep-alive heating. Sol 1 activity is expected to begin at roughly 8 a.m. Local Mean Solar Time (LMST) the following sol.

The first seven sols after Landing are known as the Characterization phase, with pre-planned activities running from a minimum of 3 hours on Sol 1 to a maximum of 6.5 hours on Sol 6 (the Lander is active for up to 7 hours during the nominal Surface or "Digging" phase). The performance of the spacecraft's power, thermal, and UHF subsystems will be thoroughly characterized during this phase, and the TEGA, MECA, and MET instruments will go through their initial checkouts and prepare for nominal operations. Concurrent with these activities, the EDL and Sol 0 data that nearly fill the non-volatile, Flash memory will be relayed to the ground, thus making available additional, precious, storage space for newly acquired data. The SSI will image as much of the Lander as it can see and characterize the workspace and surrounding

environment. Most important for mission success will be the "unstow" of the RA and the subsequent practice sample transfers that it will perform on Sol 5. The Robotic Arm Camera (RAC) located on the "wrist" of the RA will be used to image the footpads and the TEGA cover as it is the only imager that can be maneuvered into the proper viewpoint for these pictures. The seventh sol does not currently contain any planned activities because it will be used for margin against activities that fail or otherwise require additional time to complete during Characterization.

After the Robotic Arm is checked out, the Digging phase commences. The Digging phase activities include digging a trench in front of the Lander, and the analysis of soil samples at various trench-depths by the Lander instruments. This phase continues until the End-of-Mission on Sol 90. Operations during this phase will be conducted at the University of Arizona and the mission operators will be working on Mars time (one martian sol is equivalent to 1.02749125 Earth days, or 24 hours, 39 minutes, 35.244 seconds). The main objectives of the Surface phase (from Sol 0 onward), are best summarized by the Mission Success Criteria listed in Table 2.

Table 2 Minimum and Full Mission Success Criteria

Minimum Mission Success	
1.	Land successfully on the surface of Mars and achieve a power safe state.
2.	Acquire a partial 120° monochromatic panorama of the landing site.
3.	Provide samples of the surface soil as well as samples from one depth beneath the surface to either TEGA or MECA wet chemistry.
4.	If TEGA, analyze at least 2 soil samples to create a profile of H_2O (in the form of hydrated minerals, adsorbed water, or possibly ice at the deepest level) and mineral abundances near the surface. It shall also analyze an atmospheric sample in its mass spectrometer.
5.	If MECA, analyze the wet chemistry of 2 soil samples.
6.	Document all non-atmospheric samples and their collection locations with images.

Full Mission Success	
1.	Land successfully on the surface of Mars and achieve a power safe state.
2.	Acquire a true color (RGB), 360° panorama of the landing site
3.	Obtain calibrated optical spectra of at least 3 locations that include both rocks and soil.
4.	Provide temperature and pressure measurements throughout landed surface operations at a frequency that determines key atmospheric properties.
5.	Provide samples of the surface soil, and samples from two depths beneath the surface, to both TEGA and MECA.
6.	Use TEGA to analyze at least 3 soil samples to create a profile of H2O (in the form of hydrated minerals, adsorbed water, or possibly ice at the deepest level) and mineral abundances near the surface. It shall also analyze an atmospheric sample in its mass spectrometer.
7.	Use MECA to analyze the wet chemistry of at least 3 soil samples. It shall also analyze 3 additional samples in its microscopy station.
8.	Document all 9 non-atmospheric samples and their collection locations (before and after sampling) with images.

Additional criteria have been developed that define the science that would be done in an ideal scenario. These criteria basically use up the remaining ability to analyze soil samples (TEGA can do a total of eight and MECA four) and increase the number of experiments done with the TEGA mass spectrometer and the MECA microscopy station. MET measurements would be done daily, and its LIDAR would be used

throughout the Surface phase. SSI would take images every 30 sols to determine atmospheric water vapor, and MECA's thermal and electrical conductivity probe (TECP) would be used extensively.

Given the limited a priori knowledge of the environment at the landing site, it would be futile to generate a detailed plan for the Lander digging activities far in advance of landing. Yet, it is necessary to be able to demonstrate that the objectives of the mission can be achieved for the various circumstances that the Lander might encounter. A more worthwhile approach is to construct a set of scenarios that each makes certain assumptions about the landed environment and resource availability. Each scenario is comprised of a standard set of Lander activities that can be combined into a representative grouping by sol type. The activities and associated resource usage for each sol type can be evaluated once and applied to all occurrences of any particular sol type. Each scenario – an integrated timeline of surface activities – can then be used to model and track mission resources such as payload power draw or data volume generation, and to track the achievement of the mission goals and objectives over time.

The scenarios are used in strategic planning to provide a high-level roadmap for achieving mission success. In actual operations, the activities on any given sol are not likely to be restricted to those that comprise a particular sol type, but rather, will likely include additional activities that both optimize the use of the available resources and augment the science content.

To date, several surface mission scenarios using nine basic sol types have been constructed in an effort to determine how to best achieve the objectives set forth by the mission success criteria shown in Table 2 for a representative set of assumptions. As an example, an overview of a scenario for achieving Full Mission Success is shown in Figure 5. Here, the Lander digs a 35 cm trench in front of the Lander without encountering ice.

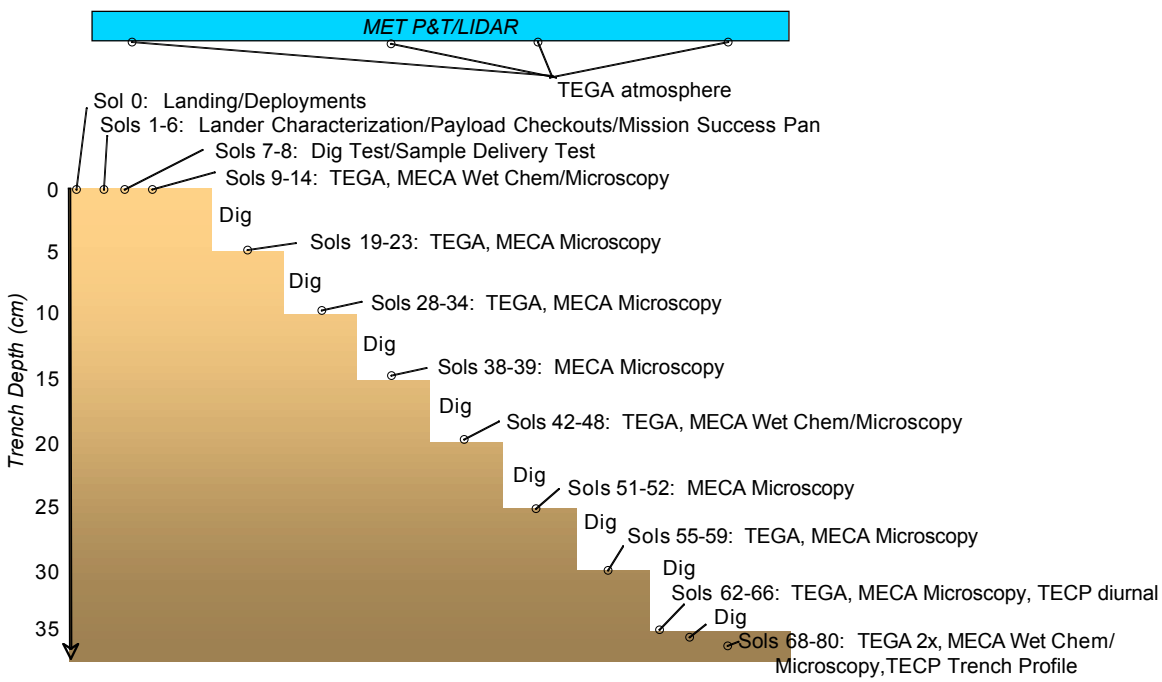

Figure 5 Mission Success Roadmap built using Standard Sol Types for 35 cm Trench/No Ice Scenario

This scenario illustrates the salient features common to the majority of Digging phase scenarios. Initially, surface samples will be collected and delivered to TEGA and MECA. As digging progresses, stereoscopic images of the digging area will be converted into range maps and input into software for RA sequencing. To evaluate when a new sample delivery is needed, soil and ice properties will be monitored

during digging by analyzing images from SSI and RAC and engineering data from the RA. TEGA will provide measurements on subsurface water-ice and their correlation with Odyssey measurements. TEGA samples will be taken every 10 – 15 cm deep, or when layering is obvious. If ice is encountered in the top 50 cm, TEGA samples in the ice will be acquired at a closer depth-spacing. MECA chemistry cells are reserved for samples from the surface, the dry regolith overburden, and the icy layer, with one spare to either repeat a measurement or to explore another layer. Throughout the Digging phase, nighttime environmental measurements will be acquired as resources allow.

LANDING SITE SELECTION

Phoenix is capable of landing almost anywhere on Mars in the latitude band between 65°N and 72°N. The process of selecting that landing site, like it was for the Mars Exploration Rover Missions before it, has been well planned on Phoenix, with an in-depth schedule of interrelated landing site activities laid out early in Phase B of the mission. As with MER, a series of Landing Site Workshops (LSWS) were strategically sprinkled throughout the schedule (see Figure 6) in order to provide science, engineering, and management stakeholders the opportunity to assess progress as the number of potential landing sites was whittled down.

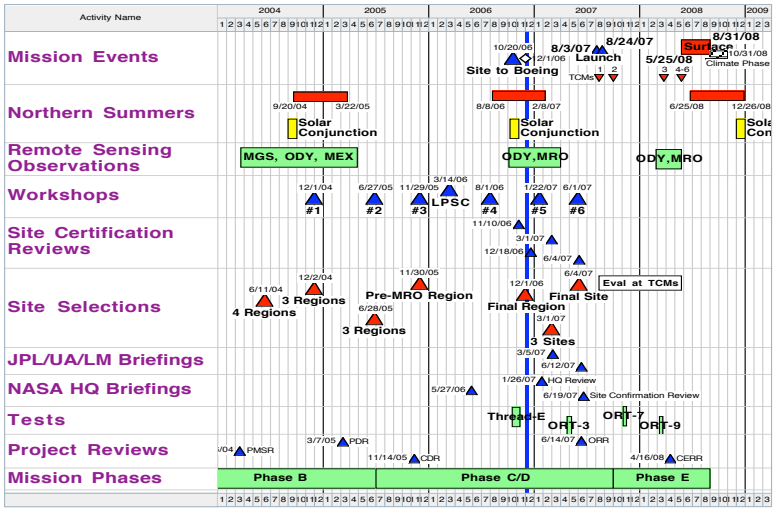

Figure 6 Landing Site Selection Schedule

From the very first Landing Site Workshop (LSWS) in December 2004, a single landing Region (centered at 130°E longitude) stood out from the four candidate 20° longitude by 7° latitude areas as the ideal location from which that final landing site would be chosen. This region appeared to have a low rock abundance, very low elevations, and, more importantly, relatively large amounts of soil (Dry Layer Thickness) over ice. Sites in this "Region B" were chosen for the initial imaging campaign of the High Resolution Imaging Science Experiment (HiRISE) on MRO, a campaign which occurred just prior to MRO's planned hiatus for solar conjunction in October 2006. At approximately 30 cm/pixel, the resolution of the HiRISE images was more than an order of magnitude better than the best images that previously existed of Region B. When these images started hitting the ground, they unfortunately revealed that Region B contained many more rocks than could safely be handled by the Lander.

After the implications of these initial images started sinking in, plans to more strategically image other areas within the latitude band were quickly made. Data sets from the THEMIS instrument on Odyssey, which cover a large portion of Phoenix' latitude band, were reassessed using the HiRISE results as ground truth. Further examination of images from these sets revealed that Regions A and D were likely to have far less rock abundance than was found in Region B. Every two-week observation cycle on MRO following solar conjunction has contained numerous Phoenix landing site imaging requests, with HiRISE images from Cycles 5 and 6 (executing in January 2007) being possibly the last ones that will be usable as clouds and haze have begun to descend upon the scene. Once the conditions deteriorate to the point that HiRISE images are no longer possible, they will likely stay that way until Phoenix is well into its Approach phase to Mars. Because of this, as many HiRISE images as possible have been requested, with key locations prioritized according to where they fit in the landing ellipse. The locations of the imaging targets are shown in Figure 7 where the selection strategy becomes readily apparent. In the Figure, red swaths represent images that have already been acquired, green swaths images that are pending, and blue swaths

images that are requested. Since MRO passes over this northern latitude band numerous times a sol, it has been possible to request a good number of images. After the first couple of Cycles, Phoenix requested more widely spread HiRISE images throughout Regions A and D. As the correlation to THEMIS got tighter, three new safe landing areas were identified based on hazard maps derived from THEMIS data. Those areas appear in blue in Figure 7 and are centered at 68.35°N, 233.0°E (Box 1), 66.75°N, 247.6°E (Box 2), and 71.2°N, 253.0°E (Box 3). Landing ellipses have been superimposed on a background of Mars Orbiter Laser Altimeter (MOLA) data from Box 3 in order to show how the HiRISE images have been chosen. Since the most likely landing will occur inside the 1-sigma ellipse following a launch at the Open of the launch period, HiRISE images should characterize that situation extremely well. Also shown are a 3-sigma ellipse for a launch at the middle of the period, and a 1-sigma ellipse for a launch at the Close of the period. Following Landing Site Workshop #5 in January 2007, these three boxes were reconfirmed as being "safe havens" for landing, with Box 1 taking the early lead as the final landing site location.

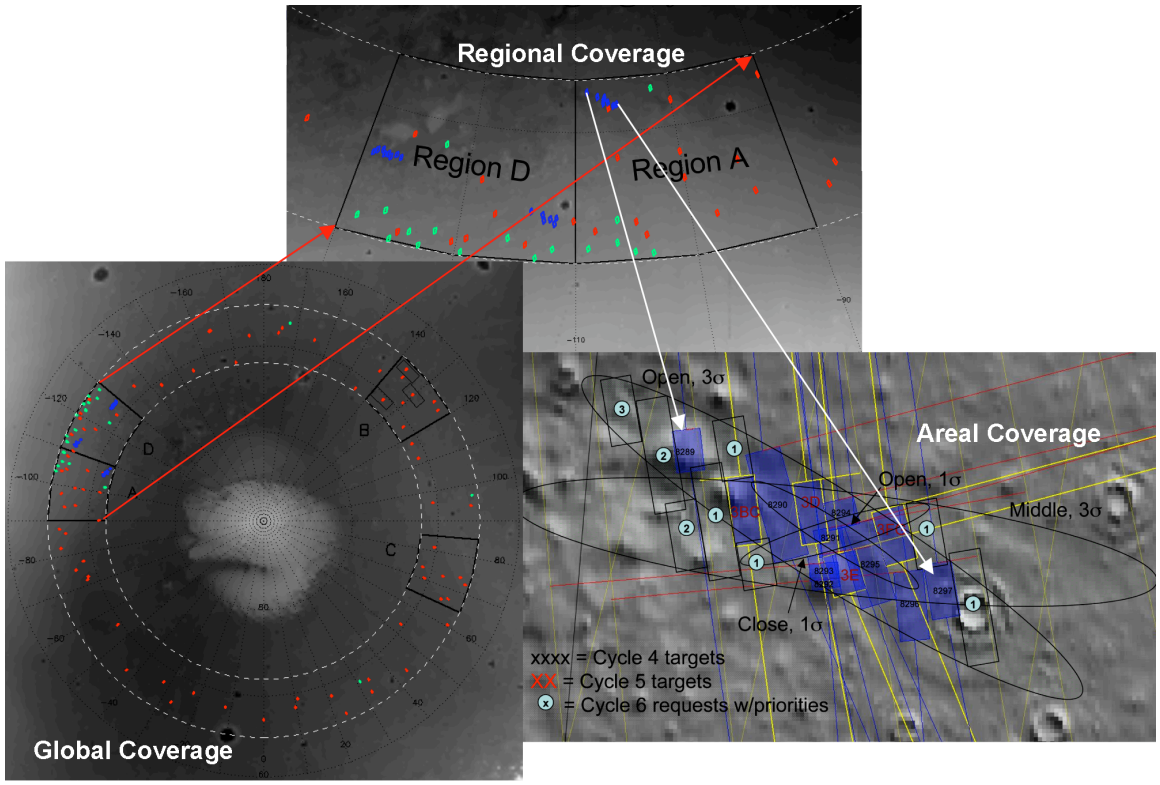

Figure 7 HiRISE Imaging Locations in the Phoenix Latitude Band circa December 2006

MISSION DESIGN HIGHLIGHTS

Phoenix has inherited a lot of hardware from MPL and MSP'01, but workarounds had to be developed in order to accommodate the drastic mission design changes highlighted in Table 1. These workarounds came in many different flavors, from modifying flight hardware to adding more ground resources, to re-optimizing flight plans. Also new for Phoenix is an increased emphasis on JPL Design Principles and the need to show that the design adheres to these principles. Of particular importance to the mission design is the need to guarantee telemetry and command capability during mission critical events; which for critical TCMs has been relaxed to be a guarantee of doppler-only communications. During EDL, the mission design challenge is not only to phase ODY and MRO so that they can close the UHF link when Phoenix flies a nominal trajectory, but to show that the phasing is robust to off-nominal trajectories (for Phoenix and the orbiters) as well. After landing, the challenge has been to answer the many questions that have been

posed concerning the timing and quality of the orbiter's overflights with regard to telecommunications. Because Phoenix has no Direct-from-Earth (DFE) or Direct-to-Earth (DTE) capability once it lands on Mars, the entire Surface operations timeline is further constrained by relay latencies, to say nothing about the fault protection implications. Many of these challenges are described here, with the notable exception of the Surface relay operations that are detailed in Reference 8.

Launch and Initial Acquisition

One may be able to tell just by looking at Figure 4 that the bulk of the spacecraft electronics are buttoned up inside the aeroshell (for all but the last minute or so of the ride to Mars). One of the implications that this has at launch is that when the spacecraft goes to internal power, it heats up fairly rapidly. It heats up so much that it is not yet known if Phoenix will be able to make use of both daily launch attempts (the current spacecraft requirement calls for a "first or second attempt" decision to be made 45 minutes prior to the first attempt). Since Phoenix is a planetary mission with a limited launch period, it is imperative that enough launch days be found to guarantee a 99% probability or better of initiating launch. A contiguous twenty-two day period leads to better than 99% for the Delta II, although the probability of launching early in the period increases if two attempts can be made per day.

The other major issue with the Phoenix launch period is that it occurs during peak summer weather at the CCAFS. Summer thunderstorms and, more importantly, the conditions that lead to induced lightning, occur predominantly in the afternoon. The short-coast trajectory that would have been flown on MSP'01 led to afternoon launches, so the long-coast option was chosen instead for Phoenix. A problem that exists in some launch cases for both long and short coast is the fact that the spacecraft is out of view of a DSN station at separation from the 3rd stage (see Figure 8). For those launch days, Phoenix relies on the ESA ground station at Kourou for line-of-sight visibility of solar array deploy since it is considered a mission critical event. On many of these same days, initial DSN acquisition occurs over the Madrid complex, which is not ideal since there is no acquisition aid there. Because of this, options are being formulated to mitigate the case where the spacecraft is outside the field-of-view of Madrid's 34-meter antenna due to injection errors. Options include using tracking data from Kourou's 15-meter station at Madrid, using Madrid's 26-meter S-band station to track the 3rd stage, as well as optimizing the search pattern based on the shape and orientation of the injection errors.

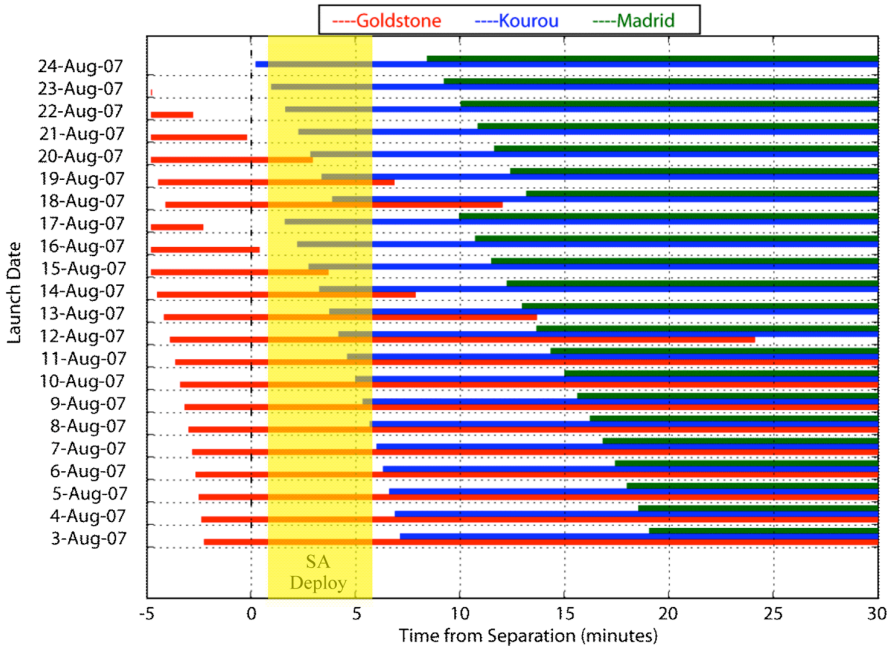

Figure 8 Post-Separation Ground Station Visibility vs. Launch Date, 93° Launch Azimuth

Cruise

Mission design and navigation during cruise is challenging due to both orbital mechanics and spacecraft design. One constraining aspect of the spacecraft design arises from the single monopropellant hydrazine propulsion system that must be shared for both Cruise and EDL. Even though each phase has a fuel allocation, the desire is to use as little fuel as possible prior to EDL. The largest potential cruise user is TCM-1 (Launch+6 days), which has a ΔV_{99} value of 45.8 m/s, mainly to overcome injection errors from the launch vehicle. Further challenges come from the fact that Phoenix is a 3-axis stabilized spacecraft that uses thrusters for attitude control during Cruise, and since these same thrusters are also used during EDL, they must extend through, and be scarfed to the contour of, the backshell.[6] TCM thruster nozzles point in the –X spacecraft axis direction, yet their thrust direction is slightly offset due to scarfing. Reaction Control System (RCS) thrusters are used for deadband maintenance and have thrust components in all three spacecraft axes. RCS thrust directions are designed to balance out in Y and Z (not X), but due to non-determinism of the attitude maintenance schedule, a ΔV imbalance may build up in these directions. Likewise, every time a thruster (RCS or TCM) is fired there is a ΔV in the +X direction. Accounting for TCM execution errors and deadband thrusting effects in navigation's Small Force model are perhaps the biggest challenges during Cruise as the spacecraft is delivered to its inertial Entry Flight Path Angle requirement of –13.0° ±0.29° (3σ) at the atmospheric entry interface (3522.2 km from the center of Mars).

Maneuver analyses have shown that a total of six TCMs are required to compensate for errors associated with launch vehicle injection, maneuver execution, and orbit determination. These six TCMs are strategically placed to meet both the mission total TCM ΔV_{99} allocation of 56 m/s and the delivery accuracy requirement stated above. In particular, TCM-1 must occur as early as 6 days after launch in order to meet ΔV_{99} requirements imposed by a 3σ injection and because of the proximity to the 180° transfer date. TCM-6 (Entry-22 hours) has been pushed as far from Entry as possible while still meeting the delivery accuracy requirement. See Figure 9 at right for the location and timing of the TCMs corresponding to a launch at the Open of the period (8/3/2007).

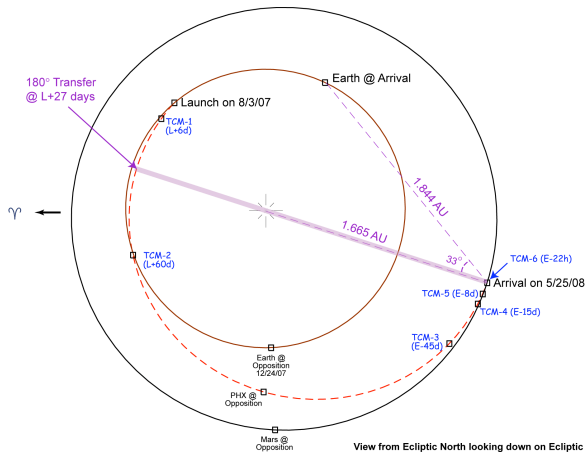

Figure 9 Interplanetary Trajectory (Open Launch)

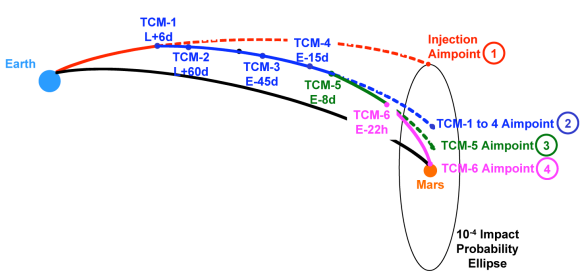

Figure 10 TCM Aimpoint Design

Also influencing the TCM design are requirements for planetary protection and critical event communications (previously mentioned Design Principle). Figure 10 at left shows how the injection aimpoint is biased so that the 3rd stage has a 10^{-4} probability or less of impacting Mars, and how only TCM-6 of the remaining maneuvers actually targets Entry. TCMs 1 through 4 target an intermediate aimpoint determined to minimize propellant consumption prior to TCM-5. TCM-5's aimpoint is biased away from Mars in a direction that allows for 99% or more of the possible TCM-6 maneuvers to be in an attitude that guarantees telecom.

Cruise activities have been planned that will improve the orbit determination accuracy (see Mission Timeline in Figure 3). Improvement during the early part of Cruise is gained by acquiring a better understanding of the small force environment (Active and Passive Thruster Calibrations) and by going

beyond the minimum necessary tracking to acquire a robust orbit determination solution for the spacecraft early in its journey to Mars (weekly ΔDOR measurements in addition to thrice weekly 8-hour ranging and Doppler passes during Cruise). During the Approach phase (E-60 days onward), the tracking ramps up considerably with continuous Doppler and ranging measurements throughout, and ΔDOR measurements going from twice weekly at the beginning of Approach to twice daily (maximum) during the last 18 days to support the design of the final three TCMs.

During Cruise, the spacecraft orientation is dictated by pointing constraints for the various cruise stage components. The main constraints are the following:

- the star tracker to Sun angle be maintained above 80° for thermal reasons (50° is the requirement for bright object avoidance)
- the Sun to SSPA boresight angle be maintained above 80°
- the Earth to LGA boresight (-X axis) be maintained below an angle (90° max) that allows 40 bps to a 34-meter DSN station out to a distance of 0.5 AU
- the Earth to MGA boresight be maintained below an angle (57.5° max) that allows 40 bps to a 34-meter DSN station beyond a distance of 0.5 AU
- the Sun to Solar Array (SA) normal angle be maintained below 60° in early cruise and below 4° in late cruise (Day 225 onward for launch at the Open of the period)

Deadbands while in the Inner Cruise Attitude (see Figure 11 where SA normal target is 53° from Sun) are tighter than they are when the switch is made to the Outer Cruise Attitude (L+88 days, green cone near +Z arrow is MGA). Once the active antenna is switched to the MGA (L+156 days), the deadbands start to tighten up again. By L+225 days, the Solar Array constraint begins to dominate as the spacecraft gets farther from the Sun and power generation becomes more difficult. In the launch period Close case, the late cruise Solar Array constraint kicks in about 30 days earlier. In order to maintain the tighter late-Cruise pointing, the number of thruster pulses goes up to almost 500/day (from an average of approximately 70/day between L+88 and L+225 days). Continuous DSN coverage during this entire period helps gain visibility into these firings, and periods of 70-meter DSN coverage allow the downlinking of onboard small force data at increased rates to aid trajectory reconstruction.

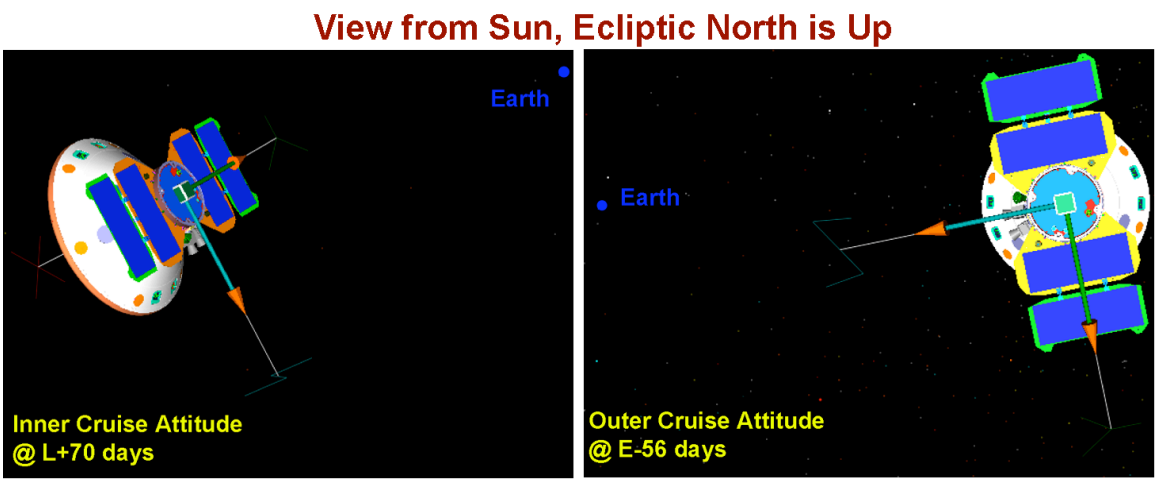

Figure 11 Cruise Attitude Profile Snapshots

Approach

The Approach subphase has the most sustained levels of high activity during Cruise for the mission operators, with the last 2 days being exceptionally busy planning the final TCM(s) and preparing for last minute updates to the EDL flight software parameters. The development timeline for the final TCMs, i.e.,

TCM-6 at E-22 hours and it's backup TCM-6x at E-8 hours, has been shortened from the 5 days available for the earlier TCMs to just 26 hours. This shortening is necessary because the Orbit Determination (OD) solution is not accurate enough to meet the delivery requirements until the spacecraft gets relatively close to Mars. In the current scenario, 26 hours gives enough time to complete all the major TCM development steps, including 8 hours to test the sequence on the simulator (see Figure 12). The timeline also allows for the backup maneuver to execute over a separate DSN station (which provides robustness to an entire DSN complex going down). The OD solution is accurate enough to meet Entry Knowledge requirements at approximately E-7.5 hours in either the TCM-6 or TCM-6x case. From this solution, an Entry State File will be generated and fed into the final EDL parameter update process. The EDL configuration file that results from this process will be uplinked to the spacecraft at E-3 hours, giving enough time to resend the file if necessary (roundtrip lighttime is approximately 30 minutes).

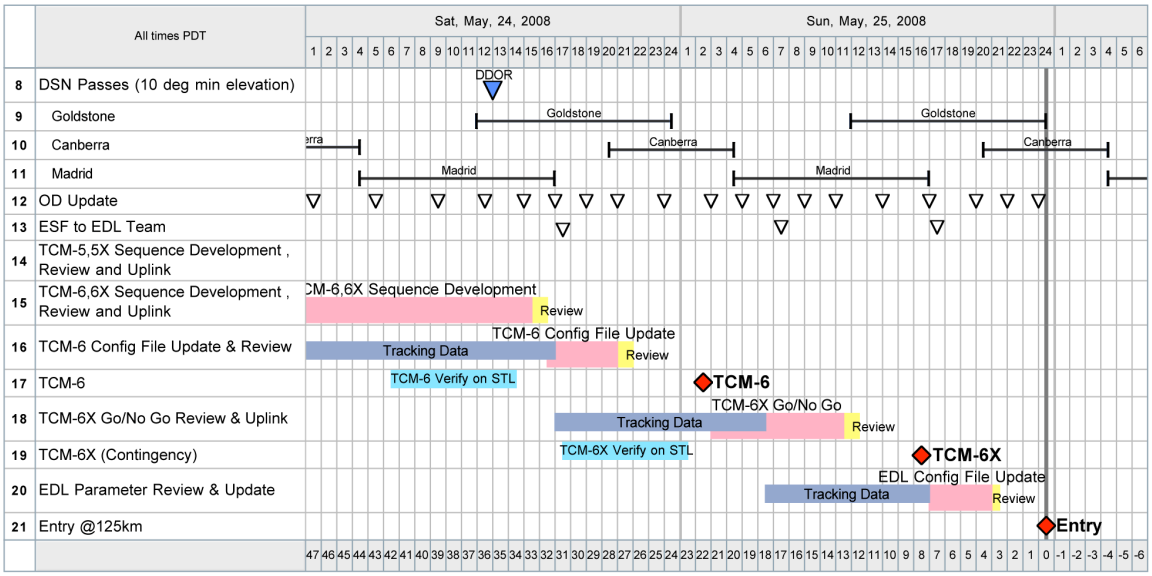

Figure 12 Approach End Game Sequence Development Timeline

EDL Communications

During most of EDL, Phoenix uses a UHF antenna that wraps around the backshell (Figure 4) to give it a wide field of view (FOV) for communications. During terminal descent (approximately 30 seconds before landing), the Lander switches to the landed Helix antenna and continues transmitting a UHF signal until one minute after landing. As can be seen in Figures 13 and 14, this wide FOV is necessary as the geometry between Phoenix and the orbiters MRO, ODY, and Mars Express (MEX) requires a very wide spread of off-boresight angles. Although not currently in the solution space, MEX is shown where it would be phased to support EDL in the event that it becomes available in the future. As can be seen in the figures, MEX has a very different EDL vantage point than do MRO and ODY.

One will notice a decided difference in the relative geometry between Phoenix and the orbiters at Open than at Close. In particular, Cruise Stage Separation (the point on the trajectory where the Phoenix spacecraft is drawn) occurs much closer to MRO's orbit plane at the Open than the Close, and landing occurs between the two orbit planes at Open and never even reaches MRO's orbit plane at Close. These differences have an effect on UHF telecommunications performance during EDL as highlighted in Figures 15 and 16. These two figures show the power received signatures at MRO for a number of possible Phoenix trajectories for Open and Close landings at the extremes of Phoenix' latitude band. The Open cases show a relatively narrow band of possible received power signatures as a function of time during EDL, no matter what Phoenix EDL trajectory simulation is used. And although MRO's received power levels at Open never get quite as high as they do at the Close, they all appear to be much more stable despite the fact that wide attitude swings can and do occur while on the chute. The wide swings are not the

only reason for the deep power drops seen in the maximum and 99% long trajectories at Close. These occur mainly because MRO happens to be roughly overhead on these trajectories and sitting near a deep null in the wrap around gain pattern. Once MRO passes out of this null the received power levels go back up much higher than they are at Open. Additional simulations are being run to determine how robust the received power levels are to orbiters that are within 30 seconds of the optimal phasing location for EDL communications. As is the case with the simulations that have already been done, it is expected that the overwhelming majority of possible trajectories will have strong and stable links for the entirety of EDL.

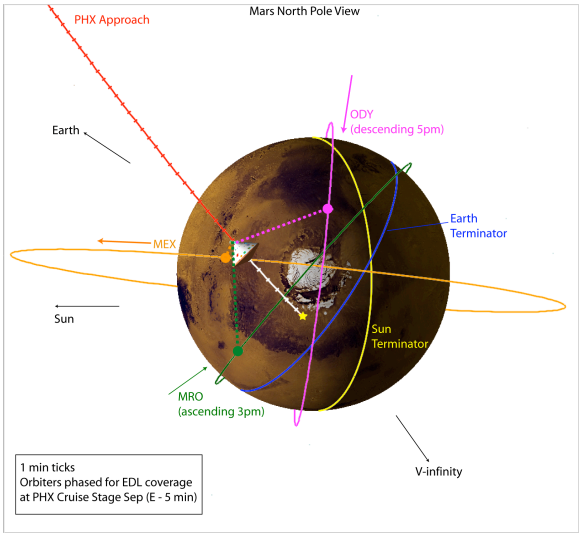

Figure 13 EDL Communications Geometry, Open Launch

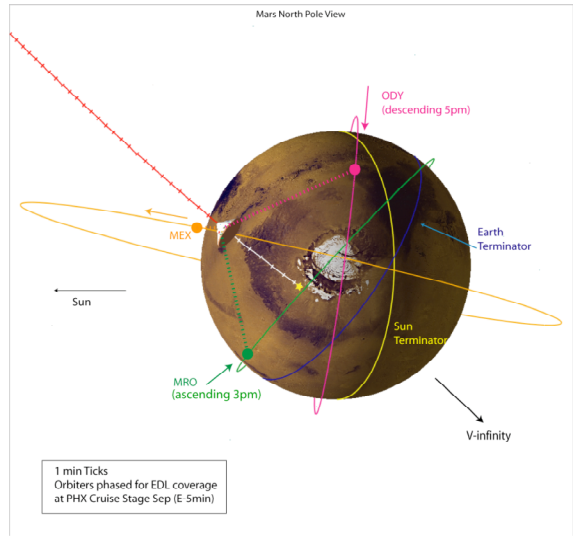

Figure 14 EDL Communications Geometry, Close Launch

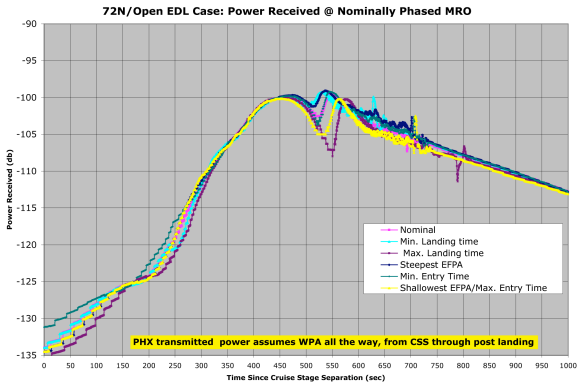

Figure 15 Power Received @ MRO, 72N/Open, Max/Min cases

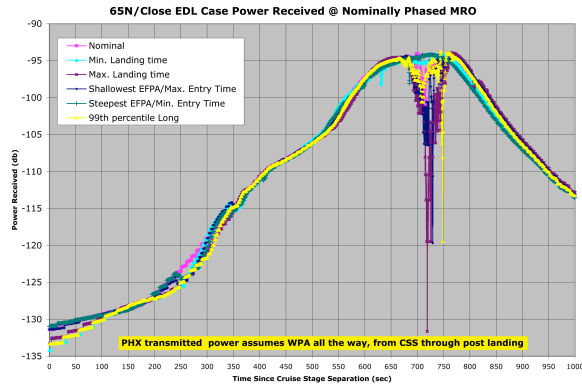

Figure 16 Power Received @ MRO, 65N/Close, Max/Min cases

CONCLUSION

The Phoenix 2007 Mars Lander has inherited much from previous Mars missions, yet its mission design has had many unique challenges that have been met head on with creative and robust solutions. Phoenix depends a great deal on the Deep Space Network and the in situ orbiters at Mars to realize these robust solutions, and is therefore very thankful of their contribution. Actually landing on another planet and digging down and touching, analyzing, and understanding its water-ice content is a goal that will make all of the cooperation well worth the effort.

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