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Flight Path Control Strategies and Preliminary ΔV Requirements for the 2007 Mars Phoenix (PHX) Mission

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Abstract

In August 2007, the Mars Phoenix (PHX) Project will launch a spacecraft to Mars whose objective is to deliver a stationary lander to a landing site in the latitude band from 65° N to 72° N. Instruments on the lander will perform in-situ and remote-sensing investigations to characterize the chemistry of materials at the local surface, subsurface, and atmosphere. Lander instruments will also identify the potential provenance of key indicator elements of significance to the biological potential of Mars, including potential organics within any accessible water ice. This paper describes the methods used to estimate the statistical ΔV requirements for the propulsive maneuvers that will deliver the spacecraft to its target landing site while satisfying planetary protection requirements. The paper presents flight path control analysis results for three different trajectories, open, middle, and close of launch period for the mission. The results for a representative landing site (70° N, 230° E) indicate that the *open* case involves the most demanding ΔV requirement (52.4 m/s) and that the inertial atmospheric entry flight path angle delivery requirement of -12.5 ± 0.27 (3σ) degrees is achievable.

Introduction

The PHX Project will launch a spacecraft to Mars in the 2007 launch opportunity with the objective of delivering a stationary lander to a landing site in the latitude band from 65° N to 72° N. During the baseline 90 Sol (~92.5 Earth days) surface mission, instruments on the lander will perform in-situ and remote-sensing investigations to characterize the chemistry of materials at the local surface, subsurface, and atmosphere. Lander instruments will also identify the potential provenance of key indicator elements of significance to the biological potential of Mars, including potential organics within any accessible water ice. PHX will be launched on a Boeing Delta II 7925 launch vehicle from Space Launch Complex 17A (SLC-17A) at the Cape Canaveral Air Force Station (CCAFS) during a 22-day launch period extending from August 3, 2007 through August 24, 2007. To meet various project constraints, the first 15 launch days target the spacecraft for arrival at Mars on May 25, 2008, while the remainder target arrival on June 5, 2008. The spacecraft will follow a Type 2 trajectory to Mars. The flight system consists of a cruise stage; an entry, descent, and landing (EDL) system (including heatshield, backshell, parachute, and terminal descent engines); and a lander structure that is enclosed within the entry vehicle. The launch mass allocation for the flight systems is 705 kg.[¥]

During the approximately 10-month interplanetary transfer, which includes the cruise and approach mission phases, six planned trajectory correction maneuvers (TCMs) will deliver the entry vehicle to the specified Mars

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[¥] The analyses reported in this paper are based on an earlier mission design baseline (e.g., landing site and first leg arrival date). Although the current baseline has some differences, the results in the paper are, nevertheless, valid.

atmospheric entry aimpoint. Moreover, telecom, navigation, and science instrument checkouts are also performed during the Cruise phase. The EDL phase begins three hours before the atmospheric entry interface point, which is defined to be at a Mars radius of 3522.2 km.

EDL will adapt the concept developed for Mars ’01 Lander baseline: first utilizing the aeroshell to decelerate the entry vehicle through the ballistic hypersonic phase, then using a parachute to slow descent through the Martian atmosphere, and finally employing the terminal descent engines and the attitude control system to place the Lander on the Martian surface in an orientation within 5 degrees of facing North. Once the Lander senses the touchdown event, the system begins to deploy the solar arrays and gyro compassing is performed to determine its landing attitude. The entry vehicle will communicate with Mars orbiters during EDL via a wrap-around UHF patch antenna mounted on the backshell.

After landing at one of the candidate landing sites contained within a latitude band between 65 deg North and 72 deg North, the PHX Lander will begin its 90-Sol (92.5-Earth-day) primary Surface Operations phase. The Lander will employ six science instruments and a robotic arm to record data about the landing sites and selected rock and soil targets. The science payload consists of three imaging instruments, two instruments for in-situ observations and a meteorological station:

The robotic arm is capable of digging up to 1m deep from which it will scoop samples for delivery to the in-situ observation instruments. Science data is returned to Earth via a UHF link to one of the Mars orbiters.

The PHX mission is comprised of the following 5 principal phases:

- **The Launch Phase** begins when the spacecraft transfers to internal power prior to launch and ends when the Flight System achieves a thermally stable, positive energy balance, with the radio link established and the cruise solar array deployed.
- **The Cruise phase** encompasses the majority of the interplanetary transfer to Mars, begins when the Launch phase ends and ends three hours prior to Mars entry interface when the final EDL parameter updates are activated in the onboard sequence.
- **The Approach phase** is a sub-phase of the cruise phase and begins 8 weeks prior to Mars entry. The end coincides with the end of the Cruise phase.
- **The Entry, Descent, and Landing (EDL) phase** begins three hours prior to the Mars atmospheric entry interface point and ends with confirmation on the Earth that at least one landed SA is deployed, positive thermal/power balance state is achieved, a functioning radio link exists, uplink loss timer is reset, and surface fault protection is enabled.
- **The Surface phase** begins when the EDL phase ends and ends when the primary mission is complete (90 sols after landing).

Spacecraft Configuration

Figure 1 shows the PHX spacecraft in cruise configuration. Figure 2 shows an expanded view of the PHX flight system. The PHX flight system is almost entirely made up of existing Mars Surveyor Program 2001 (MSP’01) spacecraft hardware. The MSP’01 design is an adaptation of the Mars Polar Lander (MPL) spacecraft design. During flight, PHX is a three-axis stabilized spacecraft with four RCS thrusters. The PHX flight system consists of four major components: cruise stage, backshell, Lander structure

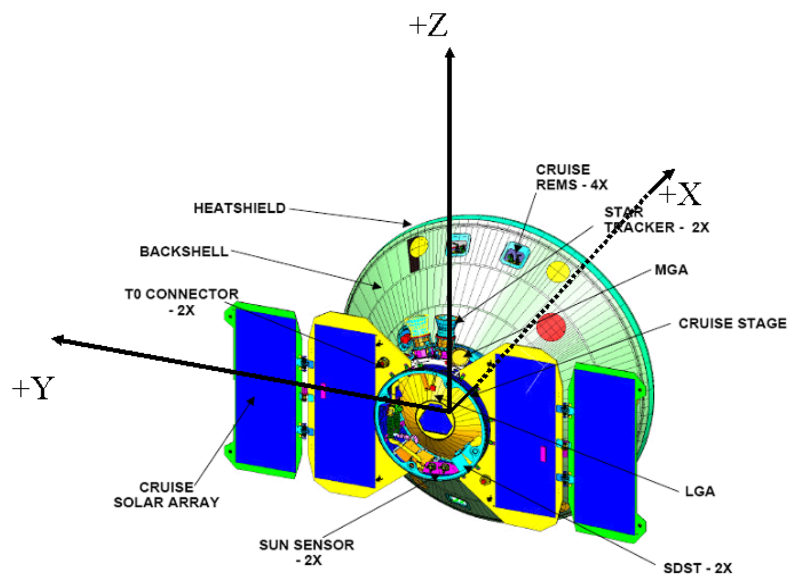


Figure 1. Spacecraft in Cruise Configuration

(containing the payload), and the heatshield. The mass allocation for the entire flight system (including propellant load) is 705 kg.

The cruise stage includes solar panels, attitude control sensors (sun sensor, star tracker), telecom antennas (LGA and MGA), and two X-band transponders. Both antennas are oriented generally in the spacecraft -X direction. The MGA boresight is in the X-Z plane and is offset from the – X-axis by about 32 degrees in order to maintain optimal telecom performance in the nominal cruise attitude. The cruise stage is separated from the entry vehicle assembly approximately 5 min prior to Entry.

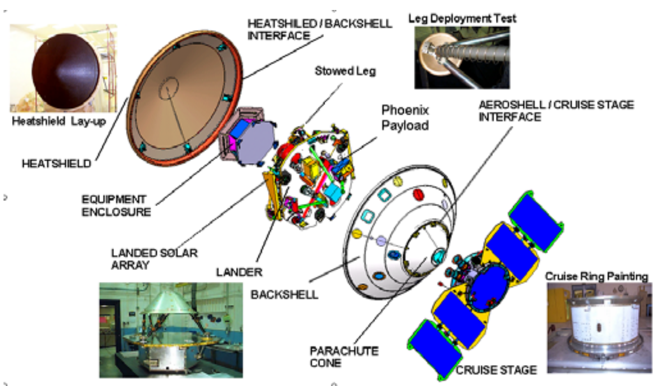


Figure 2. Spacecraft Component Diagram.

During the interplanetary transfer to Mars, the Lander structure (containing the payload and the propulsion system) is enclosed by the backshell/heatshield assembly, which is also referred to as the aeroshell. The aeroshell protects the Lander from extreme heat loads experienced during atmospheric entry and descend. The backshell includes the parachute canister used to slow the Lander prior to terminal descent. The terminal descent system, located on the Lander, is used to control the Lander for touchdown onto the surface. The backshell also includes a wrap-around UHF patch antenna for communications during EDL.

The Lander includes the science instruments described earlier, solar arrays, batteries, and a UHF antenna for the relay link to the Mars orbiters. All of the electronics that perform spacecraft functions (including during interplanetary cruise) are contained on the Lander. Figure 3 shows the Lander as it might appear on the surface of Mars.

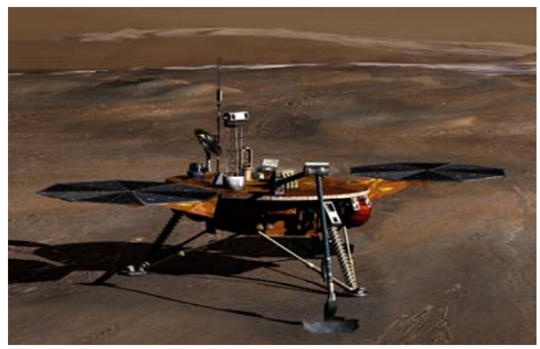


Figure 3. Lander as it might appear on the surface of Mars.

Spacecraft Propulsion System

The PHX propulsion system, inside the entry vehicle, is a monopropellant hydrazine system that operates in a blowdown mode. The system includes the hardware needed to perform attitude control, TCMs, and terminal descent control during Cruise, Approach and EDL phases. The hardware consists of two propellant tanks , four 1-lbf reaction control system (RCS) thrusters, four 5-lbf TCM thrusters, and 12 68-lbf terminal descent thrusters. The two propellant tanks are pressurized with Helium at a nominal tank pressure of 449 psia and have the capacity to carry 61.6 kg of usable propellant.

There are four rocket engine modules (REMs) that are used during the Cruise phase. Each REM consists of an RCS thruster and a TCM thruster. Both the RCS and TCM thrusters are mounted on the Lander and extend through the backshell. Each thruster is scarfed to the contour of the backshell. All TCM thruster nozzles are in the –X-axis direction in spacecraft coordinate system. Due to the scarfed thrusters, the thrust direction is offset from the nozzle direction.

Each RCS thruster has a component of thrust in all three spacecraft axes. The thrust directions are designed to be balanced in the Y and Z axes but not in the X axis. Therefore, every time an RCS thruster is fired there is a ΔV imparted to the spacecraft in the X direction. Although the Y and Z directions are designed to be balanced, the non-determinism of attitude maintenance (deadbanding) may cause one thruster to be fired more than another, which causes an over all imbalance that imparts ΔV in the Y and Z directions. Additional ΔV is imparted to the spacecraft in those directions due to thruster misalignments and thruster-to-thruster thrust variations.

The specific impulse (I_{sp}) values for each thruster vary depending on the inlet pressure and duty cycle. The range for the RCS and TCM thrusters is shown in Table 1.

Table 1. Propulsion System Isp Values.

Thrusters	Minimum	Maximum
RCS	100 s	215 s
TCM*	221.0 s	224 s

* A normal distribution with ±6.7 s (3σ) about the mean value is assumed in mission propellant calculations.

Spacecraft Telecom System

The PHX telecommunications subsystem uses X-band for direct-to-Earth (DTE) communications during the cruise phase. A UHF system is used during EDL and surface phases of the mission for relay communications through the Mars orbiters.

The X-band telecommunications system design is dual-string coherent X-Band Uplink/X-Band Downlink with electronics located on the cruise stage. The same X-band electronics are used from launch through cruise, but two different X-band antennas, an LGA and MGA, are required. For communications purposes, LGA is used from 0 to 0.5 AU Earth-range and MGA is used from 0.5 AU up to Mars atmospheric entry interface.

The UHF equipment is in the Lander and is used with two different antenna sets:

- A wrap-around patch UHF antenna on the backshell for UHF during EDL.
- A UHF antenna on the Lander for surface operations.

The X-band telecommunications equipment includes two Small Deep Space Transponders (SDST) and two Solid State Power Amplifiers (SSPAs). The SDST includes a Command Detector Unit (CDU) and a Telemetry Modulation Unit (TMU). The heart of the X-Band telecommunications systems are the SDSTs, which support phase coherent turn-around Doppler and ranging, command signal demodulation and detection, telemetry coding and modulation, and DOR tone generation (at ± 19 MHz).

Spacecraft Attitude Maintenance Strategy

The LGA boresight and the normal direction to the cruise stage solar panels are both along the spacecraft -X-axis, while the MGA boresight points 32° away from the -X-axis direction. The cruise attitude strategy is to maintain the -X-axis pointed in the direction of the Sun while keeping the MGA boresight as close as possible to the Earth. This strategy allows a telecom link to Earth using the LGA or MGA antenna, while providing sufficient power for spacecraft operations.

The PHX is a three-axis stabilized spacecraft; hence, its attitude will drift due to external perturbations. The attitude will be allowed to vary within a set of deadbanding constraints defined by spacecraft telecom, power and thermal subsystems. The Attitude Articulation and Control System (AACS) will command the thrusters to fire each time the attitude reaches the limits of the deadband. The deadbanding strategy varies during cruise based on the constraints, the Sun-Earth-probe (SEP) angle, and the spacecraft range to the Sun and Earth. The tighter the deadbands, the more thrusting is needed to keep the attitude inside the constraints. This, in turn, imparts more ΔV and uncertainty into the trajectory.

It is important to model the ΔV imparted to the system in the OD process in order to meet the delivery accuracy requirements for atmospheric entry. For this reason, the flight system records a telemetry packet with thruster information every time a thruster pulse is fired. That telemetry is downlinked and transformed into a text file known as the Small Force File (SFF), which is directly input into the OD and trajectory propagation process. The SFF contains information such as pulse time, pulse length, thruster number, estimated ΔV, and attitude at the time of the pulse.

Navigation System

The navigation system is the set of processes, procedures, software and hardware tools, and interfaces that are used to accomplish navigation functions during flight operations. The navigation system is operated by the Navigation Team, which is staffed by trained personnel who possess the capabilities and skills required to carry out the objectives set forth by the PHX navigation requirements. The principle requirement on the navigation system is to deliver the PHX entry vehicle to the atmospheric entry interface point with a 1σ accuracy of ±0.27 degrees for inertial flight path angle and ±1.5 seconds for entry time.

The navigation system consists of three general functional elements: spacecraft trajectory propagation and analysis, spacecraft trajectory and Lander position determination, and propulsive maneuver design and analysis. The primary navigation functions during PHX flight operations are the following:

- Process radiometric tracking data (Doppler, range, ΔVLBI, UHF) to estimate the spacecraft trajectory and associated uncertainties.
- Perform EDL trajectory analysis to determine desired atmospheric entry aimpoints for Trajectory Correction Maneuvers (TCMs) and to evaluate landing site coordinates and landing footprints.
- Determine the desired ΔV vector for TCMs to achieve the specified atmospheric entry aimpoint and verify the TCM implementation provided by spacecraft team.
- Generate the spacecraft ephemeris and ancillary trajectory data products.
- Provide real-time monitoring during TCMs and reconstruct the TCM ΔV using pre- and post-TCM tracking data.
- Perform EDL trajectory analysis to provide inputs for uplink of EDL parameter updates.
- Process PHX and Mars Odyssey or Mars Reconnaissance Orbiter radiometric tracking data to estimate the Lander position on the surface of Mars and the associated uncertainties.
- Provide support for the UHF communications links between the Lander and the Mars orbiters.

Trajectory Propagation

The dynamics of the spacecraft are modeled by a set of non-linear ordinary differential equations. The acceleration vector for the spacecraft (in an inertial frame) is computed by summing the forces acting on the spacecraft, including gravity, solar pressure, and other non-gravitational forces such as propulsive maneuvers (TCMs) and unbalanced forces resulting from spacecraft attitude maintenance. The computation and prediction of the spacecraft trajectory is accomplished by double precision numerical integration of the equations of motion. Figure 4 shows the PHX interplanetary trajectory, along with some of the major events during flight, for the Open of the launch period (08/03/07 launch).

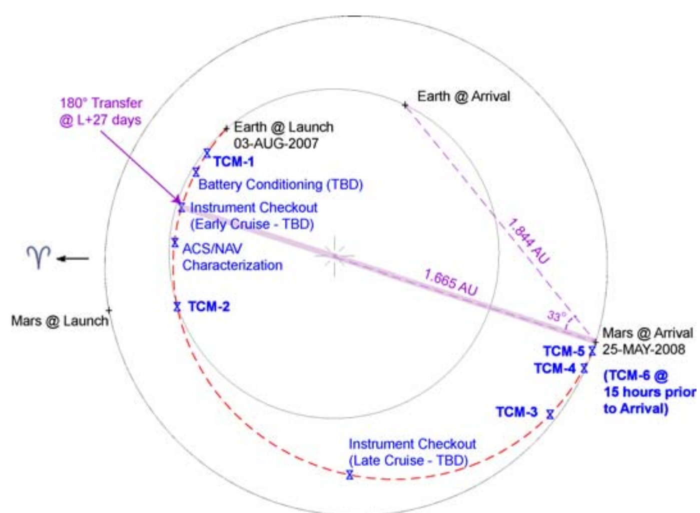


Figure 4. PHX Interplanetary Trajectory (Launch Period Open: 8/03/07).

Orbit Determination

Orbit determination (OD) is the process of determining the trajectory of the spacecraft based on radiometric tracking data. The OD solutions developed from this process are used for the generation of high-precision numerically integrated trajectories and related trajectory data products. The OD process supports:

- Prediction of the atmospheric entry conditions at Mars for propulsive maneuver design and for atmospheric trajectory simulations.
- Generation of spacecraft ephemeris files used for DSN pointing predicts and for other purposes.
- Generation of various trajectory data products used for mission planning, spacecraft engineering analysis, sequence development, and science data analysis.

- Generation of ephemeris information for AACS.
- Generation of estimates of areocentric Lander position during Surface operations.

The baseline radiometric data types that will be used for PHX orbit determination are two-way coherent Doppler, two-way ranging, and ΔVLBI measurements generated by the DSN X-band tracking system or a spacecraft to spacecraft UHF system. The first two data types are derived from a coherent radio link between the spacecraft and a receiver at a DSN ground station. ΔVLBI measurements will be acquired through the DSN in the form of Delta Differential One-way Range (ΔDOR) measurements. Spacecraft to spacecraft two-way coherent UHF Doppler will be generated by a link between the PHX spacecraft and a Mars orbiting spacecraft during the EDL phase.

Maneuver Analysis and Design

In order to achieve a successful landing on Mars, the PHX spacecraft must be delivered to the proper Mars atmospheric entry aimpoint by a series of trajectory correction maneuvers (TCMs). A total of six TCMs are planned during interplanetary cruise. These maneuvers are required to compensate for launch vehicle injection errors and subsequent maneuver execution and orbit determination errors

Propulsive Maneuver Calculations

For each maneuver, the magnitude and direction of the velocity change required to correct for errors in the desired Mars arrival conditions must be computed. These quantities are determined from an estimate of the actual arrival conditions obtained through the orbit determination process outlined above. In addition, a means of estimating the statistics of the residual guidance errors due to imperfect maneuver execution is needed. These statistics are derived from estimates of the maneuver execution accuracy and the orbit determination error statistics computed as part of the orbit determination process.

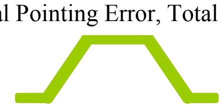
Propulsive Maneuver Implementation Modes

The PHX spacecraft performs TCMs in a turn and burn mode. The four TCM thrusters are collocated with the RCS thrusters, which are evenly distributed around the spacecraft backshell. Although TCM thruster nozzles are parallel to the X-axis, the scarfing leads to a thrust vector deviation approximately 2.5 degrees radially away from the -X-axis. However, since this deviation is very small, thrust cosine losses are negligible. In order for a TCM to take place along a desired ΔV direction, the spacecraft must turn to align the spacecraft -X-axis with the desired thrust direction (negative ΔV direction). The TCM is executed by pulsing the TCM thrusters until the desired ΔV is accomplished as measured by the IMU. The spacecraft is three-axis stabilized during the burn using the RCS thrusters. After execution, the spacecraft performs a slew back to the nominal pre-TCM attitude.

Maneuver Execution Accuracy

The accuracy with which a given maneuver can be executed is a function of the propulsion system behavior and the attitude control system, which maintains the pointing of the spacecraft during thruster firings. Maneuver execution errors are described in terms of components that are proportional to the commanded ΔV magnitude and components that are independent of ΔV magnitude. The maneuver execution errors are described as a function of ΔV in Table2.

Table 2. Maneuver Execution Errors (3σ)

Delta V Magnitude (m/s)	Fixed Magnitude Error (m/s)	Proportional Magnitude Error (%)	Fixed Pointing Error, per axis (m/s)	Proportional Pointing Error, Total (%) 
0.04 (minimum burn) <dV < 0.3	0.02 m/s	± 2 %	0.003	± 2 %
0.3 < dV <1.5	0.02 m/s	± 2 %	0.003	± (8/1.2 * |dV|) %
1.5 < dV < 5	0.02 m/s	± 2 %	0.003	± 10 %
5 < dV < 20	*	± 2 %	0.003	± ((- 8/15) * |dV| + 12.667) %
20 <<dV	*	± 2 %	0.003	± 2 %

TCM Profile

A series of six TCMs are planned during the Cruise and Approach phases of the mission in order to achieve the desired Mars atmospheric delivery accuracy. Table 3 lists, for each TCM, the name, nominal execution time, orbit determination data cutoff time, and a description of the maneuver.

Table 3. Interplanetary Cruise TCM Profile

TCM	Time*	OD Data Cutoff	Description
TCM-1	L + 10 days	TCM – 5 days	Correct fraction of injection errors, remove fraction of injection bias for planetary protection.
TCM-2	L + 60 days	TCM – 5 days	Remove most of the remainder of injection errors and bias, correct TCM-1 errors, and potentially retarget to desired landing site. Will contain a deterministic component.
TCM-3	E – 45 days	TCM – 5 days	Remove remainder of injection errors and bias, correct TCM-2 errors, and target the desired landing site. Will contain a deterministic component.
TCM-4	E – 15 days	TCM – 24 hrs	Correct TCM-3 errors.
TCM-5	E – 8 days	TCM – 24 hrs	Correct TCM-4 errors.
TCM-5x	E – 6 days	TCM – 24 hrs	Correct TCM-4 errors. Performed if TCM -5 does not occur.
TCM-6	E – 14 hrs	TCM – 8 hrs	Correct TCM-5/5x errors.
TCM-6x	E – 6 hrs	TCM – 8 hrs	Final opportunity for entry targeting maneuver. Performed if TCM-6 does not occur.

* Time measured from Launch (L) or Entry (E).

The locations of the TCMs are chosen as a compromise between competing requirements:

- Provide sufficient time between Launch and TCM-1 for spacecraft checkout and design of TCM-1.
- Provide sufficient time between TCMs to allow for TCM reconstruction, orbit determination, TCM design, and sequence generation for the upcoming TCM.
- Minimize operational complexity.
- Minimize Mars atmospheric entry delivery errors.
- Minimize total mission propellant usage.

The primary function of the three TCMs during cruise (TCMs 1, 2 and 3) is to remove the launch vehicle injection errors and bias. The remaining TCMs are for precise targeting of the atmospheric entry conditions and landing site. For all cases, TCM-1 and TCM-2 are designed together such that their combined total ΔV is minimized. For PHX, correcting all of the injection errors and bias at TCM-1 can be ΔV cost prohibitive. This is because the location of TCM-1 is close to the 180° transfer to Mars angle (See Figure 4). Splitting the combined injection error and bias removal ΔV into two TCMs allows each TCM to correct certain parameters in a more efficient manner. For example, it is generally more efficient to make energy corrections at a point in the trajectory where velocity is higher, while it is more efficient to correct orbit plane corrections where velocity is lower. From a ΔV perspective, it is only necessary to optimize TCM-1 and 2, but in some cases, that strategy does not meet the planetary protection requirement for non-nominal impact. Therefore, in some cases, it is necessary to bias the target for TCM-2 and then target the landing site for the first time at TCM-3. This necessitates using a TCM-1, 2, and 3 optimization strategy.

There are three nominal TCMs planned during the Approach phase: TCMs 4, 5, and 6. These maneuvers, as listed in Table 3, adjust the trajectory to the desired atmospheric entry conditions. TCM-6 at Entry – 14 hours is the final nominal entry targeting maneuver for landing site safety. In other words, TCM-6 is the last maneuver required to achieve the entry flight path angle delivery accuracy requirements. TCM-6x at Entry – 6 hours is the final opportunity to perform a TCM, but it is only to be used if TCM-6 does not occur because of an anomalous situation such as a DSN complex failure or other ground system failure. It is important to note that even though TCM-6x may not be executed, it is being treated and prepared for in exactly the same manner as TCM-6 and is included in the baseline mission plan.

The OD data cutoffs for TCMs 1 through 3 are placed at 5 days prior to execution of the TCMs. For TCMs 4 and 5, the OD data cutoffs are placed 24 hours prior to execution of the TCM. The data cutoff for TCM-6 (and -6x) is placed 8 hours before the execution of the TCM. The data cutoff for the final three TCMs is closer to the TCM in order to reduce navigation tracking data latency, thereby improving entry delivery accuracy. TCMs 1 through 3 will be developed as standard maneuver sequences that are built and tested on the ground and then uplinked to the spacecraft for execution. The time planned for this ground process is 5 days (of prime shift work). TCMs 4 through 6, however, will utilize an abbreviated timeline of round the clock shift work combined with a preliminary TCM design and testing cycle. A final update process will follow the preliminary design process and will start 24 hours prior to TCMs 4 and 5. The final design cycle will start at 8 hours before TCM-6 or -6x.

Landing Sites

The possible landing sites for the PHX mission are restricted to a latitude band between 65° North and 72° North. The landing site selection process will select a landing region, 20° in longitude by 7° in latitude, approximately one year before launch. The launch vehicle targets and trajectory bias will be based on a landing site within that region. Due to the size of the launch vehicle injection errors (explained later), any site within that region will be accessible with minimal ΔV (propellant) cost. Six weeks before launch, the landing site selection committee will select the nominal landing site, which will be targeted at TCM-1. At the PHX Landing Site Workshop held on December 1, 2004, the set of four candidate landing regions were selected and prioritized. The maneuver analyses reported in this paper are based on trajectories targeted to landing sites D1 (70° N latitude at 230° E longitude) and B1 (67.5° N at 130° E longitude). D1 is the previous baseline landing site, while B1 is the current highest priority site. Further navigation work will be geared toward the current high priority landing regions. The current prime candidate landing regions are listed below and are shown in Figure 5 Latitude range for all landing regions is 65°-72° N*.

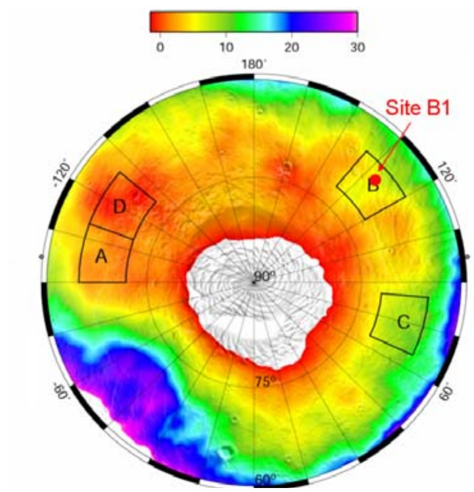


Figure 5. PHX Candidate Landing Regions (Colors indicate elevation in km).

Name	Longitude Range*
Region B	120° E - 140° E
Region A	250° E - 270° E
Region C	65° E - 85° E
Region D	230° E - 250° E

*IAU 2000 reference frame.

Maneuver Analysis Results

This section describes the results of maneuver analyses performed to determine the navigation delivery accuracy, the statistics of planned TCMs, and ΔV capability required to accomplish the PHX mission.

The goal of the maneuver strategy and design is to minimize propellant expenditure (by minimizing required ΔV) while satisfying the numerous constraints that are placed on the mission. Sufficient propellant must be allocated to accomplish the required ΔV to account for uncertainties such as launch vehicle injection dispersions and requirements such as those dealing with planetary protection. In spite of an implicit deterministic component related to injection biasing, TCMs are inherently statistical in nature (i.e., non-deterministic), since they are required to correct for dispersions caused by injection dispersions, orbit determination errors, and maneuver execution errors. The statistical maneuver analysis process estimates the ΔV budget required for a given probability level (e.g., 99%). This section describes the results of the analyses performed to establish the statistical properties of the TCMs planned for guidance of the spacecraft required for accomplishing the mission. Injection aimpoint biasing for planetary protection and results for non-nominal impact probability are also included.

For the maneuver analysis results presented below, references are made to a number of different trajectories – for example, "PHX Open". Figure 6 shows the complete PHX launch/arrival design space. The two horizontal blue lines represent the two constant arrival dates at Mars, and each star on these lines represents a launch date. The 6 rockets indicate the representative trajectories that have been analyzed to date. The launch dates, required C3 (injection energy), interplanetary transfer times, and arrival dates are as follows (all trajectories are targeted to D1 landing site at 70°N, 230°E):

Trajectory	Launch Date	C_3 (km^2/s^2)	Flight Duration (days)	Arrival Date
PHX Open	8/03/2007	29.1	297	5/26/2008
PHX Day 16	8/18/2007	24.1	292	6/05/2008
PHX Close	8/24/2007	26.9	286	6/05/2008

Delta II Injection Errors and Figure of Merit

Injection covariance matrices (ICMs) for the PHX spacecraft are provided by Boeing to describe the expected launch vehicle injection errors. These ICMs are provided for 6 launch dates including the open, day 16, and close of the 22-day launch period. The probability of commanded shutdown (PCS) of the Delta II second stage engine is assumed to be 99.7%[1]. Injection velocity deficit tables (containing injection velocity deficit magnitudes and corresponding probabilities) and the associated injection state sensitivities to velocity deficits are provided for each ICM. The ICMs are given for a nominal injection state at the Target Interface Point (TIP), in an RTN coordinate frame. These ICMs can be mapped to the Mars encounter B-plane, where the dispersions can be visualized.

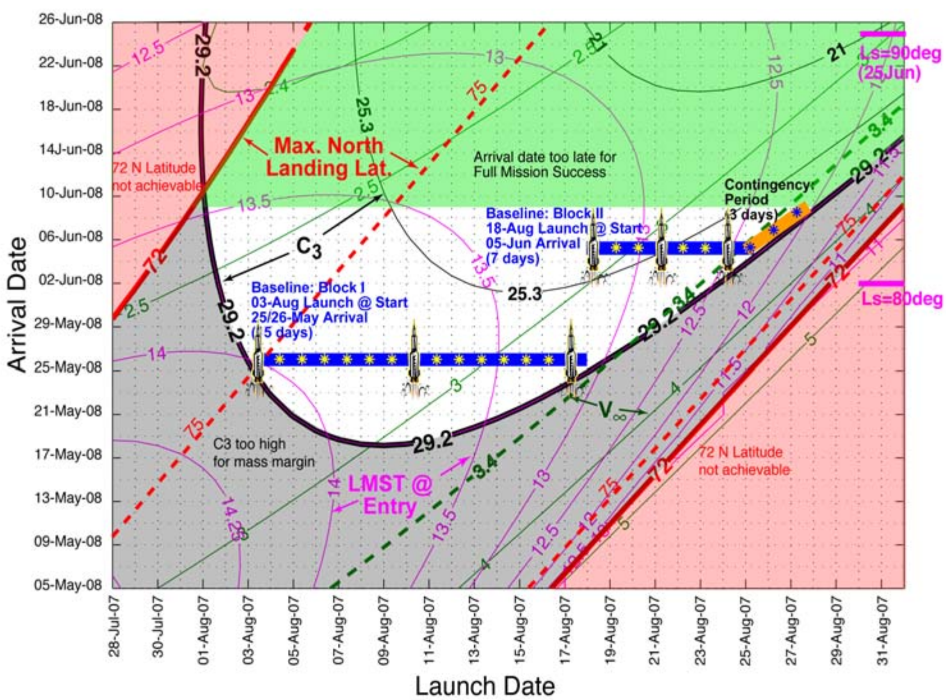


Figure 6. PHX Launch/Arrival Design Space.

The injection error is characterized by a single parameter, referred to as the Figure of Merit (FOM). FOM is defined as the square root of the trace of the velocity covariance matrix at TCM-1. FOM is a measure of the ΔV required at TCM-1 to correct for the injection errors in the absence of any other errors, target biasing, or multi-TCM targeting optimization. FOM provides a single measure for comparison of ICMs. Note that FOM represents only the errors included in the ICM and, therefore, corresponds to a PCS of 100% (i.e., an injection velocity-deficit

[1] The injected mass capability of the launch vehicle is determined to provide a PCS of 99.7% for the maximum C3 required during the 22-day launch period. Therefore, on days for which the required C_3 is less than the maximum, PCS is greater than 99.7%.

probability of zero). Since the majority of the interplanetary ΔV will be expended at TCM-1, (primarily to correct for injection errors), the injection accuracy has a significant impact on required ΔV. This, in turn, affects the spacecraft margins in areas such as EDL and AACS. Table 4 presents the FOM results and injection dispersions mapped to Mars B-plane.

Table 4. Injection Errors Mapped to Mars B-plane and FOM Data.

		Open	**Day 16**	**Close**
Injection				
Date (TIP)	(ET)	August 3, 2007	August 18, 2007	August 24, 2007
C_3	(km^2/s^2)	29.1	24.1	26.9
Flight Path Angle at TIP	(deg)	32.15	30.99	31.73
Arrival (Atmospheric Entry)	(ET)	May 26, 2008	June 5, 2008	June 5, 2008
Transfer Duration	(days)	297	292	286
180¡ Transfer Angle Occurs at	(days)	L + 27	L + 19	L + 14
Days to Entry	(days)	270	273	272
Delivery Ellipse				
Semi-Major Axis	(km)	562,070	615,846	677,572
Semi-Minor Axis	(km)	84,970	96,596	102,272
Orientation Angle	(deg)	59.0	56.1	51.3
σ LFT	(days)	4.255	2.849	1.977
Figure of Merit ÆV Estimates for TCM-1 at L+10 days				
FOM	**(m/s)**	**22.2**	**25.2**	**36.0**

LFT: Linearized Flight Time

Injection Aimpoint Biasing for Planetary Protection

Planetary protection (PP) requirements state that after injection the probability of the launch vehicle upper stage impacting Mars shall be less than 1.0×10^{-4}. Since the upper stage cannot perform maneuvers, and, therefore, flies ballistically after injection, the injection aimpoint must be biased away from Mars to satisfy those requirements.

One method used to select the biased injection aimpoint is to manually sample a representative set of points on the 10^{-4} PP ellipse (the ellipse in the Mars B-plane corresponding to a probability of impact of 1.0×10^{-4}) to identify the point that has the minimum ΔV to remove the injection bias. However, a more efficient method is to use the “capability ellipse” to determine the minimum deterministic ΔV biased aimpoint. The capability ellipse at a given maneuver epoch is defined as locus of points in the B-plane that are achievable with a fixed ΔV of 1 m/s. The center of the capability ellipse is same as the center of the 10^{-4} PP ellipse, but the size and orientation are different. The size of a representative capability ellipse increases with increasing ΔV magnitude. Conceivably, one could increase the ΔV magnitude until the corresponding capability ellipse just “touches” the 10^{-4} PP ellipse. The two points at which the capability ellipse touches the 10^{-4} PP ellipse define the two potential biased injection aimpoints that correspond to the minimum deterministic ΔV to remove the bias. However, this process can be time-consuming and tedious.

Alternatively, an approximate location for the minimum deterministic ΔV aimpoint can be determined using the semi-major and semi-minor axes of the capability ellipse. The tangent of the angle between the semi-major axis of the capability ellipse and a line drawn from the center of the ellipse through the optimized biased aimpoint is given by the ratio of semi-minor and semi-major axes of the capability ellipse. This line intersects the 10^{-4} PP ellipse at two points, one on the same side of Mars (in the B-plane) as the final (unbiased) aimpoint, and one on the opposite side. The latter point is not selected for two reasons. First, when performing TCM-1 to remove the bias, the trajectory (in general) crosses the Mars impact circle in the B-plane. If, for some reason, TCM-1 were to result in an under-burn, the spacecraft might be left on an impacting trajectory – an undesirable situation. Secondly, the biased aimpoint on the same side of Mars (in the B-plane) as the final aimpoint results in a slightly lower ΔV to remove the bias.

It should be noted that the methods described above are approximate and do not always give an accurate estimate for the location of the minimum deterministic ΔV biased aimpoint. It is possible for the minimum-ΔV biased aimpoint to be a significant distance away from the initial guess obtained using the above methods. This behavior can be explained by several factors. One is that both the 10^{-4} PP ellipse and the capability ellipse are determined using linear partials relative to the nominal unbiased trajectory. If the biased aimpoint is sufficiently far away from the final aimpoint, the linearity assumption may not provide an accurate result. A second factor is that, even if linearity assumptions are not violated, the method described above has not been demonstrated to be a universal method for locating the minimum ΔV biased aimpoint.

The biased aimpoint that minimizes the ΔV to remove the bias (however it may have been determined) is of limited usefulness, since it minimizes only the deterministic ΔV associated with the biased aimpoint. This aimpoint may not provide the minimum statistical ΔV given known error sources, such as injection dispersions, orbit determination errors, and maneuver execution errors. However, by sampling several points on the 10^{-4} PP ellipse on either side of the aimpoint corresponding to the minimum deterministic ΔV and then evaluating the statistical ΔV cost (i.e., 99% ΔV required), the aimpoint with the minimum statistical ΔV cost can be determined.

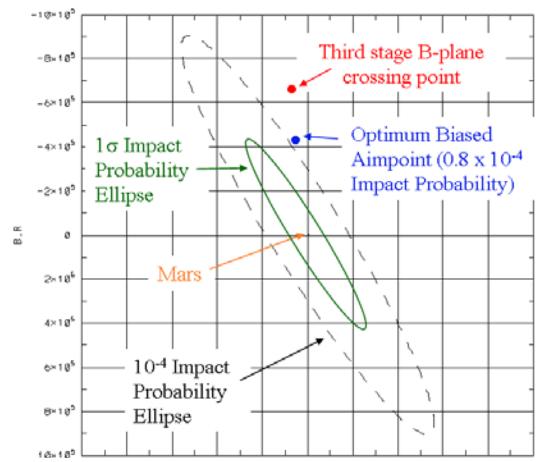


Figure 7. PHX Open (8/03/07) 1σ Injection Error Ellipse, 10^{-4} Planetary Protection Ellipse, and Biased Injection Aimpoint in Mars B plane.

Figure 7 shows, for the Open case, the 1σ injection dispersion ellipse, the 10^{-4} PP ellipse, the selected biased injection aimpoint, and the corresponding launch vehicle third stage arrival characteristics projected on Mars B-plane (the plane passing through the center of the target body and perpendicular to the incoming asymptote *S* of the hyperbolic flyby trajectory). The *T* axis is defined as the intersection of B-plane and the Mars mean equator of date ($T = V_\infty \times Pole_{Mars}$); the *R* axis completes a right-hand rule in the *TRS* orthonormal basis. The size, shape, and orientation of the 1σ and 10^{-4} PP ellipses depend on injection errors. Any aimpoint precisely on the 10^{-4} PP ellipse corresponds to a probability of impacting Mars of 1.0 x 10^{-4}. The biased injection aimpoint for the spacecraft is chosen such that the statistical ΔV cost required to remove the aimpoint bias is minimized while ensuring that the probability of the third stage impacting Mars is less than 1.0 x 10^{-4}. In order to provide margin with respect to the impact probability requirement, the biased injection aimpoint is selected such that probability of impacting Mars is 0.8 x 10^{-4}. This 20% margin is deemed prudent, because the launch vehicle trajectory design has not fully matured yet – as an example, the ICMs provided by Boeing may change in the future.

In the process of determining the biased injection aimpoint that minimizes the statistical ΔV cost, the encounter time is a free variable – i.e., it is not constrained. The B-plane coordinates for the Delta third stage differ from those for the spacecraft because of the velocity impulse caused by the spacecraft separation mechanism. The point in the B-plane corresponding to the Delta third stage is outside the 10^{-4} PP ellipse.

Table 5. Biased Injection Aimpoints and corresponding impact probabilities.

Launch Day	Open (08/03/07)	Day 16 (08/18/07)	Close (08/24/07)
Injection Bias:			
BáR (km)	-430,000	-390,000	-430,000
BáT (km)	-74,400	-63,700	-153,100
B (km)	436,389	395,168	456,442
TCA (ET)	05/29/08 04:05:52	06/06/08 23:59:13	06/06/08 13:00:28
ÆTCA* (hr)	75.6525	42.25	32.61
Impact Probability:			
Spacecraft	0.7994 x 10^{-4}	0.8001 x 10^{-4}	0.8005 x 10^{-4}
Delta Third Stage	0.1470 x 10^{-4}	0.1933 x 10^{-4}	0.2539 x 10^{-4}
Deterministic ÆV (m/s)	11.14	10.87	9.09

*ÆTCA is relative to the closest approach time for the unbiased trajectory.

Table 5 presents the following information for cases corresponding to open, day 16 and close of the PHX launch period: the B·R, B·T, time of closest approach (TCA), and ΔTCA components of the biased injection aimpoint, as well as the corresponding impact probabilities for the spacecraft and the Delta third stage, and the deterministic ΔV at TCM-1 to remove the bias.

TCM ΔV Statistics

TCM ΔV statistics, along with Mars atmospheric entry delivery accuracies, are estimated by performing 5000-sample Monte-Carlo analyses. These analyses include injection dispersions assuming 99.7% PCS, TCM execution errors, and the orbit determination uncertainties. (For a more detailed description of how each perturbed sample trajectory is generated for the Monte Carlo analysis, the reader is referred to Reference 2.)

Although in most cases it is common practice to remove the entire injection bias and injection errors at TCM-1, this strategy could not be implemented for Phoenix mission. For Phoenix, the 180° transfer angle - location on the trajectory 180° away from arriving at Mars - occurs during the first 30 days after launch across the launch period. Making trajectory corrections from about two weeks before to two weeks after the 180° transfer angle point is prohibitively costly in ΔV. However, waiting until after this time to perform TCM-1 is also costly, the longer the delay, the larger the TCM-1 ΔV magnitude will become.

As a result, in order to keep the mission-total ΔV99 from exceeding the 56 m/s maximum allowable Phoenix ΔV requirement, a TCM-1, TCM-2 optimization strategy has been implemented. This means that the Mars atmospheric entry target miss, resulting from the combined effects of injection biasing (to satisfy PP requirements) and injection errors, will not be corrected entirely at TCM-1. Rather, the TCM-1 and 2 combination will remove the miss such that the total TCM-1, 2 ΔV is minimized. This also means that, on average, TCM-1 magnitude will be smaller. However TCM-2 magnitude will be larger than if a TCM-1, 2 optimization had not been performed. Consequently, the increase in TCM-2 magnitude and resulting execution errors will cause an increase in TCM-3 statistical estimates.

Table 6. Open (8/03/07) ΔV Statistics.

Event	Location	Deterministic ÆV* (m/s)	Ideal ÆV (m/s)		
			Mean	1 σ	99%
TCM1	L + 10 d	11.1	14.6	11.8	47.1
TCM2	L + 60 d	0.00	5.7	4.91	18.9
TCM3	E - 45 d	0.00	1.40	1.27	5.83
TCM4	E - 15 d	0.00	0.25	0.15	0.76
TCM5	E - 5 d	0.00	0.16	0.07	0.34
TCM6	E - 14 h	0.00	0.41	0.18	0.88
Total ÆV		**11.1**	**22.5**	**10.2**	**52.4**

* To remove the planetary protection injection bias

The PHX TCM thrusters are pointed in the -X-axis direction. The thrust vector is, therefore, pointed in the X-axis directions, which places the nominal ΔV direction in the +X-axis direction. The thrusters are not canted, hence the combined ΔV performed by the TCM thrusters represents the actual ΔV imparted on the spacecraft. All ΔV results in the following sections assume turn and burn maneuver implementation with no constraints on spacecraft pointing. Table 6 presents the deterministic ΔV required to remove the injection aimpoint bias (in the absence of any injection errors), and the ΔV statistics for the PHX Open (8/03/07 launch) as a representative case.

Mission ΔV Requirements

The mission ΔV requirements are estimated (to a 99% confidence level) by the analysis shown above. The mission propellant requirements are verified by the flight system. The total mission propellant needed is the combination of propellant needed for AACS, propellant needed for TCMs, and propellant needed for the terminal descent phase of EDL.

The flight system team runs an end-to-end Monte Carlo on propellant usage that combines the NAV TCM ΔV statistics with the spacecraft propellant usage simulation models to determine the cruise usage. The NAV TCM ΔV information is provided to the flight system in sets of 2000 ΔV samples per TCM per trajectory. These samples are used in the flight system Monte Carlo process. The ΔV results shown in Table 6 are based on a 5000 sample Monte Carlo run and do not include any factors of margin. In the event TCM-6x, instead of TCM-6, is performed, the delay in time to correct errors from TCM-5 causes a net increase in the amount of ΔV needed for TCM-6x. The TCM-6 delay ΔV cost is approximately 0.5 m/s. Hence, for the purpose of determining the mission-total propellant budget, the results for the flight system include a margin factor of 0.5 m/s that is added to the ΔV results to account for a situation where TCM-6x is performed instead of TCM-6.

Table 7 shows the nominal current best estimate (as of April 2005) for the 99 percentile statistical ΔV for Open, Day 16, and Close of launch period. Mission-total ΔV requirement is based on the most demanding 99 percentile ΔV estimate across the launch period. The three trajectories presented are representative of the 99% ΔV estimate variations across the launch period. As such, the open of the launch period with a 52.4 m/s ΔV99 value, represents the *nominal* highest ΔV required to successfully target the entry conditions at Mars.

However, in determining a ΔV budget for the mission, other factors, which will affect total ΔV requirement, must be considered. The most prominent of these are included in Table 7 as additional line items and will be discussed here. The baseline mission plan requires that the landing site region be selected one year prior to launch. Nonetheless, the exact landing site within the region is not determined until 6 weeks prior to launch. This necessitates a minor landing site adjustment at TCM-1. Given the large injection dispersions, the statistical ΔV cost for this adjustment is estimated to be 0.0 m/s. Moreover, TCM-6 is scheduled to take place at Entry minus 14 hours. If, for any reason, TCM-6 execution is postponed to TCM-6x (entry minus 6 hours), the delay results in an increase in the ΔV magnitude. The mission-total ΔV cost for this delay across the launch period is estimated to be approximately 0.5 m/s.

Table 7. TCM Total ΔV Budget

	Open	Day 16	Close
Launch	08/03/07	08/18/07	08/24/07
Arrival	05/26/08	06/05/08	06/05/08
TCM-1	L+10	L+10	L+10
Mission Total ÆV99 (January 2005 CBE)	**52.4**	**48.5**	**46.5**
TCM-1 Landing Site Retargeting (within selected Region)[1]	0.0	0.0	0.0
TCM-6 delayed to E-6 hr; (i.e., TCM-6X instead of TCM-6)	0.5	0.5	0.5
Mission Design Margin[2]	0.0	0.0	0.0
Total ÆV99	**52.9**	**49.0**	**47.0**
Margin relative to TCM ÆV budget of 56 m/s	**3.1**	**7.0**	**9.0**

$ÆV_{99}$ is the required ÆV at 99% probability.

[1]Negligible if constrained within the ±10 longitude and ± 3.5¡ latitude region.

[2]Liens on mission design margin: finite (±15 s) launch window, ICM changes, PCS decreases, non-nominal impact probability constraints, full analysis with new ground rules, etc.

Note: Earth and Sun pointing constraints (if any) have no effect on the desired ÆV (deterministic or statistical). These constraints only affect the implementation of a ÆV,therefore, they will affect the propellant requirements to achieve a particular ÆV.

It is also common for mission design teams to maintain some margin above current best estimate to account for future changes in the inputs to the ΔV estimate, such as changes in the launch-arrival space, injection dispersions, PCS estimate, etc. However, in the case of Phoenix, because the spacecraft is already built and the propellant tank size can not be changed, and also because cruise propellant requirements are an integral part of mission total propellant requirements, it has been decided by the project that a mission design margin line item will not be maintained by the mission design/navigation (MD/NAV) team. Consequently, with respect to the 56 m/s ΔV limit levied on the MD/NAV team, a 3.1 m/s worst-case ΔV margin remains available to guard against all adverse variations in mission-total ΔV requirement.

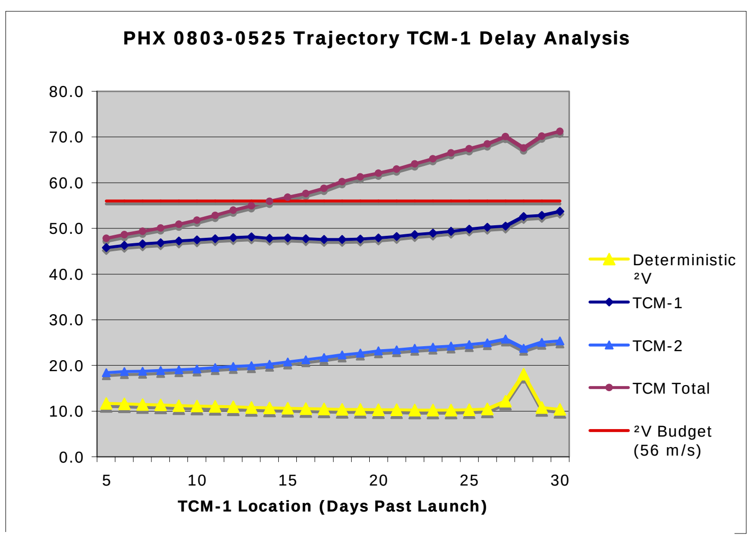


Figure 8. TCM Total ΔV Requirement for Delayed TCM

The 99% ΔV requirements for TCMs shown in Table 7 assume that TCM-1 is executed at L + 10 days. Any delay in TCM-1 execution causes the magnitude of the maneuver to increase, thereby increasing the mission ΔV, hence propellant, requirements at

99% probability, or, equivalently, reducing the probability level below 99% assuming TCM propellant was allocated for TCM-1 at L + 10 days. Figure 8 shows that mission-total ΔV99 will exceed the 56 m/s allocation if TCM-1 execution is delayed beyond L+14 days. However, in the event TCM-1 is delayed to L+30 days, the 56 m/s ΔV capability still provides slightly better than 96% success probability (Table 8). It should be noted that although these results are for the scenario where TCM-6 (not TCM-6x) is executed, performing TCM-6x instead of TCM-6 would not change the conclusions.

Table 8. Probability of Sufficient ΔV for Delayed TCM-1.

	Total TCM ÆV (m/s)					
Allocation	**95%ile**	**96%ile**	**97%ile**	**98%ile**	**99%ile**	**Probability**
56.0	54.3	55.5	59.2	63.4	71.3	>96%

Moreover, the above analysis has only been performed for the scenario when launch occurrs on the open of the launch period. However, since this trajectory has the most demanding ΔV requirements, the above conclusions hold true for all other launch days as well.

The injection velocity deficit tables used for these analyses assume that the second stage of the Delta II launch vehicle is loaded with sufficient propellant to provide a 99.7% PCS for a flight system injection mass of 705 kg. Hence, the 56 m/s ΔV allocation for PHX will be sufficient to meet the 99% probability ΔV requirement as indicated in Table 9. The current projections for Flight System mass indicate that it is unlikely to exceed the 705 kg injection mass capability of the launch vehicle. In the unlikely event the Flight System injection mass increases beyond 705 kg, the PCS will decrease below 99.7%. Table 9 shows the estimated ΔV confidence levels for PCS values below 99.7%. Although the 99% ΔV requirement for a 99% PCS remains below the 56 m/s ΔV allocation, for a 95% PCS, it well exceeds the allocation. However, the 56 m/s allocation will be sufficient for an approximate 98% ΔV probability. (It should be noted that the results in Table 9 are for the scenario where TCM-6 is performed; however, the general conclusions derived apply equally well for the scenario where TCM-6 does not occur, and TCM-6x is performed instead.)

Table 9. Open (8/03/07) ΔV Probability Estimates for Different PCS Levels.

	Mission Total ÆV (m/s)					
	90%ile	95%ile	96%ile	97%ile	98%ile	99%ile
PCS 100%	35.9	40.7				51.3
PCS 99.7%	36.1	41.2				51.9
PCS 99.0%	36.3	41.6				53.4
PCS 95.0%	38.0	45.1	47.2	50.4	56.4	69.3

<u>ΔV Cost to Retarget Landing Site After Launch</u>

Landing site selection is an ongoing process, and the final site selection must be completed at least 6 weeks prior to the PHX launch. However, final launch vehicle injection target specification document must be completed well before the final site selection. Thus, to accommodate the launch vehicle targeting process, the landing site selection team is required to select the final landing *region* one year prior to launch.

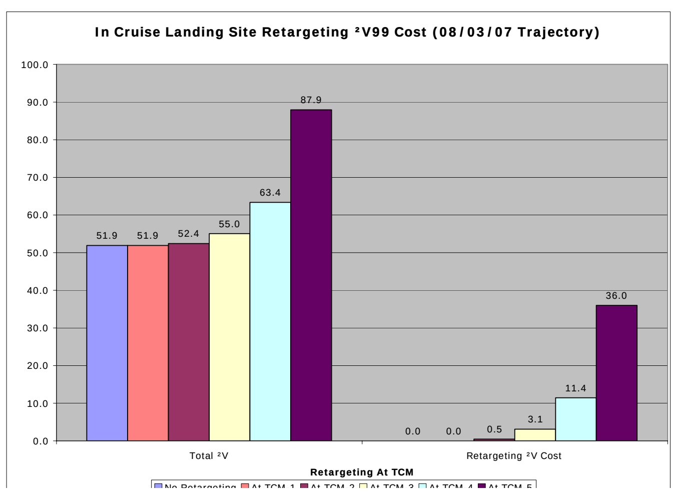


Figure 9. ΔV Cost to Retarget Landing Site within a Region.

The launch vehicle uncertainties are such that targeting anywhere in the selected region at TCM-1 will not increase the overall statistical ΔV needed for the mission. However, it is understood that it may be desirable to change the targeted landing site at later TCMs. For all landing site retargeting results, the baseline trajectory (before retargeting the landing site) was aimed at D1 landing site (70°N, 230°E). Figure 9 shows the worst-case scenario cost of changing the landing site target from one extreme corner of the region to the other (i.e. 65N, 220E to 72N 240E) at TCMs 2 through 5. The nominal case in Figure 9 (blue bar) uses TCM-1 to target from the injection biased aimpoint to the southwest corner of the landing region (65N, 220E). Each of the remaining bars represents a case where the northeast corner of the box is targeted at a later TCM. This analysis shows that targeting the opposite corner of the box at TCM-2 only costs 0.5 m/s, but as the retargeting is delayed, ΔV cost increases significantly.

Mars Reconnaissance Orbiter (MRO) is scheduled to launch in 2005 and is capable of providing much higher resolution images of the surface of Mars than existing Mars orbiters. The earliest the MRO collected images will be available is in the spring of 2007, that is, after the deadline for the final landing region selection for PHX. Therefore, it is also recognized that it may be necessary to retarget the trajectory from one region to another after the final launch vehicle injection targets are set. Preliminary analysis shows that the ΔV cost of covering the potential 7° latitude retargeting is negligible. However, changes in landing site longitude (that is, time of arrival) are significantly more costly. The current list of the candidate landing regions indicates the maximum longitude range to be covered is slightly more than 180 degrees. Therefore, if launch vehicle injection targets were developed for a midpoint landing site between the most extreme landing regions, a ±93° longitude change capability would be sufficient to cover all candidate landing sites.

Initial analyses for this contingency scenario indicate that retargeting to another region will almost certainly have to be done at TCM-1 in combination with TCM-2 (i.e., TCM-1, 2 optimization). Figures 10 and 11 show the ΔV cost of landing region retargeting (longitude change) at TCM-1 for launch period open (08/03/07) and close (08/24/07), respectively. At the open, the ΔV cost of retargeting eastward is at most 1 m/s, remaining below the 56 m/s ΔV allocation throughout the range. However, going westward, ΔV99 reaches 56 m/s for a longitude change of 50 degrees, and reaches 60.4 m/s at 93° retargeting, exceeding the ΔV allocation by 4.4 m/s. Conversely, at the close of launch period, going west is less costly than going east. ΔV99 increases from 46.5 m/s to 52.8 m/s going 93 degrees west, while it increases to 58.6 m/s going 93 degrees east, exceeding the allocation by 2.6 m/s.

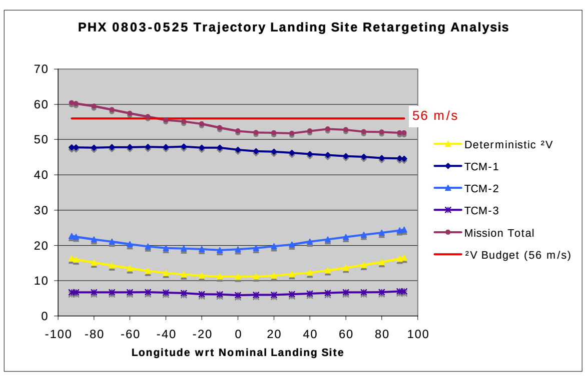


Figure 10. ΔV Cost to Retarget Landing Region at TCM-1 for PHX open.

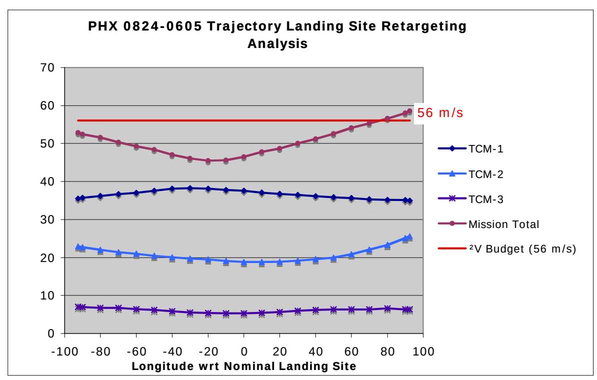


Figure 11. ΔV Cost to Retarget Landing Region at TCM-1 for PHX close.

It can be argued that the probability of launching in the early part of the launch period is considerably higher than launching during the last few days of the launch period. Hence, it might be prudent to select launch vehicle injection aimpoints corresponding to an intermediate landing site somewhat to the west of the exact center between the extreme landing regions, thereby increasing the probability to cover the entire ±93 degree retargeting range while remaining below the 56 m/s ΔV allocation.

TCM Delivery Accuracy (Monte Carlo Analysis)

One of the products of the OD process is Mars atmospheric entry interface delivery accuracy estimates. These estimates are generated using a covariance analysis method. In this section, delivery statistics for all TCMs based on 5000-sample Monte Carlo analyses are presented and compared with the OD results. The

Monte Carlo delivery statistics are considered to be more accurate due to the higher fidelity maneuver execution error model used in the Monte Carlo analysis compared to the spherical model used in the covariance analysis. Table 10 shows the 1σ delivery statistics (B-plane coordinates and entry flight path angle) for each TCM for the Close (8/24/07 launch) trajectory, as a representative case. This trajectory has the worst-case delivery accuracy estimates among all trajectories analyzed to date. Columns 1 and 2 show the 1σ uncertainty in B·R and B·T and column 3 shows the corresponding correlation coefficient. Column 4 presents the 1σ uncertainty in linearized time of flight (LFT). The next three columns of this table present the size and orientation (relative to the T axis)

Table 10. Close (8/24/07) Trajectory Delivery Accuracy in Mars B-plane Coordinates.

		σ BáR (km)	σ BáT (km)	ρ	σ LFT (sec)	SMAA (km)	SMIA (km)	θ (deg)	σ B (km)	σ FPA (deg)
TCM1	L + 10 d	6841	3888	0.887	1965	7706	1595	61.9	137877	N/A
TCM2	L + 60 d	4329	1898	0.765	1177	4584	1155	70.2	2957	N/A
TCM3	E - 45 d	159.4	171.0	-0.241	45.70	184.8	143.1	-36.8	175.0	7.33
TCM4	E - 15 d	36.49	36.71	-0.029	10.74	37.13	36.05	-39.0	36.89	**1.54**
TCM5	E - 5 d	12.50	12.66	0.004	3.676	12.67	12.50	8.7	12.51	**0.52**
TCM6	E - 14 h	1.91	2.00	-0.164	0.606	2.12	1.78	-36.8	2.03	**0.085**
Accuracy Requirement (-12.5 ± 0.27¡ 3σ)					**1.5**					**0.090**

ρ: σ BáT andσ BáR correlation coefficient

θ: Delivery ellipse orientation angle relative to BáT axis

of the delivery ellipse in the B-plane. Finally, column 8 shows the uncertainty in the Mars atmospheric entry (inertial) flight path angle (FPA). The LFT and inertial entry FPA 1σ delivery requirements for PHX are ±1.5 s and -12.5° ± 0.09°, respectively. The achieved 1σ LFT and FPA delivery accuracies for TCM-6 satisfy the requirements.

In general, delivery accuracy results from OD covariance analyses compare very well with those from the maneuver Monte Carlo analyses. The 1σ TCM-4 FPA delivery errors differ by at most 0.01 deg, and since the TCM-4 results are rounded to the nearest 0.01 deg, the actual difference may be smaller. For TCM-5 and TCM-6, the FPA errors agree to within a few thousandths of a degree.

It should be noted that since the completion of the analyses for this work, NASA Deep Space Mission System has reduced the accuracy level of the baseline tracking data services they provide. As a result, all delivery accuracy estimates for PHX would be degraded. However, as of the time of this writing, the results of the updated analyses using the new tracking data assumptions were not available yet.

Non-nominal Impact Probability

Earlier the process of selecting an injection aimpoint bias such that the probability of impact of Mars by the launch vehicle upper stage does not exceed 1.0×10^{-4} was described. Additionally, Planetary Protection requirements state that the overall probability of non-nominal impact of Mars due to failure during the Cruise and Approach phases shall not exceed 1.0×10^{-2}. A non-nominal impact is defined as an impact that could result in the break-up of the spacecraft and release of terrestrial contaminants on Mars. Overall non-nominal impact probability is the cumulative sum of the probability of non-nominal impact following each TCM. The probability of non-nominal impact for TCMs 1 through 5 is defined as the probability of impact after each TCM multiplied by the probability that the following maneuver does not occur. This is illustrated in Table 11 by the P(i) and Q(i+1) values, respectively. The probability of non-nominal impact for TCM-6, on the other hand, is defined as an impact resulting from a Mars entry flight path angle outside the specified entry corridor: -12.5 deg ± 0.27 deg.

Table 11 shows the overall non-nominal impact probability for the Open, Day 16 and Close trajectories. It is interesting to note that TCM-1 is not a significant contributor but TCMs 2, 3 and 6 are major contributors to the overall probability of non-nominal impact. The original TCM strategy used TCM-1 and TCM-2 optimization to remove the injection bias and errors in the most ΔV efficient manner. However, in the close case this strategy does not meet the non-nominal impact probability requirement.

It was necessary for the close case to bias TCM-2 from the nominal aimpoint by approximately 500 km radially away from Mars in order to meet the non-nominal impact probability limit of 1.0×10^{-2}. However, the 500 km radial bias caused an increase in TCM-3 and mission total ΔV by delaying the remaining injection error and bias correction to TCM-3. In order to minimize the impact of biasing TCM-2, TCM-3 was added to the TCM (ΔV) optimization process. The result of optimizing TCMs 1, 2, and 3 together was a zero net increase to the mission total ΔV requirement for the close case. The reason is that although TCMs 3,4,5 and 6 increased in statistical magnitude TCM-2 decreased because of not correcting the full amount of the remaining bias left from TCM-1, therefore the overall effect is a net wash.

Table 11. Probability of Non-nominal Impact

			OPEN			Day 16			CLOSE	
Launch			08/03/07			08/18/07			08/24/07	
Arrival			05/26/08			06/05/08			06/05/08	
Nominal FPA			-12.5¡ ± 0.27¡			-12.5¡ ± 0.27¡			-12.5¡ ± 0.27¡	
Flyby FPA			-9.85¡			-9.85¡			-9.85¡	
Event	**Location**	**P(i)**	**Q(i+1)**	**P(i) x Q(i+1)**	**P(i)**	**Q(i+1)**	**P(i) x Q(i+1)**	**P(i)**	**Q(i+1)**	**P(i) x Q(i+1)**
Launch		0.0	1.34E-06	0.00E+00	0.0	1.34E-06	0.00E+00	0.0	1.34E-06	0.00E+00
Injection		7.99E-05	7.03E-04	5.62E-08	8.00E-05	7.03E-04	5.63E-08	8.00E-05	7.03E-04	5.63E-08
TCM-1	L + 10 d	0.001	3.51E-03	2.46E-06	0.003	3.51E-03	8.81E-06	0.00284	3.51E-03	9.96E-06
TCM-2	L + 60 d	0.502	1.34E-02	6.73E-03	0.486	1.31E-02	6.38E-03	0.40163	1.27E-02	5.10E-03
TCM-3	E - 45 d	0.756	2.08E-03	1.57E-03	0.743	2.08E-03	1.55E-03	0.70823	2.08E-03	1.48E-03
TCM-4	E - 15 d	1.000	6.94E-04	6.94E-04	1.000	6.94E-04	6.93E-04	0.99521	6.94E-04	6.90E-04
TCM-5	E - 5 d	1.000	3.06E-04	3.06E-04	1.000	3.06E-04	3.06E-04	1.00000	3.06E-04	3.06E-04
TCM-6	E - 14 h	3.58E-04	1.00	3.58E-04	5.46E-04	1.00	5.46E-04	1.60E-03	1.00	1.60E-03
			Total	**9.66E-03**		**Total**	**9.48E-03**		**Total**	**9.178E-03**

P(i) : probability of impact after maneuver i: Using mean TCM-1 delivery and sigmas relative to final aimpoint to account for TCM-1,2 optimization; TCM-1n2 biased, and optimized to meet the NNIP requirement)

= total impact probability (100 km atmosphere) for all maneuvers except TCM-6

= probability of impact for non-nominal entry flight path angles for TCM-6

Q(i+1) : probability of not being able to execute maneuver i+1 given that maneuver i has occurred

Conclusions

In order to determine the statistical maneuver requirements for the Phoenix mission while satisfying all mission constraints, a selected set of trajectories have been analyzed. To reduce the probability of impact at Mars by the launch vehicle upper stage to less than $1. \times 10^{-4}$, the launch vehicle injection aimpoint is biased approximately 395,000 – 456,000 km (depending on the launch date). Current best estimates suggest that 52.4 m/s of ΔV capability (including 0.5 m/s for delaying TCM-6 to Entry – 6 hours) would be sufficient to satisfy the mission ΔV requirements to a 99% probability level. Therefore, the current 56 m/s allocation allows for a 3.6 m/s ΔV margin to safegaurd against further future uncertainties in our assumptions such as those related to deliveries of new injection covariance matrices by Boeing. The delivery accuracy results show that the stringent inertial atmospheric entry flight path angle delivery requirements of –12.5±0.27 (3σ) deg flight path angle and ±1.5 seconds arrival time for PHX are achievable at TCM-6 (Entry – 14 hours). However, to allow for a final opportunity to improve atmospheric entry delivery accuracy, the current mission plan includes a TCM-6x at E-6 hours. The current ΔV allocation enables a landing site retargeting within a region as late as TCM-3. However, landing site retargeting outside a region can only be accomodated up to a 50 degree longitudinal distance before the 56 m/s ΔV alocation is exceeded.

Appendix

The B-plane, shown in Figure 12, is a plane passing through the center of the target body and perpendicular to the incoming asymptote **S** of the hyperbolic flyby trajectory. Coordinates in the plane are given in the **R** and **T** directions, with T being parallel to the Mars Mean Equator plane of date. The angle θ determines the rotation of the semi-major axis of the uncertainty ellipse in the B-plane relative to the T axis and is measured positive right-handed about the S axis.

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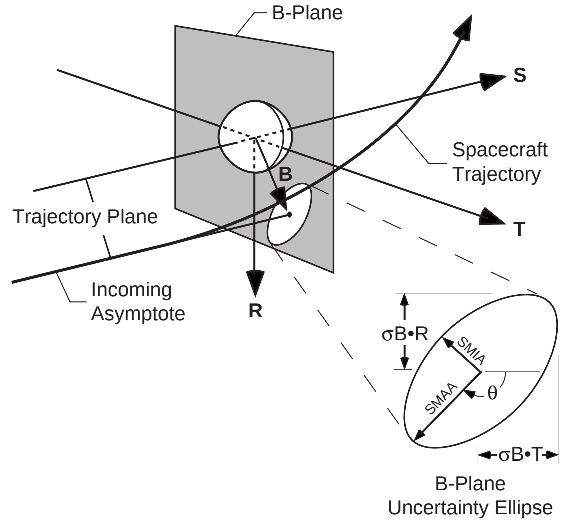

Figure 12. The B-plane coordinate system.

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