

Mars Exploration Rovers Propulsive Maneuver Design

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The Mars Exploration Rovers Spirit and Opportunity successfully landed respectively at Gusev Crater and Meridiani Planum in January 2004. The rovers are essentially robotic geologists, sent on a mission to search for evidence in the rocks and soil pertaining to the historical presence of water and the ability to possibly sustain life. In order to conduct NASA's "follow the water" strategy on opposite sides of the planet Mars, an interplanetary journey of over 300 million miles culminated with historic navigation precision. Rigorous trajectory targeting and control was necessary to achieve the atmospheric entry requirements for the selected landing sites. The propulsive maneuver design challenge was to meet or exceed these requirements while preserving the necessary design margin to accommodate additional project concerns. Landing site flexibility was maintained for both missions after launch, and even after the first trajectory correction maneuver for Spirit. The final targeting strategy was modified to improve delivery performance and reduce risk after revealing constraining trajectory control characteristics. Flight results are examined and summarized for the six trajectory correction maneuvers that were planned for each mission.

Nomenclature

ΔV	=	delta velocity
<i>TCM-1</i>	=	Trajectory Correction Maneuver, #1
<i>TCM-A1</i>	=	Trajectory Correction Maneuver, Spirit (or MER-A), #1
<i>TCM-B1</i>	=	Trajectory Correction Maneuver, Opportunity (or MER-B), #1

I. Introduction

The closest approach between the Earth and Mars in nearly 60,000 years characterized an exceptional launch opportunity in 2003 to deliver payload mass to the surface of Mars. The Mars Exploration Rover (MER) mission was conceived to take advantage of this notable celestial alignment by sending two identical rovers to investigate unique sites with evidence of past water. Amazingly, the mission was proposed, designed, built, tested, and launched in approximately three years. Spirit (also known as MER-A) launched on June 10, 2003 from Space Launch Complex 17A at the Cape Canaveral Air Force Station in Florida. The Opportunity (MER-B) launch followed on July 8, 2003 from Space Launch Complex 17B at the Cape. The interplanetary trajectories each covered over 300 million miles in 7 months. Spirit would arrive on January 4, 2004, with Opportunity following exactly 3 weeks later on January 25, 2004.

The intended landing target for Spirit was within Gusev Crater at an areocentric latitude of -14.59 deg. The Opportunity landing target was at Meridiani Planum, located on the opposite side of Mars at an areocentric latitude of -1.98 deg. Between the two sites, it was essential to begin the science mission at Gusev Crater first in order to accommodate the lower latitude and decreasing local Sun elevation for the solar powered rover. Gusev Crater represented a more hazardous landing site due to winds and terrain type. Analysis to certify Gusev Crater as an acceptable landing target continued even after launch. Consequently, in the event of a single launch failure the remaining spacecraft would be targeted to Meridiani Planum. These circumstances forced the need for Spirit targeting to remain flexible between Gusev Crater, Meridiani Planum, as well as a third landing site, Elysium. The Elysium site was near Gusev Crater, and provided an alternative if analysis revealed that the risks at Gusev Crater were too high. Furthermore, Spirit needed to maintain the landing site flexibility beyond the Opportunity launch.

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The surface targets are achieved after a direct atmospheric entry from the interplanetary trajectory, followed by a ballistic descent through the Martian atmosphere. The unguided landing profile requires utmost navigation delivery accuracy to the atmospheric entry aimpoint, defined at a Mars radius of 3522.2 km (equivalent to 125 km altitude with respect to the Mars equatorial radius). The atmospheric entry target is determined by iterating until the spacecraft entry state maps precisely to the desired landing position. The entry flight path angle (FPA) is a key parameter that determines the ballistic trajectory of the Entry, Descent, and Landing (EDL) system through the atmosphere. The delivery uncertainty in the entry flight path angle directly influences the dimension of the landing ellipse, along with uncertainties in modeling the atmosphere and spacecraft aerodynamics.

The Mars Exploration Rover mission provided numerous challenges to the maneuver design and analysis element of navigation. This paper describes how the key requirements were achieved, while maintaining landing site flexibility and adapting to newfound constraints imposed to reduce risk.

II. Flight System

The Mars Exploration Rover flight system consists of four major elements: an interplanetary cruise stage, an aeroshell (composed of a backshell and heat shield), the lander structure, and the science rover. The flight system components are illustrated in Fig. 1. The cruise stage and aeroshell possess significant heritage with the Mars Pathfinder systems used to successfully land on the surface of Mars in 1997. A noticeable difference with the Mars Pathfinder system is the flight system mass. The Mars Pathfinder launch mass was 890 kg. The MER flight system was approximately 20% heavier. The Spirit flight system mass was 1061.6 kg at launch, and the Opportunity launch mass was 1064.4 kg.

The cruise stage is responsible for transporting the aeroshell to the top of the Martian atmosphere to begin the Entry, Descent, and Landing (EDL) sequence. Consequently, the cruise stage includes all the subsystems required for interplanetary travel: power, telecommunications, propulsion, attitude control, and thermal control. Commanding is done via the flight computer located within the rover.

The cruise stage is jettisoned 15 minutes prior to entry. Upon its release, the aeroshell begins a completely unguided, ballistic descent through the Martian atmosphere. Over the next 6 minutes, the incoming velocity has to be reduced from an atmosphere relative 5.4 km/s (12,000 mph) to essentially zero. The heat shield reduces approximately 90% of the energy, followed by a parachute, solid rockets, and redesigned airbags to cushion a final

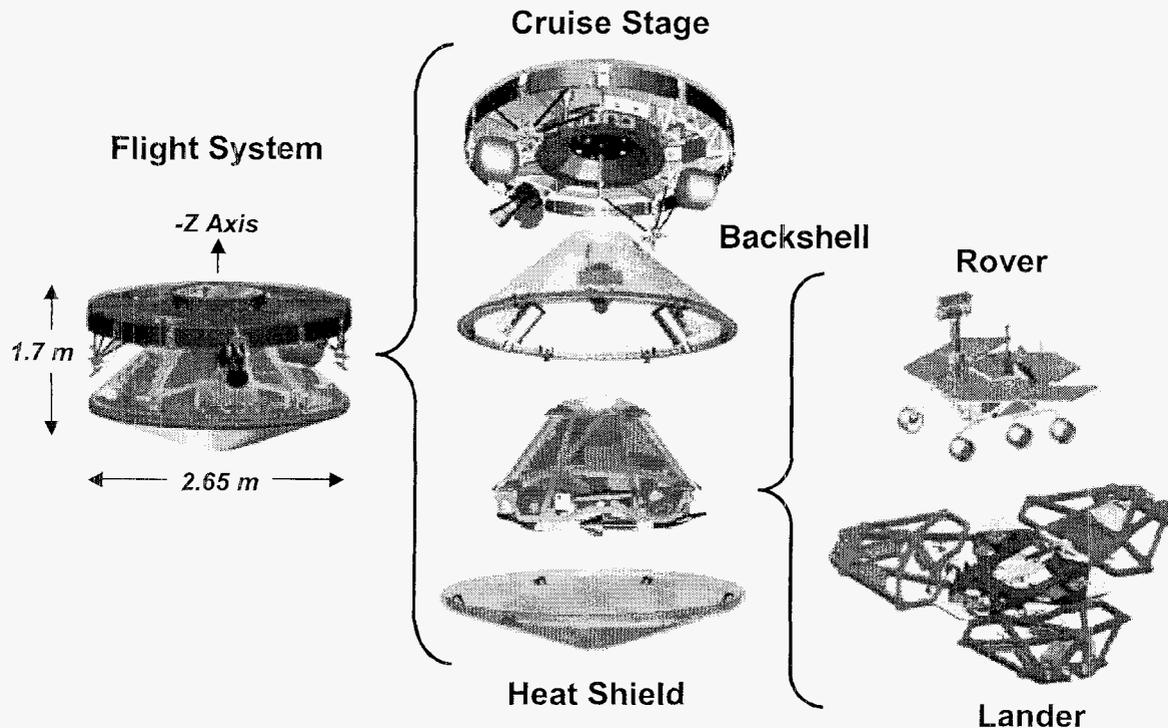


Figure 1: Mars Exploration Rover Flight System and Major Elements

free-fall from about 10-15 meters above the surface. After approximately 2 minutes of bouncing on the Martian surface, the airbags are deflated, retracted, and the lander petals are opened to reveal the stowed rover. The lander volume is from Mars Pathfinder heritage, so the large rover must undergo numerous deployments before egress from the lander. See Ref. 1 for additional details on the flight system, including the rover's scientific instrument payload.

A. Telecommunications

The cruise stage telecommunications system includes a low gain antenna (LGA) and medium gain antenna (MGA) for communications during interplanetary flight. The LGA and MGA point in the direction of the $-Z$ axis, which is along the spacecraft spin axis. (See spacecraft cruise configuration in Fig. 2) The telecommunications system is a single-string design, with coherent X-Band Uplink/X-Band Downlink. The X-Band telecommunications system relies upon a Small Deep Space Transponder (SDST) for two-way Doppler and ranging, command signal demodulation and detection, telemetry coding and modulation, and differential one-way range (DOR) tone generation. The DOR tones support Δ VLBI (Delta Very Long Baseline Interferometry) measurements for navigation. This measurement complements the traditional two-way Doppler and ranging data, and enables higher accuracy navigation delivery to Mars.²

The telecommunications system also includes a UHF capability. The UHF system is utilized to relay communications to the Earth through the orbiting assets at Mars: Mars Global Surveyor (MGS) and Mars Odyssey. This relay link is advantageous during EDL and also from the surface of Mars.

B. Attitude Control

The attitude control system includes five digital Sun sensors, a star scanner, and two inertial measurement units (IMUs). Two of the sun sensors are pointed in the direction of the spacecraft $-Z$ axis, while the other three point normal to the spin axis. The sun sensors combine to almost provide full sky coverage, except for an 11-degree cone obscuration about the $+Z$ axis direction. One IMU is located in the backshell, and the other is in the rover. Each IMU contains three axis accelerometers and gyros.

The spacecraft is spin-stabilized at a nominal rate of 2 rpm with active nutation control. The attitude control system utilizes the Sun sensors and the star scanner to determine complete 3-axis knowledge of the spacecraft orientation in inertial space. This is the nominal mode of operation: celestial mode. In this mode, the spacecraft is placed in safe attitudes for power and telecom, spin and nutation are controlled, and trajectory correction maneuvers are executed.

C. Propulsion

The MER propulsion system performs spacecraft spin rate corrections, attitude control, and all trajectory correction maneuvers. It is a monopropellant hydrazine system, operated in a blow-down mode. The propulsion system includes two spherical propellant tanks, line feeds, a propellant filter, redundant pressure transducers, two latch valves, catalyst bed heaters, and eight 4.4-N (1.0 lb_f) thrusters or Rocket Engine Assemblies (REAs). The eight thrusters are grouped into two clusters of four thrusters each. Each latch valve leads to one of the thruster clusters. The system was initially pressurized to 392 psia using Helium gas.

The A and B thruster clusters are diametrically opposed, with each thruster symmetrically canted 40 deg with respect to the spacecraft $\pm X$ axis direction. Figure 3 defines the spacecraft axes and illustrates the thruster configuration. Cluster A contains thrusters 1-4, which have $-X$, $+Z$ position components and the exhaust nozzles are all aligned 40 degrees off the $-X$ direction. Thrusters 1 and 2 are aligned in the X-Z plane, while thrusters 3 and 4

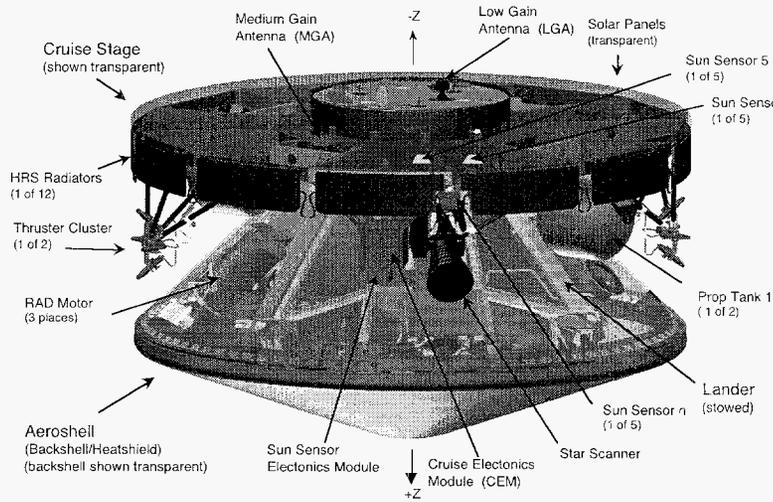


Figure 2: MER Spacecraft Components in Cruise Configuration

are aligned parallel to the X-Y plane. Thrusters 5-8 of cluster B are a mirror image of cluster A on the opposite side of the spacecraft.

The thruster configuration design is nearly ideal to support the orbit determination aspect of navigation. Spacecraft pointing and spin rate control are accomplished by pulse-mode firing of coupled thruster pairs. Thrusters 3 and 7 are synchronously pulsed to produce a torque in the $-Z$ direction for a decrease in angular momentum, or a negative spin rate change. Likewise, thrusters 4 and 8 produce a positive spin rate change. The symmetric thruster alignment produces equal and opposite thrust vectors, resulting in zero net ΔV .

Pointing control is achieved in a similarly balanced mode. Thrusters 1 and 5 pulse simultaneously to generate a torque in the spacecraft $-Y$ direction. One half revolution later, thrusters 2 and 6 pulse to create a torque in the same inertial direction. The timing of the pulses determines the direction of the precession.

The propulsion design and spin stabilized system provides a plethora of options for the implementation of trajectory correction maneuvers, but necessitates strict attention to details for accurate propulsive maneuver design. All velocity corrections are commanded with burn duration parameters in an open loop process. Axial burns along the spacecraft spin axis are executed steady state with a continuous thruster firing. This type of velocity correction can be performed in the spacecraft $+Z$ (thrusters 2 and 5) or $-Z$ (thrusters 1 and 6) direction.

Lateral burns produce a velocity correction approximately normal to the spin axis, and must be performed in a pulse mode operation. The four thrusters of one cluster are fired in unison for typically 5 seconds, producing a 60 deg burn arc at the nominal spin rate of 2 rpm. The timing of the pulse centers the burn arc about the desired inertial clock angle. This burn pulse is followed by a 10 second wait time, and then the 5 second pulse / 10 second wait time is repeated for the other cluster. In this manner, a lateral velocity change operates with a 33% duty cycle.

Lateral velocity corrections are further complicated by the need to direct the thrust vector through the estimated spacecraft center of mass, in order to minimize attitude perturbations. Relative to the thruster clusters, the spacecraft center of mass has a $+Z$ component. Thrusters 1 and 6 produce a thrust vector with a $-Z$ component. By reducing their pulse duration, the net thrust from each cluster is rotated in the $+Z$ direction. The pulse duration is shortened such that the burn arc remains centered about the same clock angle as the other three thrusters in the cluster. This center of mass targeting process results in a lateral ΔV that is approximately 99 degrees from the spacecraft $-Z$ axis. Note that any remaining small Z axis error in the lateral thrust vector pointing with respect to the actual spacecraft center of mass produces a torque perpendicular to the thrust vector. To first order the resulting spacecraft attitude perturbation rotates about the desired ΔV direction, thus having only a secondary effect on ΔV pointing errors. Additionally, the size and direction of the attitude perturbation helps determine the Z component error between the actual spacecraft center of mass and the effective lateral thrust direction. Consequently, the pointing performance of a lateral ΔV segment can be used to adjust the off-pulsing of thrusters 1 and 6 to reduce attitude perturbations of subsequent lateral ΔV segments.

Unlike many MER subsystems, the propulsion system is designed to be single fault tolerant. The system includes redundant thrusters, catalyst bed heaters, tank pressure transducers, and latch valves. All the propulsion functions can still be performed with a single thruster cluster, albeit in a degraded fashion. The loss of a thruster cluster obviously eliminates the benefit of coupled-pair thruster firings. Attitude control and fault protection software included the capability to operate with a single thruster branch. A detailed description of the in-flight performance of the propulsion system can be found in Ref. 3.

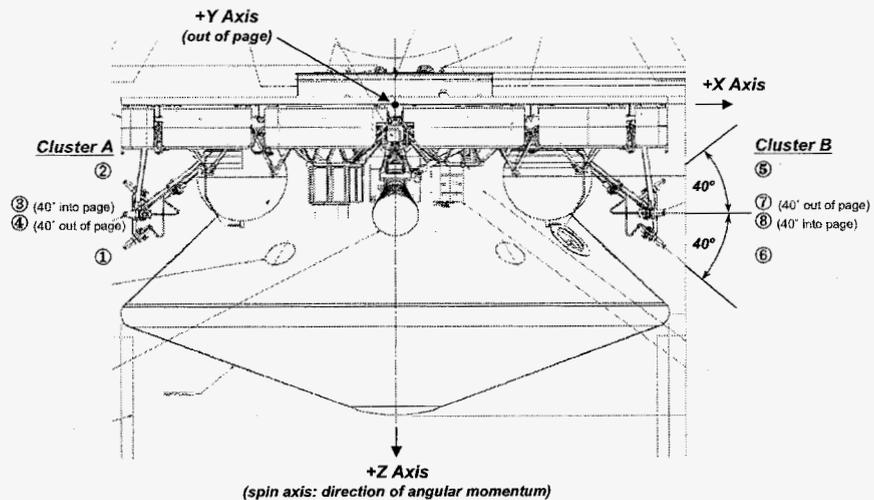


Figure 3: Spacecraft Coordinate System and Thruster Configuration Line Drawing

III. Navigation

During MER flight operations, navigation performs three main functions: state estimation and trajectory prediction, propulsive maneuver design and analysis, and EDL analysis including landing dispersion assessment. Reference 4 provides a complete overview of the successful MER navigation results. Within the navigation system, the orbit determination (OD) element processes tracking data to estimate the spacecraft state and future trajectory, including knowledge uncertainty estimates. The MER missions relied upon radiometric tracking data via two-way coherent Doppler, two-way ranging, and Δ VLBI (Delta Very Long Baseline Interferometry). Δ VLBI measures a spacecraft position component (plane-of-sky) that is orthogonal to the components measured by Doppler and range data (Earthline or line-of-sight). Delta Differential One-way Range (Δ DOR) is the type of Δ VLBI measurement utilized extensively by the MER missions. The complementary data types empowered remarkably accurate and stable trajectory estimates with one-sigma uncertainties of approximately 400 meters in the Mars target plane at a distance of nearly 200 million km. For an in-depth analysis of the MER orbit determination methodology and results, see Ref. 5-8. The EDL analysis is covered in Ref. 9-10. The additional navigation task of estimating the rover's position on the surface of Mars using in-situ radio measurements is discussed in Ref. 11.

A. Mission Requirements

There are five key navigation requirements that drive the MER maneuver analysis and design.

1. Mission Propellant Statistics

The MER mission requires delivery to the desired atmospheric entry conditions at Mars with a probability of 99% with respect to the available propellant. Sophisticated Monte Carlo simulations of the entire mission are necessary to verify this requirement¹². These simulations include launch vehicle injection errors spanning the launch period, orbit determination uncertainties, TCM execution errors, spacecraft implementation constraints, and modeling of spacecraft implementation modes. This analysis was further complicated by the delay in the official landing site selection for Spirit.

2. Biased Injection Aimpoint

Mars planetary protection from biological contamination requires that the launch vehicle upper stage have a probability of impact $< 1.0 \times 10^{-4}$. To satisfy this requirement, the launch vehicle injection target must be biased away from Mars. The amount of bias is determined by mapping the injection covariance from the launch vehicle provider to the target plane at Mars. The biased launch target is selected after analysis to minimize the statistical propellant costs. This analysis considers the spacecraft Δ V implementation capability¹².

3. TCM-1 Delay

The propellant requirements shall provide a 90% probability of mission success for a TCM-1 delay until launch plus 30 days. This requirement provides margin against an initial spacecraft fault that necessitates a TCM-1 execution delay. The requirement also begins to address the project desire to delay the Spirit landing site selection until after the Opportunity launch. This flexibility is desirable to allow a Meridiani Planum landing even in the event of an Opportunity launch failure.

4. TCM Development Timeline

The time allowed from navigation data cutoff to maneuver execution is 5 days for cruise TCMs 1-3. This time includes orbit determination, maneuver design, TCM command generation, validation, and uplink. For the final approach TCMs 4-6, the schedule is reduced to 6 hours. The rapid development timeline is indicative of the desire to include the latest and most informative navigation tracking data to support extremely accurate control of the ballistic trajectory through the atmosphere to the desired landing site.

5. Atmospheric Entry Delivery Accuracy

The interplanetary trajectory is targeted to an inertial atmospheric entry flight path angle (EFPA) of -11.5 degrees with a 3-sigma TCM-5 (at Entry - 2 days) delivery uncertainty of less than ± 0.12 degrees for Gusev Crater, and ± 0.14 degrees for Meridiani Planum. The EFPA delivery uncertainty was desired to be as small as possible to reduce the Mars landing footprint and enable the greatest number of potential landing sites for science to choose from. The EFPA delivery accuracy was capability driven based on navigation pre-launch analysis. An accurate surface landing obviously requires additional targeting accuracy in latitude and time of atmospheric entry, but the EFPA uncertainty represents the dominant parameter to control the downtrack component of the landing ellipse.

B. TCM Location

Six TCMs were planned to meet the mission requirements placed on Navigation. Table 1 lists each TCM location relative to launch and entry events, the designed burn start epoch, and a brief description of the maneuver rationale for both Spirit and Opportunity. The first three TCMs were placed in the cruise phase of the mission. Figure 4 illustrates the TCM locations on the interplanetary trajectory to Mars. TCM-1 was nominally scheduled to occur 10 days after launch to remove the launch bias for planetary protection and correct launch vehicle injection errors. This location was chosen to provide adequate time for the initial spacecraft checkout and TCM-1 design with reasonable margin. The Launch + 10 day epoch was appropriate to satisfy the 99% mission propellant requirement. Delaying the execution date results in an undesirable statistical propellant cost. It was recognized that the TCM-1 execution date could be moved earlier if warranted due to a launch vehicle anomaly. TCM-1 would be the largest velocity correction required, resulting in potentially significant maneuver execution errors. As such, TCM-2 was positioned near Launch + 60 days to clean up the TCM-1 execution errors which were proportional to the magnitude of

Table 1: TCM Profile

Spirit (MER-A)

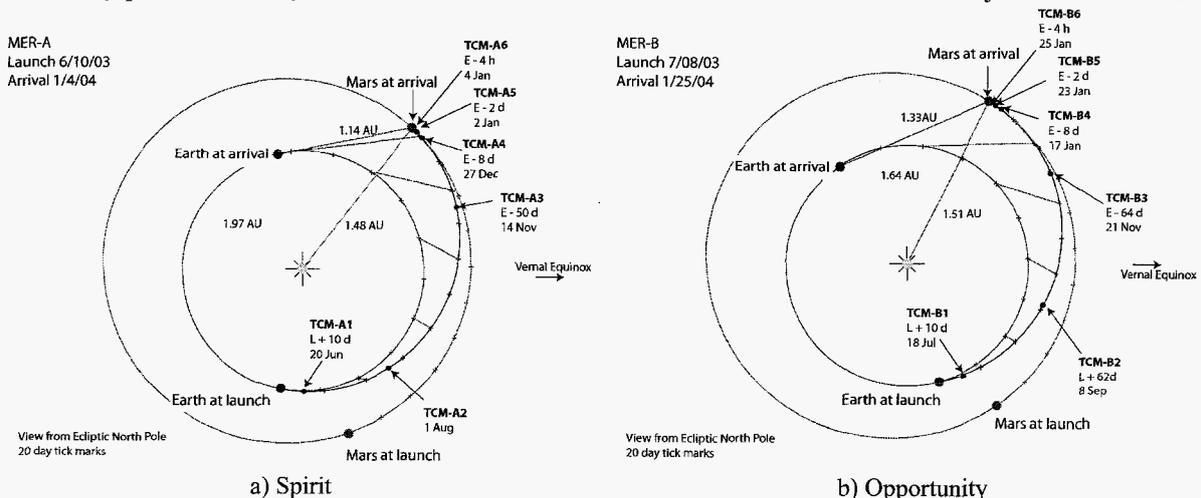
Event	Location	Epoch (UTC-SCET)	Description
Launch		10-Jun-2003 17:58:47.00	Biased from Mars for planetary protection.
TCM-A1	Launch + 10 days	20-Jun-2003 17:00:00.00	Remove launch bias and correct injection errors.
TCM-A2	Launch + 52 days	01-Aug-2003 18:00:00.00	Correct TCM-A1 execution errors and target to Gusev site.
TCM-A3	Entry - 50 days	14-Nov-2003 18:30:00.00	Correct TCM-A2 delivery errors.
TCM-A4	Entry - 8 days	27-Dec-2003 02:00:00.00	Correct TCM-A3 delivery errors.
TCM-A5	Entry - 2 days	02-Jan-2004 02:00:00.00	Final entry targeting maneuver.
TCM-A5X	Entry - 1 day	03-Jan-2004 02:00:00.00	Backup opportunity for TCM-A5.
TCM-A6	Entry - 4 hours	04-Jan-2004 00:20:00.00	Late contingency maneuver.
Entry		04-Jan-2004 04:19:51.72	3522.2 km areocentric radius (~125 km altitude)

Opportunity (MER-B)

Event	Location	Epoch (UTC-SCET)	Description
Launch		08-Jul-2003 03:18:15.00	Biased from Mars for planetary protection.
TCM-B1	Launch + 10 days	18-Jul-2003 19:30:00.00	Remove launch bias and correct injection errors.
TCM-B2	Launch + 62 days	08-Sep-2003 16:00:00.00	Correct TCM-B1 execution errors.
TCM-B3	Entry - 64 days	21-Nov-2003 18:30:00.00	Correct TCM-B2 delivery errors.
TCM-B4	Entry - 8 days	17-Jan-2004 02:00:00.00	Correct TCM-B3 delivery errors.
TCM-B5	Entry - 2 days	23-Jan-2004 02:00:00.00	Final entry targeting maneuver.
TCM-B5X	Entry - 1 day	24-Jan-2004 02:00:00.00	Backup opportunity for TCM-B5.
TCM-B6	Entry - 4 hours	25-Jan-2004 00:50:00.00	Late contingency maneuver.
Entry		25-Jan-2004 04:48:41.72	3522.2 km areocentric radius (~125 km altitude)

the velocity correction. TCM-3 was scheduled near the end of the cruise phase of the mission, approximately 60 days before atmospheric entry. This location corrects TCM-2 execution errors along with the residual navigation modeling errors that accumulate during the previous 3 months of interplanetary cruise.

The final three maneuvers are planned during the end of the Approach phase, which begins 45 days from entry. TCMs 4-6 are scheduled to provide the final trajectory adjustments to achieve the desired entry conditions. The TCM placement strategy centered about meeting the landing site requirements with TCM-5 at Entry -2 days. TCM-4, planned at Entry -8 days, corrects TCM-3 delivery errors and keeps TCM-5 small in size. A small TCM-5 keeps the proportional maneuver execution errors to a minimum. Scheduling a backup opportunity, TCM-5X at Entry -1 day, recognized the critical nature of TCM-5. Finally, a very late contingency maneuver was scheduled as late as effectively possible at Entry -4 hours. The TCM-6 orbit determination data cutoff occurred just 8.6 hours before



a) Spirit

b) Opportunity

Figure 4: Interplanetary Trajectories with TCM Locations

entry to provide an opportunity to begin to detect the gravitational pull of Mars on the spacecraft trajectory. In the unlikely event that a significant navigation error had somehow previously gone undetected, TCM-6 provided a final opportunity to react.

IV. Propulsive Maneuver Analysis and Design

Propulsive maneuver analysis and design must achieve the mission requirements while accommodating spacecraft operating constraints. A successful design maintains an acceptable level of project flexibility, utilizes the unique spacecraft capabilities, and avoids any unnecessary complexity.

A. Implementation Modes

As discussed previously, the propulsion system can execute axial and lateral propulsive velocity corrections in the spacecraft reference frame. A vector mode maneuver is one that combines the axial and lateral segments so that the vector sum produces the desired inertial ΔV magnitude and direction. This is a powerful maneuver implementation mode that spinning spacecraft can accomplish without executing a turn. A no-turn vector mode maneuver reduces operational risk by eliminating the estimation and control of a new attitude with potentially unknown characteristics. Additionally, the existing attitude is part of the nominal plan, well characterized, provides adequate spacecraft power, and supports ground communication. The downside to vector mode maneuvers is mainly higher propellant costs, especially for large ΔV corrections.

Combining the axial and lateral velocity correction capability with a spacecraft turn (or turns) provides additional design flexibility in the maneuver implementation mode. For a desired inertial ΔV , the MER spacecraft could execute a turn to position the spin axis along the ΔV direction. Because the spacecraft can execute either +Z or -Z velocity corrections, there are two possible attitudes whereby a purely axial ΔV can be performed. At any given spacecraft attitude, a lateral ΔV can be performed approximately 99 degrees from the spacecraft -Z axis at any clock angle. Consequently, a 99 degree cone about an inertial ΔV direction represents the locus of spacecraft attitudes (-Z axis) that can accomplish the velocity correction with a turn and purely lateral burn.

By combining a spacecraft turn with both an axial and lateral ΔV , the propulsive maneuver design space becomes infinite. The spacecraft can turn to any possible attitude and still execute an axial and lateral ΔV combination that will produce the desired inertial velocity correction. This mode is used when a turn and purely axial or lateral burn option is unavailable due to the violation of a spacecraft constraint. The turn is utilized to improve an unfavorable characteristic of the no-turn vector mode option, which is most likely propellant cost.

B. Design Constraints

TCM-1 had the largest mean ΔV and the greatest statistical variation in the mission. Propellant considerations dictated maintaining implementation mode flexibility for the design of TCM-1. Significant pointing constraints had to be considered in the design of any turn and burn implementation. The most restrictive constraint was a 46 deg or less spacecraft -Z angle from the Sun for adequate power margin. The off-Sun pointing constraint for thermal protection was 60 degrees. To maintain an 1185 bps downlink data rate, an off-Earth pointing constraint ranged from 90 deg at launch +10 days to 53 deg at launch +50 days. Turning the spacecraft also requires a reliable star set within the star scanner field of view at the proposed burn attitude to support the attitude control system (ACS).

After TCM-1, all propulsive maneuvers were planned for vector mode execution without a spacecraft turn from the nominal cruise attitude. The maneuver design was therefore constrained to occur at a fixed attitude determined by the TCM location within the nominal spacecraft attitude profile. Burn start times were negotiated with the Spacecraft-Rover Engineering Team (SRET) based on Deep Space Network (DSN) tracking coverage and view periods. The expected thrust levels and timing of the axial and lateral burn segments were also provided by SRET and incorporated into the ΔV design. The timing information includes the wait times between propulsive thruster firings to accommodate spacecraft spin and pointing corrections.

All TCMS were commanded using Auto-TCM, a high level sequence command that controls spacecraft pointing, breaks up the lateral burn duration into appropriately sized burn segments, and includes options to determine the level of fault protection response. The Auto-TCM command capability simplified the TCM sequence development process and enabled a quick response to the late orbit determination knowledge updates required for the final entry targeting maneuvers. Auto-TCM is event driven, resulting in reduced execution durations for maneuvers with a large lateral ΔV . Without an event driven command, the wait times between lateral burn segments would have to be maximized to protect for worst case spin and pointing excursions. A minor navigation detriment with Auto-TCM is the uncertainty in the actual thruster firing time. This uncertainty is only on the order of minutes for the start of a burn, but could grow significantly by the end of a long duration lateral maneuver.

C. Design Strategy

The fundamental design strategy is to essentially eliminate any deterministic design error that results in a propulsive maneuver being offset from the intended target on the surface of Mars. To achieve this goal, two separate iterations steps are required in the maneuver design process. The first of these involves modeling the spacecraft implementation mode and the resulting effects on the desired ΔV . Software tools were developed and tested to accurately model the expected timing of propulsive thruster firings for the selected implementation mode. This spacecraft ΔV execution model feeds back into the design of the desired inertial velocity change. The spacecraft implementation influence on the desired inertial ΔV is greatest in non-linear trajectory regions (e.g., gravity wells) or when the time between maneuver execution and the target event is the shortest.

The second area requiring maneuver design iteration is the transition from atmospheric entry targeting to landing site determination. The atmospheric entry event is defined to occur at an areocentric radius of 3522.2 km, which is an altitude of 125 km with respect to the Mars equatorial radius. The state targets at entry include inertial flight path angle (-11.5°), target plane orientation angle (latitude), and entry time (longitude). In order to control the desired landing point, these targets are determined from the nominal spacecraft state vector at entry. Because of the large incoming energy of the spacecraft, the velocity components at entry are only slightly perturbed by an earlier propulsive maneuver. However, for precise landing control the entry targets are iterated until the post TCM trajectory propagates directly to the desired landing point on the surface of Mars. This same iterative procedure was exercised for all propulsive maneuver designs.

V. TCM-5/6 Execution Criteria

The MER project recognized early on that potentially critical operations decisions would have to be made regarding whether or not to execute the TCMs within the final two days before entry, when time was of the essence. These last maneuver opportunities had broad implications throughout the flight team and obviously the science community as well. There was extreme confidence in the reliability of the TCM design and execution process, but the decision to execute a propulsive maneuver should always be justified by the benefits to the mission objectives. A TCM decision process was carefully developed to identify the participants and examine all the relevant factors. The result is a TCM checklist that provides a side-by-side comparison of key parameter results with and without the successful execution of the designed TCM. See Table 4 in the following Flight Results section for an example of a completed TCM checklist.

The identified TCM execution criteria were divided into primary and secondary decision factors. There were a total of 7 primary decision factors. All the primary factors had to be satisfied before a decision path was considered acceptable, and they were all objectively measured against a specific criterion. The first two factors considered the size of the velocity correction. A minimum ΔV size was identified based on the three sigma fixed execution error requirement, and a sufficient propellant factor was included to protect future spacecraft activities required for entry. Monte Carlo analysis was performed to evaluate the probability that atmospheric entry and descent was within pre-qualified system capability based upon the flight path angle uncertainty. Of particular importance is the probability of a safe landing based upon hazard maps and terrain classes. For the final TCM Go/No-Go meeting, a "Go" was required based upon the current assessed state of the spacecraft and the mission operations system. The final and ultimate decision factor necessary to proceed with a TCM was a "Go" from the project manager.

The secondary factors were a qualitative assessment, based on a red, yellow, or green "fever" chart value. These factors were not measured against specific criteria. The secondary decision factors were not individually critical, in that a "red" assessment would not necessarily rule out continuing with a TCM decision path. Seven secondary decision factors were identified and evaluated. The first pertained to confidence in the current orbit determination estimate in that the solution history is consistent and stable. Secondly, there is a preference to have the orbit determination uncertainty be small with respect to the desired correction, in order to provide a statistical justification for the maneuver. The surface path of the maneuver was evaluated against identified hazards that might be crossed during the course of the TCM execution. Implementation errors resulting from converting the desired ΔV to spacecraft commands must be small. The EDL parameters should be within the ground analysis envelope. From a science assessment, there should be confidence in the surface and wind characterization for the landing site. The final science factor was the relative science return between the sites with and without the TCM. The science return categories were based on a preference for Mars Orbiter Camera (MOC) coverage, relative confidence of landing in a scientifically interesting area, and landing in a warmer region within Meridiani Planum.

VI. Final Approach Targeting Strategy

During the interplanetary cruise, operational readiness tests were performed and revealed a need to reinvestigate the targeting strategy being used for the final approach TCMs. The final maneuvers were intended to provide the slight corrections necessary to improve the probability of a safe landing to an acceptably high level. Very small velocity corrections on the order of cm/s could be required to avoid hazardous areas and allow precise control of the deterministic surface target. Numerous issues became evident in the first two system tests that included the design of TCM-5 or TCM-6. The ΔV was larger than expected based upon statistical analysis that assumed corrections were performed in the targeting plane rather than the entry targets. The ΔV and surface path were extremely sensitive to apparently minor changes in the input models. Of particular concern was the observed sensitivity to modeling assumptions in the atmospheric propagation. These types of changes were expected and did occur very late in the approach phase. The TCM surface path demonstrated large longitude or along-track variation during the course of a vector mode maneuver implementation. The axial segment would move the projected landing site extremely uptrack or downtrack, followed by a lateral segment that brought the surface aimpoint all the way back. The cumulative result of the large surface movement was the desired minor correction in the landing site. In order to provide this slight overall improvement in landing site safety, the vector mode TCM path was crossing extremely hazardous regions on the surface. This scenario posed significant risk if a TCM execution failed to complete, or if Auto-TCM worked through a spacecraft fault with the result being a significant delay to the final maneuver segment. Either of these faults could seriously reduce the probability of a successful landing.

Additional analysis was performed on the control capability of the late approach maneuvers. By examining the partial derivatives of FPA at entry, latitude, and longitude of the landing point with respect to spacecraft velocity, it was apparent that the desired control parameters were very highly correlated on the approach trajectory. For TCM-A6, the linear correlation between entry FPA and landing point longitude was 0.9999, and 0.98 between entry FPA and landing point latitude. While it was previously recognized that these parameters were closely correlated, the ramifications of correcting small time of flight errors (that resulted in small longitude errors on the surface) with a numerically fixed entry FPA target and a vector mode maneuver implementation, were suddenly realized.

Fortunately, the trajectory characteristic that created the control dilemma also provided an elegant solution to the problem. The entry and descent system was well equipped to accommodate variations in the entry FPA of up to ± 0.75 degrees. The high correlation between entry FPA and latitude/longitude results in most of the FPA correction occurring naturally by only targeting latitude and longitude on the surface. The partial of entry FPA change necessary to correct time of flight errors was only $0.001^\circ/s$. The one sigma time of flight errors were only expected to be approximately 1 second at the time of TCM-5, and even less at TCM-6. Consequently, by accepting an expected entry FPA variation of a few millidegrees about the nominal -11.5 degree target, the number of TCM control parameters was reduced from three to two. The MER spacecraft were well equipped to handle a two

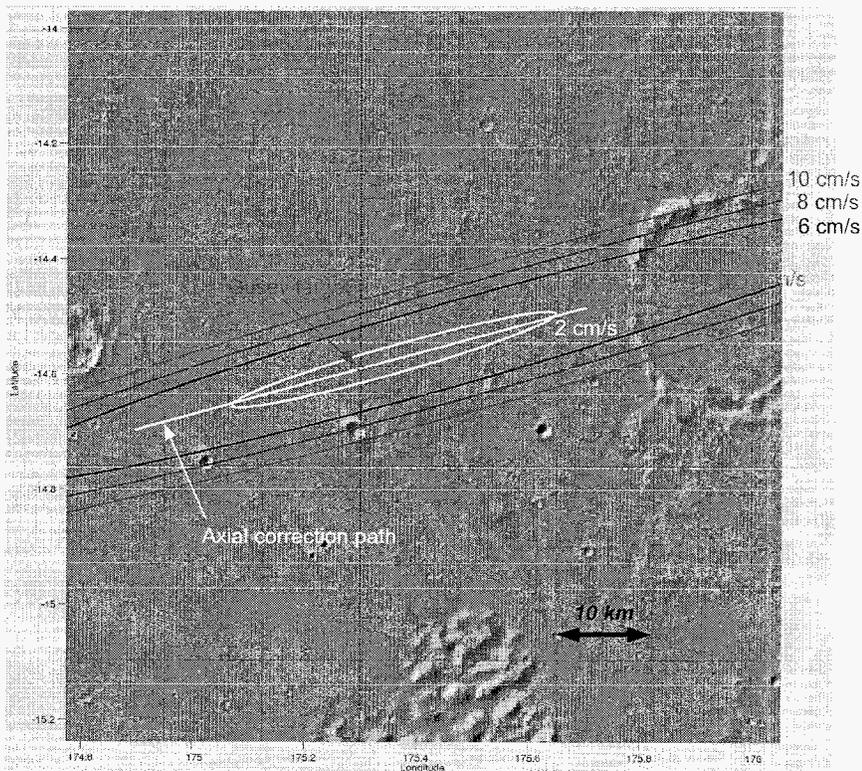


Figure 5: TCM-A5 Lateral and Axial ΔV Cost Contours at Gusev Crater

degree of freedom control problem using ΔV magnitude and clock angle associated with lateral maneuvers. The result is complete control of surface latitude and longitude with a direct surface path by executing only a lateral maneuver component.

A single control dimension could be provided with an axial velocity correction. Based upon the nominal spacecraft attitude, which kept the $-Z$ axis near Earth point for communications, an axial velocity correction mainly adjusted along-track errors on the surface. This maneuver mode could correct the majority of the surface target error, but would leave the cross-track component uncorrected. An axial velocity correction would be directly aligned with the Earth line-of-sight direction, which is directly observable with Doppler data. Based on the assumption that the greatest TCM execution error *a priori* uncertainty is ΔV magnitude, an axial maneuver could provide the quickest and most accurate ΔV reconstruction estimate.

Figure 5 shows the ΔV cost contour at Gusev Crater for TCM-A5. The ellipses define the landing point error that can be completely corrected to the target with a purely lateral maneuver for the labeled ΔV magnitude. The elongation of the ellipse is a consequence of the high correlation between latitude and longitude corrections on the approach trajectory. Also notice that the ellipse contour is offset from the surface target. This is caused by the non-orthogonal nature of a purely lateral maneuver. The along-track line in the figure represents the one-dimensional axial correction path. For a downtrack error (to the right and up of the target), an axial maneuver is slightly more efficient than a lateral only implementation. For an uptrack error, an axial maneuver is almost twice as efficient as the lateral only option. TCM-A6 cost contour analysis revealed nearly identical characteristics, but with ΔV costs that scaled linearly with time-to-go. The ΔV cost contours for Meridiani Planum were very similar, but the major axes of the capability ellipses were more aligned with the longitude direction.

Although never seriously considered, this targeting strategy could even be used to avoid a hazard that might exist on the direct surface path. By combining the axial and lateral targeting capability, an infinite number of surface paths will arrive at the desired target. The axial path has a limited direction, but could be included to provide a more advantageous surface path for the lateral correction to follow. In this manner, the surface path could actually go around a ground hazard.

VII. Flight Results

A targeting reconstruction is listed in Table 2. The table includes the B-plane target (see appendix for definition), achieved result, delivery error (achieved - target), and the predicted one-sigma delivery uncertainty for launch vehicle injection and all TCMs. The achieved parameters are estimated via the orbit determination process. In the last column of the table, the delivery error is represented at the sigma level of the predicted delivery uncertainty (reconstructed delivery error divided by the predicted one-sigma delivery uncertainty). For both missions, the delivery errors rarely exceeded the one-sigma predicted accuracy.

Table 3 summarizes the reconstructed TCM execution errors, along with the execution mode, desired inertial ΔV , and the spacecraft burn segments that comprise the total ΔV . Per the pre-launch plan, all maneuvers after TCM-1 were executed vector mode at the nominal cruise attitude (i.e., the maneuver was designed to execute without an initial turn). All TCM execution errors were easily within the three-sigma flight system performance requirements. The largest total magnitude error was 1.4 sigma at TCM-A2, and the largest total pointing error of 2.0 sigma occurred at TCM-B4.

A brief chronological description follows of the unique characteristics of each TCM. Reference 13 includes further details regarding launch and TCM-1, and Ref. 4 contains additional maneuver B-plane plots.

A. Spirit Launch

Analysis of statistical ΔV requirements for both missions was primarily driven by the uncertainty associated with a single event: launch. The performance of the launch vehicle effectively determined the propellant margin for the interplanetary cruise. The spacecraft propellant tanks were filled to their capacity with 52 kg of propellant. The 99% statistical propellant requirements were approximately 44 kg (including 3 kg allocated for attitude control) with an additional 5 kg required to accommodate delaying the final landing site selection until after TCM-1, leaving only 3 kg of margin. The Spirit liftoff occurred via a Boeing Delta II 7925 launch vehicle on June 10, 2003 at 17:58:47 UTC with a 93 degree launch azimuth. Spirit launched on the 12th day of the launch period after repairs were completed on suspect circuit boards.

The launch vehicle injected the Spirit spacecraft on the desired trajectory to Mars within the expected dispersions. The injection energy per unit mass (C_3) at the targeting interface point had an error of $-0.0331 \text{ km}^2/\text{s}^2$ from the target value of $8.8550 \text{ km}^2/\text{s}^2$. Compared to the expected dispersion statistics, this represents a -0.6 sigma error. The right ascension and declination of the launch asymptote had errors of 0.9 and 1.1 sigma respectively. These injection errors map to less than 1-sigma errors in the Mars B-plane parameters, as seen in Figure 6.

B. Spirit TCM-A1

Within hours of launch, the navigation tracking data provided a solid estimate of the injection error. Work began immediately to evaluate TCM-A1 design trades relating to execution date, landing site, mission propellant costs, maneuver implementation mode, execution duration, off-Sun angles for adequate power margin, and off-Earth angles to support a minimum of 1185 bits per second telemetry data rates. The nominal injection resulted in the ability to delay TCM-A1 to launch +50 days and still maintain approximately 18 kg of propellant margin (99% probability level). Performing the maneuver at launch +10 days would improve the propellant margin by at least an additional 8 kg. With the

statistical uncertainty of launch complete, propellant reserves were now viewed as insurance against potential trajectory anomalies during cruise. Consequently, additional propellant would be used if it provided a benefit to flight operations and maintained adequate margin.

Deciding the TCM-A1 execution date was ultimately driven by schedule and workforce considerations. Understandably, some interest was expressed in delaying TCM-A1 until after the upcoming Opportunity launch, which at the time was scheduled for June 26 (Spirit launch +16 days). This would allow the flight team, which had just completed intense launch activities, to begin to focus on the Spirit launch and free resources to work any launch issues. The concern with delaying TCM-A1 was the resulting dependence on the Opportunity launch and the possibility of launch delays. TCM-A1 development would have uncertainty in execution date and landing site target until after the Opportunity launch. This would make it difficult to pre-generate the maneuver design. If there was an anomaly associated with the Opportunity launch, a schedule and resource conflict could result between TCM-A1 and TCM-B1. A TCM-A1 strategy had been developed to correct the injection bias for planetary protection and the injection errors and still maintain landing site flexibility until after the Opportunity launch. By targeting at launch +10 days to a central landing site on Mars, the significant known errors could be corrected early while maintaining

Table 2: Targeting Reconstruction

Spirit (MER-A)

Event	Parameter	Units	Target	Achieved	Delivery Error	Delivery Uncertainty (1 σ)	Error (σ)
Launch	B•R	km	104,184	292,891	188,707	285,337	0.7
	B•T	km	235,634	407,923	172,289	291,198	0.6
	TCA	ET	1/5/04 06:08:44	1/6/04 23:17:24	1.714 days	2.506 days	0.7
TCM-A1	B•R	km	1,067	3,415	2,348	5,519	0.4
	B•T	km	7,084	7,378	294	7,102	0.04
	TCA	ET	1/4/04 10:26:42	1/4/04 11:11:15	44.6 min	63.1 min	0.7
TCM-A2	B•R	km	2,503	2,929	426	1,340	0.3
	B•T	km	6,712	7,356	644	2,037	0.3
	TCA	ET	1/4/04 04:24:03	1/4/04 04:40:38	16.6 min	11.8 min	1.4
TCM-A3	B•R	km	2,502.9	2,516.0	13.1	44.0	0.3
	B•T	km	6,711.6	6,700.3	-11.3	50.7	-0.2
	TCA	ET	1/4/04 04:24:02.5	1/4/04 04:24:17.7	15.2 s	16.1 s	0.9
TCM-A4	B•R	km	2,504.99	2,504.94	-0.05	1.53	-0.03
	B•T	km	6,711.03	6,710.85	-0.18	1.50	-0.1
	TCA	ET	1/4/04 04:24:15.7	1/4/04 04:24:15.8	0.1 s	0.5 s	0.2
TCM-A5	Cancelled						
TCM-A5X	Cancelled						
TCM-A6	Cancelled						

Opportunity (MER-B)

Event	Parameter	Units	Target	Achieved	Delivery Error	Delivery Uncertainty (1 σ)	Error (σ)
Launch	B•R	km	219,754	204,197	-15,557	172,547	-0.1
	B•T	km	456,623	274,289	-182,334	210,575	-0.9
	TCA	ET	1/26/04 19:03:52	1/26/04 16:23:22	-0.111 days	0.947 days	-0.1
TCM-B1	B•R	km	466	3,588	3,122	5,112	0.6
	B•T	km	6,870	11,642	4,772	8,799	0.5
	TCA	ET	1/25/04 04:53:13	1/25/04 05:39:45	46.5 min	39.8 min	1.2
TCM-B2	B•R	km	466	420	-47	148	-0.3
	B•T	km	6,870	6,815	-56	222	-0.3
	TCA	ET	1/25/04 04:53:12	1/25/04 04:52:58	-14 s	36 s	-0.4
TCM-B3	Cancelled						
TCM-B4	B•R	km	465.81	466.88	1.07	2.49	0.4
	B•T	km	6,870.18	6,870.86	0.68	2.38	0.3
	TCA	ET	1/25/04 04:52:59.1	1/25/04 04:53:00.1	1.0 s	0.8 s	1.2
TCM-B5	Cancelled						
TCM-B5X	Cancelled						
TCM-B6	Cancelled						

Table 3: TCM Execution Errors

Spirit (MER-A)

TCM	Mode	Inertial ΔV (m/s)	Implementation ΔV			Maneuver Execution Errors							
			+Z (m/s)	-Z (m/s)	L (m/s)	Magnitude (%)				Direction (mrad)			
						+Z	-Z	L	Total	+Z	-Z	L	Total
A1	Vector (Lat Cal)	16.460	9.103		12.376	-3.9	+1.0	-0.7		11.6		0.1	22.5
A2	Vector	6.008	2.317		5.207	-1.4	-2.6	-2.4		0.3		2.5	2.3
A3	Vector	0.577	0.513		0.200	-1.6	-0.4	-1.7		12.9		3.8	9.9
A4	Lat Only	0.025			0.025			-1.4	-1.4			5.5	5.5

Opportunity (MER-B)

TCM	Mode	Inertial ΔV (m/s)	Implementation ΔV			Maneuver Execution Errors							
			+Z (m/s)	-Z (m/s)	L (m/s)	Magnitude (%)				Direction (mrad)			
						+Z	-Z	L	Total	+Z	-Z	L	Total
B1	Turn & +Z Burn	16.172	16.172			-1.4			-1.4	3.0			3.0
B2	Vector	0.534	0.496		0.136	+1.8	-0.6	+1.1		7.2		11.4	11.1
B4	Vector	0.108		0.083	0.081	+2.9	-1.9	+0.6			8.7	7.7	34.0

3-Sigma Error Requirements: Proportional Magnitude = 5% Proportional pointing = 50 mrad per axis
 Fixed Magnitude = 6 mm/s Fixed pointing = 6 mm/s per axis

the ability to target Spirit for Gusev Crater or Meridiani Planum at the next maneuver opportunity. The decision was made to retire the TCM-A1 risk by performing the maneuver at launch +10 days.

Without a clearly favorable turn and burn implementation mode available at launch +10 days, TCM-A1 was executed in vector mode at the current injection attitude. A 25 deg attitude correction turn was nominally scheduled to occur shortly after the TCM at launch +13 days. To simplify spacecraft commanding and reduce flight team workload, this turn was incorporated into the Auto-TCM command via the post maneuver attitude. A conscious decision was made to perform the attitude correction after the TCM to increase the reliability of the maneuver. The vector mode implementation had a 9.1 m/s +Z axial component and a 12.4 m/s lateral component. The continuous axial burn duration was 28 minutes, followed by 22 minutes of lateral burn pulses divided into 16 segments. The

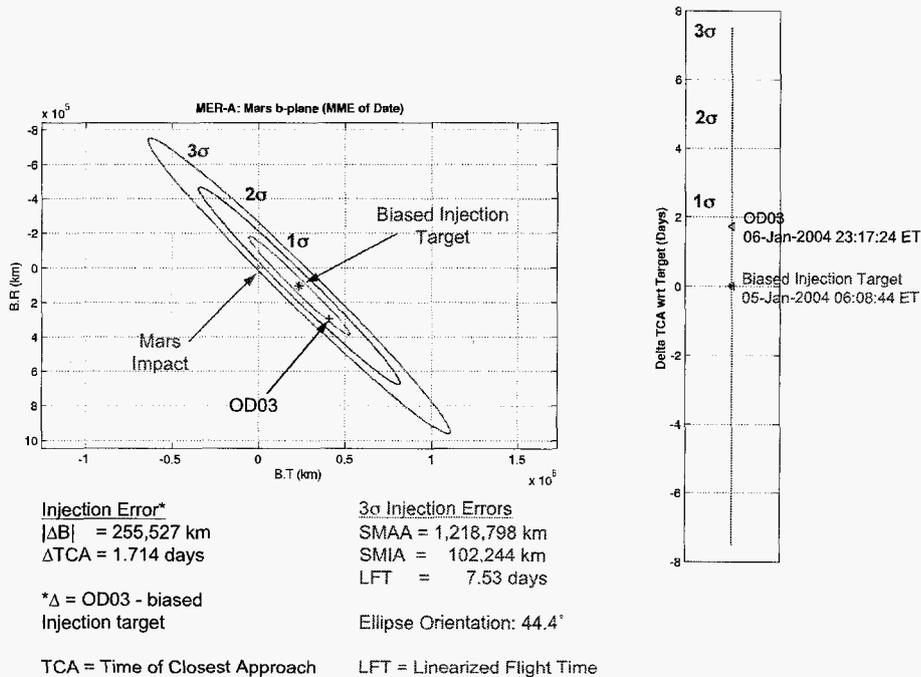


Figure 6: Spirit Injection in the Mars B-Plane

first two lateral burn segments were designed as a lateral ΔV calibration activity, which significantly reduced the total duration of the maneuver events. This activity helped align the lateral thruster firings through the spacecraft center of mass, increasing the amount of ΔV that could be performed before requiring a pointing correction. The event driven Auto-TCM capability also helped to reduce the TCM-A1 duration by completing spin and pointing corrections as needed and progressing to the next sequence command without delay. The maneuver used 14.7 kg of propellant.

C. Opportunity Launch

The Opportunity spacecraft propellant tanks were also filled to their capacity with 52 kg of propellant. The 99% statistical propellant requirement was approximately 38 kg (including 3 kg allocated for attitude control). The Opportunity spacecraft was intended for Meridiani Planum, and therefore did not require any additional propellant to maintain landing site flexibility. Consequently, the 99% statistical propellant margin was a robust 14 kg at launch.

The Opportunity (MER-B) liftoff occurred via a Boeing Delta II 7925H launch vehicle on July 8, 2003 at 03:18:15 UTC with a 99 degree launch azimuth. This was the second instantaneous launch opportunity of the day. The initial attempt was halted within seconds of liftoff due to a sluggish first stage fill-and-drain valve. Opportunity launched on the 14th day of the launch period due to numerous delays caused by range safety, high-altitude winds, debonded insulation on the first stage of the Delta II, and battery replacement in the rocket's self-destruct system.

Once again, the launch vehicle injected the Opportunity spacecraft on the desired trajectory to Mars within the expected dispersions. The injection energy per unit mass (C_3) at the targeting interface point had an error of -0.0024 from the target value of $14.3247 \text{ km}^2/\text{s}^2$. Compared to the expected dispersion statistics, this represents only a -0.04 sigma error. The right ascension and declination of the launch asymptote had errors of 1.3 and -0.8 sigma respectively. Considering expected correlations, these injection errors map to a 1.5-sigma error in the two-

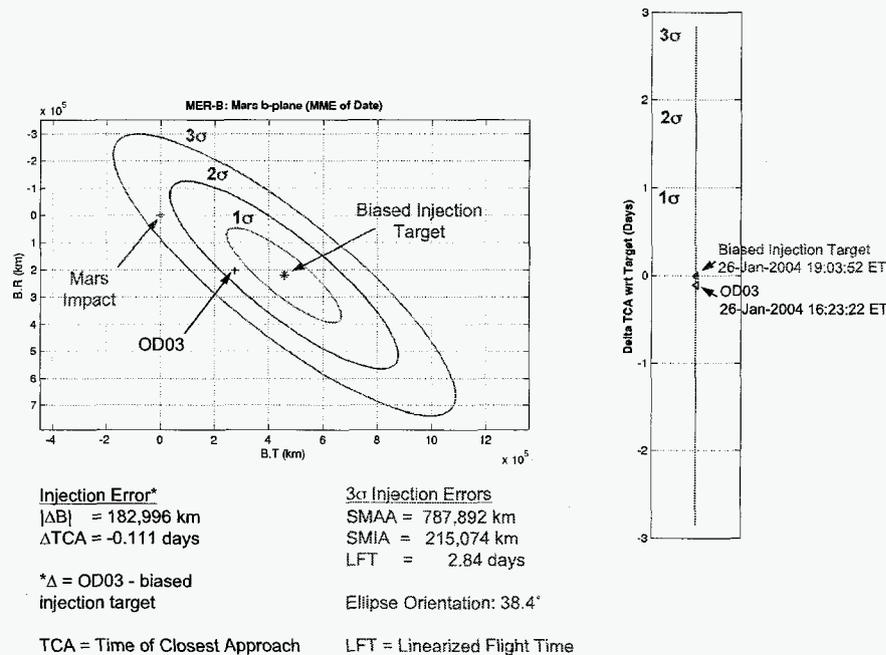


Figure 7: Opportunity Injection in the Mars B-Plane

dimensional Mars B-plane, and a -0.1 sigma error in time of closest approach. The mapped injection errors are illustrated in Fig. 7.

D. Opportunity TCM-B1

The navigation tracking data once again provided a reliable estimate of the injection error within hours of launch. Similar design trades were analyzed for TCM-B1 as were done for Spirit's first TCM, except that having

only the Meridiani Planum landing site to consider significantly simplified the trade space. TCM-B1 execution dates were evaluated to launch +50 days. The nominal injection and favorable pre-launch propellant status resulted in almost 27 kg of propellant margin with TCM-B1 execution at launch +50 days. Executing TCM-B1 at launch +10 days would increase the robust propellant margin by an additional 8 kg.

In a manner similar to Spirit, Opportunity's first TCM would not need to be decided based on propellant requirements. A favorable implementation option available for TCM-B1 was a turn and +Z ΔV . This mode provided minimum propellant costs, favorable off-Sun and off-Earth angles, a continuous burn that reduced execution duration, and no need for a separate lateral thruster calibration activity. Analysis of this mode revealed that the off-Sun angle was 12 deg at launch +10 days, and decreasing for later execution dates. An ACS flight rule required that the spacecraft spin axis always be greater than 5 deg from the Sun, in order to maintain spin rate estimates and control. The turn and +Z axial burn mode would violate this ACS flight rule between launch +22-41 days. Additionally, launch +15-24 days were already scheduled for an operations readiness test immediately followed by TCM-A2 development. Consequently, this favored TCM mode had a short window of opportunity from launch +10-14 days. The decision was made to execute TCM-B1 at launch +10 days using the turn and +Z axial burn mode.

A 49.3 deg turn was required to align the spacecraft +Z axis with the desired ΔV direction, followed by a continuous +Z axial burn of 54 minutes. ACS thrusters #2 and #5 provided a velocity correction of 16.2 m/s, using 12.2 kg of propellant. TCM-B1 removed the bias in the trajectory that was introduced at launch to direct the third stage of the Delta II rocket away from Mars, and also corrected injection errors caused by the launch vehicle. The target was the Meridiani Planum landing site on Mars, although the semi-major axis of the delivery error was still over 10,000 km (1-sigma) in the Mars B-plane. To simplify spacecraft commanding and flight team workload, a nominal ACS attitude correction of 28.1 deg was incorporated into the Auto-TCM command via the post maneuver attitude.

E. Spirit TCM-A2

With Opportunity successfully on a trajectory to the Meridiani Planum landing site, Spirit was able to release this landing site option. Although Gusev Crater had yet to be officially approved as the Spirit landing site target, indications were that it had a high probability of acceptance. The favorable propellant status would also allow further landing site changes if needed. Consequently, rather than target a second central landing site between Elysium and Gusev, TCM-A2 would target directly to Gusev.

TCM-A2 was executed 52 days after launch, on August 1, 2003. The maneuver was performed in vector mode, with no spacecraft turn required. TCM-A2 consisted of a continuous axial burn for 9 minutes followed by 11 minutes of lateral burn pulses at 99 deg to the negative spin axis, using a total of 5.0 kg of propellant. The lateral velocity correction was achieved with 7 burn segments. The total inertial velocity change of 6.0 m/s corrected the TCM-A1 execution errors and also removed the remaining arrival time bias in order to target the Gusev Crater landing site.

F. Opportunity TCM-B2

Opportunity completed its second course correction, TCM-B2, on September 8, 2003. The maneuver was performed 62 days after launch in vector mode. TCM-B2 consisted of a continuous axial burn for 2 minutes, followed by 16 seconds of lateral burn pulses at 99 degrees to the negative spin axis. The total velocity change required to correct TCM-B1 execution errors was only 0.5 m/s, using less than 0.5 kg of propellant.

G. Spirit TCM-A3

TCM-A3 was the final maneuver in the cruise phase of the mission, executed 50 days before atmospheric entry. The maneuver was executed on November 14, 2003, one week later than originally planned due to recovery activities from intense solar flares. The navigation team redesigned the maneuver for the new execution date, and there was no effect on delivery accuracy. The maneuver was again performed in vector mode, and consisted of a continuous axial burn for 2 minutes followed by 27 seconds of lateral burn pulses. An inertial ΔV of 0.6 m/s corrected TCM-A2 delivery errors, and used 0.5 kg of propellant. The size of TCM-A3 was a direct result of the delayed landing site selection for Spirit, and the relatively large magnitude of the previous maneuver. Pre-launch statistics had not considered this strategy for maintaining flexible landing site targets in flight.

H. Opportunity TCM-B3

TCM-B3 was scheduled for November 21, 2003, just one week after TCM-A3. The maneuver was planned to occur 64 days before atmospheric entry, and would be the final maneuver in the cruise phase. Because of excellent spacecraft and navigation performance during cruise, the velocity correction would have been extremely small at

less than 13 mm/s. Although the velocity correction was very small, the corresponding entry flight path angle correction was 2.2 deg with a knowledge uncertainty of ± 0.8 deg, resulting in a significant 2.8 sigma correction. Additionally, executing a maneuver of this small size could provide valuable spacecraft performance data in a region that might otherwise not be observed until two days before atmospheric entry. Despite these arguments, the project placed more value in providing perhaps a final opportunity to reduce workload on an oversubscribed flight team. The entry flight path angle correction could wait 56 days until the next maneuver opportunity at entry -8 days. TCM-B3 was cancelled and the correction in the entry target was delayed until TCM-B4.

I. Spirit TCM-A4

TCM-A4 was scheduled to occur 8 days before entry in order to allow sufficient post maneuver tracking data to support the expected final targeting maneuver, TCM-A5. The original plan was to perform a complete three-dimensional correction at TCM-A4, which would be followed by the two-dimensional surface path control strategy for the remaining maneuvers. The flight reality was that the outstanding navigation performance had produced a delivery accuracy that was almost a maneuver ahead of predicted performance. The one-sigma knowledge uncertainty in entry flight path angle at the time of the final TCM-A4 design was only ± 0.013 deg. The spacecraft subsystems mostly responsible for TCM design and performance (Navigation, Attitude Control, and Propulsion) realized that an accurate TCM-A4 velocity change would probably be the last maneuver required to land safely in Gusev Crater.

Early analysis of the three-dimensional targeting strategy at TCM-A4 showed the familiar vector mode behavior in the surface path. As seen in Figure 8, the axial component would have moved the surface point ~ 100 km uptrack in a direction opposite the desired target. Reversing the order of the vector mode segments would cause the surface point after the lateral segment to completely overshoot Gusev Crater on the downtrack side. This feature of the vector mode surface path was expected, but still undesirable.

Analysis of a lateral only implementation revealed several advantages over the vector mode option. The magnitude of the velocity correction was only 25 mm/s, nearly three times smaller than the vector mode solution. Thus, the proportional maneuver execution errors are three times smaller, improving delivery accuracy. Because the lateral velocity correction was so small, the spacecraft would need to execute a single lateral pulse of only 3.4 seconds. A major ACS fixed error source for a lateral TCM was due to the nutation and precession that occurs during the course of a lateral burn segment. Since the entire velocity correction would be accomplished with less than a complete lateral pulse, there was reason to believe that the fixed execution error would also be minimal. The lateral only maneuver was smaller in part because it did not completely correct the arrival time error that resulted from the TCM-A3 delivery. The lateral implementation would only correct 2 of the 15 seconds late error. Arriving 13 seconds later results in the surface target rotating slightly further downtrack with respect to the atmospheric entry point. Consequently, the entry flight path angle target had to be shallower by 0.013 deg in order to travel slightly

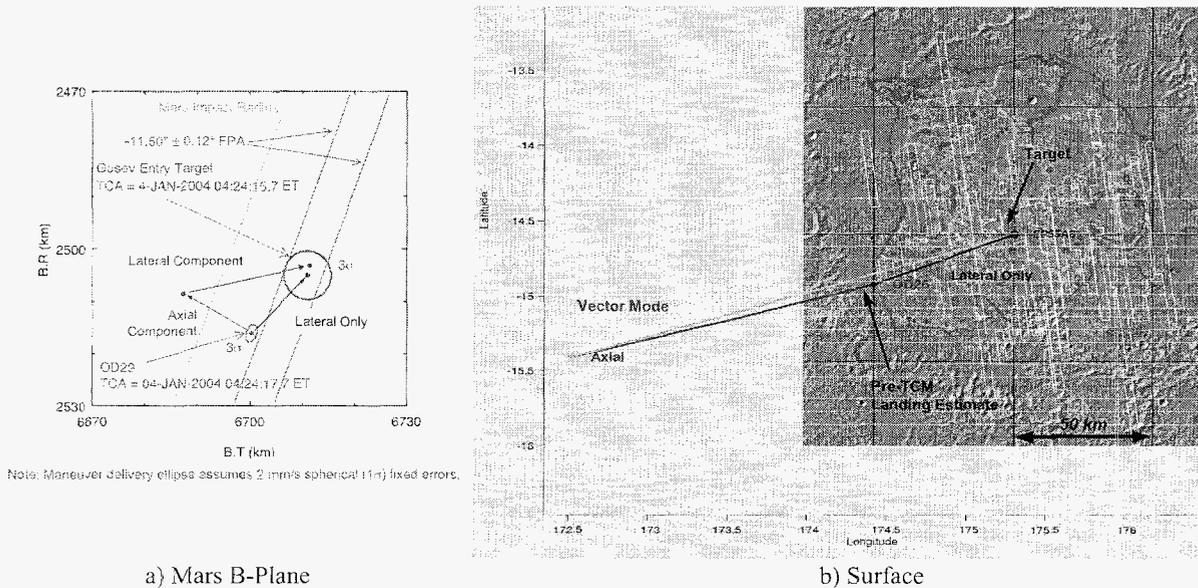


Figure 8: Spirit TCM-A4 Implementation Options and Path

further downtrack in an inertial sense to arrive at the desired target. The new target for entry flight path angle (-11.487 deg) was easily within the capability of the entry system. Finally, the lateral only implementation enabled a direct surface path, making the maneuver design more robust in the unlikely event of a spacecraft fault during execution.

Because of the advantages in delivery accuracy and surface path, TCM-A4 was executed as a lateral only maneuver on December 27, 2003 (UTC). The maneuver consisted of a single pulse lasting 3.4 seconds. The lateral pulse provided a velocity correction of 25 mm/s, using 16 grams of propellant.

J. Spirit TCM-A5

TCM-A5 was the final planned course correction to control Spirit’s landing dispersion within Gusev Crater. It was scheduled to execute 2 days before entry on January 2, 2004 (UTC). Orbit determination solutions showed that TCM-A4 had produced an exceptionally accurate delivery. The reconstructed delivery error in the B-plane was less than 200 meters and the time of closest approach error was -0.1 seconds. At the decision point for TCM-A5 execution, the landing estimate was just 2.3 km uptrack from the desired target. The 3-sigma entry flight path angle uncertainty was ±0.028 deg, easily within the ±0.12 deg requirement. Table 4 shows the TCM-A5 decision checklist. Because the current trajectory estimate was so close to desired, the probability of an “In-Spec” or safe landing would not improve by executing the maneuver. Furthermore, the maneuver size would be too small to reliably obtain the desired velocity correction. Based on the small correction relative to the larger current trajectory uncertainties, the maneuver was not statistically justified. These last two items are the basis for the “red” assessment factors in row 1 (primary decision factor) and row B (secondary decision factor) in table 4. Two days before the maneuver, the decision was made to cancel TCM-A5 along with TCM-A5X, which was the backup opportunity at Entry -1 day.

Table 4: TCM-A5 Decision Checklist

	TCM-5 <input checked="" type="checkbox"/>	TCM-6 <input type="checkbox"/>			
X	TCM Status Meeting 1	TCM - 4 days		Date / Time	A
	TCM Status Meeting 2	TCM - 2 days		30-Dec-03 18:00 PST	
	TCM Final Status Meeting	TCM - 1 day	TCM - 1 day		
	TCM Go/No-Go Meeting	TCM - 9.5 hours	TCM - 2.8 hours		

PRIMARY DECISION FACTOR (PDF)	Without TCM	With TCM	Criterion
FLIGHT SYSTEM CAPABILITY			
1 TCM Magnitude Larger than Lower Limit		3.668 m/s	≥ 0.006 m/s
2 Sufficient Propellant (for TCM, for TTE)		31.1 kg	≥ 2.0 kg
EDL SYSTEM CAPABILITY			
3 Number of (ED) Out-of-Spec Cases is Small	6.0%	0.0%	≤ 1.0%
LANDING SAFETY			
4 Probability of an "In-Spec" Landing is High	97.4%	97.4%	≥ 91.0%
PROJECT *			
5 Spacecraft is "Go" for TCM			
6 Mission Operations System is "Go" for TCM			
7 Project Manager is "Go" for TCM			

SECONDARY DECISION FACTOR (SDF)	Without TCM	With TCM
ORBIT DETERMINATION		
A OD Solutions are Consistent and Stable	G	
MANEUVER		
B OD Errors are Small Relative to Desired Correction		R
C Path of Implemented ΔV		G
D ACS ΔV Implementation Errors are Small **		
EDL SYSTEM CAPABILITY		
E EDL Parameters within Analysis Envelope	G	G
LANDING SAFETY / SCIENCE ASSESSMENT		
F Environmental Safety Assessment	G	G
G Relative Science Return (between w/ and w/o TCM)	G	G

PDF	SDF	LEGEND
G	G	} No Hard Criterion, Qualitative Assessment.
R	Y	
R	R	

* Required only for TCM Go/No-Go Meeting. ** NAV will report results at the Maneuver Approval Meeting.

K. Spirit TCM-A6

TCM-A6 was a late contingency course correction scheduled for January 4, 2004 (UTC). If necessary, this maneuver would execute 4 hours before entry. However, orbit determination trajectory estimates remained consistent and on target. There was no need for a contingency correction, and the maneuver was cancelled.

Landing site perturbation estimates were dominated by model uncertainties in the Mars atmospheric density and spacecraft aerodynamics. The 99% “un-margined” landing ellipse was estimated to be 63 km by 3 km, nearly centered on the target within Gusev Crater. The actual landing point was 10.1 km from the target, generally in the downtrack direction. A detailed description of the landing dispersion analysis and results are provided in Ref 9.

L. Opportunity TCM-B4

With the Spirit rover safely on the surface of Mars, the navigation team became immediately focused on Opportunity. Serious consideration was given to changing the nominal entry flight path angle to -11.25 deg. The shallower entry would provide a few additional seconds of EDL timeline margin. To make such a late change, a new maneuver would be required (TCM-B4F) a week prior to TCM-B4. The arrival time would have to change 4 minutes later, requiring a 0.5 m/s velocity correction. Quick analysis by the navigation team showed the trajectory adjustment was supportable, although there were risks involved with such a late change. Ultimately, the project decided against making the change.

TCM-B4 was scheduled to occur 8 days before entry. As a result of canceling TCM-B3, the existing B-plane error was 72 km, and the miss on the surface was 384 km. Analysis was done to compare the different targeting strategies: 3 dimensional vector mode, 2 dimensional lateral only, and 1 dimensional axial only. For such a large correction, the lateral or axial only strategies did not present any significant advantages. Thus, a vector mode implementation was selected. The separate maneuver re-designs leading up to execution were noticeably sensitive to small target adjustments based on updated atmospheric density models. This behavior was indicative of the known targeting singularities, but did not cause any problems.

TCM-A4 was executed as a vector mode maneuver on January 17, 2004 (UTC). The maneuver consisted of a 20 second continuous axial burn followed by 2 lateral burn pulses for a total of 10 seconds. The maneuver provided a velocity correction of 0.1 m/s, using 0.1 kg of propellant. TCM-B4 execution reconstruction showed an axial burn magnitude error of +3% that was partially offset by a lateral burn magnitude error of -2%. This combination produced the largest maneuver execution pointing error in the mission.

M. Opportunity TCM-B5

TCM-B5 was the final planned course correction to control Opportunity's landing dispersion at Meridiani Planum. It was scheduled to execute 2 days before entry on January 23, 2004 (UTC). Orbit determination solutions showed that the TCM-B4 delivery error was still very good, but slightly larger than Spirit after TCM-A4. The reconstructed delivery error in the B-plane was 1.3 km and the time of closest approach error was -1.0 second. At the decision point for TCM-B5 execution, the landing estimate was slightly less than 10 km downtrack from the desired target. The 3-sigma entry flight path angle uncertainty was ± 0.035 deg, well within the requirement of ± 0.14 deg. The landing site error estimate of 10 km downtrack had no effect on the probability of landing safety. The predicted delivery errors at Meridiani Planum were acceptable from a safety and science standpoint. The decision to cancel TCM-B5 was made one day before the scheduled execution date. The backup opportunity, TCM-B5X at Entry -1 day, was also cancelled.

N. Opportunity TCM-B6

TCM-B6 was a late contingency course correction scheduled for January 25, 2004 (UTC). If needed, the maneuver would execute 4 hours before entry. Orbit determination and trajectory estimates remained consistent. Landing probability ellipses were being updated using the latest Mars atmospheric density models, resulting in minor adjustments to the predicted landing point. The conclusion remained the same; there was no need for a contingency correction. TCM-B6 was cancelled.

As with Spirit, landing site perturbation estimates were dominated by model uncertainties in the Mars atmospheric density and spacecraft aerodynamics. The 99% "un-margined" landing ellipse was estimated to be 61 km by 4 km, offset ~ 10 km downtrack from the target. The actual landing point was 24.6 km downtrack from the target, and ~ 15 km downtrack from the pre-entry estimated landing point.

VIII. Conclusions

The propulsive maneuver design and analysis contributed to the outstanding navigation precision obtained by the Mars Exploration Rovers Spirit and Opportunity. All of the key navigation requirements that influenced the propulsive maneuver design were achieved. Additionally, a targeting strategy was employed that maintained a 99% probability of sufficient propellant while enabling post-launch flexibility in selecting the final landing sites on Mars. The delivery uncertainty in the atmospheric entry flight path angle had to be minimized and defensible to enable the selected landing sites, especially Gusev Crater. All aspects of the MER navigation system performed as advertised or better, resulting in delivery uncertainties significantly better than the capability driven requirements for entry flight path angle. In fact, the entry flight path angle requirements were met after executing 4 TCMs for Spirit and only 3 TCMs for Opportunity, out of the 6 maneuvers scheduled for each mission.

The Auto-TCM event driven command capability performed as advertised, simplifying the sequencing process for propulsive maneuvers. It also provided an automated ability to respond to spacecraft faults during TCM execution, although this capability was fortunately never needed in operations. Unfortunately, Auto-TCM made the process of reviewing the TCM sequence for adherence to mission flight rules more difficult. Additionally, there was some loss of control of the TCM burn times, which can affect performance. Future improvements might include an algorithm to adjust the commanded burn time or desired velocity correction based upon variations in the actual burn time.

The modified final approach targeting strategy was successful in controlling the surface path of the late propulsive maneuvers when the correction to be made was relatively small. The strategy provided additional TCM design options to consider, and was used very successfully with TCM-A4. The sub-rank targeting approach was an ideal fit for the lateral capability of the MER spacecraft, and completely avoided the need to consider a turn and burn mode for the final maneuvers. The trajectory singularities encountered on MER are fundamental to atmospheric entry trajectories, including Earth sample return missions. Such missions should recognize and fully investigate this characteristic of limited trajectory control, and incorporate a feasible targeting strategy early in the mission plan.

Appendix

Hyperbolic approach trajectories are typically described in aiming plane coordinates, often referred to as “B-plane” coordinates (see Fig. A-1). The B-plane is defined as the plane passing through the center of the target body and perpendicular to the incoming asymptote **S** of the hyperbolic trajectory. The miss vector **B**, which lies in the **R** and **T** plane, defines the aimpoint for an encounter. The miss vector is where the point of closest approach would be if the target body had no mass and did not deflect the flight path. Coordinates in the plane are given in the **R** and **T** directions, with **T** being parallel to the reference plane (Mars Mean Equator plane of date). Orientation angles are measured relative to the **T** axis in a right-hand positive sense about the **S** axis.

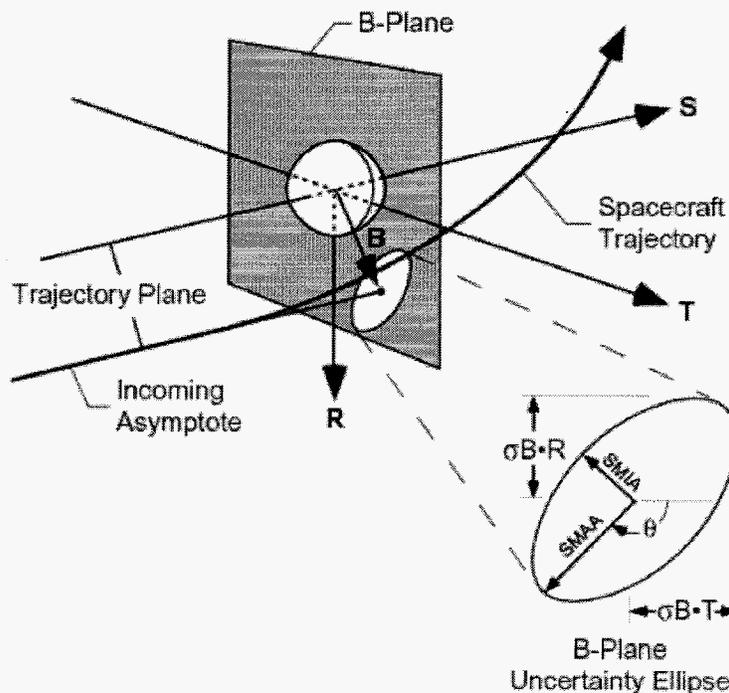


Figure A-1: B-plane Coordinate System Definition

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