

Mars Exploration Rovers Launch Performance and TCM-1 Maneuver Design

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The Mars Exploration Rover (MER) project successfully landed two identical rovers on Mars in order to remotely conduct geologic investigations, including characterization of rocks and soils that may hold clues to past water activity. Two landing sites, Gusev crater and Meridiani Planum, were selected out of nearly 200 candidate sites after balancing science returns and flight system engineering and safety. Precise trajectory targeting and control was necessary to achieve the atmospheric entry requirements for the selected landing sites within the flight system constraints. This paper discusses the expected and achieved launch vehicle performance and the impacts of that performance on the first Trajectory Correction Maneuver (TCM-1) while maintaining targeting flexibility in accommodating additional project concerns about landing site safety and possible in-flight retargeting to alternate landing sites.

I. Introduction

The Mars Exploration Rover (MER) Project successfully placed two Rovers at different near-equatorial landing sites on Mars. MER-A (Spirit) was launched on 6/10/2003 on a Boeing Delta II 7925 and arrived at Mars on 1/4/2004 (UTC). MER-B (Opportunity) was launched on 7/8/2003 on a Boeing Delta II 7925H and arrived at Mars on 1/24/2004 (UTC). Both rovers have surpassed their 90 sol (or 90 Martian day) nominal mission, and at the time of this writing are continuing their exploration and investigation into past water activity on Mars. A full discussion of the MER mission can be found in Reference 1.

In order to successfully and accurately land on Mars, the spacecraft must first be accurately launched to the desired Earth-relative departure conditions, or launch targets, in order to place the spacecraft onto the required interplanetary trajectory to Mars. After launch, the spacecraft must then be delivered to the proper Mars atmospheric entry aimpoint by a series of Trajectory Correction Maneuvers (TCMs) during interplanetary cruise. The first TCM (TCM-1) removes the planetary protection bias and also corrects for launch vehicle injection errors. Subsequent maneuvers, which are addressed in an accompanying paper (Ref. 2), correct for maneuver execution errors and orbit determination errors.

The generation of the launch vehicle targets was strongly influenced by planetary protection requirements and the choice of the landing site, which in turn strongly influenced the TCM strategy. Planetary protection requirements stated that after injection the probability of the launch vehicle upper stage impacting Mars shall be less than 1.0×10^{-4} . To meet this requirement, the spacecraft was targeted at injection to an aimpoint biased away from Mars. To provide margin, the aimpoint was selected such that the probability of impacting Mars was approximately 0.8×10^{-4} while minimizing the statistical ΔV cost required to remove the aimpoint bias at TCM-1. For each launch date, biased aimpoints were determined which minimized the deterministic DV at TCM-1 to retarget the spacecraft to the desired landing site. Reference 3 gives a more detailed account of the determination of the biased aimpoints as well as strategies for TCMs during MER cruise.

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Initially, landing sites for Spirit and Opportunity were to be chosen several months prior to launch. However, balancing flight system engineering constraints and science goals while attempting to identify safe landing sites that were scientifically interesting proved complex. By the time of the generation of the final launch targets three candidate landing sites existed for each rover: Gusev Crater, Isidis Planitia, and Meridiani Planum for Spirit and Meridiani, Isidis, and Elysium Planum for Opportunity. These locations are illustrated in Figure 1.

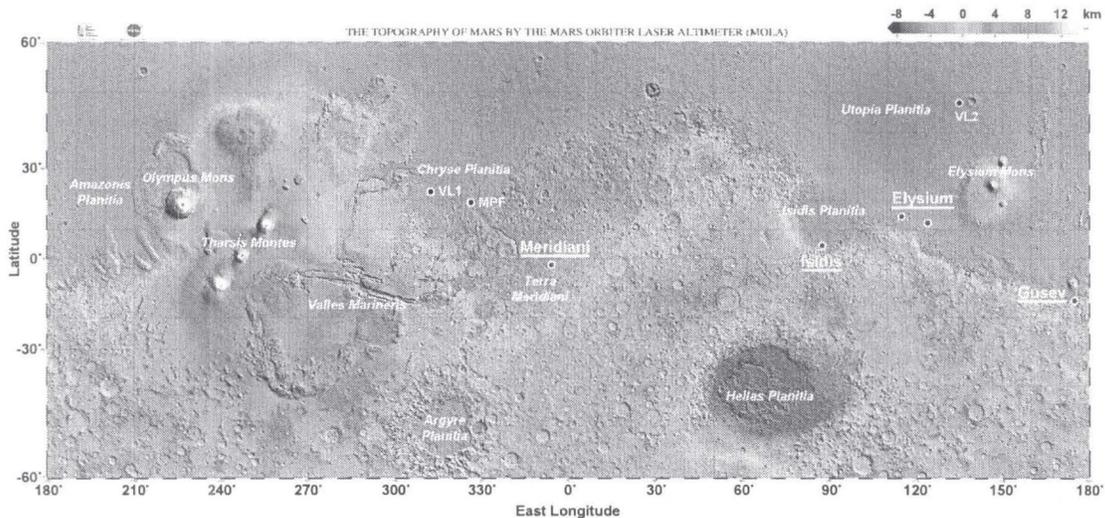


Figure 1. Mars Map and Candidate Landing Sites

In order to allow a delay in landing site selection and to minimize the propellant cost for late changes in landing site selection, intermediate or “Central” landing sites (CLS) were created approximately midway between the sites being considered for each rover prior to the generation of the final launch targets. The biased aimpoints for the launch vehicle targets were generated for these Central sites. However, shortly prior to launch the Isidis landing site was dropped from consideration. While Meridiani was considered safe and was strongly desired as a landing site for Opportunity, the landing site for Spirit had not been finalized. Gusev was the desired landing site for Spirit but concerns over winds led to more analyses of the flight system in an attempt to classify Gusev as ‘safe’. If landing at Gusev could not be demonstrated to be safe, then the spacecraft would be retargeted to Elysium, a ‘wind-safe’ site. A further complication would arise should Opportunity fail during or shortly after launch, at which point it would be desirable for Spirit to land at Meridiani. The original strategy to retarget at TCM-1 to one of the candidate sites was modified for Spirit (which is discussed in greater detail in Section III.) In order to increase flexibility in landing site selection and protect against a failure of Opportunity, a second Central landing site, CLS-2, was chosen for Spirit midway between Gusev and Elysium. Figure 2 shows a schematic of these central landing sites for Spirit and Opportunity as viewed from the Mars north pole. The arrows show the target longitudes, and the arcs show the range of landing sites that could be achieved. A shorter longitude range, with a resultant smaller propellant cost to retarget, could have been constructed for Opportunity, but would have resulted in a variable arrival date as a function of landing site, which was not desirable.

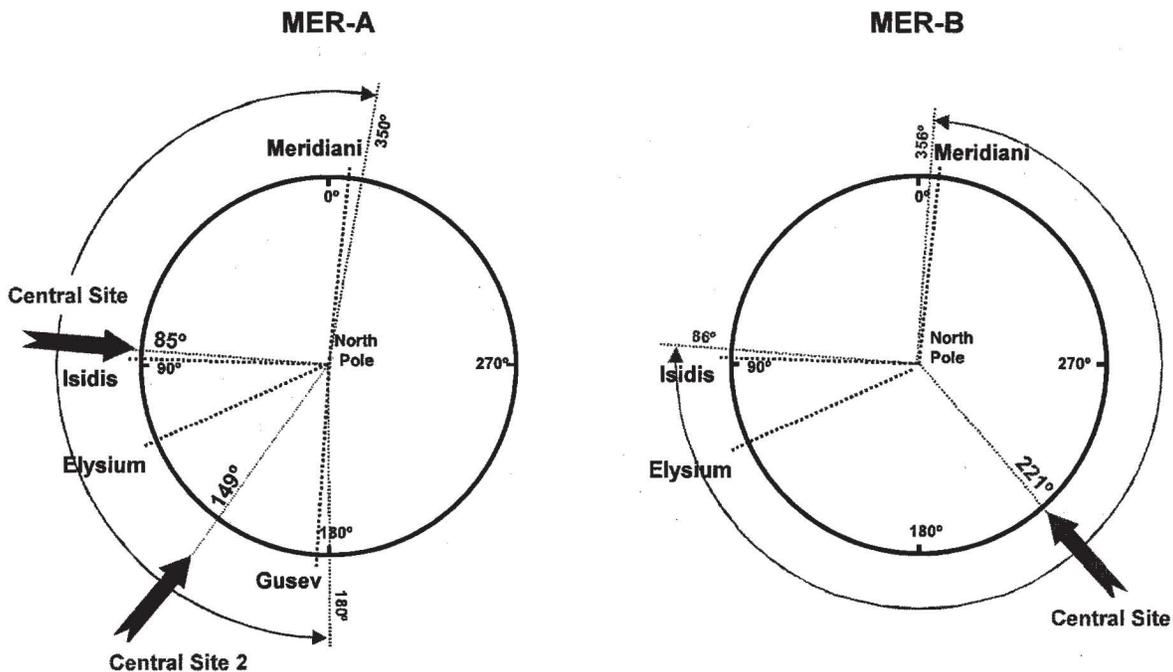


Figure 2. Landing Site Schematic with Central Sites

II. Launch Vehicle Performance

The launch vehicle targets were specified as the injection energy per unit mass (C3), the declination of the departure (or launch) asymptote (DLA), and the right ascension of the launch asymptote (RLA) at a specific time. This time is referred to as the targeting interface point (TIP) and was defined to be 10 minutes after the ignition of the third stage of the Delta launch vehicle. These targets represent conditions on an osculating departure hyperbola at TIP.

After sufficient tracking of the spacecraft, a navigation assessment of the launch vehicle performance can be made by mapping the spacecraft state back to TIP where the values of C3, DLA, and RLA are compared to the desired targets. (Reference 3 discusses MER orbit determination in depth.) The spacecraft state can also be mapped to the Mars B-plane (Appendix) where the expected dispersions and impact probabilities can be visualized. Injection covariance matrices (ICMs) provided by Boeing were used to determine the expected launch vehicle dispersions.

Table 1 shows the target and achieved injection targets at TIP and in the Mars B-plane for Spirit. The achieved orbital elements at TIP were consistent to the 1σ when compared to the target parameters. Figure 3 shows the spacecraft state mapped to the Mars B-plane, the biased injection target, the expected 1-, 2-, and 3- σ uncertainty ellipses, and the difference in time of closest approach (TCA) and the expected uncertainties in TCA. Table 2 and Figure 4 show the equivalent information for Opportunity. The achieved orbital elements at TIP for Opportunity are consistent to the 1.2σ level when compared to the target parameters. Launch vehicle performance for both Spirit and Opportunity was favorable and resulted in a small amount of ΔV and propellant to correct, thus allowing for a wide variety of TCM-1 options to be considered.

Table 1: Spirit Launch Performance

Spirit (MER-A) Launch						
Launch Date 6/10/2003, Launch Time 17:58:47 UTC, 93° Launch Azimuth						
Injection Targets (TIP)						
		Target	Achieved	Error (A-T)	1 σ Uncertainty (ICMs only)	Error (σ) (ICMs only)
C_3	km ² /s ²	8.8550	8.8218	-0.0332	0.0647	-0.5
DLA (EME2000)	deg	-2.4302	-2.3221	0.1081	0.1120	1.0
RLA (EME2000)	deg	347.1990	347.3526	0.1536	0.1888	0.8
Mars B-plane (MME) at Mars Close Approach						
		Target	Achieved	Error (A-T)	1 σ Uncertainty (ICMs only)	Error (σ) (ICMs only)
B•R	km	104,184	294,386	190202	285,337	0.7
B•T	km	235,634	409,494	173860	291,198	0.6
TCA (ET)	dd-mmm-yy hh:mm:ss	5-Jan-04 6:08:44	6-Jan-04 23:37:24	1.728 days	2.506 days	0.7

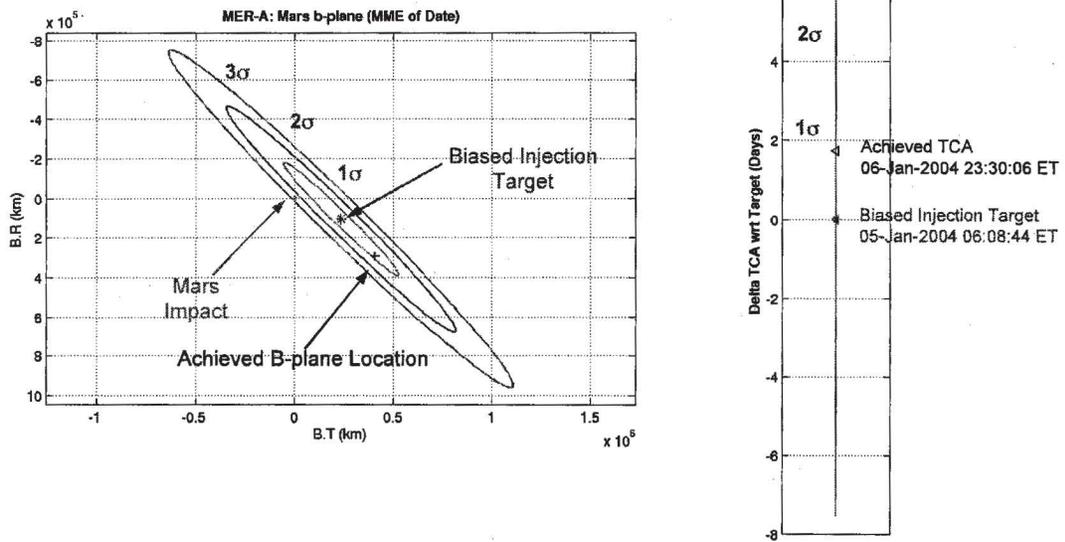


Figure 3. Spirit Launch Performance Mapped to the Mars B-plane

Table 2: Opportunity Launch Performance

Opportunity (MER-B) Launch						
Launch Date 7/08/2003, Launch Time hh:mm:ss UTC, 99° Launch Azimuth						
Injection Targets (TIP)						
		Target	Achieved	Error (A-T)	1 σ Uncertainty (ICMs only)	Error (σ) (ICMs only)
C_3	km ² /s ²	14.3247	14.3223	-0.0024	0.0669	0.0
DLA (EME2000)	deg	-3.8136	-3.8930	-0.0794	0.1027	-0.8
RLA (EME2000)	deg	334.4537	334.6545	0.2008	0.1641	1.2
Mars B-plane (MME) at Mars Close Approach						
		Target	Achieved	Error (A-T)	1 σ Uncertainty (ICMs only)	Error (σ) (ICMs only)
B•R	km	219,754	204,196	-15,558	172,674	-0.1
B•T	km	456,623	274,502	-182,121	211,194	-0.9
TCA (ET)	dd-mmm-yy hh:mm:ss	26-Jan-04 19:03:52	26-Jan-04 16:22:56	-0.112 days	0.946 days	-0.1

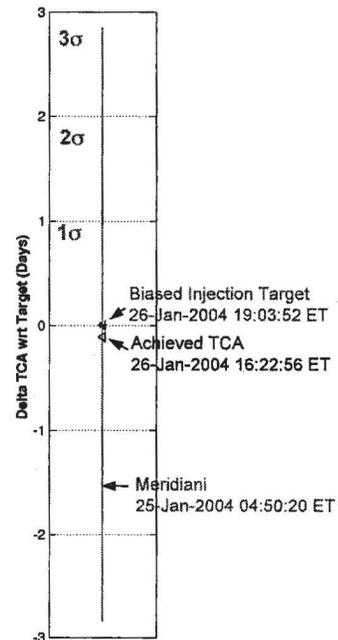
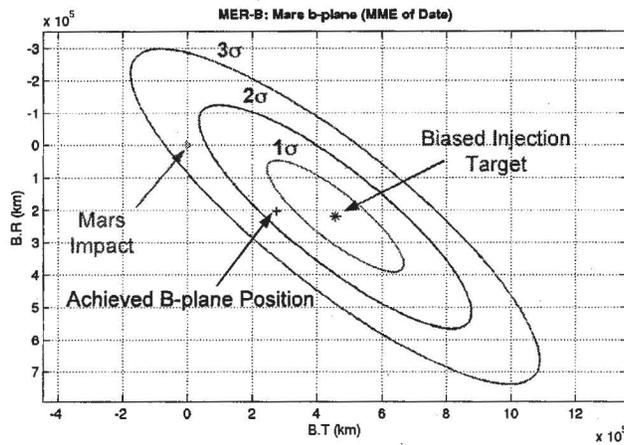


Figure 4. Opportunity Launch Performance Mapped to the Mars B-plane

III. Spacecraft Propulsion System and Maneuver Modes

Figure 5 shows the MER spacecraft configuration during the cruise phase. Adapted from the Mars Pathfinder spacecraft, the MER spacecraft were spin-stabilized with a nominal spin rate of 2 rpm about the +Z axis. There are two diametrically opposed thruster clusters, containing four thrusters each. The thruster clusters are on the +X and -X axes of the spacecraft with each thruster oriented 40 deg off the +X or -X axis; that is, starting from +X or -X, a thruster is pointed 40 deg towards the +Z direction and 40 deg towards the -Z direction in the X-Z plane, and 40 deg toward the +Y direction and 40 toward the -Y direction in the X-Y plane. While it is not labeled in this figure, it should be noted that the Low Gain Antenna (LGA) and the Medium Gain Antenna (MGA), used for X-band communication with the Earth, are both oriented in the -Z axis direction.

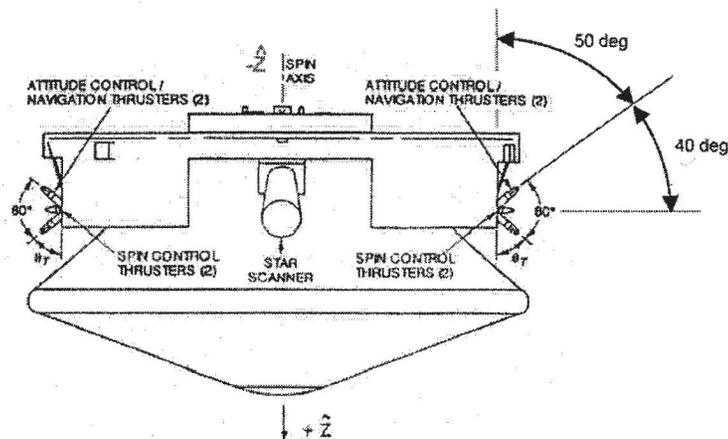


Figure 5. Spacecraft Thruster Configuration

An axial burn imparts a ΔV in the +Z or -Z direction and is performed by firing pairs of thrusters in a steady state (i.e., constant) mode. A lateral burn imparts a ΔV in a direction approximately normal to the spin axis. At the appropriate orientation in the spin cycle, the four thrusters of one cluster are pulse fired, typically for 5 seconds. One half revolution later (10 seconds), the other cluster's four thrusters are pulse fired. Because the spacecraft's center of mass is located further along the +Z axis than the thruster clusters, the two thrusters which provide ΔV in the -Z direction are fired for a shorter duration than the other thrusters. This causes the net thrust from each cluster's thrusters to point through the spacecraft center of mass thus eliminating attitude perturbations. To better calibrate the spacecraft center of mass, two small lateral burns (< 1 m/s total) could be performed approximately 2.5 hours prior to the start of the TCM-1 main burn. This lateral calibration allowed for more thruster pulses per lateral segment before attitude and spin rate corrections were required, which greatly decreases the total duration of the maneuver.

For each TCM, three maneuver modes were possible. A desired ΔV can be achieved by a turn and a pure axial burn, a turn and a pure lateral burn, or a vector sum of two ΔV components, where each component can be an axial or lateral burn. A turn could also be performed prior to a vector mode maneuver. The choice of maneuver mode was constrained by the need to provide communication with the Earth and to satisfy power and thermal constraints. The angle between the -Z axis of the spacecraft and the direction to the Sun was required to be less than 46° from Launch to L+52 days and less than 32° after L+53 days. The off-Earth pointing angle constraint for Spirit was 90° from Launch to L+10 days, 73° from L+11 days to L+30 days, and 53° from L+31 days to L+50 days. For Opportunity the off-Earth pointing angle constraint was 90° from Launch to L+10 days, 67° from L+11 days to L+30 days, and 47° from L+31 days to L+50 days. The spacecraft could not be pointed in any arbitrary direction; rather, the -Z axis must lie within the constraint overlap region defined by the Earth and Sun constraints.

IV. Central Landing Sites and Maneuver Design Strategy

Because of the desire to maintain flexibility in retargeting Spirit during flight, the TCM strategy for that spacecraft differed significantly from that of Opportunity. The nominal date of TCM-1 for Opportunity was L+10 days, although analyses were conducted on dates from L+10 days to L+50 days, and this maneuver was to target the spacecraft on a trajectory directly to Meridiani. Up to five subsequent maneuvers were scheduled to remove maneuver execution errors and orbit determination uncertainties. The strategy for Spirit was more involved. TCM-1 was nominally scheduled for L+10 days, with analyses conducted for L+10 days to L+50 days, but four target locations, CLS, CLS-2, Gusev, or Meridiani, were possible. (Elysium was not as desirable a landing site and any decision to target to Elysium would be at a maneuver later than TCM-1.) If the target at TCM-1 were Gusev or Meridiani, then subsequent TCMs would be cleanup maneuvers. If the target at TCM-1 were CLS or CLS-2 then two further maneuvers could be made before a final decision on landing site was required. TCM-2 was scheduled for 8/1/2003 with possible targets of Meridiani (in case of a failure of Opportunity during or shortly after launch) or CLS-2 for another chance to delay the final landing site decision. Finally, TM-A2EG was scheduled for 10/10/2003 with possible targets of either Gusev or Elysium. Of course, Gusev and Meridiani were also potential targets for TCM-2 but choosing one or the other would have removed flexibility in retargeting at a future TCM. In flight, however, after the successful launch of Opportunity and further analyses removing concern regarding the safety of the Gusev site, Spirit was retargeted directly to Gusev at TCM-2. Figure 6 shows the heliocentric trajectories of Spirit and Opportunity and the nominal locations for the possible deterministic maneuvers. Table 3 shows the nominal TCM strategy for Spirit and possible TCM targets.

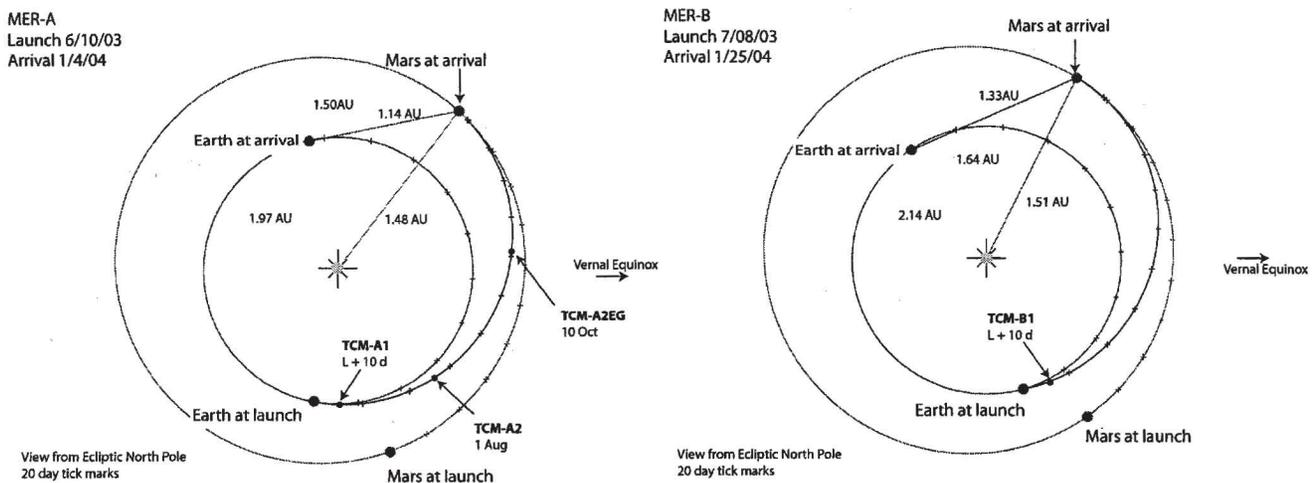


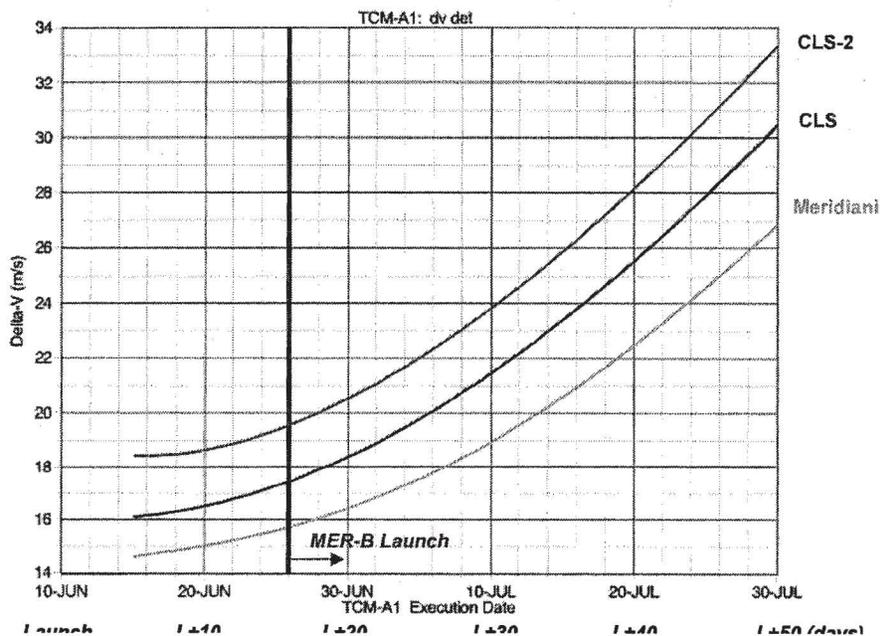
Figure 6. Spirit and Opportunity Interplanetary Trajectories and TCM Dates

Table 3: Spirit TCMs and Possible Targets

Case Name	TCM-1 Target	TCM-2 Target	TCM-2EG Target
C1C2-Gusev	CLS	CLS-2	Gusev
C1C2-Elysium	CLS	CLS-2	Elysium
C1-Merid	CLS	Meridiani	
C2-Gusev	CLS-2	CLS-2	Gusev
C2-Elysium	CLS-2	CLS-2	Elysium
Merid	Meridiani		
Gusev	Gusev		

V. Spirit TCM-1 Maneuver Design

Figure 7 shows the Spirit TCM-1 inertial ΔV as a function of launch date and landing site. The solid line at 6/26/2003 represents the start of the Opportunity launch period. The ΔV is shown for TCM targets of CLS, CLS-2, and Meridiani. Figure 8 shows the 99% mission propellant cost for all maneuvers as a function of TCM-1 time and target strategy. (The case names given are listed in Table 3.) Abrupt changes in the curves are due to changes in the spacecraft pointing profile during cruise. As shown in the figure, the propellant cost varies most significantly due to the choice of targets for TCM-1 and the time of TCM-1. The choice for TCM-A2 or TCM-A2EG impacts the 99% mission propellant cost only slightly. For all cases, however, the total mission propellant cost is less than the 52 kg propellant loaded onboard the cruise stage by a large margin. The propellant costs for TCM-1 only are given in Figures 9 for CLS, and Figure 10, for CLS-2 as a function of TCM-1 date and maneuver mode. Figure 11 shows the TCM-1 duration, assuming that a lateral calibration was performed, as a function of maneuver date and maneuver mode.



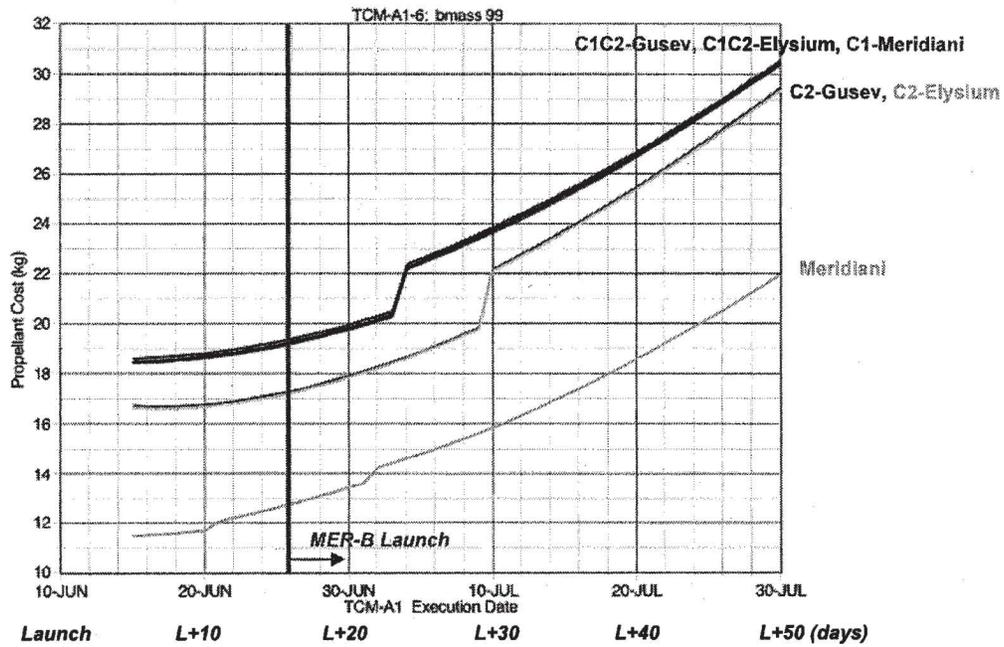


Figure 8. Spirit Total 99% Mission Propellant Cost

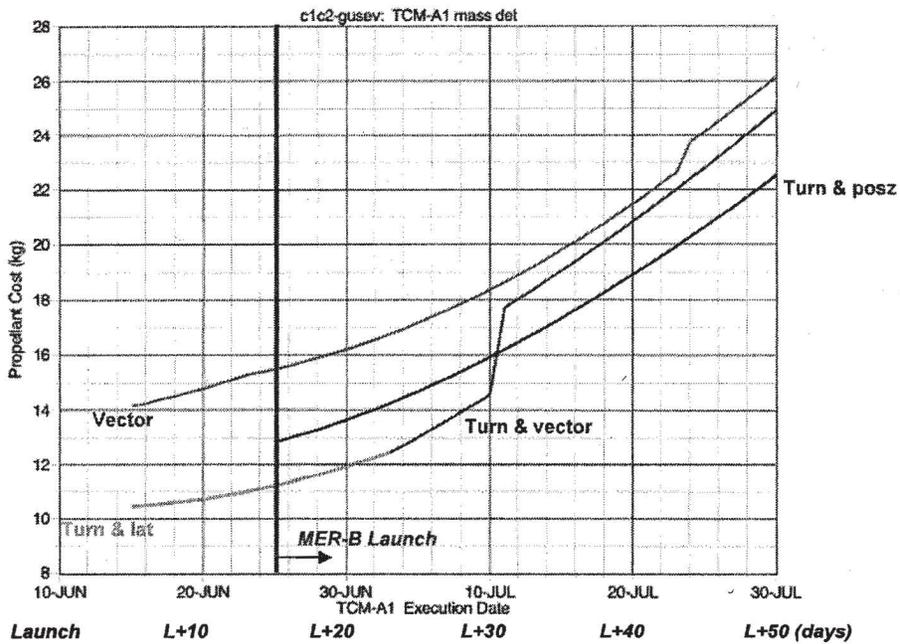


Figure 9. Spirit TCM-1 Propellant Cost to CLS

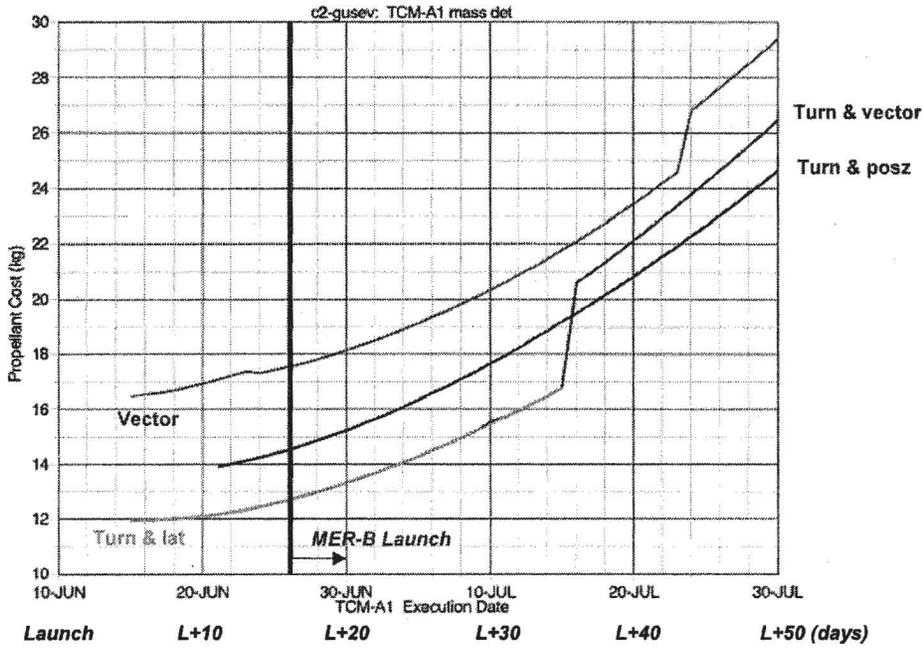


Figure 10. Spirit TCM-1 Propellant Cost to CLS-2

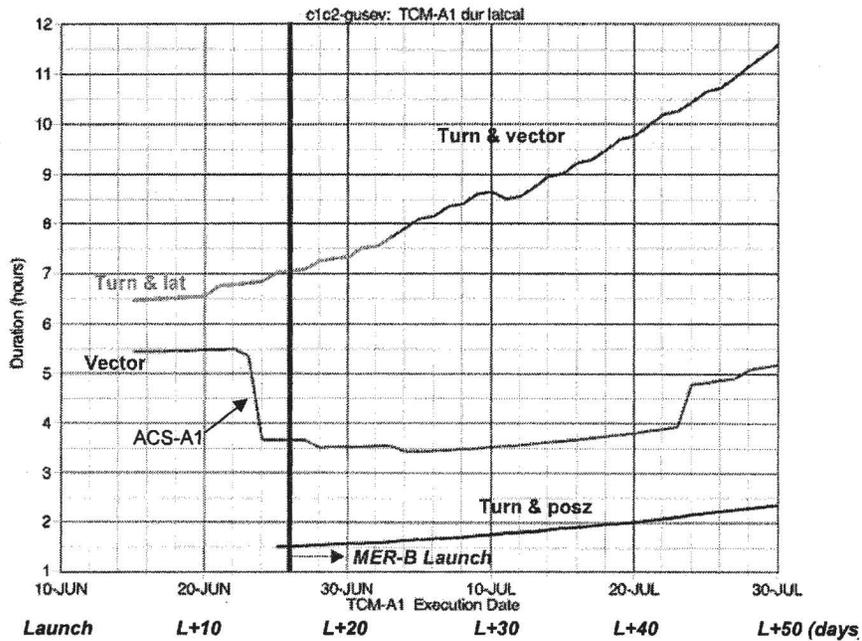


Figure 11. Spirit TCM-1 Duration to CLS (with lateral calibration)

The project decided to perform the Spirit TCM-1 at the nominal date of L+10 days (June 20, 2003) and to target to the Central Landing Site. At L+10 days the possible maneuver modes were a turn and lateral burn and a vector mode maneuver. The vector mode maneuver had a higher propellant cost but a much shorter duration. With a large margin of propellant remaining, it was decided to execute TCM-1 in vector mode with a lateral calibration. The TCM-1 inertial ΔV was 16.46 m/s and propellant cost was 14.7 kg. Table 4 shows the TCM-1 maneuver characteristics, and Figure 11 shows the maneuver in the Mars B-plane. The location marked OD03 represents the orbit determination solution used in the maneuver design.

Table 4: Spirit TCM-1 Parameters

Spirit TCM-1 Characteristics	
Mode	Vector (Lateral Calibration/Axial (+Z)/Lateral Burn
Inertial ΔV Magnitude	16.46 m/s
- Axial ΔV	9.10 m/s
- Lateral ΔV (*)	12.38 m/s
TCM-1 Propellant	14.7 kg
99% Mission Propellant	25.8 kg
99% Propellant Margin	25.7 kg
-Z to Sun angle	19 deg
-Z to Earth angle	59 deg
Axial Duration	0.46 hours
Main Lateral Duration	3.00 hours

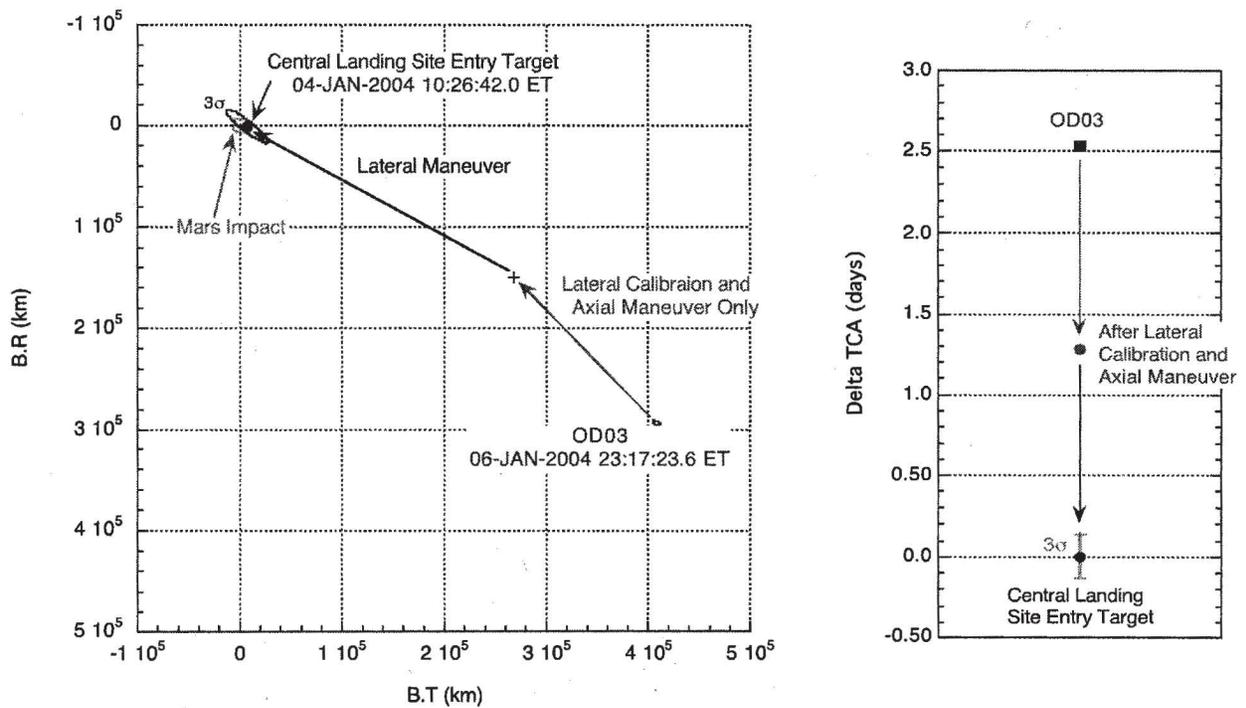


Figure 12. Spirit TCM-1 in the B-plane

VI. Opportunity TCM-1 Maneuver Design

The TCM-1 decision process was much less complex for Opportunity. Meridiani was the choice for the landing site, and there was no need to perform analyses for other landing sites at that time. Figure 13 shows the TCM-1 inertial ΔV as a function of maneuver date. Figure 14 shows the 99% mission propellant cost as a function of maneuver date. Figures 15 and 16 show the TCM-1 propellant cost and duration as functions of maneuver date and maneuver mode.

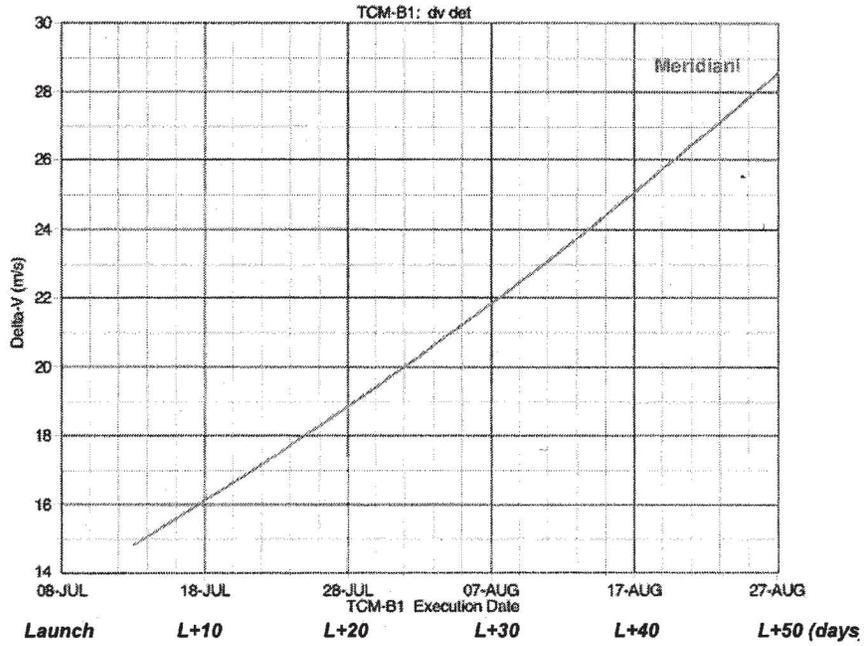


Figure 13. Opportunity TCM-1 Inertial ΔV

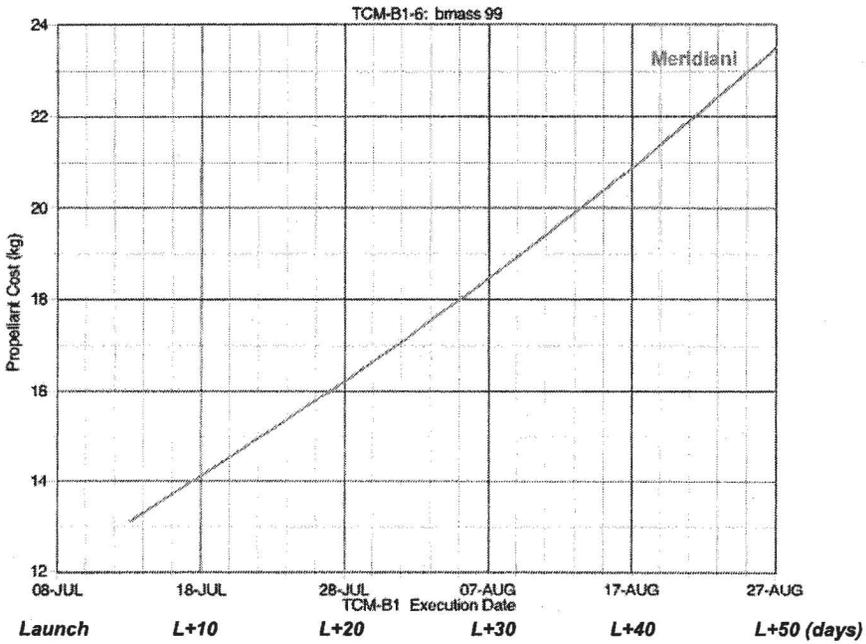


Figure 14. Opportunity Total 99% Mission Propellant Cost

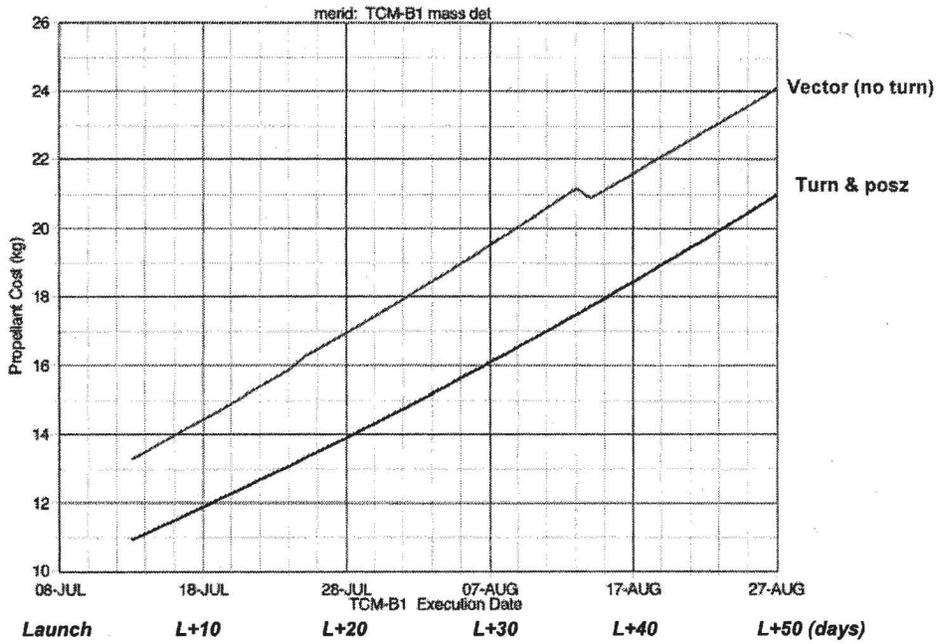


Figure 15. Opportunity TCM-1 Propellant Cost

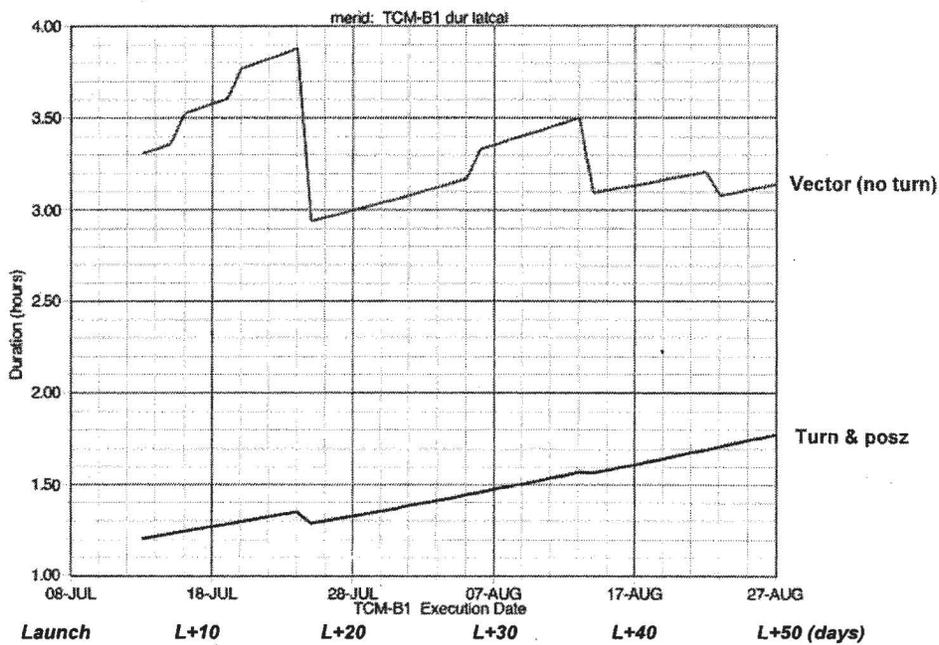


Figure 16. Opportunity TCM-1 Duration

In the absence of project concerns and no obvious need to delay the maneuver, the Opportunity TCM-1 was scheduled for the nominal date of L+10 days (July 18, 2003) and was targeted to the Meridiani landing site. The two possible maneuver modes were a vector mode maneuver and a turn and +Z maneuver. The turn and +Z maneuver had a significantly shorter duration and a slightly lower propellant cost than the vector mode maneuver. It was decided to take advantage of the shorter duration and it was decided to execute TCM-1 as a turn and +Z maneuver. The TCM-1 inertial ΔV was 16.17 m/s and the propellant cost was 12.2 kg. Table 5 shows the TCM-1 maneuver characteristics, and Figure 17 shows the maneuver in the Mars B-plane. The location marked OD03 represents the orbit determination solution used in the maneuver design.

Table 5: Opportunity TCM-1 Characteristics

Opportunity TCM-1 Characteristics	
Mode	Turn and +Z Axial Burn
Inertial ΔV Magnitude	16.17 m/s
- Axial ΔV	16.17 m/s
- Lateral ΔV	NA
TCM-1 Propellant	12.2 kg
99% Mission Propellant	15.1 kg
99% Propellant Margin	33.5 kg
-Z to Sun angle (before turn)	44.1 deg
-Z to Earth angle (before turn)	51.7 deg
-Z to Sun angle (after turn)	11.7 deg
-Z to Earth angle (after turn)	28.7 deg
Axial Duration	53.6 minutes
Main Lateral Duration	NA

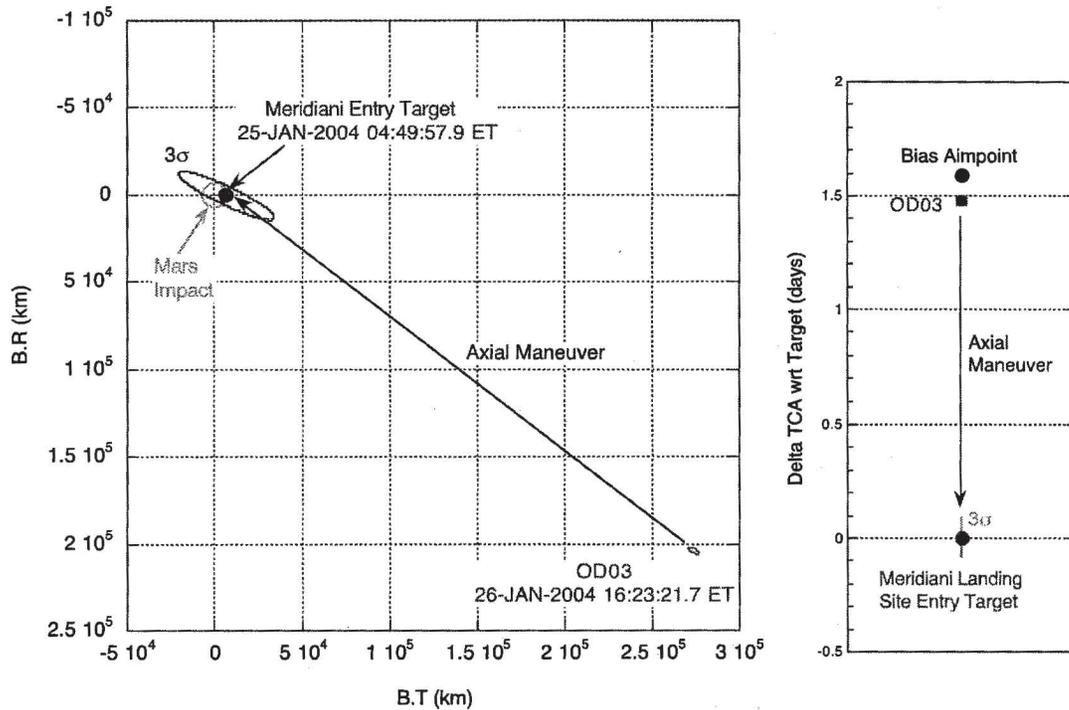


Figure 17. Opportunity TCM-1 in the B-plane

VII. Conclusions

The MER rovers Spirit and Opportunity were successfully launched onto interplanetary trajectories with launch injection errors at the 1σ level for Spirit and the 1.5σ level for Opportunity. These accurate injections allowed an analysis of an extensive trade space for the design of TCM-1 for both spacecraft. This trade space was especially large for the Spirit TCM-1 design. Four target landing sites, Gusev, CLS, CLS-2, or Meridiani, were possible targets for the Spirit TCM-1. Engineering analyses for landing site safety were still being conducted for the desired landing site, Gusev. Had Opportunity failed during or shortly after launch, Spirit would have been retargeted to Meridiani. In order to delay the final landing site selection, up to four months after launch, either of the central sites, CLS or CLS-2, could be chosen as a target for TCM-1. In order to maintain flexibility, the project decided to target CLS at the Spirit TCM-1. In order to reduce the maneuver duration, it was decided to execute the maneuver in the vector mode with a lateral calibration. The maneuver was performed at L+10 days (June 20, 2003). The inertial ΔV was 16.53 m/s and the duration was 3.47 hours, not including the lateral calibration or time between the axial and lateral burns. The TCM-1 propellant cost was 14.8 kg and the 99% mission propellant cost was 25.8 kg, giving a 99% propellant margin of 25.7 kg.

The trade space was simplified for the Opportunity TCM-1. The choice of the landing site was Meridiani. In order to reduce the maneuver duration, a turn and +Z axial maneuver mode was chosen. The maneuver was performed at L+10 days (July 18, 2003). The inertial ΔV was 16.17 m/s and the duration was 53 minutes. The TCM-1 propellant cost was 12.8 kg and the 99% mission propellant cost was 15.1 kg, giving a 99% propellant margin of 33.5 kg.

Appendix

Figure 18 shows the B-plane. 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. Coordinates in the B-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 in a clockwise direction about the S axis.

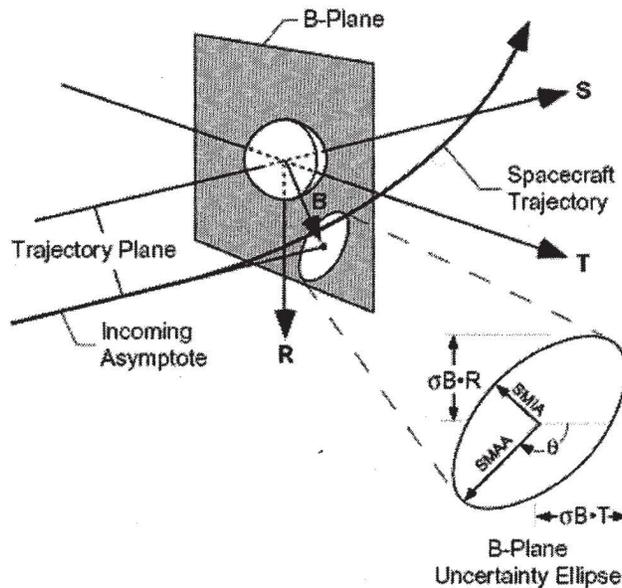


Figure 18. B-plane Coordinate System

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References

- ¹Roncoli, R. B., and Ludwinski, J. M., "Mission Design Overview for the Mars Exploration Rover Mission," *AIAA/AAS Astrodynamics Specialist Conference*, AIAA-2002-4823, AIAA, Washington, DC, 2002.
- ²Potts, C., L., Raofi, B., and Kangas, J. A., "Mars Exploration Rovers Propulsive Maneuver Design," *AIAA/AAS Astrodynamics Specialist Conference*, AIAA-2004-4985, AIAA, Washington, DC, 2004.
- ³Raofi, B., Bhat, B. S., and D'Amario, L. A., "Flight Path Control Strategies for the 2003 Mars Exploration Rover (MER) Mission," *AIAA/AAS Astrodynamics Specialist Conference*, AIAA-2002-4824, AIAA, Washington, DC, 2002.
- ⁴Portock, B. M., Graat, E. J., McElrath, T. M., Watkins, M. M., and Wawrzyniak, G. G., "Mars Exploration Rovers Cruise Orbit Determination," *AIAA/AAS Astrodynamics Specialist Conference*, AIAA-2004-4981, Washington, DC, 2004.

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