Flight Path Control Strategies for the 2003 Mars Exploration Rover (MER) Mission

Behzad Raofi [braofi@jpl.nasa.gov, (818)354-4523],
Ramachandra S. Bhat [Ramachand.bhat@jpl.nasa.gov, (818)393-0979],
Louis A. D'Amario [louis.damario@jpl.nasa.gov, (818)354-3209]
Jet Propulsion Laboratory, California Institute of Technology,
Pasadena, CA 91109-8099

The MER Project will launch two spacecraft (MER-A and MER-B) to Mars in 2003 with the objective of delivering two Rovers to different landing sites on Mars to study the surface composition and to look for evidence of present or past water. This paper describes the methods used to estimate the statistical ΔV and propellant requirements for propulsive maneuvers necessary to deliver the two Rovers while ensuring that planetary protection requirements are satisfied. Maneuver analysis results for four different trajectories, open and close of launch periods for each of the two MER missions, are presented. The results for the two representative landing sites (MER-A: Melas Chasma, MER-B: Hematite) indicate that the MER-A Open case has the most demanding propellant requirement (~45 kg), and that the inertial atmospheric entry flight path angle delivery requirements of -11.5 ± 0.17 (3σ) deg for MER-A and -11.5 ± 0.20 (3σ) deg for MER-B are achievable.

Flight Path Control Strategies for the 2003 Mars Exploration Rover Mission

Behzad Raofi [braofi@jpl.nasa.gov, (818)354-4523],
Ramachandra S. Bhat [Ramachand.bhat@jpl.nasa.gov, (818)393-0979],
Louis A. D'Amario [louis.damario@jpl.nasa.gov, (818)354-3209]
Jet Propulsion Laboratory, California Institute of Technology,
Pasadena, CA 91109-8099

The Mars Exploration Rover (MER) Project will launch two spacecraft to Mars, referred to as MER-A and MER-B, in the 2003 launch opportunity with the objective of delivering two surface Rovers to different near-equatorial landing sites on Mars. During the baseline 91 Sol (~93.5 Earth day) surface mission, each Rover will collect data about the composition of targeted Martian soil and rocks and also will provide images and spectra to document the target surroundings and the landing sites. MER-A will be launched first on a Boeing Delta II 7925 launch vehicle from Space Launch Complex 17A (SLC-17A) at the Cape Canaveral Air Force Station (CCAFS) during an 18-day launch period extending from May 30, 2003 through June 16, 2003. MER-A will arrive at Mars on January 4, 2004. MER-B will be launched on a Boeing Delta II 7925H launch vehicle from SLC-17B during an 18-day launch period extending from June 25, 2003 through July 12, 2003. MER-B will arrive at Mars on January 25, 2004. Both spacecraft follow a Type 1 trajectory to Mars. The MER flight systems are planned to be interchangeable, and consist of a Cruise Stage, an Entry, Descent and Landing (EDL) system (including heatshield, backshell, parachute, retro-rockets, airbags and Lander structure), and a Rover, which is enclosed inside the Lander. The launch mass allocation for both flight systems is 1063 kg.

This paper describes the methods used to estimate the statistical ΔV and propellant required for propulsive maneuvers to deliver the two Rovers to their targeted Mars landing sites while ensuring that planetary protection requirements are satisfied. During the approximately 7 month interplanetary transfer for each spacecraft, which includes the Cruise and Approach mission phases, six Trajectory Correction Maneuvers (TCMs) are planned to deliver each flight system to the specified Mars atmospheric entry aimpoint. The EDL phase begins at the atmospheric entry interface point, which is defined to be at a Mars radius of 3522.2 km. MER EDL will be nearly identical to that developed for 1997 Mars Pathfinder mission.

This paper includes maneuver analysis results for four different trajectories: open and close of launch periods for each of the two MER missions. The launch dates, required C_3 (i.e., injection energy), and representative landing sites associated with each trajectory are as follows (the final landing sites have not yet bee selected):

Trajectory	Launch Date	C_3 (km^2/s^2)	Landing Site
MER-A Open	5/30/03	9.3	Melas Chasma in Valles Marineris
MER-A Close	6/16/03	9.3	Melas Chasma in Valles Marineris
MER-B Open	6/25/03	10.4	Hematite in Terra Meridiani
MER-B Close	7/12/03	16.3	Hematite in Terra Meridiani

Planetary protection (PP) requirements state that after injection the probability of the launch vehicle upper stage impacting Mars shall be less than 1.0 x 10^{-4}. Since the upper stage cannot perform maneuvers and, therefore, flies ballistically after injection, it is necessary to bias the injection aimpoint away from Mars to satisfy the PP requirement. Table 1 shows the biased injection aimpoint coordinates for all four trajectories in Mars B-plane (plane passing through the center of the target body and perpendicular to the incoming asymptote **S** of the hyperbolic flyby trajectory). The **T** axis is defined as the intersection of B-plane and the Mars mean equator of date ($\boldsymbol{T} = \boldsymbol{V}_\infty \times \boldsymbol{Pole}_{Mars}$), and the **R** axis completes a right-handed rule in the **TRS** orthonormal basis. Table 1 also shows the time of closest approach (TCA) and its difference with respect to the unbiased entry time, the injection impact probability for the spacecraft and the launch vehicle upper stage, and the deterministic ΔV required to remove the injection bias at TCM-1 (at launch plus 15 days).

Table 1: Biased Injection Aimpoints and Corresponding Impact Probabilities

	MER-A (Melas)		**MER-B (Hematite)**	
Launch Day	**Open (5/30/03)**	**Close (6/16/03)**	**Open (6/25/03)**	**Close (7/12/03)**
Injection Bias:				
BáR (km)	100,000	85,000	240,000	250,000
BáT (km)	250,500	258,000	484,000	561,200
B (km)	269,723	271,641	540,237	614,366
TCA (ET)	1/5/04 13:01	1/5/04 17:58	1/26/04 10:22	1/26/04 12:53
ÆTCA* (hr)	15.689	20.296	18.539	32.035
Impact Probability:				
Spacecraft	7.98 x 10^{-5}	8.16 x 10^{-5}	8.10 x 10^{-5}	7.99 x 10^{-5}
Delta Third Stage	2.98 x 10-5	3.70 x 10-5	3.47 x 10-5	4.20 x 10-5
Deterministic ÆV (m/s)	14.83	15.04	15.86	18.80

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

TCM ΔV and propellant statistics, along with Mars atmospheric entry delivery accuracies, are estimated by performing 5000-sample Monte-Carlo analyses. These analyses include dispersions from the launch vehicle injection covariance and the 99% Probability of Commanded Shutdown (PCS) data (for the Delta second stage burn), orbit determination uncertainties, and TCM execution errors. Table 2 presents the mission ΔV and propellant mass requirements at 99% probability for MER-A Open and Close and

MER-B Open and Close. The MER-A Open case (launch on 5/30/03) has the most demanding mission ΔV and propellant requirements.

Table 2: Mission ΔV and Propellant Requirements (99%)

	MER-A (Melas)		MER-B (Hematite)	
Launch Day	**Open (5/30/03)**	**Close (6/16/03)**	**Open (6/25/03)**	**Close (7/12/03)**
ÆV$_{99}$ (m/s)	87.8	80.3	74.5	80.6
ÆM$_{99}$ (kg)				
TCM	41.9	38.4	35.7	38.6
ACS	3.0	3.0	3.0	3.0
Total	44.9	41.4	38.7	41.6
Propellant Allocation	50.0	50.0	50.0	50.0
Propellant Margin	5.1	8.6	11.3	8.4

ÆV$_{99}$ and ÆM$_{99}$ are the required ÆV and propellant mass at 99% probability.
ACS refers to the spacecraft Attitude Control System
Value for ACS propellant represents the difference between TCM-only and combined TCM and ACS distributions propellants.

The inertial entry flight path angle (FPA) delivery requirements are -11.5 ± 0.17 (3σ) deg for MER-A (Melas) and -11.5 ± 0.20 (3σ) deg for MER-B (Hematite). As a representative case, Table 3 presents TCM delivery accuracy for MER-A open. The 3σ FPA delivery accuracy for TCM-5 and TCM-6 (0.138° and 0.093°, respectively) satisfy the delivery accuracy requirements.

Table 3. MER-A Open (5/30/03) Delivery Accuracy in Mars B-plane Coordinates

		σ BáR (km)	σ BáT (km	ρ	σ LFT(sec)	SMAA (km)	SMIA (km)	θ (deg)	σ FPA (deg)
TCM-1	L + 15d	9072	11140	0.9384	5494	14150	2467	38.8	N/A
TCM-2	L + 60d	264.1	395.8	0.7421	123.0	449.6	155.8	30.4	N/A
TCM-3	E Ğ 60d	46.16	45.71	0.0731	14.30	47.60	44.21	48.9	1.86
TCM-4	E Ğ 8d	5.29	3.67	-0.2620	1.39	5.44	3.45	-72.4	0.14
TCM-5	E Ğ 2d	2.99	1.47	-0.6540	0.58	3.17	1.05	-69.9	0.046
TCM-6*	E Ğ 6h	2.11	1.21	-0.9765	0.08	2.42	0.23	-60.4	0.031

ρ: σ BáT andσ BáR correlation coefficient
LFT: Linearized flight time
SMAA/SMIA: Delivery ellipse semi-major and semi-minor axes
θ: Delivery ellipse orientation angle relative to BáT axis
* Assumes TCM-5 does not occur