AAS 94-119

NAVIGATING MARS OBSERVER: LAUNCH THROUGH ENCOUNTER AND RESPONSE TO THE SPACECRAFT'S PRE-ENCOUNTER ANOMALY

Mars Observer Navigation Team
P.B. Esposito, W.G. Bellman, L.A. Cangahuala, S. Demcak*, C. Diarra, A. Halsell, E. Graat+, M.D. Johnston, R. Mase and D. Roth
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California

This paper provides a review of the Mars Observer Navigation Team's activities throughout 333 days of the spacecraft's interplanetary cruise to Mars and our response to the spacecraft's loss of communications which occurred approximately 68 hours before encounter.

Throughout the interplanetary phase, three independent data-types were analyzed to determine the flight path of the spacecraft. These were two-way coherent Doppler, round-trip time delay and Very Long Baseline Interferometric (VLBI) angular measurements. The accuracy of all data types were within the requirements. After injection into the trans-Mars trajectory, three trajectory correction maneuvers (TCM) were executed in order to refine the Mars targeting in preparation for the Mars Orbit Insertion (MOI) maneuver. The final targeting results, due 12 days before the MOI maneuver, were

B•T (km) = 7.1*1O
B•R (km) = -8397,1 ± 18
Encounter (UTC,SCET) = 24 August 1993
20:40:06 ± 5.3sec

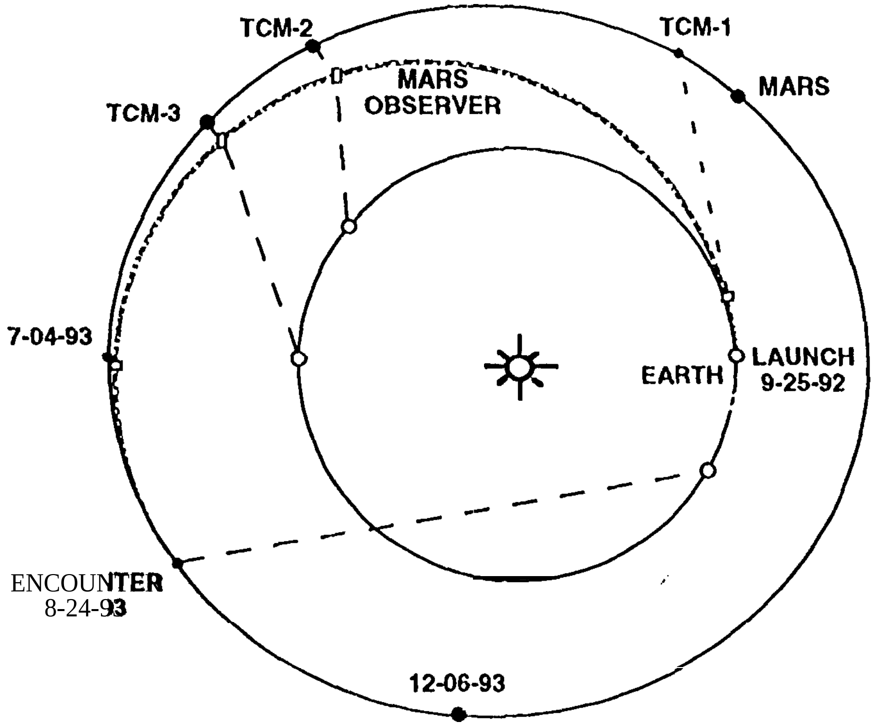
When the loss-of-communications occurred, a contingency plan was implemented to addess the possibility that the spacecraft might be on a flyby trajectory. This was to design a post-encounter maneuver which still allowed the spacecraft to be captured, In addition, another plan involved the execution of a maneuver at about 30 days after the original encounter. This would allow a second encounter and capture approximately 10 months after the original encounter.

During the weeks after encounter, predicted ephemerides for both the flyby and capture scenarios were developed. For the flyby case, the next closest approach to the earth shall occur on May 13-14, 1995 at a distance of 82.4 million kilometers.

• OAO Corporation, Altadena, CA
\+ Sterling Software, Pasadena, CA

OVERVIEW OF NAVIGATION OPERATIONS

Mars Observer was launched from Cape Kennedy on 25 September 1992, 17:05 :01.5 UTC using a Titan III launch vehicle with an upper stage called the Transfer Orbit Stage (TOS). Having been successfully injected into the trans-Mars trajectory, three trajectory correction maneuvers (TCM) were completed, in the propulsive system's "blow-down" mode, in order to refine the spacecraft's targeting at Mars in preparation for the Mars orbit insertion (MOI). Although a fourth maneuver (TCM-4) was planned, it was unnecessary due to the targeting accuracy achieved as a result of TCM-3. An overview of the spacecraft's heliocentric trajectory stressing these maneuvers is given in Figure 1. These targeting results as well as those of the Titan III/TOS injection are shown in Figure 2, The coordinates are referenced to a target plane centered on Mars and perpendicular to the spacecraft's velocity asymptote (Appendix 1).



	TCM-1	TCM-2	TCM-3	TCM-4	MOI
DATE	10/10/92	02/08/93	03/18/93	08/04/93	08/24/93
ΔV (MB)	50.0	9.65	0.46	---	761.7
AT (SEC)	138.5	34.5	17.4	---	28m 50s
ENGINES	490N (1,3)	490N (2,4)	22N (4,5,6,7)	‘--	490N (1,3)

Figure 1 The **Spacecraft's Interplanetary Flight Path**

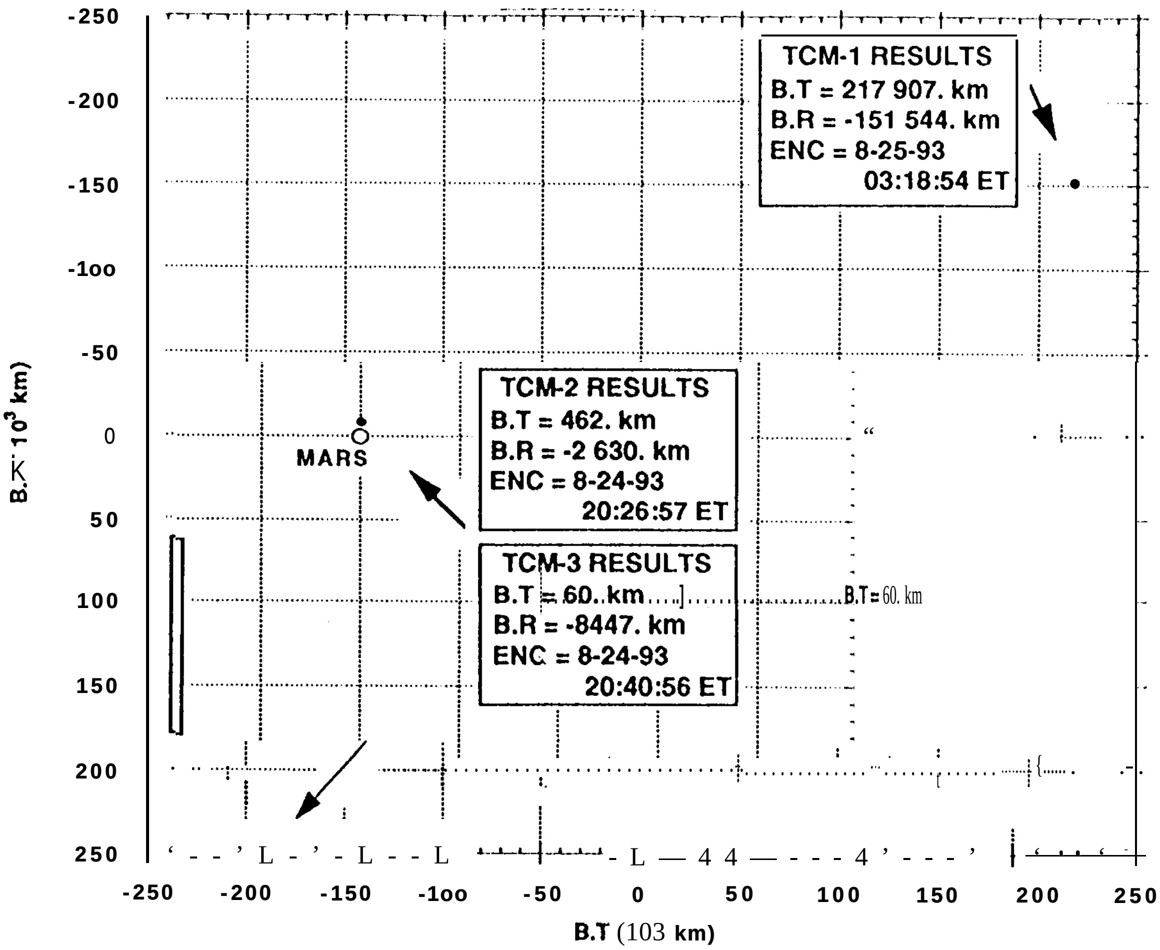


Figure 2 Summary Of Targeting Results Due To Injection and Three TCMS

Although previously expressed as targeting coordinates, the basic encounter conditions were the encounter time (24 August 1993, 20:42:00.0 E.T.), orbit inclination (92.8°) and the periapsis distance (3950 km). However, during interplanetary cruise these were modified due to a) the decision to complete a "power-in" maneuver after MOI, b) the decision not to execute TCM-4 and c) to a lesser degree the decision to encounter Mars' natural satellite Phobos. The "power-in" maneuver was planned to occur eleven days after MOI and had an out-of-plane component such that the longitude of the ascending mode would change by about 15 degrees. This would have allowed the spacecraft to be in its mapping orbit twenty-one days earlier than originally planned.

The encounter conditions based upon the final orbit determination result, provided on 11 August 1993, in preparation for the final design of the MOI maneuver, arc given in Table 1.

Table 1

ORBIT DETERMINATION TARGETING RESULTS USED TO DESIGN THE FINAL MOI MANEUVER

Encounter (UTC,SCET)	=24 August 1993, 20:40:06.2
B•T (km)	= 7.1
B•R (km)	= -8397.1
Inclination (degrees)	= 89.95
Periapsis Distance (km)	= 3877.4

Coordinate System: Mars centered, inertial, Mars mean-equator of date

The MO] maneuver was designed to be an "in-plane" burn with the thrust vector or $\overline{\Delta V}$ specified to be in a fixed orientation throughout the burn. The planned magnitude of the velocity change was 761.7 m/s with a burn duration of 28 minutes 45 seconds using two 490N engines in the propulsive systems' pressurized mode. Just prior to the ignition of the 490N engines, a five second ullage burn was to be completed using four 22N engines. Nominal capture orbit elements are given in Table 2.

Table 2

PLANNED CAPTURE-ORBIT ELEMENTS RESULTING FROM THE MOI MANEUVER

Epoch (Apoapsis UTC,SCET) :26 August 1993, 10:12 :04.4
Semi-Major Axis (km) :42,946.69
Period (days) :3.127
Eccentricity: 0.909409
Periapsis distance (km) : 3890.58
Apoapsis distance (km) :82002.79
Longitude of Ascending Node (degrees) :-106.724
Inclination (degrees) :89.957
Argument of Periapsis (degrees) : 116.498
Coordinate System: Mars centered, inertial, Mars mean-equator of date

1NTERPLANETAR% NAVIGATION AND RESULTS

Immediately after injection, the major objectives were a) determine the spacecraft's flight path, b) assess the accuracy of the injection and c) evaluate the accuracy of the X-band tracking data. The Titan III/TOS system delivered the spacecraft on a flight path within the expected two-sigma error bound (Ref. 1) and the quality of the data was within the requirements. The initial results of data accuracy are given in Table 3.

Table 3

DOPPLER AND RANGE DATA INHERENT NOISE EVALUATED DURING THE FIRST HALF-HOUR OF FLIGHT OPERATIONS

Tracking Data	Quantity	Count Time (sec)	Standard Deviation (mHz)	Standard Deviation (mm/sec)	Requirement (one sigma , mm/sec)
Two-way	1674	1	22.5	0.40	..
Coherent	166	10	3.67	0.065	..
Doppler	27	60	1.12	0,021	0.2

	Quantity	Standard Deviation (Range Units)	Standard Deviation (Meters)	Requirement (one sigma meters)
Sequential Ranging Assembly (SRA) Range	49	0.50	0,07	5

The first five days of the mission were devoted to refining the spacecraft's heliocentric orbit and propagating those results to Mars encounter. The first two propulsive maneuvers (TCM- 1 on 10/10/92 and TCM-2 on 02/08/93) were designed to move the spacecraft's aimpoint progressively closer to the nominally planned MOI aimpoint. For TCM- 1, the first set of 490 N engines (1 and 3) were used and the resultant targeting was within one-sigma of the combined orbit determination (OD) and maneuver execution uncertainties. Execution errors dominated and were about a factor of twenty larger than the OD errors. For TCM-2, the second set of 490 N engines (2 and 4) were used and the resultant targeting was within two-sigma of the combined errors. Again execution uncertainties dominated OD uncertainties by a factor of fifteen,

The purpose of TCM-3 was to refine the targeting based on the TCM-2 results and for TCM-4, it was to provide a final opportunity to adjust the targeting as necessary. TCM-3 was successfully performed on 03/18/93. It resulted in the spacecraft being within the one-sigma error ellipse of the planned targeting at MOI. Because of the small velocity change and thus execution errors, the OD errors dominated. The preliminary target results established within three days of each of these TCMS are summarized in Table 4.

Table 4

SUMMARY OF TCM TARGETING DESIGN VERSUS ACHIEVED

TARGET COORDINATES	TCM-1	TCM-2	TCM-3
B•T (km)	256,347.	-430.	153.
	217,902.	+462.	59.7
B*R (km)	-193,247	-8481.	-8478.
	-151,544	-2630.	-8447.
Encounter (1993, ET)	8/25, 08:05:55	8/24, 20:42:00	8/24, 20:42:00
	8125, 03:18:54	8424, 20:26:57	8/24, 20:40:56

Based upon the determination of the spacecraft's flight path immediately after TCM-3 and its continuous monitoring until the preparation cycle for TCM-4, a decision was made not to execute TCM-4. The post-TCM-3 evolution of the spacecraft's location and accuracy at encounter are shown in Fig. 3. The primary uncertainties influencing this accuracy are due to the Mars ephemeris, solar radiation pressure and other non-gravitational accelerations (e.g. angular momentum desaturations) and the earth-based tracking station locations. A representative set of tracking data residuals extending from launch to just prior to encounter are shown in Figs, 4, 5 and 6. In all three sets of residuals a) the noise is below the accuracy requirement, b) there are little or no systematic patterns and c) these residuals are indicative of an accurate modeling of all phenomena influencing the motion of the spacecraft. A detailed review of the OD process and results is given in Ref. 2.

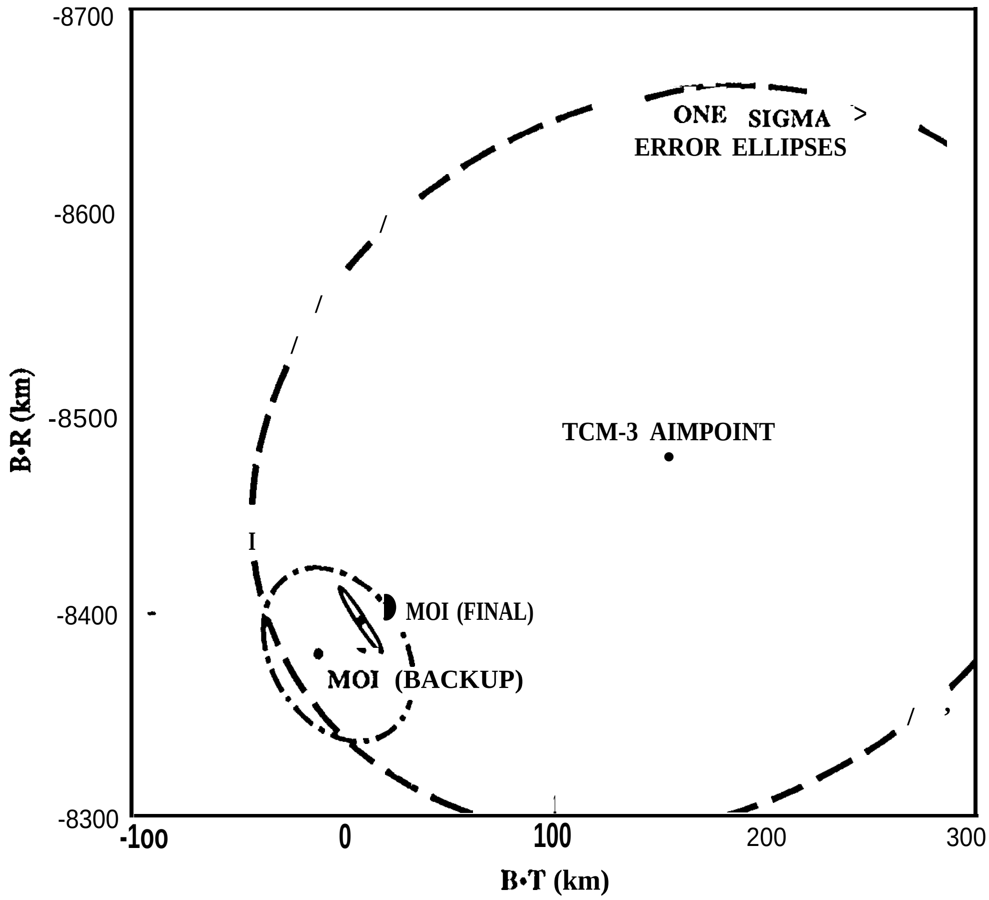
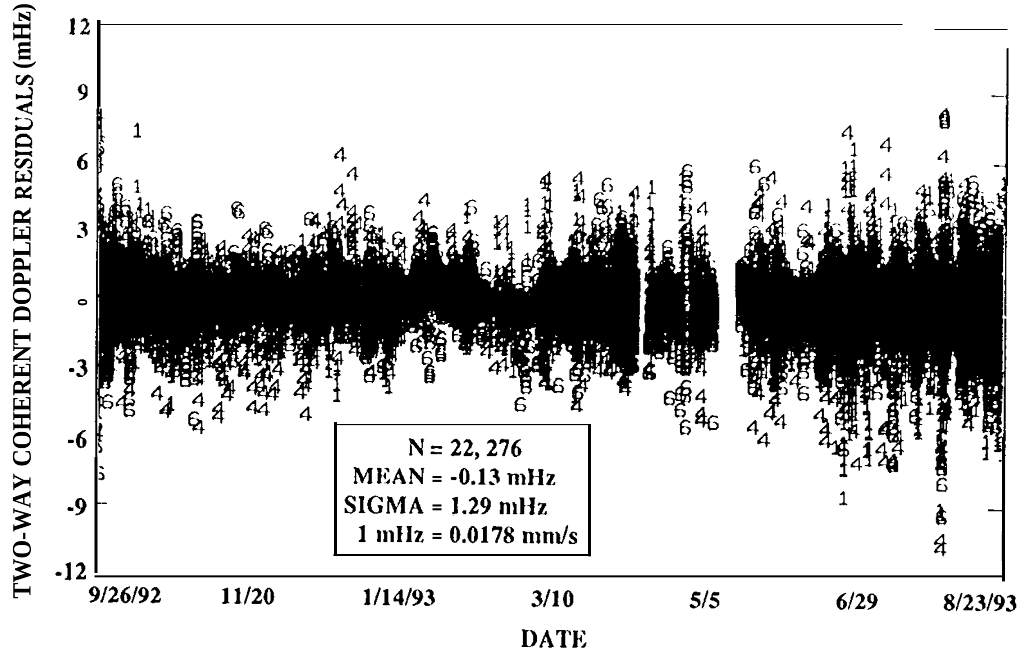


Figure 3 The Spacecraft's Planned Target for TCM-3 and the Resultant Evaluation and Uncertainty



Figu.:e 4 Representative Doppler Residuals Throughout ɷe Interplanetary Phase

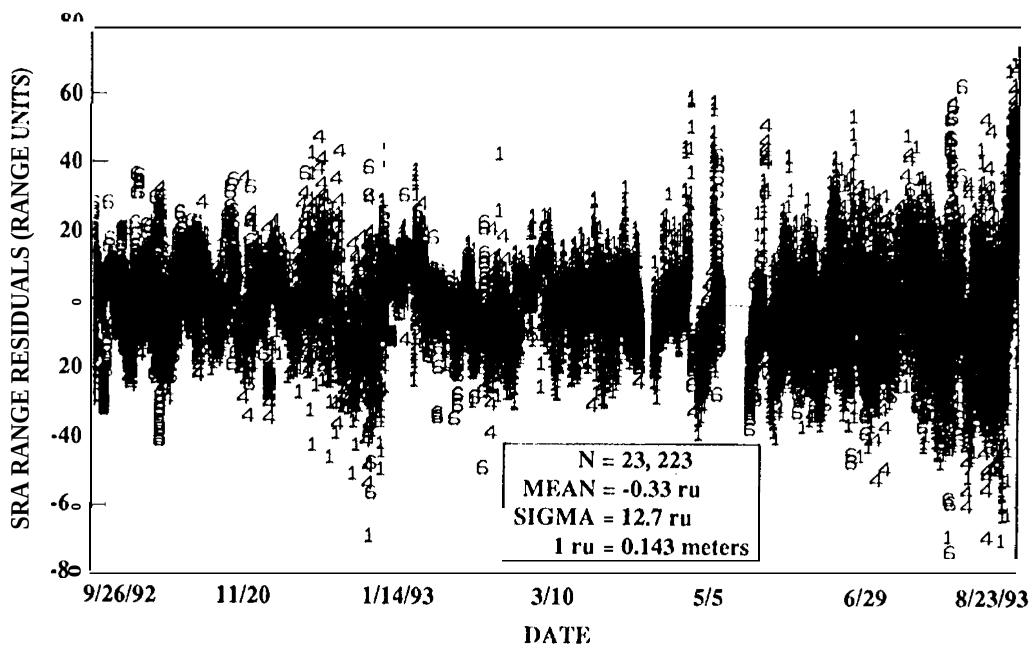


Figure 5 Representative Range Residuals Throughout the Interplanetary Phase

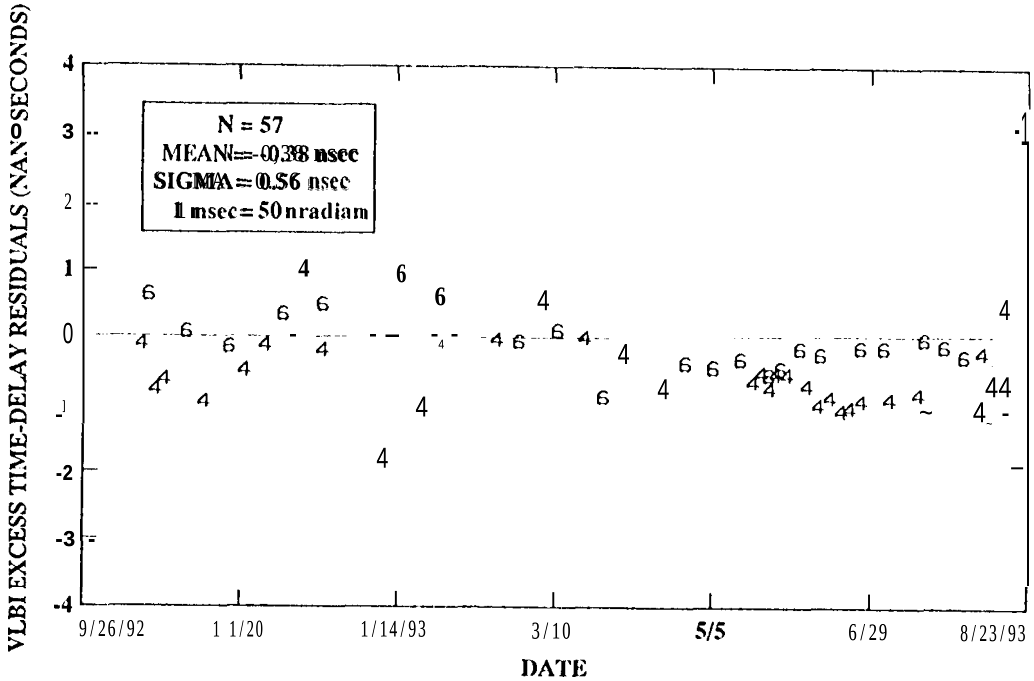


Figure 6 Representative VLBI Residuals Throughout the Interplanetary Phase

MARS ORBIT INSERTION PREPARATION AND CONTINGENCY PLANNING

Previously, we have described the process leading to the final preparations for MOI. However, two other pre-MOI plans were developed; these were a) a backup-MOI maneuver design as completed on 06/23/93 and transmitted to the spacecraft on 08/06/93 and b) a maneuver plan was developed to react to an unexpected regulator leakage in the propulsion's hi-propellant system. If the latter were to occur after the pressurization sequence, high pressure might build up in the fuel and oxidizer tanks (Ref. 3). This pressure could be relieved by performing a pair of nearly self-canceling propulsive maneuvers. They were designed such that their implementation would have little effect on the previously established targeting and the final MOI maneuver design. This plan was developed as a contingency and was never executed on the spacecraft.

Post-Encounter Preparations

The loss of communications with the spacecraft occurred on 08/21/93. Since the nature of the anomaly was unknown at that time, it was still possible that the critical capture maneuver might have been executed as originally scheduled. However, contingency plans were developed to address the possibility that the capture maneuver was aborted and the spacecraft was on a flyby trajectory. The first contingency plan was to prepare a maneuver design such that if executed 24 to 36 hours after encounter the spacecraft could still be inserted into Mars orbit. Such a plan had been discussed nine months earlier during mission design studies (Ref. 4) so some background information was already available. This late propulsive maneuver would ensure capture but the orbital period was approximately 46 days and all of the hi-propellant capability would be exhausted. The velocity-change capability available for this maneuver was 2246 m/sec.

A second plan was also prepared that addressed the flyby scenario and the possibility that communications could not be established until several days after encounter thus negating the above plan. 'I'his involved executing a propulsive maneuver about one month after encounter. Since the spacecraft was falling behind Mars, energy could be injected into its orbital motion thus allowing a second encounter ten months after the original encounter. In addition, analysis indicated that a mapping orbital period of 12 to 18 hours could be achieved.

Since communications were never established with the spacecraft, neither of these contingencies was executed on the spacecraft.

Spacecraft PREDICTED EPHEMERIS

If the spacecraft had executed the MOI maneuver successfully then the resultant capture-orbit elements are as shown in Table 2. In addition, OD and maneuver execution uncertainties have been transformed to orbit element uncertainties. Of these, the most significant was the orbital period; the three-sigma uncertain y was 4.8 hours. Another factor worth mentioning is that as a result of the anomaly, the spacecraft may have gone autonomously into a contingency mode. In this mode, the spacecraft's rotation axis is sun-pointed as opposed to the nominal earth-pointed orientation. Over the three days prior to MOI, this effect would have slightly perturbed the nominal targeting and thus slightly influenced the resultant capture-orbit elements.

If the spacecraft was unable to execute the MOI maneuver then a flyby would have resulted with a corresponding perturbation to the orbit due to Mars. Pre and post-encounter heliocentric orbit elements are given in Table 5.

Table 5

Mars Observer Heliocentric Orbit Elements Before and After Encounter

Orbit Element	Pre-Encounter	Post-Encounter
Period (Days)	552,3	585.8
Eccentricity	0.239	0.174
Inclination (Deg.)	1.30	6.67
Long. Asc. Node (Deg.)	-177.5	35,5
Arg. Perihelion (Deg.)	-173.7	-20.4
Epoch	08/1 5193	09/01/93

Coordinate System: Heliocentric, inertial, Earth Mean Orbit and Equinox J2000

For both cases, heliocentric orbits are shown in Fig. 7. Some corresponding dates and geometries are given in Table 6. Additional position information for the flyby orbit is given in Figs. 8 and 9.

Table 6

Post Encounter Spacecraft Geometry and Dates

Quantity	Flyby Orbit	Mars (Capture) Orbit
Superior Conjunction	1 2/1 9/93	1 2/27/93
Sun-Earth-Spacecraft Angle		
40 Deg	1 0/06/94	06/27/94
50 Deg	1 1/06/94	08/04/94
Minimum Geocentric Distance (km)	82.4×10^6 05/1 3/95	101,1X106 02/1 1/95

To date, hundreds of commands have been sent to the spacecraft, employing a variety of strategies in order to communicate, but no communication has been established.

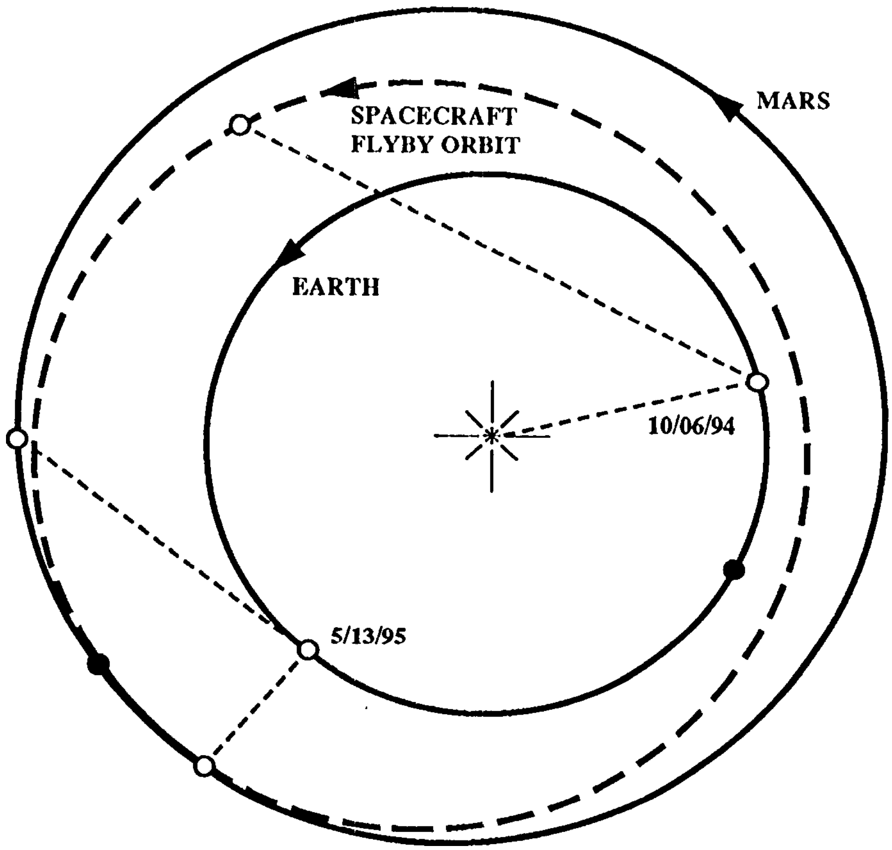


Figure 7 Post Encounter Heliocentric Orbits for the Flyby and Capture Scenarios

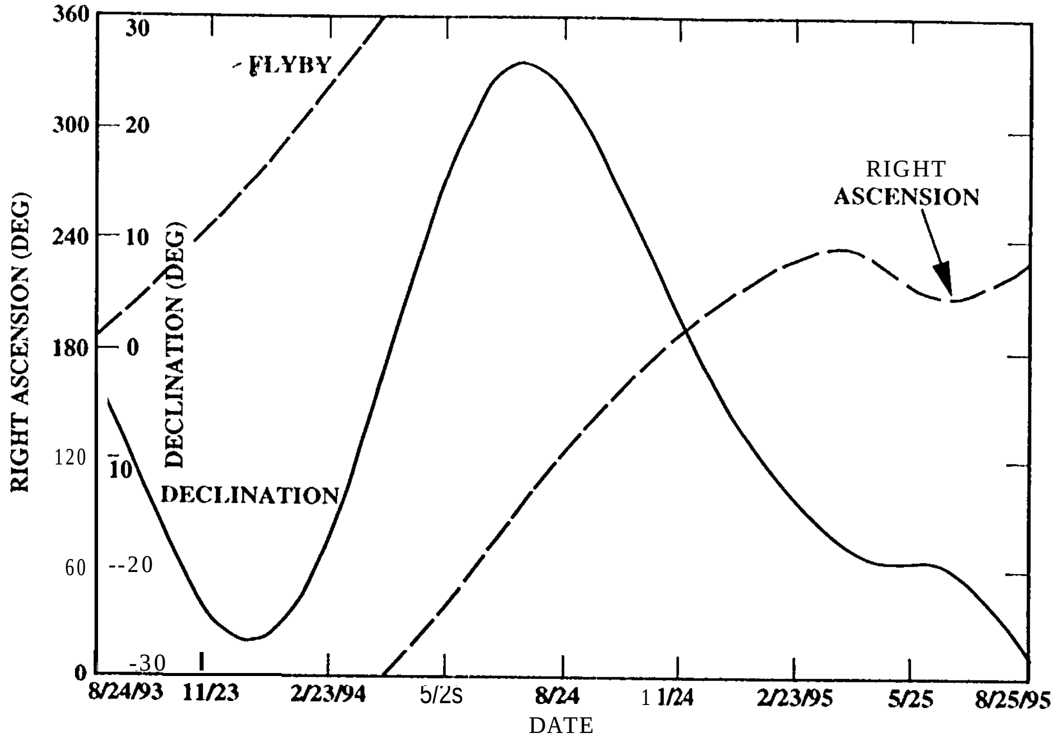


Figure 8. Angular Coordinates for Flyby Case

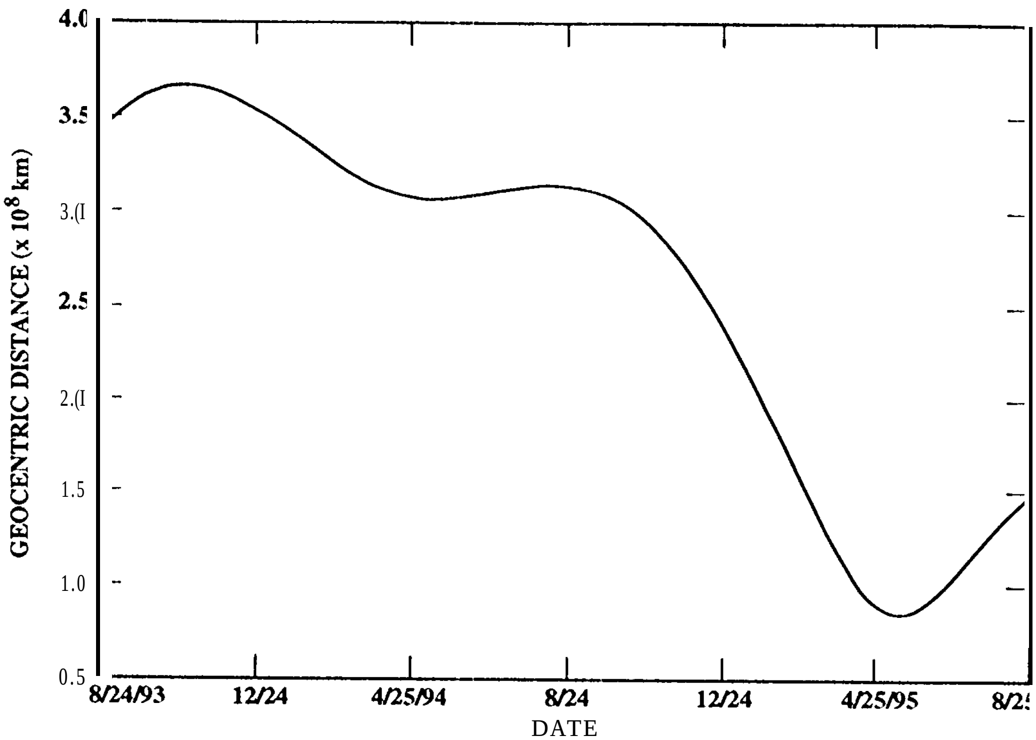


Figure 9. Geocentric Distance for Flyby Case

ACKNOWLEDGEMENT

We thank J. Border for his planning efforts for the VLBI data acquisition, R. Roncoli, for assisting in the post-encounter capture orbit maneuver planning and J. Giorgini for assisting in post-encounter spacecraft ephemeris analysis. The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

REFERENCES

1. A. Halsell, MO Mission Delta - V99 and Injection Accuracy Evaluation - NAV Analysis, IOM NAV-92-093, 10/08/92 (JPL Internal Document).

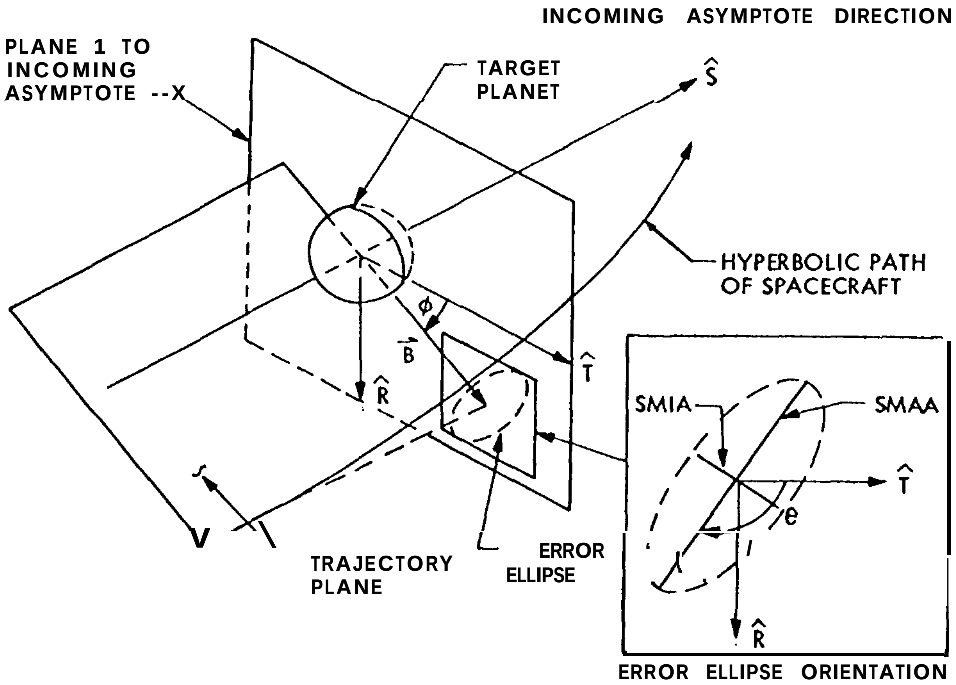
2. L.A. Cangahuala, et al, Mars Observer Interplanetary Cruise Orbit Determination, Paper AAS 94-133, AAS/AIAA Spaceflight Mechanics meeting, February 14-16, 1994.

3. W.J. O'Neil, et al, Viking Navigation, p. 18, JPL Publication 78-38, 11/15/79.

4. Private communication from R. Roncoli, Dec. 1992.

APPENDIX 1: Target Coordinate System

The Mars centered targeting or encounter coordinate system in which the target parameters (i.e. B vector as shown and time of encounter) are expressed is commonly referred to as the B-plane system.



$\vec{B}$ = MISS PARAMETER=& (S x $\vec{H}$), i.e., $\vec{B}$ x (V∞ S) = $\vec{H}$

$\vec{H}$ = ANGULAR MOMENTUM VECTOR

V∞ . VELOCITY AT INFINITY

$\hat{T}$ = PARALLEL TO EQUATORIAL PLANE AND NORMAL TO S