Navigation and the Mars Global Surveyor Mission

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ABSTRACT

The Mars Global Surveyor (MGS) spacecraft was successfully launched from Cape Canaveral by a Delta II 7925 rocket on 11/7/96, 17:00:50 UTC. Injection into the trans-Mars trajectory went smoothly with the achieved or reconstructed injection targeting within 1.3 sigma of the planned targeting.

As of 6/1/97, we are 205 days into the mission. Two trajectory correction maneuvers (TCM-1 and TCM-2) were successfully completed on 11/21/96 and 3/20/97. TCM-3, which was to have occurred on 4/22/97, was cancelled because of the accuracy of previous targeting. The final TCM shall occur on 8/25/97 in order to adjust arrival conditions for the Mars Orbit Insertion (MOI) maneuver which shall occur on 9/12/97. The planned capture orbit is highly elliptical with a 45 hour orbital period, a 300 km periapsis altitude and a descending node at 5:43 pm local mean solar time.

Two-way coherent doppler (range-rate) and time-delay (range) measurements, at an X-band frequency (8.4 GHz), are being acquired by Deep Space Network (DSN) stations near GoldStone, California, Madrid, Spain and Canberra, Australia. These data are being used to navigate the spacecraft. Representative data noise or precision is 0.85 mHz (0.015 mm/s in range-rate), over a ten minute count-time, for the doppler and 0.4 meters for the range data.

After capture, the orbit shall be circularized by aerobraking (AB) and propulsive maneuvers. AB is divided into three phases: a) a cautious "walk-in" period in which the periapsis altitude is lowered from 300 km to 110 km, b) the main phase in which most of the orbital circularization occurs, and c) the walk-out phase during which the spacecraft steps out of the atmosphere and the mapping orbit is established by two propulsive maneuvers.

With the initiation of the mapping phase on 3/1 5/98, science data acquisition shall be continuous for one Mars year or 687 earth days. Navigation shall maintain a 2:00 pm descending node, sun-synchronous, low altitude, short periodic and "frozen" orbit throughout this time. In addition, the ground track coverage shall be nearly uniform in order to maximize data acquisition from the nadir pointed science instruments. From Feb 2000 to Jan 2003, a relay phase shall be established during which MGS shall be available as a relay satellite for the Mars '98 rover mission.

1. NAVIGATION DURING THE INTERPLANETARY PHASE

Two-way, time-delay and coherent doppler data, squired at an X-band frequency, are being analyzed to navigate the spacecraft. At various times throughout the interplanetary phase, the resultant, reconstructed trajectory and the spacecraft's predicted motion are being used to design the TCMS, provide the DSN with angular direction and frequency predictions to track MGS, used on-board the spacecraft to determine its location and provided to other flight teams for planning and analysis. Typical analysis results, showing doppler and time-delay residuals (measured minus computed data), are given in Figs. 1 and 2. Both are representative of longer time spans and are indicative of accurate navigation.

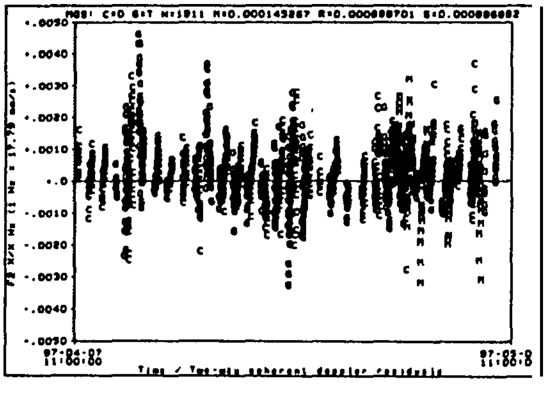

Figure 1. Representative doppler data residuals during the interplanetary phase (1 Hz = 17.8 mm/s in range-rate).

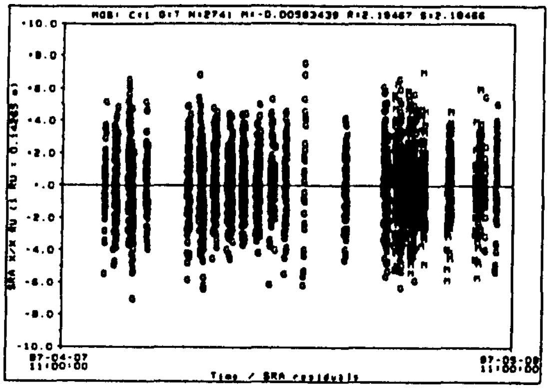

Figure 2. Representative range data residuals during the interplanetary phase (10 Range Units = 1.43 meters in range).

The major, non-gravitational accelerations acting on the spacecraft are due to solar radiation pressure (SRP) and spacecraft self-induced perturbations due mainly to angular momentum desaturations (AMDs). Deviations from a nominal spacecraft attitude influencing the SRP modeling are due to a) star and earth imaging for calibrations of the Mars Orbiter Camera (MOC), b) calibrations for the magnetometer involving spacecraft rotations, c) eight tests performed during Jan '97 in order to assess the state of the minus Y-axis solar array (i. e. it is 20.5 degrees away its fully deployed position) and d) the recent entry of the spacecraft into safe mode on 5/7/97. In safe mode, the plus X-axis of the spacecraft is pointed toward the sun instead of its nominal earth pointing direction. Recovery from safe mode was successfully accomplished on 5/25/97. MGS is now back in its nominal attitude, called array-normal-spin or ANS, with the plus X-axis earth pointed and rotating with a 100 minute period about this axis.

With respect to the AMDs, the spacecraft has three mutually orthogonal reaction wheels which absorb the effect of torques, primarily due to SRP, which otherwise would tend to rotate the spacecraft away from its nominal attitude. Whenever an angular momentum threshold is reached, the wheels are desaturated by transfer of angular momentum back to the spacecraft which in turn is counter balanced by thrusting. The degree of unbalance in coupled thrusters firing during these events is modeled as a nearly instantaneous velocity-change (delta-v) to the spacecraft's motion. As of 6/1/97, there have been approximately 95 AMDs with an average delta-v of 1.2 mm/s per event. This level of perturbation is easily observed in the doppler data and is being accurately modeled.

The progressive targeting of the spacecraft, due to propulsive maneuvers from launch to encounter, is given in a Mars centered, target plane (Fig. 3). Shown are planned and achieved targeting for three trajectory correction maneuvers. In addition, the final targeting prior to the MOI maneuver is indicated. Tables 1 and 2 provide TCM execution parameters and targeting results respectively. MOI is being planned as a pitch-over maneuver, which will improve the efficiency of this main-engine bum, with a velocity-change of 976 m/s resulting in a 45 hour capture orbit period. The post-MOI spacecraft mass is estimated at 767.8 kg as compared to an injection mass of 1061.9 kg. Mass changes are accounted for throughout the mission and are due to propulsive maneuvers, AMDs, and thrusting during the solar panel assessment period and the recent entry into the safe mode.

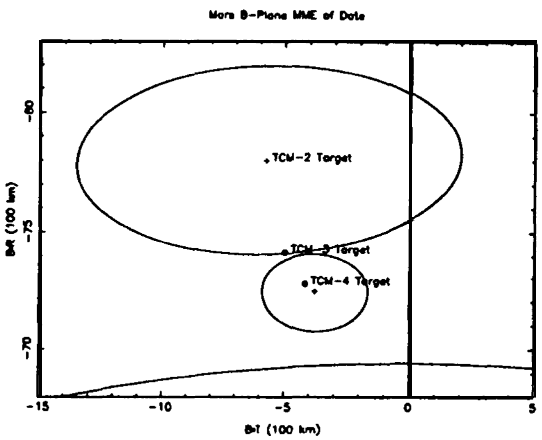

Figure 3. Spacecraft B-plane targeting for the TCMS with one sigma uncertainty ellipses. The plus sign below the TCM-4 target is the present location of the spacecraft; the curve below that is the Mars impact zone,

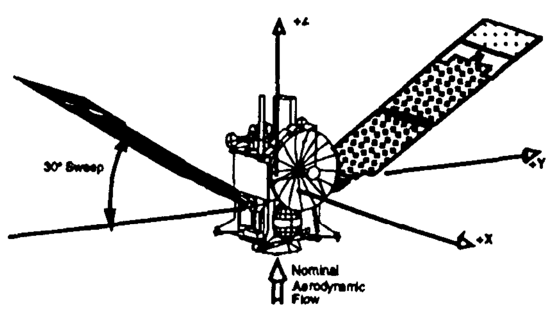

Figure 4. Overview of the MGS spacecraft.

An overview of the spacecraft is given in Fig. 4. Shown are two sets of solar arrays, 3.53 m by 1.85 m each, drag flaps, the high gain antenna with a diameter of 1.5 m, the nadir panel on which most of the science instruments are mounted, and the equipment and propulsion modules.

Table 1. MGS Interplanetary Propulsive Maneuvers

Maneuver	Start Time UTC, SCET	Planned Total Delta-V (m/s)	Maneuver Implementation Engine: Thrust (N): Duration (s)
TCM-1	11/21/96 16:00:00	27.1	8 thrusters (ullage); 17.1; 20 main engine; 656.4; 43 (pressure regulated)
TCM-2	03/20/97 18:00:00	3.86	8 thrusters (ullage); 29.9; 20 main engine; 617.4; 5.6 (blow-down mode)
TCM-3	04/22/97 00:00:00	0.04	not executed due to previous targeting accuracy, small delta-v and orbit determination uncertainty
TCM-4	08/25/97	0.4	8 thrusters; 28.8; 14 (blow-down mode) (estimated)
MOI	09/12/97 01:15:13	976.0	8 thrusters (ullage); 28.8; 20 main engine; 655.5; 1343. (pressure regulated) (estimated)

All maneuvers are planned to account for planetary protection (there must be less than a one percent probability that the spacecraft will be on a Mars impact trajectory) and solar exclusion angle (the spacecraft's plus Z axis must not point within thirty degrees of the Sun) constraints.

Table 2. MGS TCM Target Coordinates (Planned and Achieved)

Maneuver	T Coordinate (km)	R Coordinate (km)	Encounter Periapsis Time (ET)
Injection	-34,000. -459,279.	-54,000. -19,709.	09/12/97, 06:26:09 09/03/97, 04:41:48
TCM-1	22,626. 26,687.	-38,435. -38,501.	09/12/97, 02:51:40 09112197,03:47:40
TCM-2	-574.8 -1058.0	-7801.2 -7406.3	09/12/97, 01:26:09 09/12197, 01:26:06
TCM-3	-497.5 not executed	-7414.2	09/12/97, 01:26:09
TCM-4	-448.7	-7255,3	09/12/97, 01:26:09

For each of these maneuvers, the first line refers to the planned target coordinates and the second to the achieved coordinates. These coordinates, usually called B-plane coordinates, are Mars centered and referenced to the Mars mean equator and IAU vector of date. The B-plane is Mars centered and perpendicular to the spacecraft's incoming velocity asymptote.

2. PLANNING FOR AEROBRAKING (AB) AND ESTABLISHMENT OF THE MAPPING ORBIT

After capture into a highly elliptical orbit (eccentricity of 0.88 and periapsis altitude of 300 km), the overall plan is to nearly circularize the orbit with aerobraking. In addition, we need to establish the mapping orbit when the mean sun has drifted into the 2:00 pm local mean solar time orientation (LMST is measured at the descending node). Thereafter, the orbit precesses at the same rate as the apparent motion of the mean sun around Mars (0.524 deg/day) to maintain this sun synchronous condition. This sun-synchronous orbit is required for science observations. The aerobraking technique is being used because it achieves approximately 1200 m/s in velocity change for circularization which would otherwise have to be produced by on-board propellant (Ref. 1).

During walk-in, the periapsis altitude shall be lowered cautiously from 300 km to 110 km, using a series of five propulsive maneuvers. This will allow the flight team to estimate atmospheric densities around periapsis and compare them with estimates assumed during planning. Our primary density planning tool is the Mars-GRAM, version 3.5 software developed by Justus (Ref. 2). However, at the AB altitudes, the atmospheric density is very uncertain. For our planning, we have assumed a 70 percent orbit-to-orbit density variation,

During the main phase of AB, the challenge is to maintain a balance between enough atmospheric drag to achieve the nearly circular orbit and a 2:00 pm sun-synchronous condition and protect the spacecraft from undue heating, Unacceptable heating of spacecraft components can occur either because the spacecraft dipped too far into the atmosphere or an unanticipated increase in density occurred due to intrinsic density variation. Thus, a corridor has been defied based on the dynamic pressure experienced by the spacecraft. Currently the upper bound is 0.68 N/m**2 which is derived from the allowable torque the minus Y-axis solar array can tolerate while in a powered gimbal hold condition. The lower bound is 0.58 N/m**2 which is determined by the minimum amount of drag required to maintain the AB baseline plan. Small changes to these corridor conditions are also being planned. Close monitoring of the progress of AB is required. Small propulsive maneuvers, to raise or lower the periapsis altitude, shall provide the control mechanism to remain within the previously mentioned corridor. These maneuvers, 28 for the AB baseline and another 22 for contingencies, are referred to as "off-the-shelf' because they have already been generated, tested and delivered to the spacecraft team for implementation.

Table 3 summarizes key AB information and Figs. 5 and 6 show the expected orbital period change due to the drag perturbation and dynamic pressure limits established throughout AB.

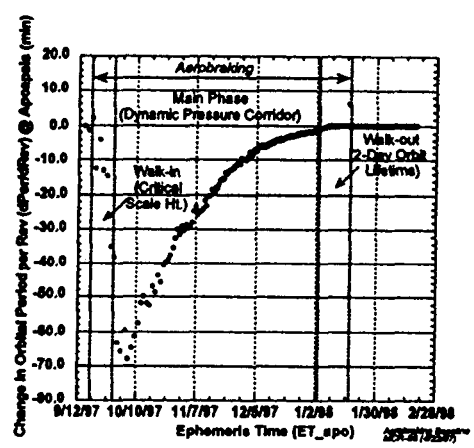

Figure 5. Orbital period change per orbit due to atmospheric drag.

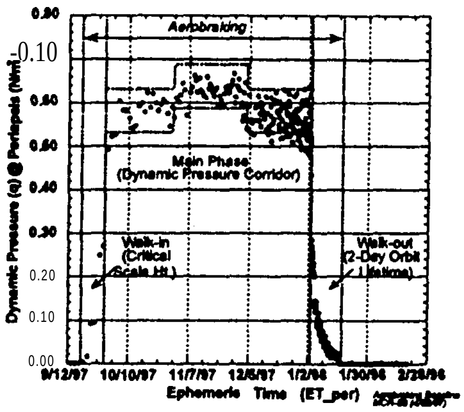

Figure 6. Dynamic pressure corridor and variation throughout **aerobraking.**

Throughout AB, navigation is required to predict the time of **periapsis** passage to 225 seconds and the radial distance at **periapsis** to within 1.5 kilometers. This will insure that the **spacecraft's** planned angle-of-attack is maintained throughout the drag pass and atmospheric density variation due to altitude uncertainties will be minimized, Two-way coherent **doppler** shall be acquired continuously throughout AB. Thus, navigation will be continually updating orbital elements and model **parameters,** especially the atmospheric density. This database plus related information obtained **from** the engineering and science instruments will **allow** density trending, variation and short term predictions to be made.

Table 3. Summary of Key Aerobraking **Baseline** Information

Phase/ Mnvr	**Start Walk-In**	**Main Phase**	**Start Walk-Out**	**Mnvr To End AB (ABX)**
Date	09/19/97	09130/97	01/04/98	01/18/98
Period, hrs	44,8	42,0	2.39	1.88
Eccentricity	0.88	0.88	0.19	0.043
LMST, **pm**	**5:32**	**5:09**	**2:09**	**2:07**
Altitude,* km	150.	105.5	96.7	387,6
Latitude,* deg	31.8	32.6	80.6	32.6
Density,* **kg/km**3**	0.246	42.4	32.9	O.44X1O**-5
Mnvrs ++	4	26	12	**1**
Delta-v, ++ **m/s**	**1.8**	4.6	**18.**	60.

* At **periapsis** following a maneuver. ++ Total number of maneuvers and delta-v in that phase. The **first** in-orbit maneuver, AB-1, occurs at the fourth **apoapsis** at 9/1 8/97, **14:55** ET. The time interval **from MOI** (9/12/97) to the start of the mapping phase (3/15/98) is 180 days.

3. MAPPING PHASE AND SCIENCE OBJECTIVES

Navigation is required to establish and maintain the mapping orbit specified in Table 4. From this orbit, the nadir pointed, science instruments shall continuously acquire data which will allow the the science objectives (Ref. 3) to be satisfied. Maintaining the orbit can be achieved by executing small propulsive maneuvers at monthly intervals. This is necessary to counteract the effects of atmospheric drag and gravity perturbations. The mapping phase begins on 3/15/98 and extends until 1/31/2000.

In addition to orbit parameter specification, spacecraft position knowledge (reconstruction) and prediction are required at the levels shown in Table 5. With the planned tracking data schedule (one ten-hour pass per day), these requirements can be satisfied throughout mapping except for the solar conjunction period (May, 1998) and during Mars' perihelion, 11/25/99, when the solar cycle will be approaching maximum. More information on expected navigation accuracies and planning can be found in the MGS Navigation Plan (Ref. 4). In addition, JPL's URL (http://www.jpl.nasa.gov) and that of the Mars Surveyor Operations Project [redacted] provide background and up-to-date information on the progress of the mission.

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Table 4. Mapping Orbit Specification

Element	Mean Value	Bound
a, km	3775,1	+0.7 / -1.2
e	0.0072	+/- 0.007
Descending node, deg	Sun synchronous at 2:00 pm	+/- 3.0
Arg of Periapsis, deg	-90.	+/- 10.0
Inclination, deg	92.87	—
Frozen orbit	minimize altitude variation	

Table 5. MGS Position Accuracy Requirements During Mapping

Position Component	Knowledge (3 σ, km)	Prediction Over 14 Days (3 σ, km)
Down track	9	25
Cross track	5	9
Radial	2	8

4. ACKNOWLEDGMENT

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.

5. REFERENCES

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