MGS AND ODYSSEY – RELAY SATELLITES FOR THE MER MISSION

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Abstract

Both Mars Global Surveyor (MGS) and Mars Odyssey are currently in low altitude, nearly circular and highly inclined orbits about Mars. Thus, they are available and compatible to serve as relay satellites for the Mars Exploration Rover (MER) mission. Consequently, the MER project developed requirements for MGS to be overhead, at a specific time with a 30 second tolerance, during the atmospheric entry, descent and landing (EDL) phase of both MER vehicles. The result, after execution of a single orbit synchronization maneuver (OSM) on 10/03/03, 92.4 days or 1130 orbits before Spirit's EDL, was that MGS was over Spirit 8 seconds past the required time. This maneuver, with a delta-velocity of 0.534 m/s, caused the orbital period to change by 3.34 s and resulted in a time-phasing change of 62 min 19 s in order to achieve the EDL over-flight. Based on the navigation and execution of an OSM on 01/04/04, MGS was overhead for the Opportunity EDL on 01/25/04, 3.5 seconds after the required epoch.

Requirements also existed for the Odyssey over-flight of the MER rovers after landing and various equipment deployments had been completed. Thus, these requirements were that Odyssey should rise no earlier than specified times with respect to each of the landing sites. The Odyssey over-flights of both Spirit and Opportunity on sol 1 were equally successful. This paper will present the navigation plan, trajectory propagation accuracy and maneuver execution for the successful MGS and Odyssey over-flights of both the MER rovers.

Introduction and MER Project Requirements Specification

Both Mars Global Surveyor (MGS) and Mars Odyssey are currently in low altitude, nearly circular and highly inclined orbits about Mars and mapping the planet (Refs 1, 2). Thus, they were and are available, and are UHF frequency compatible with the MER rovers, to serve as relay satellites for the MER rovers during EDL and the rover mission. MGS and Odyssey were injected into Mars orbit on 09/12/97 and 10/24/01 respectively and began their respective mapping mission phase on 03/09/99 and 02/19/02. Presently, MGS is in its second extended mission, having completed its primary mission on 02/01/01, and will begin its third on 09/26/04 for a duration of one Mars year. On 08/24/04, Odyssey will complete its primary mission and begin its first extended mission lasting for one Mars year.

In order to utilize these satellites in a relay configuration during the critical phase of EDL and immediately after the rovers' successful landing, the MER mission developed the following requirements. MGS shall be phased within its orbit such that it is at maximum elevation as viewed from the targeted MER landing site at these times: 01/04/04, 04:24:55 UTC/SCET (MER-A, Gusev) and 01/25/04, 04:54:02 UTC/SCET (MER-B, Meridiani). A tolerance of ±30 sec was established for these times with the landing site target coordinates specified in Table 1. Odyssey shall be phased within its orbit such that the rise time (zero deg elevation) of an Odyssey pass as viewed from the targeted MER landing site on sol 1 after EDL is no earlier than: 01/04/04, 06:34:00 UTC/SCET (MER-A, Gusev), and 01/25/04, 07:03:00 UTC/SCET (MER-B, Meridiani).

The maximum elevation of the Odyssey pass as viewed from the targeted MER landing site shall be at least 30 deg.

In order to satisfy these over-flight requirements, propulsive maneuvers were necessary. For MGS, there was a strong desire to minimize propellant usage since this is a limiting factor for spacecraft lifetime. Thus, an allocation of 4 m/s (equivalent to 1.3 kg of propellant) was established for these maneuvers and only in-plane maneuvers were allowed. Another factor important in developing a navigation strategy was the accuracy of predicted trajectories over an interval of 3 to 6 months. The primary factor influencing this accuracy was the frequency of angular momentum desaturations (AMDs). These are executed autonomously, on-board MGS in order to control the angular momentum of the spacecraft or of the reaction wheels inside the Reaction Wheel Assemblies. They influence the accuracy of predicted trajectories because each desaturation imparts a translational velocity perturbation, approximately 11 to15 mm/s, effectively acting as a very small maneuver. Depending on their frequency and when propagated over a 3 to 6 month interval, they can affect event-timing significantly.

For Odyssey, a different approach was used for desaturation or AMD control. The AMDs are not autonomous but are executed every 23 hours 42 minutes currently. Furthermore, the desaturation threshold is lower and generated a translational velocity perturbation of approximately 4 to 5 mm/s per desaturation during the latter half of 2003. The consistency of these AMDs both in time and velocity-magnitude results in an effective prediction model and accurate, predicted event-times.

Navigation Planning for the MER Over-flights

Early during the MGS mapping phase in which the spacecraft was in a nadir configuration (that is, the spacecraft's +Z axis was pointed at nadir), the ability to accurately predict event-times (for example, the time of descending equator crossing, Tdeqx) was marginal. Errors in the predicted Tdeqx after six months could be as large as 30 to 60 minutes. This was due primarily to the frequent spin-axis AMDs which were occurring autonomously every 6 to 8 hours with an effective velocity-magnitude perturbation of approximately 15 mm/s. When the relay-16 spacecraft configuration (that is, the spacecraft's +Z axis was pointed 16 deg off nadir) was operationally implemented on 08/16/01, the rate of angular momentum change, especially along the spacecraft's Y-axis, was reduced. Thus, spin-axis AMDs, occurred less frequently, approximately every 1.5 to 2.0 days. However, the component of the velocity perturbation along the spacecraft's +X-axis (which nearly coincides with the spacecraft's anti-velocity direction) increased due to the 16 deg offset.

Due to these in-flight results, the MGS MER-A EDL over-flight plan was developed as follows: a) execute OSM-1 at 3 months before the MER-A over-flight date; 6 months before the over-flight was rejected because of the anticipated, large errors in the predicted Tdeqx, b) plan for OSM-2, on 11/07/03 and OSM-3, on 12/19/03, to

systematically refine the over-flight timing as necessary. OSM-2 also served as a contingency maneuver. A similar set of three OSMs for the MER-B EDL over-flight was developed. However, since there were only 21 days between the MER EDLs, the first was set for 01/04/04, 12 hours and 23 min after the MER-A landing, and the remaining two at 7 and 14 days later.

In addition to AMDs, it was observed that a small but persistent atmospheric drag effect was acting on the spacecraft. Thus, as the orbital period was being reduced the arrival time of an equator crossing was occurring earlier as compared to a no-drag case. Consequently, an estimate of a mean atmospheric drag acceleration was modeled in all of our predictions; accelerations ranged from 1 to 8 $x10^{-12}$ km/s*s from September 2002 to August 2004.

For Odyssey, initially AMDs were used to provide a small correction for the over-flight timing since these are effectively very small maneuvers. Fortunately, the nominal trajectory generated in October 2003 was satisfying the MER-A sol 1 over-flight requirement without resorting to an orbit trim maneuver (OTM). We projected that the Odyssey rise time over the Gusev site would be 01/04/04, 06:36:04 UTC/SCET which is 2 minutes and 4 seconds after the required time. Furthermore, the maximum elevation angle for this over-flight would be 40.1 deg. Unfortunately, Odyssey entered a configuration called "safe mode" on 10/29/03, for a duration of 8.5 days, which was caused by unusually large solar activity. In this mode, significant thrusting occurs in order to maintain a stable spacecraft attitude and to maintain a communication capability with the earth. For navigation, "safe mode" thrusting caused translational velocity perturbations effectively acting as a small OTM. The net result of the "safe-mode" event was that Odyssey no longer satisfied the MER-A sol 1 over-flight requirement. Now the Odyssey rise time over Gusev was projected to be 01/04/04, 06:09:09 UTC/SCET or 24 minutes and 51 seconds too early. Consequently, OTM-2 was planned for and executed on 11/22/03 in order to bring the over-flight time back in compliance with the MER-A requirement.

Trajectory Propagation and Maneuver Design and Execution

Trajectory Perturbations Due To Angular Momentum Desaturations

For both spacecraft, the key to an accurate trajectory propagation is to either accurately account for all AMDs or minimize their frequency. For MGS, there are two types of AMDs; yaw-axis and spin-axis desaturations. An on-board algorithm monitors the spacecraft's angular momentum in three axes. The x and z components of angular momentum (Lx, Lz) exhibit a sinusoidal trend with increasing amplitude and a period equal to the orbital period. Desaturation occurs automatically whenever Lz reaches a value of either +6 Nms or –6 Nms. These desaturations, called yaw-axis desaturations, occur every 12 to 20 hours depending on the spacecraft's configuration. They are not a problem for navigation because the thrusters used in the desaturation process cause no discernable translational delta-velocity or trajectory perturbation. The other type of desaturation, called a spin-axis desaturation, occurs automatically when the y-component

of angular momentum, Ly, reaches a threshold value of +10 Nms or –10 Nms. It's variation with time is also sinusoidal with increasing amplitude but, in addition, exhibits a strong systematic component. The latter trend is dominant having a mean value of approximately +30 Nms/day during the nadir orientation of the primary mapping mission. During the desaturation process, a net translational delta-velocity of 12 to 15 mm/s has been observed acting along the +Z-axis of the spacecraft. Although the relay-16 mode reduced the desaturation frequency, there was now a large perturbative delta-velocity (e.g. 15 sin(16)= 4.1 mm/s) acting opposite to the spacecraft's velocity and effectively acting as an atmospheric drag perturbation. Hereafter, the designation AMD shall refer to a spin-axis desaturation.

Prior to the MER requirements, MGS was having success in minimizing the frequency of AMDs by managing the spacecraft's angular momentum. This operational concept was developed after 08/16/01 when MGS went from a nadir orientation, the +Z-axis is pointed along the nadir direction, to a relay-16 orientation, the +Z-axis is offset by 16 deg from nadir while still in the orbit plane. This new operational mode was adopted because AMDs were occurring less frequently, from every 6 to 8 hours to approximately every 1.5 to 2.0 days, thus reducing propellant usage and extending spacecraft lifetime. However, a further refinement was introduced which reduced the AMD frequency even more. During flight operations, when MGS was in the nadir orientation, the y-component of angular momentum, Ly, exhibited a systematic positive trend at a mean rate of about +30 Nms/day. However, when in the relay-16 orientation, the mean Ly rate was approximately –4.4 Nms /day. Thus, in principle over an interval of one day, the mean Ly would be near zero if the nadir configuration were maintained for 3 hours while the relay-16 configuration was maintained for 21 hours. As the plan developed, in order not to interfere with science data acquisition, the nadir configuration called nadir dwells (ND) was only allowed during geocentric occultations. After an initial trial period, angular momentum management (AMM) achieved an interval of 94 days, from 08/29/02 to 12/02/02, in which no AMD occurred using a ND strategy of 180 min/day. By implementing AMM, there were two immediate results: a) the accuracy of the predicted trajectory improved significantly and b) the hydrazine usage was reduced. The former was especially important for high resolution, targeted imaging for which accurate short-term predicted ephemerides is essential. Representative results for the accuracy of Tdeqx over a 90 day prediction interval for six trajectories in 2003 are shown in Fig. 1. As indicated, three cases have Tdeqx errors beyond 60 s after 90 days of trajectory propagation.

Atmospheric Drag Acceleration Estimate

The accuracy of an MGS prediction analysis is very dependent on the quality of the predicted forces acting on the spacecraft. The two most important models that are difficult to predict are due to the atmospheric drag and velocity perturbations caused by angular momentum desaturations. We will concentrate on estimating the acceleration due to the atmospheric drag. Note that current, average, orbital altitudes at periapsis and apoapsis are 373 and 436.5 km respectively. A prediction analysis is composed of two

parts: analyzing the Doppler tracking data to determine the orbit and generating the appropriate force models to apply to the predicted portion of a typical 20 day trajectory (Ref 3). The Doppler data are fit with no atmospheric density model. This is done for three reasons: a) the atmospheric drag is small, and does not perturb the trajectory greatly over the short time interval of the orbit determination, b) an atmospheric density is difficult to estimate over the short data analysis interval, usually 3 to 4 orbits. The filter has little capability to determine the density as noted by the estimated density uncertainty which is almost the same as the apriori uncertainty and c) estimating for a density makes it much more difficult to generate a predict force model.

In our approach, the predicted atmospheric model is simply a constant acceleration. Since the trajectory is most sensitive to a perturbation in the down-track direction, only one component of the acceleration is determined. This component is perpendicular to the nadir direction, approximately along the spacecraft's minus velocity direction. To determine this constant acceleration value, the quality of the previously delivered predicted trajectory is examined. This assessment is made by analyzing the Doppler data residuals generated from the most recent, previous trajectory. If the residuals are small then we conclude that the previous atmospheric acceleration model was correct and still applies to the present analysis. If the residuals are large then the atmospheric acceleration becomes a parameter in the previous trajectory and several new trajectories are generated. Now one can determine the acceleration model which minimizes the Doppler residuals thus using that model for the current predict trajectory. This direct and quick procedure is quite advantageous in the flight operations environment and gives as good results as much more complicated procedures. In summary, we use the best acceleration results of the recent past to guide the present analysis for its short-term prediction. Note that the acceleration model used in the predicted trajectory can be an aggregate of other mismodeled forces. However, we have concluded that the atmospheric drag is the major portion of such mismodeling. A summary of the accelerations due to atmospheric drag applied to our predicted trajectories is given in Fig. 2.

Trajectory Propagation and Synchronization Maneuver Design

Based on analysis of Doppler data on 09/29/03, two predicted trajectories were generated which ended on 02/01/04 after the MER EDLs. The first did not include any OSM maneuvers and was used to determine where MGS would be at the MER-A EDL target time, 01/04/04, 04:24:55 UTC/SCET. MGS was almost exactly on the opposite side of Mars with respect to the MER-A target location. This trajectory was used to design OSM-1 in order for the over-flight to occur per the MER-A EDL requirements. The purpose of OSM-1 was to change the orbital period such that MGS will be over the target site (East longitude=175.061 deg, latitude=-14.59 deg) instead of at its presently expected location (East longitude=343.3 deg, latitude=6.8 deg). It is critically important that the propagated trajectory be accurate since the maneuver design is based on where MGS is predicted to be on 01/04/04. If the trajectory propagation is not accurate then the

maneuver design, even if perfect, will not deliver the spacecraft to the MER-A EDL location. Thus, the need for OSM-2 and OSM-3 to continually refine that targeting.

The second predicted trajectory included the designed OSM-1 to be executed on 10/03/03. If the executed or actual maneuver were to have substantial errors then the expected over-flight location would not be as expected. In this case, OSM-2 and OSM-3 would be required to correct these errors. Actually, the executed maneuver was extremely close to the designed maneuver and well within the maneuver execution errors. Over the next three months, we monitored this trajectory by comparing the predicted Tdeqx with the actual Tdeqx. The actual Tdeqx were determined weekly from Doppler data analysis and are accurate to about 0.005 seconds. The predicted trajectory included these important model parameters: a) a 65 th degree and order Mars gravity field, b) a velocity perturbation due to anticipated AMDs, c) a mean acceleration to account for an atmospheric drag perturbation, d) the designed OSM-1, e) a solar radiation pressure model as well as other models and f) a preliminary OSM-4 for the MER-B EDL over-flight. More specifically, we included a three part constant acceleration model acting along the anti-velocity direction as given in Table 2. The AMDs were not modeled directly as a velocity perturbation because their epochs were very uncertain. Thus, an acceleration acting over n days was preferred which integrated to the velocity which was determined from analysis of previous AMDs.

Fig 3 summarizes the accuracy of these models and the 09/29/03 trajectory propagation as measured by the small errors in the Tdeqx especially on 01/04/04. The conclusion is that the integrated effect of these models was accurate thus making OSM-2 and OSM-3 unnecessary. However, a close examination of this figure reveals the following: a) three AMDs actually occurred on 10/08/03, 04:43, 10/12/03, 04:39 and 10/15/03, 19:40 UTC/SCET and none thereafter. The estimated velocity-magnitude perturbation was 17.7, 17.7, and 12.3 mm/s respectively as determined by Doppler data analysis as compared to the model value of 12.0 mm/s. The model epochs for the AMDs were reasonably close to the actual times. Therefore, the predicted model did not fully account for the real effect and the Tdeqx error curve increased as shown. Around mid-November, the Tdeqx error curve flattens and the develops a negative trend. There are two reasons for this. First, the prediction model assumes two AMDs would occur once per month from 10/23/04 to the MER-A EDL; in fact none occurred. Second, the model atmospheric drag acceleration was larger than was observed. Thus the models over-estimated the true effects and the Tdeqx error trend decreased as shown. However, at the MER-A over-flight epoch, the Tdeqx error is only 9 seconds.

Fig 4 shows the MGS ground track on 01/04/04 before and after the execution of OSM-1 and how it corrected the over-flight time by 62.3 minutes or almost 170 deg in longitude. Note that the initial orbit goes right over the Gusev site but at the required over-flight time MGS is on the other side of Mars. Note also that with a timing correction of 62.3 minutes, Mars rotation caused the ground track to shift to the West by 14.4 deg resulting in a smaller, maximum elevation angle. Even without an OSM-4 maneuver on 01/04/04 and after a trajectory propagation of 20 days, MGS was near the Opportunity-Meridiani over-flight location. Thus, OSM-4 needed to correct the over-flight time by

only 5.4 minutes. Fig 5 shows the MGS ground track on 01/25/04 before the execution of OSM-4.

Odyssey Trajectory Propagation and Maneuver Design

MGS and Odyssey: MER Relay Results

Both MGS and Odyssey satisfied the MER requirements and were over Spirit and Opportunity during the critical EDL phase and immediately after the rovers had landed. Critical MER telemetry data were transmitted, at UHF frequency, to both spacecraft and then relayed to Earth at an X-band frequency. A summary of the navigation performance during the MER EDLs and sol 1 is given in Tables 3 and 4. Even though Odyssey's elevation angle was slightly less than 30 deg on this first over-flight, all telemetry data were received as expected. With the rovers safely on the ground, a sample of the MGS over-flights for the first 7 days of the surface mission is given in Table 5. The over-flight durations are relatively short due to the low altitude, nearly circular MGS orbit. This situation is similar for Odyssey. With these multiple over-flight opportunities, a significant quantity of MER telemetry was transmitted to earth by way of these relay satellites.

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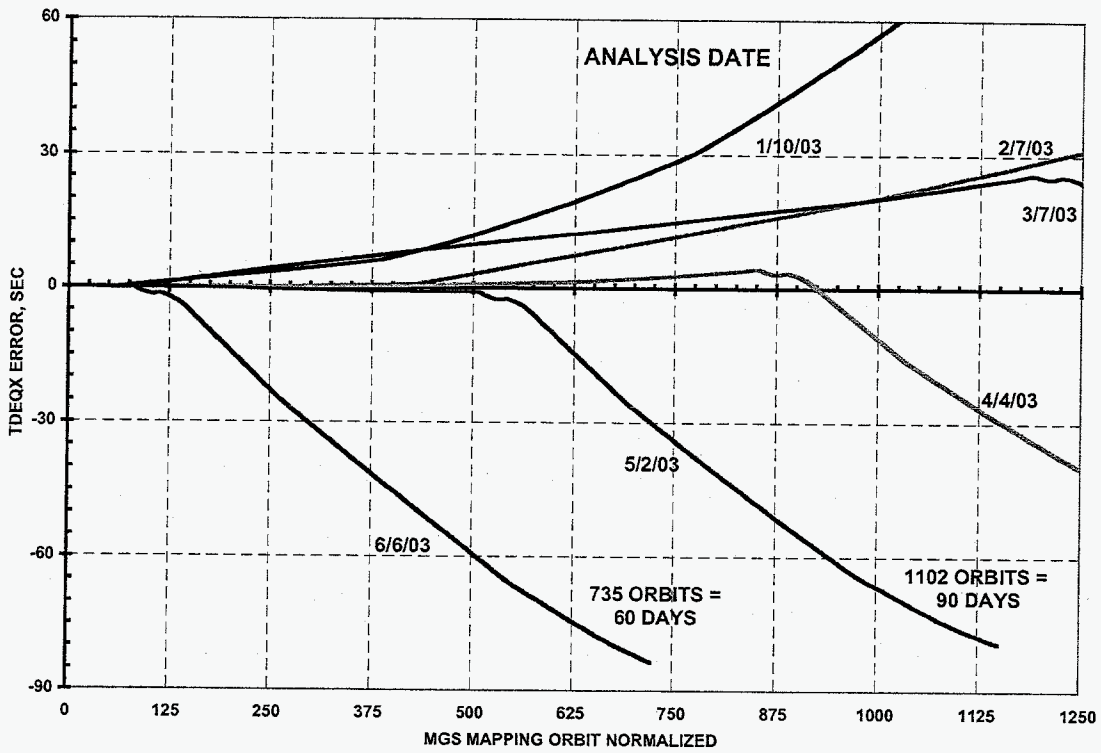

Fig 1 Error in the Tdeqx (predicted minus reconstructed Tdeqx) over a 90 day interval for six trajectories; the generation dates are in 2003 as shown.

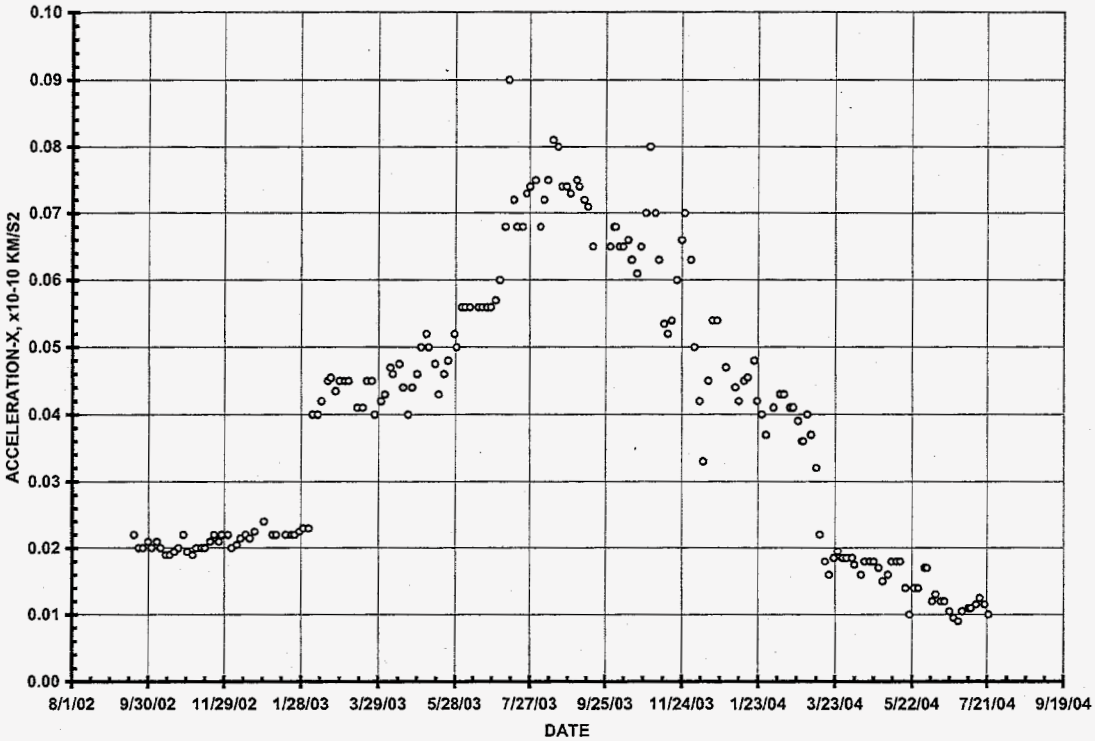

Fig 2 MGS acceleration model, x-component, used to account for an atmospheric drag perturbation.

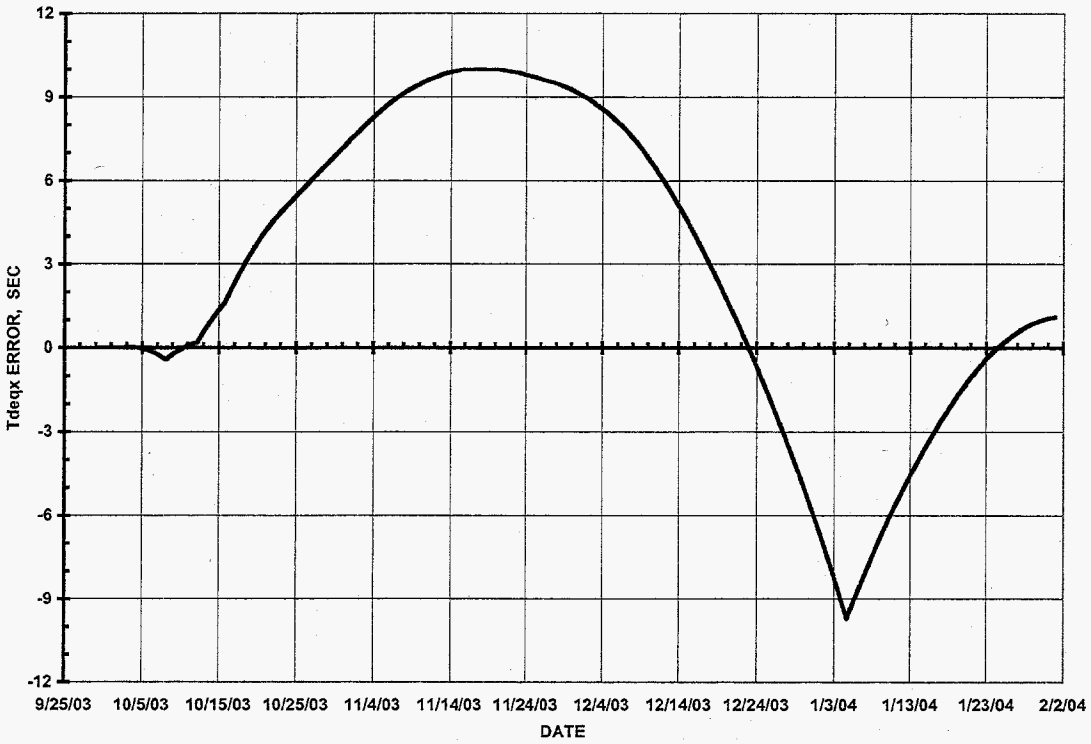

Fig 3 Error in the Tdeqx (prediction minus reconstruction Tdeqx) for the MGS trajectory generated on 09/29/03 and used to design OSM-1.

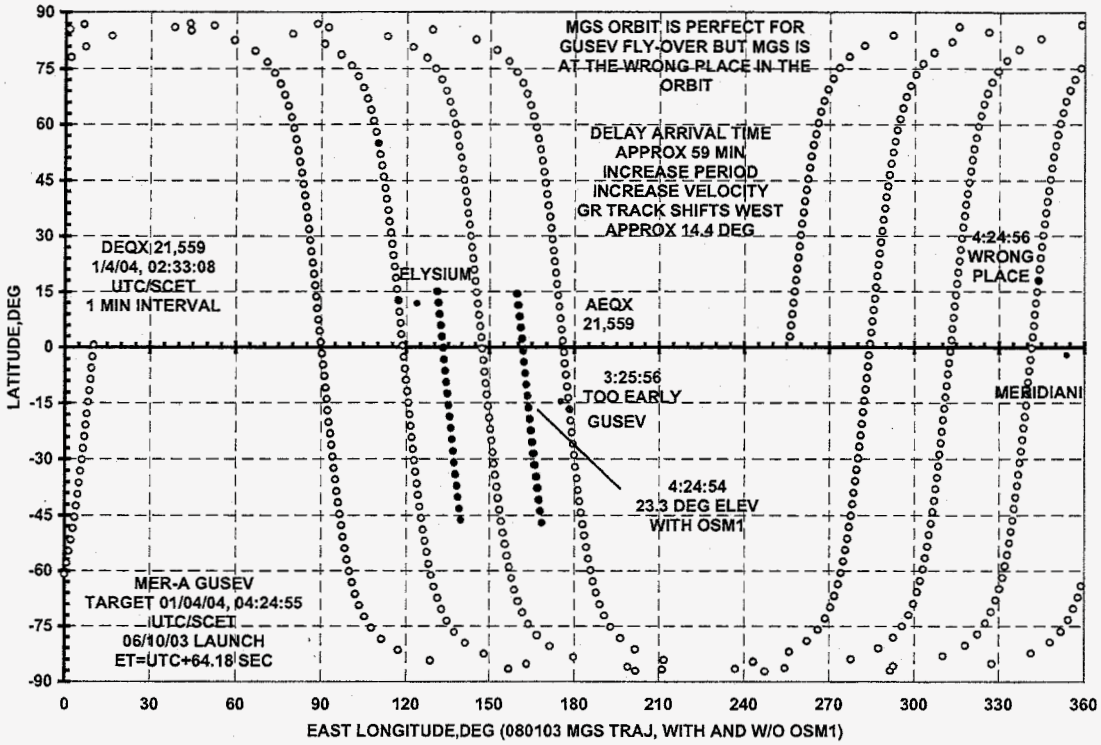

Fig 4 MGS ground tracks used for planning the OSM-1 maneuver.

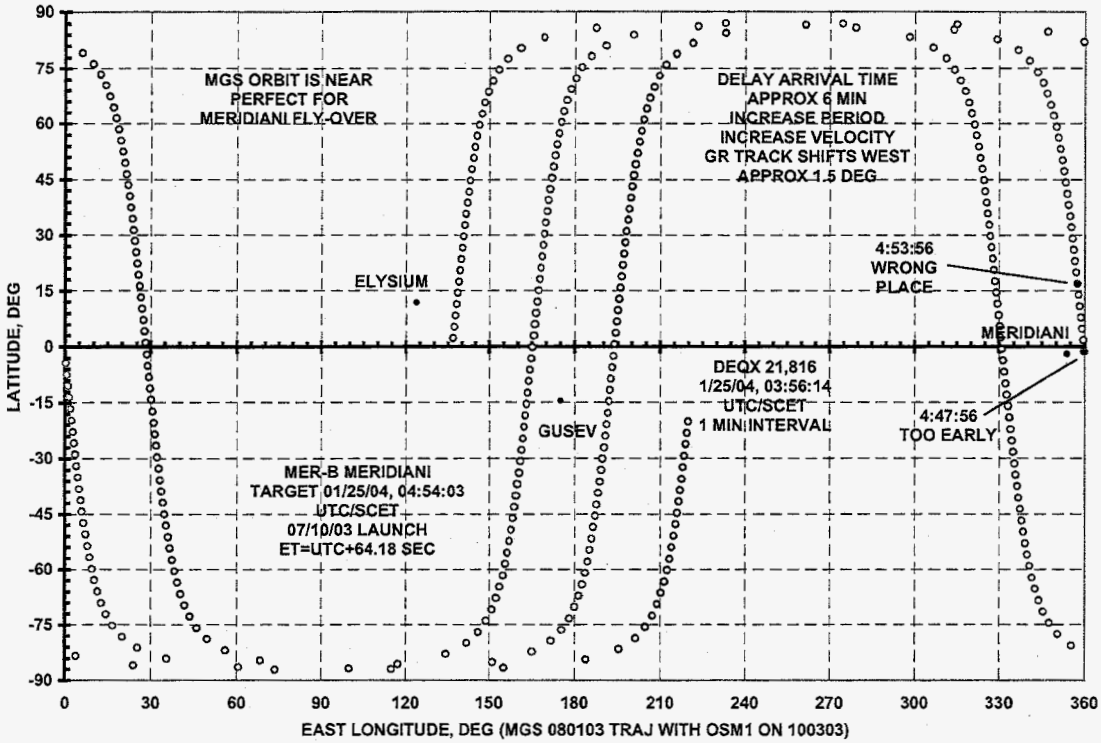

Fig 5 MGS ground tracks used for planning the OSM-4 maneuver.

Table 1 Landing Site Target Coordinates (IAU 1991)

Location	Gusev Crater	Meridiani Planum
Areocentric Latitude, deg	-14.59	-1.98
East Longitude, deg	175.061	353.821
Ground Radius, km	3392.33	3394.09

Table 2 Atmospheric Drag and AMD Models

Acceleration, $x10^{-12}$ km/s2	From-To	Purpose
6.5	09/29/03 – 10/04/03	Atmospheric drag estimate
12.0	10/04/03 – 10/23/03	Atmospheric drag estimate and AMD every 7 days
7.8	10/23/03 – 02/01/04	Atmospheric drag estimate and AMD every 28 days

Table 3 Summary of MGS EDL Over-flights

Quantity	Spirit EDL	Opportunity EDL
OSM epoch, UTC/SCET	10/03/03	01/04/04
Days/Orbits from OSM to over-flight	92.4/1130	20.5/251
Delta-velocity, m/s	0.534	0.211
Delta-period, s	3.34	1.31
Time phasing required for over-flight, min:s	62:19	05:24
Over-flight epoch difference (achieved-required), s	+8. (± 30. s tolerance)	+3.5 (± 30. s tolerance)
Maximum elevation, deg	23.2	51.7

Table 4 Summary of Odyssey OTM and Sol 1 Over-Flights

Quantity	Spirit, Gusev	Opportunity, Meridiani
OTM Epoch	11/22/03	--
Days/Orbits from OTM to over-flight	42.6/517	--
Delta-velocity, m/s	0.543	--
Delta-period, s	3.25	--
Rise Time Reqt, UTC/ SCET (no earlier than)	01/04/04 06:34:00	01/25/04 07:03:00
Actual Rise Time, UTC/SCET	01/04/04 06:39:22	01/25/04 08:27:41
After Reqt time	00:05:22	01:24:41
Maximum elevation angle, deg	36.8	28.1