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A STRATEGY TO ROTATE THE MARS OBSERVER ORBIT NODE LINE TO ADVANCE THE MAPPING SCHEDULE

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The Mars Observer (MO) spacecraft was successfully launched on September 25, 1992 and will arrive at Mars on August 24, 1993. At Mars, the spacecraft will study the planet's surface, atmosphere, and gravitational and magnetic fields. In order to achieve these scientific objectives, MO will be placed in a 2 PM (descending node) sun-synchronous orbit. Upon arrival at Mars, however, the longitude of the descending node will be approximately 15° greater than the desired value. The baseline plan requires a 59 day "waiting" period for the correct solar orientation to occur. During this period, 28 days are required for scientific experimentation but the remaining 30.6 days potentially could be eliminated. The strategy developed in this study examined the possibility of using any "excess" ΔV available at Mars arrival to rotate the node line to the desired value and thus allow mapping to begin earlier. A preliminary analysis completed prior to launch is described that examined the entire launch period including the required ΔV to perform the needed nodal rotation. A more detailed study performed after launch is also summarized.

INTRODUCTION

The Mars Observer (MO) spacecraft was successfully launched on September 25, 1992 aboard a Titan III/TOS launch vehicle and will arrive at Mars on August 24, 1993. At Mars, the spacecraft will study the planet's surface, atmosphere, and gravitational and magnetic fields.[1] In order to achieve these scientific objectives, MO will be placed in a near-circular 2 PM (descending node) sun-synchronous orbit. However, upon arrival at Mars, the node line of the initial orbit about Mars will be approximately 15° east of the desired position. The baseline plan requires a 59 day "waiting" period for the correct solar orientation to occur while the spacecraft "drifts" in

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an elliptical orbit that is nearly fixed with respect to inertial space. During this period 28 days are required for scientific experimentation but the remaining 30.6 days potentially could be eliminated. The strategy developed in this study, referred to as "power-in", examined the possibility of using any "excess" ΔV capability available at Mars arrival to rotate the node line to the desired value and thus allow mapping to begin earlier. An earlier start to mapping before the dust season begins not only increases the science return from the mission but also provides more time to ensure successful spacecraft deployment into the mapping configuration before solar conjunction. The main goal of this study was to develop a preliminary node-shift strategy consistent with the baseline orbit insertion design and to identify the ΔV requirements to perform the node line rotation. A preliminary analysis completed prior to launch is described that examined the entire launch period and provides the required ΔV to perform the needed nodal rotation for each possible arrival date at Mars. A more detailed study performed after launch is also summarized that addresses the operational considerations of implementing the power-in option corresponding to the actual launch date.

BASELINE ORBIT INSERTION DESIGN

The baseline orbit insertion strategy involves a series of seven maneuvers executed over a period of approximately three and a half months to maneuver the spacecraft from its initial capture orbit with a dayside, descending node near 5 PM local mean solar time to the desired 2 PM mapping orbit solar orientation. Fig. 1 illustrates the difference in solar geometry between the approach hyperbola and the desired mapping orbit orientation. One of the primary guidelines in the design of the baseline orbit insertion strategy was to minimize the propulsive requirements on the spacecraft. Since rapid transition to the 2 PM orientation could not be achieved without incorporating a substantial out-of-plane component, all of the baseline orbit insertion maneuvers were designed as in-plane maneuvers. With this strategy, transition to the desired solar orientation would be achieved by employing a "waiting" period in which the Sun would appear to move eastward with respect to the nearly inertially fixed orbit node line due to the orbital motion of Mars about the Sun.

The baseline orbit insertion design would, if used, result in the deployment of MO in the mapping orbit in early to mid-December, depending on the actual launch date.[2] (For the actual launch date of September 25, 1992, mapping would begin on December 12, 1993.) Fig. 2 displays a timeline for the sequence of seven orbit insertion maneuvers and Fig. 3 shows a sketch of the insertion sequence. In Fig. 2, the abscissa represents the dates at which maneuvers or other events occur, while the ordinate lists the range of possible launch dates for MO. The dashed horizontal line corresponds to the actual launch date.

As shown in Fig. 3, the first orbit insertion maneuver, labeled Mars Orbit Insertion (MOI), brakes the spacecraft from its hyperbolic approach into a capture ellipse. This ellipse has a period of 72.0 hours, radius of periapsis of 3950 km (553 km altitude), and a radius of apoapsis of 79,594 km. The magnitude of MOI ranges from approximately 700 m/s to around 800 m/s, depending on the launch date.

The second orbit insertion maneuver, Ellipse Change Maneuver-1 (ECM-1), is performed 10.5 days after MOI and is a small maneuver (approximately three m/s) used to lower periapsis altitude to 453 km. ECM-1 is performed at apoapsis.

The third orbit insertion maneuver, Ellipse Change Maneuver-2 (ECM-2), is performed near periapsis 10.5 days after ECM-1 and lowers apoapsis radius to 36,314 km. The magnitude of this maneuver is approximately 12.7 m/s. The resulting orbit has a period of one day and is nearly fixed with respect to inertial space due to its relatively large size (i.e., the perturbation forces from the gravitational harmonics of Mars are relatively small). This orbit is termed the one-day "drift" orbit. This time spent in this orbit is 59.0 days for the actual launch date of MO.

The fourth maneuver, ECM-3, is performed 14 days prior to the fifth maneuver, Transfer to Low Orbit-1 (TLO-1). ECM-3 is used to correct any errors in the orbital elements, particularly periapsis and inclination. TLO-1 is performed (at periapsis) when the orbit is close to a 2:16 PM descending node orientation and reduces the orbit period to 4.2 hours. This maneuver was designed to remove approximately half of the energy required to reach the mapping orbit and has a magnitude of 560 m/s. Removing the energy in two TLO maneuvers instead of one reduces the gravity losses.

the node. orientation reaches 2:00 P.M. slid lowers the spacecraft into the mapping orbit. The magnitude of this maneuver is approximately 626 m/s. Seven (lays after TLO-2 the filial maneuver, Orbit Change Maneuver-1 (OCM-1), is used to correct any errors in the orbital elements of the mapping orbit.

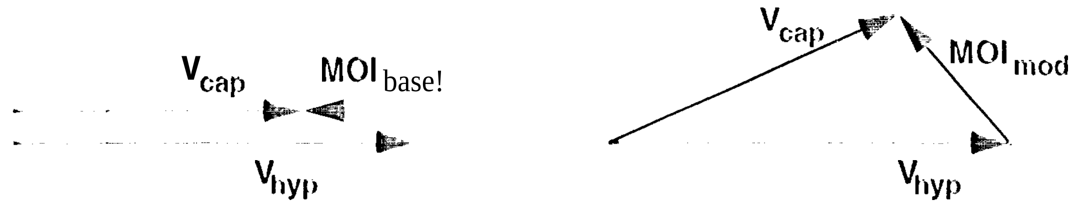
PRE-LAUNCH ANALYSIS OF POWER-IN

Before launch, a study was completed to determine how much propellant would be needed to rotate the line of nodes to advance the beginning of the mapping phase. This "power-in" idea was analyzed using conic orbits and impulsive maneuvers (although it is expected that future refined calculations will produce results close to those computed in this study). Since, of course, the actual launch date. was not known prior to launch, the study included examination of Av costs that would be required to perform power-in given any of the possible launch date.s (September 16 through October 13, 1992).

Prior to launch, MOI and ECM-1 were identified as maneuvers [hat could be modified to incorporate the power-in idea. No maneuvers could be added to the insertion sequence, although the location of ECM-1 could be varied. Recall that in the baseline orbit insertion squc.rice., MOI and ECM-1 would be performed as in-plane maneuvers. In order to rotate the node line, some amount of out-of-plane maneuver component must be added to MOI or ECM-1 (or both). However, adding these components would also affect the inclination of the orbit following both MOI and ECM-1. In order to achieve the. correct mapping orbit, the inclination following ECM-1 must have a specific value between 92.6° and 92.9°, depending on the time. spent in the drift orbit. For this preliminary analysis an average value of 9?,"/5" was used, To attain this value after ECM-1 the incoming hyperbolic inclination must be adjusted, or "biased", from the. dc.sired inclination (although an exception is noted later). A description of the algorithm used to talc.ulatc. the. incoming hyperbolic inclination follows.

Basic Algorithm

Three basic inputs to the algorithm are used: the excess amount of A V available to apply to power-in, the Av "split", and the location (true anomaly) of ECM-1. The AV split, f_{split}, is defined such that a value of 0.0 corresponds to all excess A V being applied at ECM-1 while a value of 1.0 results in all excess expended at MOI. Thus a split of 0.5 would divide the. extra A V equally between MOI and ECM-1. Given a launch date, the corresponding arrival V_{∞}, declination, and right ascension at Mars are readily computed. Choosing the inclination of this approach hyperbola then determines the longitude of the ascending node and the argument of periapsis. Now the. magnitude and dire.ction of the MOI maneuver is computed to produce the required capture orbit. In addition, however, an out-of-orbit-plane component is included in the MOI maneuver to



Baseline

-Power-in

Fig. 4 Addition of Out-of-Plane Component to MOI

rotate the orbit, affecting both the node line and the inclination. The magnitude of the modified MOI maneuver is specified as

$$MOI_{mod} = MOI_{base} + (\Delta V_{excess})(f_{split}), \tag{1}$$

where MOI_{mod} is the modified MOI maneuver, MOI_{base} is the baseline MOI maneuver computed without power-in, ΔV_{excess} is the excess ΔV available for use with power-in, and f_{split} is the ΔV split defined previously. Fig. 4 illustrates the vector relationships that define the baseline and the modified MOI maneuvers. In the figure, V_{hyp} represents the velocity of MO at periapsis on the approach hyperbola and V_{cap} is the velocity of MO on the capture ellipse at periapsis after MOI is performed. Note the modified MOI maneuver is computed such that the magnitude of V_{cap} is unchanged from the baseline design.

With the calculation of the modified MOI maneuver complete, the orbital elements of the resulting capture orbit are easily found. Then, the magnitude of the modified ECM-1 maneuver is computed as

$$ECM\text{-}1_{mod} = ECM\text{-}1_{base} + \Delta V_{excess}(1.0 - f_{split}), \tag{2}$$

where $ECM\text{-}1_{mod}$ is the modified ECM-1 maneuver and $ECM\text{-}1_{base}$ is the baseline ECM-1 maneuver computed without power-in. As with the modified MOI maneuver, the remainder of the excess ΔV is expended to further rotate the node line. An out-of-plane component is added such that the modified ECM-1 maneuver rotates the node line as well as lowering periapsis as required.

The orbital elements following execution of the modified ECM-1 maneuver are now easily found. The semi-major axis and eccentricity were constrained to match the post-ECM-1 baseline values so that the calculation of the modified ECM-1 would preserve the periapsis altitude following ECM-1. The inclination, however, was not specifically targeted. In general, the inclination following ECM-1 will differ from the inclination before MOI. This requires the inclination of the hyperbolic approach to be adjusted or "biased". The determination of the hyperbolic inclination is accomplished by use of an iterative process. A simple Newton method iterates on the value of a first "guess" of the hyperbolic inclination until the correct post-ECM-1 inclination is obtained. Once the iteration is complete, the post-ECM-1 inclination will equal the desired value of 92.75° and the resulting longitude of the ascending node following ECM-1 can be evaluated to determine the nodal rotation achieved.

Results of Pre-Launch Analysis

As outlined in the previous section, given an excess ΔV amount, a ΔV split, and a true anomaly for ECM-1, the resulting nodal rotation can be found. To make the numerical output more easily understood, the amount of nodal rotation was converted to an equivalent "reduction in drift time". (Recall that following ECM-2, MO "drifts" in a one-day orbit until the correct node orientation is reached.) This reduction in drift time represents the potential advance in the mapping schedule provided by power-in. The reduction in drift time is (approximately) the change in the ascending node divided by the average angular rate of Mars' motion about the Sun (0.524° per day). Also, in order to produce results that can be meaningfully evaluated, some operational constraints for the MO mission were first considered. First, the true anomaly of ECM-1 was constrained to lie between 60° and 240° in order to keep the in-plane component of ECM-1 small and to allow for effective nodal rotation. Another constraint involves the magnetometer aboard the spacecraft for which experimenters require that MO remain in the one-day drift orbit for at least 28 days. The results presented here for the pre-launch study were calculated to leave exactly 28 days in the one-day orbit.

Using the algorithm presented in the previous section, each date of the launch period was examined to determine the ΔV requirements for implementing the power-in strategy. For a particular launch date and excess ΔV amount, reductions in drift days (i.e., the node rotation) were calculated for a range of ECM-1 true anomalies and ΔV splits. These results are readily interpreted if displayed on a contour plot. Fig. 5 shows an example of such a contour plot for the actual launch date of September 25, 1992. The abscissa of the figure shows the ΔV split and the ordinate represents the true anomaly of ECM-1. Each contour shows the reduction in number of drift days. Note that the location on the plot that corresponds to the maximum drift day reduction is obvious. In this case, a true anomaly of 175° and a ΔV split of 0.03 results in the maximum drift day reduction. Thus at the optimal condition 97 percent of the excess ΔV is applied at ECM-1 and only 3 percent at MOI. It is interesting to note that for all possible launch dates the optimal conditions are very similar, with the ΔV split varying between 0.0 and 0.09 and the ECM-1 location varying between 175° and 177°.

Given a launch date (and thus an arrival date), the number of desired drift days is known. The algorithm can be iteratively run until the maximum reduction of drift days matches the desired number. In this manner, the required minimum ΔV can be identified. Fig. 5 was computed in this manner, and it was found that a ΔV excess of 71.0 m/s is required to achieve the desired node rotation.

Fig. 6 is shown in a format identical to Fig. 5 but instead displays contours of the required (biased) hyperbolic inclination. Recall that the baseline (non-biased) hyperbolic inclination used in the analysis was 92.75°. At the optimal point on the plot the required biased inclination when implementing power-in is 86.10°. Since Fig. 6 indicates that a contour corresponding to 92.75° exists, then performing power-in at some point along this contour would require no biasing of the hyperbolic approach. Of course, this would not correspond to the optimal location and would require additional ΔV to eliminate all of the desired drift days. The next section addresses this issue in more detail.

Both Figs. 5 and 6 have regions where no contours are plotted. These regions occur near higher values of the ΔV split and near larger or smaller values of ECM-1 true anomaly. In these regions, the required magnitude of ECM-1 to just lower periapsis (and not perform any node rotation) becomes larger than the ΔV allotted to ECM-1 by the input value of the ΔV split. Thus these regions are "excluded" areas for the power-in strategy.

As an example, the power-in sequence corresponding to the location on Fig. 5 of the maximum node line rotation is summarized. Table 1 shows the orbital elements of the spacecraft's orbit prior to and after the MOI and ECM-1 maneuvers. In this example, MOI magnitude is 718.37 m/s and ECM-1 magnitude is 71.57 m/s, compared to baseline values of 716.24 m/s and 2.7 m/s.

Table 1

POWER-IN SUMMARY FOR 9/25/1992 LAUNCH DATE

Orbital Element*	Pre-MOI	Post-MOI	Pre-ECM-1	-Post-ECM-1
Semi-Major Axis (ire)	-7139.7	4 17??s)	4 17m.o	41721.5
Eccentricity	1,5533	0.9054	0.9054	0.9077
Inclination (deg)	86.07	86.36	86.36	92.75
Argument of periapsis (deg)	115.91	115,95	115,95	116.01
Longitude of ascending node (deg)	-105.89	-106.48	-106.48	-113.0
True anomaly (deg)	0.0	0.0	175.0	175.07

"Mars Centered, Mars mean equator and equator crossing vector of J2000 (IAU)

Fig. "/ shows the Av required to perform power- in as a function of launch day number, assuming that the optimal condition is used. A second, dashed line is included that shows the expected AV excess available that was calculated prior to launch within a 99 percent certainty. The figure indicates that, by pre-launch estimates, sufficient excess Av would be available to perform power-in for any launch date except for the last few days of the launch period. (The benefits of power-in are not as great toward the end of the launch period since the time sprint in the drift orbit approaches the 28 day minimum constraint. Thus power-in might not have been considered in these cases even if enough excess ΔV existed.)

POST-LAUNCH ANALYSIS OF POWER-IN

With the successful launch of MO on September 25, 1992, attention returned to the question of power-in for the specific arrival conditions at Mars corresponding to the actual launch date. After the first of four interplanetary Trajectory Correction Maneuvers (TCMs) was performed, it was estimated that significant spacecraft ΔV capability (approximately 134 m/s) would be available over and above the baseline mission ΔV requirements. Since the pm-launch analysis had shown that this amount would suffice for power-in, a working group was formed to determine a particular power-in strategy. The scope of the working group's task expanded from purely a ΔV performance perspective to include a reconsideration of the entire orbit insertion phase from an operational point of view as well.

The pre-launch analysis had shown that in all cases the optimal method for performing orbit rotation was to apply nearly all of the excess ΔV available for power-in at ECM-1. This approach corresponds to a ΔV split value near 0.0. It was also found that a slightly modified approach in which all of the available ΔV is applied at ECM-1

(AV split = 0.0) costs only 1 to 2 m/s more than the optimum. Thus to simplify both the analysis and operations for power-in, a decision was made to plan to do all the orbit rotation at ECM-1 and to continue to plan MOI as an "in-plane" maneuver. This decision enabled new ways (o look at the. problem. instead of plotting days reduced in the drift orbit or incoming inclination as a function of true anomaly of ECM-1 and percentage of maneuver done at ECM-1 (for some fixed excess A V cost, solving for incoming inclination), one could now plot the number of days reduced in the drift orbit (relative to the baseline orbit insertion strategy) as a function of total A V cost and incoming inclination (solving for true anomaly of ECM-1). Such a plot is shown in Fig. 8.

Again for operational masons, a constraint was emphasized that a minimum of ten days was required between maneuvers. This led 10 a change in the way that the drift reduction was accounted for, so that "the. number of days in the drift orbit" became "the number of days between MOI and "I'1 01". This change occurred because it became apparent that the. 1Kh4-1 and ECM-2 dates could vary when the true anomaly of ECM-1 changed. If the true anomaly of ECM-1 islet;'cl]o~lp,l),tl]c,l~ four-and-a-fraction orbits is required between MOI and ECM-1 instead of three-and- a-fraction orbits to meet the ten day constraint. Thus the executio n of both ECM-1 and ECM-2 would be delayed relative to the baseline, by one orbit period in the.msc.of ECM-2, which would reduce the time in the drift orbit without making mapping start any earlier.

After consideration of the tradeoffs between the science objectives (to start mapping earlier yet also to do certain measurements in the one-day drift orbit) and the operational concerns (to allow enough time between maneuvers yet also to inc.mast. the time between spacecraft deployment and solar conjunction), a final modified orbit-insertion sequence was developed. The time spent in the one-clay drift orbit after a nominal ECM-2 date was set at 33 days (it had been ?.8 in the pre-launch analysis), or more precisely TLO-1 was set to be 54 days after M 01. 'Jim ECM-3 mane.uvcx was set 10 be 10 days before TLO-1 instead of 14 days, the time between '1'1 ,O-1 and '1'1 ,0-2. was increased from 10 to 11 days, and the time between TL.0-2 and OCM- 1 was increased from "/ to 1 1 days. On this schedule (shown in Fig. 9), mapping begins on November 2.2, 1993, instead of December 12, 1993, for the baseline (no power-in) orbit insertion sequence, corresponding to a 26 day reduction in the time from MOI to TLO- 1.

Two candidate designs for power-in were identified (they are labeled CASE A and CASE B on Fig. 8) which meet all the conditions discussed above. Case A implements power-in without biasing the hyperbolic inclination. As mentioned earlier, this approach would require more A V, but does not require any change to the interplanetary trajectory design. One advantage. to this is that the decision to do power-in can be deferred until MOI has occurred and its performance is known. The Case A design requires that ECM-1 be performed at a true anomaly of about 1 S6", where 96 m/s is required to eliminate 26 days in the one-day drift orbit as desired. Case B, which is nearly optimal from a Av point of view, is done. at a true anomaly of 17flC) at a cost of 59 m/s. This design, however, does require modification of TCM-3 to achieve the biased inclination at Mars arrival. At this date, the Mars Observer project has approved power-in, and has nearly completed its evaluation of Cases A and B.

As post-launch analysis continued operational considerations became more focused on contingency plans, and this led to another proposed change from the baseline orbit insertion. If an anomaly occurred between '1'101 and 'J'] ,0-?. which required delaying 'J'] .0-? by more than about a week, then the cost of adding an out-of-plane component to '1'1 .0-2. to move the node back to its nominal position would be excessive. To allow more time in the event of such an occurrence it was proposed that the nominal node position would be at 2:08 PM local mean solar time instead of 2:00 PM. Work is continuing to verify that 2:08 PM descending node. orientation is acceptable to both spacecraft engineers and the. science community.

Another change was proposed basal partly on AV considerations and partly on operational considerations. Since the initial orbit period at Mars depends on the accuracy of the MOI execution it can vary by a few hours. Combined with the. possible selection of an anomaly other than 180" for ECM-1 execution, this increased the probability of an extra orbit being needed to satisfy the constraint of having ten days between maneuvers. It turned out that by planning on a longer initial orbit we could reduce the variance in the expected ECM-2 elate as well as reduce [he. size of the ECM-1 maneuver slightly, so a 75-hour period was chosen for the. initial capture orbit instead of the baseline 72-hour pc.lied. Both the node change and the initial period change affected the cost of power-in, as shown in Fig. 10. Case A now corresponds to a cost of 75 m/s at a true anomaly of 156° and Case B corresponds to 49 m/s at a true anomaly of 173°. Figure 10 also shows the continuation of the contours into higher-cost, lower-days-reduction regions for contingency planning.

CONCLUSION

At this time., it appears that successful implementation of the power-in strategy will result in a 20 day advancement of the start of mapping. This is desirable since solar conjunction will disrupt the communication link to Earth from December 21, 1993 through January 3, 1994 and the dust storm season at Mars begins just after this time period and could adversely affect mapping. in addition, the 20 day advancement provides more time to complete deployment of the space.claft into the mapping configuration prior to solar conjunction. Work continues to re.fine the strategy and to determine the most effective implementation of power-in.

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