JPL Quarterly Technical Review Volume 1, Number 3 October 1971

A Viking Satellite Orbit Trim Strategy

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The Viking Project places a number of interesting and stringent requirements on the control of the satellite orbit to obtain reconnaissance and to prepare for lander release. To satisfy these requirements, different orbit trim maneuver strategies have been developed for two typical Viking missions. This article describes one of these strategies. In addition, a summary of recent numerical results is included to show that this strategy satisfies the mission requirements which have been identified.

Introduction

The Viking Project[1] will send two spacecraft to Mars during the 1975 launch opportunity. Each of these spacecraft will orbit Mars and deploy a soft-lander to the surface of the planet.

The pre-flight navigation analysis for this project has included the analysis of two typical Viking missions. The initial Mission A (launch date August 17, 1975, arrival date June 23, 1976) is a typical candidate for the first spacecraft, while the initial Mission B (launch date September 1, 1975, arrival date August 7, 1976) is a typical candidate for the second spacecraft.

During the Mars orbit trim (MOT) phase of each flight, a sequence of orbit trim spacecraft propulsive maneuvers is performed to remove the effects of orbit-determination and maneuver-execution errors remaining after earlier maneuvers in the flight. The sequence of trim maneuvers is performed according to a pre-determined strategy designed to achieve the mission objectives. This article describes the orbit trim strategy developed for Mission B. A summary of numerical results is included to show that this strategy satisfies the Mission B requirements defined in Reference 1. Reference 2 describes details concerning the analysis of both Missions A and B.

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[1] The Viking Project is managed for NASA by the Langley Research Center. Jet Propulsion Laboratory responsibilities in the project include navigation analysis.

Trim Strategy Objectives

The objectives of the orbit trim maneuver strategy for Mission B are:

(1) To satisfy the requirements for landing. The orbit of the spacecraft must be controlled to pass through a prescribed space-time region from which the lander can maneuver to the desired landing site without violating any design constraints. The orbit is specified for that revolution during which the Viking lander separates from the orbiter. The five control parameters are shown in Figure 1 and include the downrange and crossrange error in the landing site latitude relative to the PER point,[2] the orbital period, the periapsis altitude, and the timing error at the periapsis passage immediately following lander touchdown. The current specified tolerances for these five control parameters are given in Table 1.

(2) To provide site reconnaissance at the ninth periapsis passage following the orbit insertion maneuver. This requirement permits the orbiter to execute three site-certification reconnaissance sequences of 3 days each and allows 2 days for the decision to deorbit the lander just prior to the twentieth periapsis passage after Mars orbit insertion (MOI). For a site-certification reconnaissance sequence, Reference 1 specifies that the orbiter remain within an 8-deg central angle and 2000-km slant range of the site for at least 3 min.

(3) To provide adequate orbit determination and command generation time between maneuvers by allowing at least 1½ revolutions between successive maneuvers.

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[2] The PER point in the satellite orbit occurs at a fixed value of true anomaly for a given entry angle and is the true anomaly of the spacecraft in the nominal orbit when it is directly above the nominal landing site.

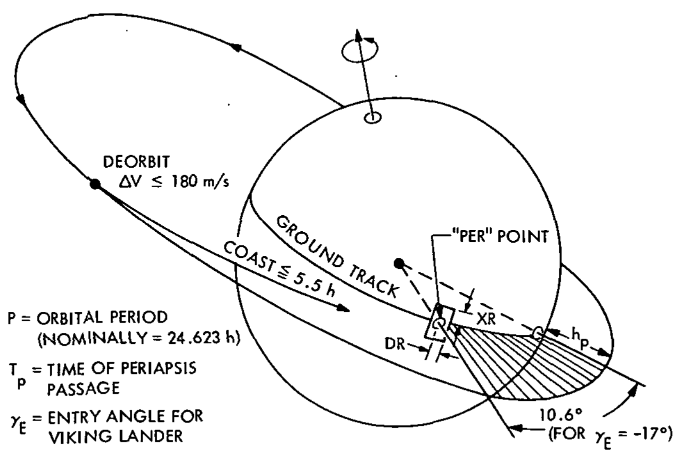

Figure 1. Satellite orbit control for lander deorbit

Table 1. Final control 99% dispersions

Parameter	Reference 1 tolerances	Latest desired tolerances	Final control 99% dispersions
Period, min	±5	±5	-4.9 to +4.6
h_p, km	±300	±150	-148 to +133
Timing, min	±5	±5	-4.9 to +4.9
DR, deg	±1.75	±2	-1.2 to +1.2
XR, deg	±4	±3	-1.6 to +1.6

(4) To satisfy the velocity-magnitude requirement that each trim maneuver be within specified bounds. Each maneuver velocity increment must be larger than 0.25 m/s (determined by a 534-N-s (120 lb-s) minimum impulse constraint) and less than 80 m/s.

(5) To make efficient use of propellant capability. In particular, the velocity increment budget of 175 m/s for all pre-capsule-release orbit trims, together with the variation from the nominal of the MOI maneuver velocity, must not be exceeded.

The orbit trim maneuver strategy is analyzed by means of a Monte Carlo error analysis. If the five objectives above are satisfied for 99% of the Monte Carlo samples, the strategy is acceptable.

MOI Timing Biases

The first facet of the MOT strategy also affects the Mars orbit insertion (MOI) maneuver in the selection of the initial satellite orbit period and timing biases. The initial (nominal) longitude displacement between the landing site and the initial PER point is determined by the selection of a spacecraft arrival time at Mars which permits overlapping two-station coverage by the Deep Space Network (DSN) during MOI command loading and the actual MOI maneuver. This initial longitude displacement is equivalent to an initial timing bias, i.e., the initial longitude offset of the landing site relative to the PER point is equivalent to a certain amount of Mars rotation time east or west of the initial PER point. The initial orbital period bias is determined from this timing bias in the manner discussed below.

A principal feature of the strategy described in this article is the need for time-phasing maneuvers, where an orbital period asynchronous with the rotational period of Mars is used to remove the site longitude offset by the end of a specified number of revolutions. For the initial Mission B, the initial timing bias due to longitude offset of the landing site is –17 h, or about 249 deg west of the initial orbit PER point. The initial period bias is determined from this timing bias and the number of revolutions to each of the two time-phasing maneuvers MOT_2 and MOT_3.

All of the trim maneuvers are described in the next section. However, at this point in the discussion, it is necessary to know that the second trim maneuver MOT_2 is performed at the fifth periapsis passage P_5, and the third maneuver MOT_3 is performed at the eighth periapsis P_8. (See Figure 2, which indicates the trim maneuver timeline for Mission B.) Given this information, it is possible to select the appropriate initial period bias ΔP_0 relative to the synchronous period (24.623 h). In this selection, the period change introduced by MOT_1 is neglected. If $\Delta P_0 = 17/5 = 3.4$ h, the initial timing bias would be removed in five orbits and the orbiter could synchronize over the landing site via a trim at the fifth periapsis passage P_5, following MOI. If ΔP_0 were selected as $17/8 = 2.1$ h, the initial timing bias would be removed in 8 orbits. In the latter case, a trim at P_5 would only be needed to correct errors and the synchronizing trim could be made at P_8. Any initial period bias between these two extremes would minimize $\Delta V_{MOI} + \Delta V_{MOT_2} + \Delta V_{MOT_3}$ since, in any of these cases, each maneuver reduces the size of the orbit, removing energy from the system. If the initial period were slightly less than 26.7 (24.6 + 2.1) hours, then MOT_2 at P_5 would have to enlarge the orbit, wasting energy. (See Figure 3, which indicates the effect of the initial period bias on the timing offset.) If the initial period were slightly greater than 28.0 (24.6 + 3.4) hours, then MOT_2 would have to move the spacecraft into a subsynchronous (i.e., less than 24.623 h) orbit, causing energy to be wasted. Thus, the ΔV-optimal interval [26.7, 28.0] is determined. A second ΔV-favorable interval [29.8, 32.9] is obtained by waiting until the next Mars revolution. The left- and right-hand endpoints of this second interval are obtained by dividing (17 + 24.6) hours over 8 and 5 orbits, respectively. Succeeding optimizing intervals are indicated in Figure 4. Because of the large anticipated post-MOI period dispersions for Mission B, an initial period in the first interval was rejected. For the analysis given in Reference 2, the second interval was chosen rather than a later interval to reduce the size of the trim maneuvers, and, hence, to reduce the effect of the proportional execution errors. Since the post-MOI period dispersions were expected to be fairly symmetric, the midpoint of this second interval was chosen for the nominal initial period to maximize the probability that the actual spacecraft orbit period would fall inside the optimizing interval. By selecting this biased period, the fan of dispersed paths (cf Figure 2) is pointed downwards for all except about 10% of the low-period dispersed cases to ensure that each maneuver shrinks the size of the orbit.

Several modifications of this strategy for selecting the value of ΔP_0 are possible (cf Figure 4). For example, selecting the initial period so that only 1% of the low-period dispersions are less than 26.7 h would ensure that no energy is wasted for 99% of the samples. However, large post-MOI period dispersions would introduce a large period bias which would require large trim maneuvers. Hence, the effects of execution errors must be considered in such ΔP_0 strategies. Also, note that the intervals in Figure 4 depend on the

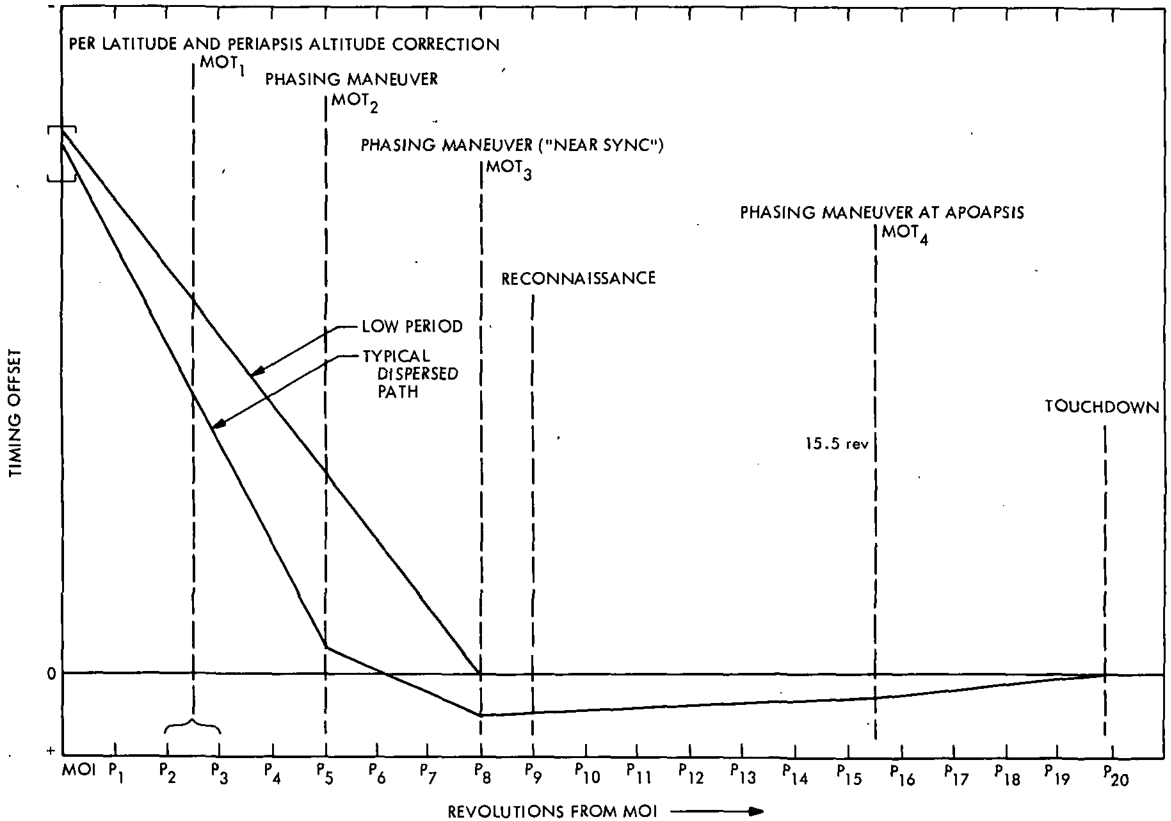

Figure 2. Orbit trim strategy for Mission B

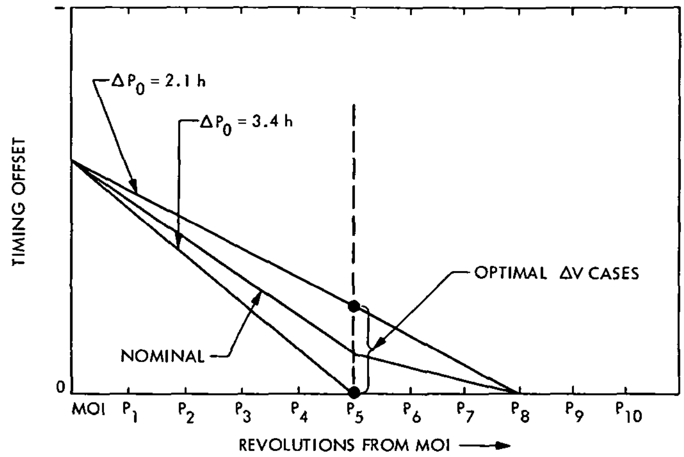

Figure 3. Effect of initial period bias for Mission B

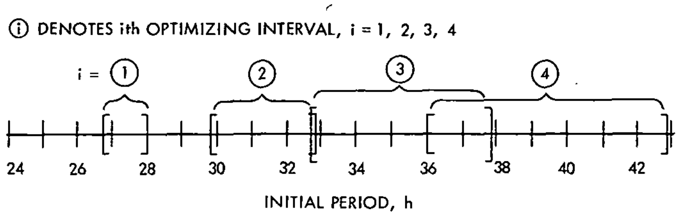

Figure 4. Optimal initial period intervals

initial timing bias. Some of these ΔP_0 strategy modifications are being utilized in current studies.

The MOT Strategy

The first trim maneuver is a three-dimensional maneuver designed to correct the periapsis altitude to the nominal value 1500 km and to place the PER point at the required latitude. The large post-MOI dispersions in periapsis altitude h_p ($\approx$ ±800 km) dictate that this parameter must be corrected early to provide satisfactory reconnaissance at the ninth periapsis. The h_p correction is combined with an orientation change because it is possible to make this change with very little additional ΔV. Only the latitude of the PER point is corrected in this maneuver since the longitude error can be interpreted as a timing error and corrected very economically in the phasing sequence (MOT_2 and MOT_3) to follow. Thus, the landing site is merely allowed to rotate under the PER point in an orbit having a large period dispersion.

The first maneuver MOT_1 is performed in a ΔV-optimal manner and occurs between the second and third periapsis passage after the orbit insertion maneuver. The maneuver direction and position in the orbit is determined by a numerical search which minimizes the magnitude of the velocity increment as a function of the eccentric anomaly and the desired change in inclination.

Once the periapsis altitude has been corrected to the desired (nominal) value, except for small errors, it is possible to correct the period and timing errors by changing the height h_a at apoapsis only. These corrections are made in two time-phasing maneuvers performed at periapsis. The maneuver MOT_2 is performed at P_5 to achieve an orbital period such that the site longitude offset is exactly nullified at P_8, where MOT_3 is performed to achieve a near-synchronous orbit. In the absence of errors, these maneuvers would synchronize the PER point to the landing site longitude. However, in order to improve the final timing control of the PER point with respect to the landing site, the third maneuver is actually designed to nullify this final timing error. The maneuver strategy is designed so that this phasing sequence always shrinks the size of the orbit if possible. For those dispersed orbits for which this is not possible at both MOT_2 and MOT_3, MOT_2 is selected to achieve the supersynchronous or subsynchronous post-MOT_2 period which minimizes $\Delta V_{MOT_2} + \Delta V_{MOT_3}$.

The locations of the maneuvers MOT_2 and MOT_3 have been chosen to satisfy Objectives 2 and 3. MOT_3 must be performed before P_9 so the first reconnaissance pass can be made at P_9. Performing the maneuver earlier than P_8 would only allow more time for the timing error to accumulate linearly in time due to period dispersions. Hence, P_8 was chosen for MOT_3. Another consideration in the spacing of these maneuvers is the desirability to maximize the interval between the maneuvers MOT_2 and MOT_3. This maximization reduces the size of MOT_3 to minimize the effect of the proportional execution errors. It also minimizes the amount of velocity that is wasted when it is not possible to shrink the size of the satellite orbit at both MOT_2 and MOT_3.

It should also be noted that performing the maneuvers at periapsis minimizes the velocity increment needed for period changes. It also permits making the maneuvers along the orbiter's velocity vector, which nullifies the first-order effects of maneuver pointing errors. (A description of maneuver execution errors is given in Reference 3.)

The fourth and final pre-capsule release trim maneuver is performed at the sixteenth apoapsis after MOI to achieve accurate timing control of the deorbit orbit. This maneuver removes the timing error which accumulates during the 7½ orbits after MOT_3. Performing MOT_4 at apoapsis reduces the effect of execution errors to about ⅛ that of a maneuver at periapsis. Hence, having neutralized the effects of execution errors, the timing error at touchdown is approximately 4½ times the uncertainty in estimating the orbital period.

The placement of MOT_4 must be properly balanced between P_8 and P_{20}. Location too soon after P_8 permits too much time for timing error growth (which accumulates linearly in time) by P_{20}, violating the 5-min periapsis passage time control requirement of Objective 1. Location too near P_{20} would not allow enough time before P_{20} to correct the accumulated timing error without violating the tight h_p tolerances shown in Table 1. This concern for h_p is introduced by the fact that the maneuver at apoapsis adjusts h_p to change the period in removing the timing error. Selection of the sixteenth apoapsis was determined to achieve the best tradeoff between the two extremes.

Summary of Numerical Results and Conclusions

The orbit trim computer program provides a Monte Carlo error analysis for the selected trim strategy. This program has the capability to target to an input downrange, crossrange (DR × XR) tolerance zone. If the DR × XR error for a particular dispersed orbit is acceptable or can be made acceptable by a longitude change only, the latitude change in MOT_1 is omitted. Such tolerance zones are considered below.

The input parameter values for the orbit trim program were chosen to be compatible with Reference 1 and current hardware capabilities. The performance of the selected strategy relative to each of the five strategy objectives is evaluated next.

When the orbit trim program was targeted for a 1- × 2-deg DR × XR tolerance zone, the 99% dispersions for the five control parameters of the first objective were determined. The values are stated in Table 1, which shows that the control requirements are met.

The requirement for site reconnaissance at the ninth periapsis is satisfied because the timing error at this periapsis is within ±10 min. An error of ±30 min would be acceptable.

The 99% high ΔV values for each of the four trim maneuvers for the 1- × 2-deg target case are given in Table 2, showing that the requirements on the magnitudes of the velocity increments are met.

The total of the velocity increments required for corrective navigation is shown in Figure 5 as a function of the size of the targeted DR × XR tolerance zone. This figure shows that the corrective navigation ΔV budget of 175 m/s is adequate.

The following conclusions may be drawn from the data presented here and are supported by the detailed results of the simulation.

(1) The initial Mission B can be flown satisfying the requirements of Reference 1 and current hardware capabilities. However, if it

Table 2. 99% MOT velocity increment requirements[a]

Trim No.	ΔV, m/s
1	37
2	54
3	45
4	7

[a] These requirements are for Mission B with a 1- × 2-deg target DR × XR tolerance zone.

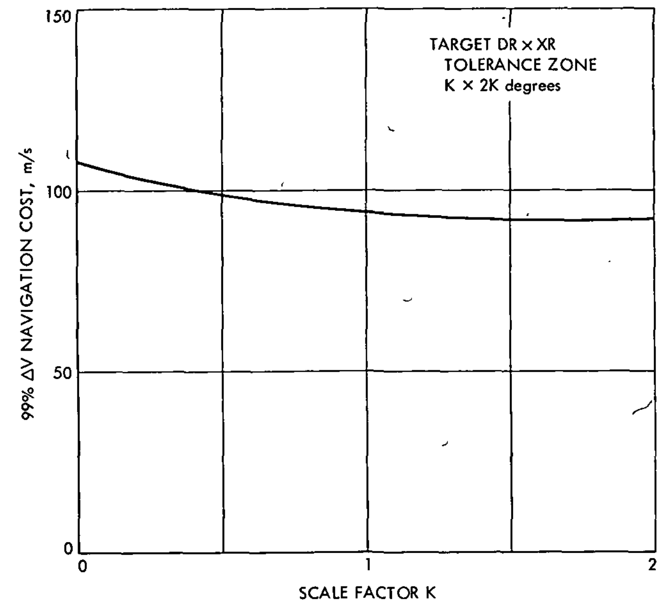

Figure 5. Navigation cost vs targeted DR × XR tolerance zone size

becomes necessary to tighten any of the final control tolerances, it might be necessary to remove some of the conservatism in the current orbit-determination accuracy estimates. For example, to reduce the final timing error, it would be necessary to reduce the error in estimating the orbital period.

(2) For Mission B, very little ΔV is saved by targeting to a non-zero DR × XR tolerance zone. However, the small ΔV savings realized for Mission B by expanding the DR × XR tolerance zone are not repeated for lower-inclination Viking missions. The small savings for Mission B reflect the large post-MOI h_p dispersions and the relatively small post-MOI orientation errors.

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