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Contingency Maneuver Strategies for the Total Ozone Mapping Spectrometer-Earth Probe (TOMS-EP)*

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Abstract

The Total Ozone Mapping Spectrometer-Earth Probe (TOMS-EP) is a polar-orbiting spacecraft designed to measure total ozone levels in the Earth's atmosphere. The nominal mission orbit is a 955-kilometer circular Sun-synchronous orbit with an ascending node mean local crossing time (MLT) between 11:02 a.m. and 11:25 a.m. These two mean local ascending node times constitute the boundaries of the MLT box for this mission. The MLT boundaries were chosen to maintain the Sun-to-Earth-to-vehicle orbit-normal (SVN) angle within a preselected set of seasonally independent boundaries. Because the SVN angle is seasonally dependent, but the MLT is not, contingency options for correcting the MLT of orbital states that fall outside of the required MLT range become time dependent.

This paper focuses on contingency orbit adjustment strategies developed at the Goddard Space Flight Center (GSFC) Flight Dynamics Division (FDD) during the mission planning phase of TOMS-EP. Time-dependent delta-V strategies are presented for correcting mission orbit states lying outside of the MLT range. Typically, passive control of the MLT drift rate can be used to restore the orbit state to the required MLT before a seasonal violation of SVN angle constraints can occur. Passive control of the MLT drift rate is obtained through adjustment of the semimajor axis and/or the inclination. The time between initial arrival on orbit at an "out-of-the box" MLT state and violation of the SVN angle constraints is always less than or equal to 1 year. The choice of which parameter(s) to adjust is dictated by the duration of this time period, the desired mission lifetime, the delta-V cost, and operational constraints

Introduction and Mission Overview

The scientific goal of the Total Ozone Mapping Spectrometer-Earth Probe (TOMS-EP) mission is to map the total ozone content of the Earth's atmosphere over a minimum period of 2 years. The original vision of the TOMS-EP project was for a 3-year nominal mission lifetime. TOMS-EP will continue the mission of the Nimbus 7 spacecraft by providing continuous total ozone coverage of the Earth. To accomplish this task, the spacecraft will be placed in a circular polar orbit of approximately 99.3-degrees inclination at an altitude of 955 kilometers (km). Figure 1 is an illustration of the TOMS-EP spacecraft. As with other Earth observing, polar orbiting missions, the need to maintain consistent back-lighting conditions requires the spacecraft to maintain an orbit that is synchronous with the motion of the Sun. Additionally, the angle between the TOMS instrument normal vector and the position vector of the Sun must be maintained within a specified range to properly calibrate the TOMS instrument. Because of the orientation of the mounted TOMS instrument, spacecraft and orbital geometry allow this requirement to be translated directly into a restriction on the angle between the orbit normal vector and the Sun's position vector. This angle is defined as the Sun-to-Earth-to-vehicle orbit-normal (SVN) angle.

Prior to assuming its station on orbit, TOMS-EP will be injected in to a 339-km × 960-km parking orbit. Table 1 gives the parking orbit parameters and 3σ errors for the parking orbit. A series of ascent maneuvers will be performed to bring the spacecraft from the parking orbit to the proper apogee and perigee altitudes and to bias the inclination to maximize the available lifetime of the mission. The propulsion system is a simple monopropellant hydrazine system with one tank and four 1-pound thrusters. Figure 2 graphically displays the nominal TOMS-EP mission lifecycle.

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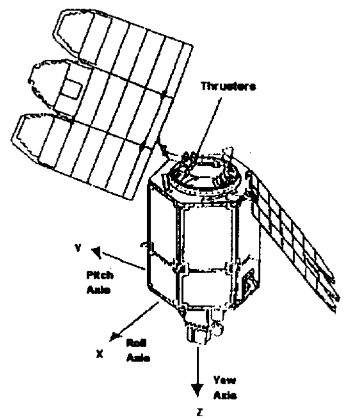

Figure 1. The TOMS-EP Spacecraft

Table 1. Nominal and 3σ Injection Parameters

Orbital Parameter	Nominal Value	3σ Error
Perigee Height (km)	339	3.5
Apogee Height (km)	960	80
Inclination (degrees)	99.3	0.22

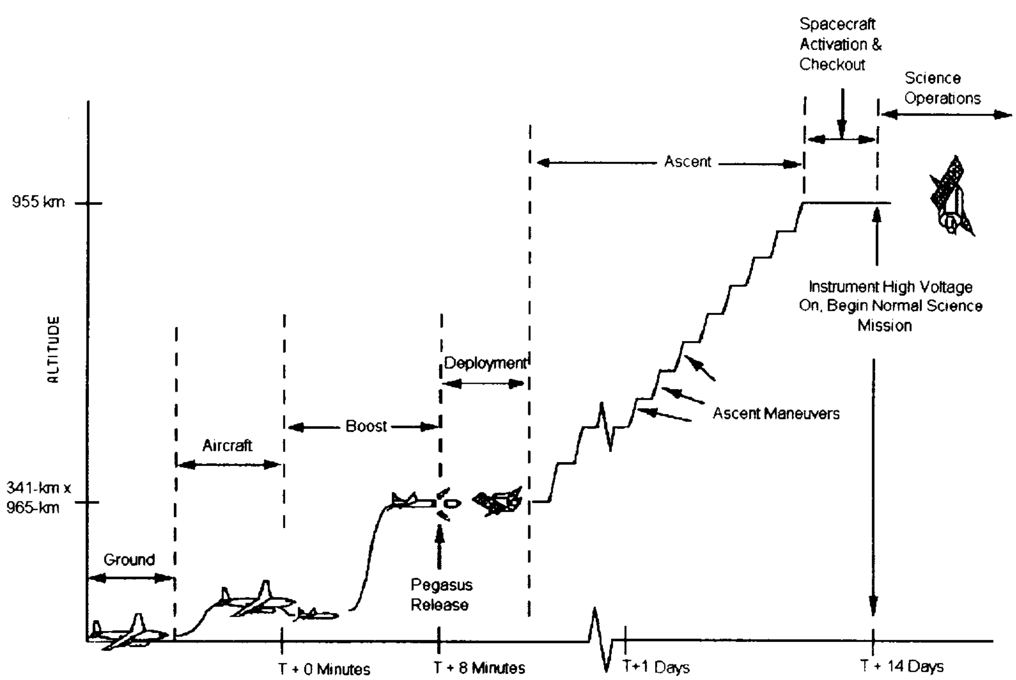

Figure 2. TOMS-EP Nominal Postlaunch Mission Phases

Design of the Nominal Mission Orbit

The nominal mission orbit for TOMS-EP was designed to ensure that the SVN angle constraints would be met, regardless of the launch date. The mission orbit has three constraints related to the mean local crossing time (MLT) of the ascending node and one constraint related to the operational altitude range of the spacecraft. These constraints are as follows:

- The MLT of the ascending node must be between 11:00 a.m. and 12:00 p.m. to satisfy the backlighting conditions required by the TOMS instrument.
- The SVN can be no greater than 107.5 degrees and no less than 91.0 degrees.
- The spacecraft can perform science operations in circular orbits in the 800-km to 1100-km altitude range, if necessary.

Because the SVN angle and MLT are both functions of the position of the Sun, it is useful to examine the dependence of the SVN angle on the MLT for mission orbits at the 99.3-degree inclination The minimum, maximum, and average SVN were determined over the course of the year as a function of ascending node MLT in the 11:00 a.m. to 12:00 p.m. range allowed by the instrument. Figure 3 shows the dependence of the SVN values on the MLT for this range. The figure shows that at approximately 11:02 a.m. the maximum SVN angle over the course of the year will be 107.5 degrees. An orbit with a fixed MLT earlier than 11:02 a.m. would violate the maximum SVN angle constraint at least once per year. Figure 3 also shows that the minimum SVN angle constraint would be violated for orbits with fixed MLTs later than 11:25 a.m. Representing the SVN angle extremes as a function of MLT in this manner provides a straightforward method of determining the MLTs at which SVN angle constraints may be violated. This allows MLT boundaries to be set for the mission, thereby defining an MLT box that guarantees no violation of the SVN angle limits. Figure 3 shows that the SVN angle limitations have, in effect, confined the available mission orbits to MLT values between 11:02 a.m. and 11:25 a.m. (Note that hh:mm in Figure 3 represents hours:minutes.)

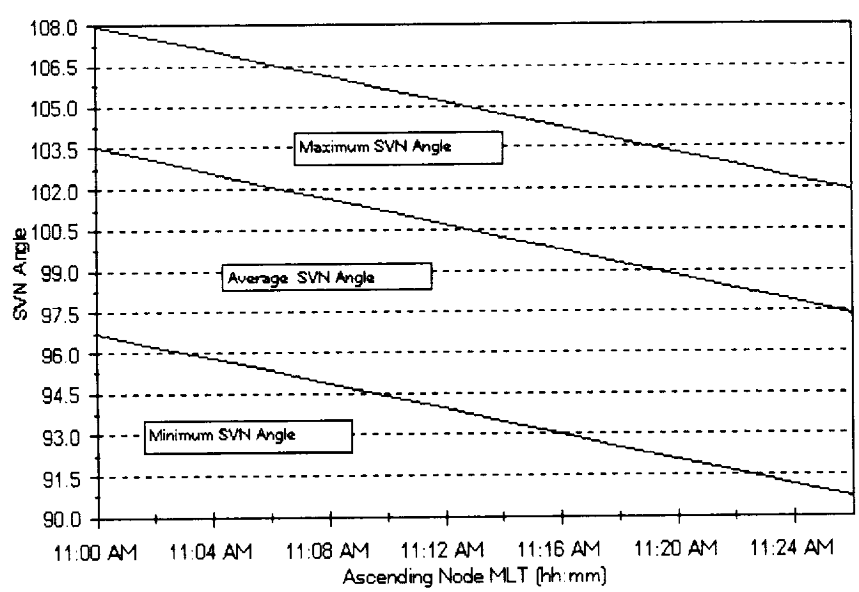

Figure 3. SVN Angle Represented as a Function of Ascending Node MLT

Representing the SVN angle variations as functions of MLT does not, however, indicate when during the year SVN angle minimums and maximums would be reached. For any allowable MLT at the 99.3-degree inclination, the SVN angle will vary over the course of a year by approximately 10 degrees. To explain this, consider the definitions of MLT and the SVN angle. MLT is based on the angle between the right ascension of the ascending node and the right ascension of the mean Sun. The right ascension of the mean Sun moves at a constant rate of approximately 0.9856 degree/day (deg/day). However, the SVN angle is defined as the angle between the orbit normal vector and the position vector of the true Sun. Because the Earth's orbit around the Sun is inclined and not exactly circular, the right ascension of the true Sun changes at a rate that varies throughout the year. This causes a seasonal variation in the SVN angle due to the difference between the mean motion of the Earth about the Sun and the actual motion of the Earth about the Sun. Because the TOMS-EP orbit is polar, this variation in the right ascension of the true Sun has a strong effect on the SVN angle throughout the year. It therefore becomes important to keep the spacecraft orbit in an MLT range that will ensure that the SVN angle variation throughout the year does not cause a constraint violation.

To see when during the year the bounding SVN angles would be reached, the SVN angle was determined as a function of the day of the year for each of the boundary MLTs. Figure 4 shows the SVN angle as a function of the day of the year for the 11:02 a.m. and 11:25 a.m. MLT orbits. For the early boundary of the MLT box, Figure 4 shows that the SVN angle reaches a maximum of 107.5 degrees near day 210. For the late boundary of the MLT box, the SVN angle reaches the minimum limit around day 319. As the MLT of the orbit increases toward noon, the SVN angle for any given day of the year decreases.

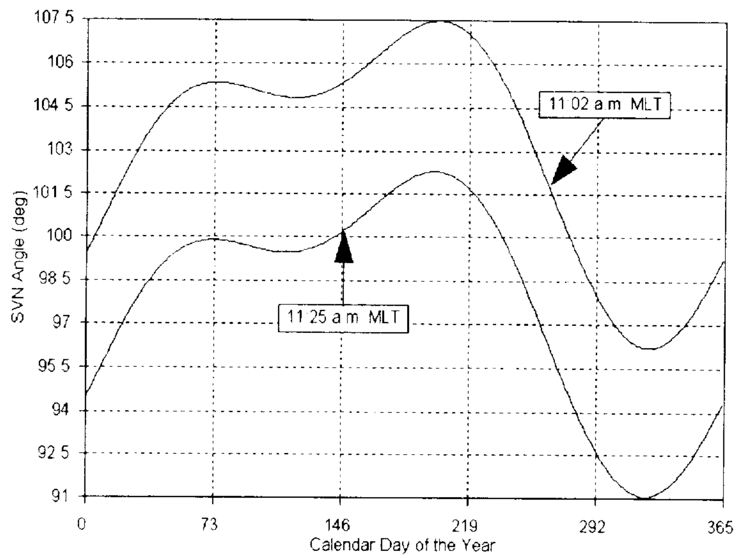

Figure 4. TOMS-EP SVN Angle Ranges Throughout The Year

Figures 3 and 4 represent the SVN angle as functions of MLT and day of the year for fixed MLTs. These figures show the effects of the Solar geometry on the angular limits. It should be noted, however, that the mission orbit MLT will change as a function of time over the course of the mission. This is partially due to drag but mainly due to the perturbative effect of the Sun's gravity on the spacecraft orbit (References 1 and 2). The solar gravitational perturbation exerts a torque on the spacecraft orbit, altering the inclination over time. This change in inclination in turn effects the rate of change of the node, causing an MLT drift rate. For orbits with MLTs earlier than noon, the Sun's gravity tends to decrease the inclination over time. To see what effect this has on the MLT of the orbit, consider the first-order equation for the nodal rate (Reference 3):

$$\frac{d\Omega}{dt} = \frac{-3\sqrt{\mu}\, J_2 R_e \cos(i)}{2a^{7/2}(1-e^2)^2} \tag{1}$$

where Ω = right ascension of the ascending node; i = orbital inclination
a = semimajor axis; e = eccentricity
μ = gravitational constant of the Earth; J_2 = coefficient of the second zonal harmonic
R_e = equatorial radius of the Earth; t = time

Because the Sun-synchronous condition relies on the nodal rate being equal to the average angular velocity of the Earth about the Sun, any change in nodal rate will cause the MLT to drift away from its initial value. Inspection of Equation (1) shows that a decrease in the inclination will cause a decrease in the drift rate when the inclination is greater than 90 degrees. For TOMS-EP, the solar perturbation decreases the inclination by approximately 0.02 degree per year. A thorough discussion of the effects of solar, lunar, and other perturbations on the evolution of MLT can be found in Reference 4.

Because MLT is not constant over the mission life, it is necessary to choose an initial inclination that will maximize the time spent in the MLT box (References 5 and 6). To determine the best choice of initial inclination for mission orbits inside the MLT box, the evolution of initial mission orbits, corresponding to the boundaries of the box, was modeled using the Goddard Mission Analysis System (GMAS). The modeling was performed using the average variation of parameters (AVGVOP) propagator with an order 21 zonal field, the Jacchia-Roberts atmospheric density model, and solar and lunar gravitational perturbations. Figures 5 and 6 display the MLT evolution for initial mission orbits with MLTs of 11:02 a.m. and 11:25 a.m., respectively. From Figure 5, it can be seen that for the 11:02 a.m. case the initial inclination would have to be set to approximately 99.37 degrees to maximize the mission lifetime. In this case, the initial nodal rate is greater than the angular rate of the mean Sun to offset the reduction of nodal rate that the Sun's gravity will affect on the orbit over time. Figure 6 shows that for the 11:25 a.m. case the initial inclination would have to be set to 99.30 degrees. In this case, there is no choice but to match the nodal rate to that of the mean Sun and accept the decrease in MLT over time. From both figures, it is clear that the available mission lifetime, without correction maneuvers, is approximately 5 to 10 years, depending on the initial MLT of the mission orbit. This is 2 to 5 times as long as called for in the mission requirements and 1.5 to 3 times as long as the originally envisioned 3-year nominal lifetime.

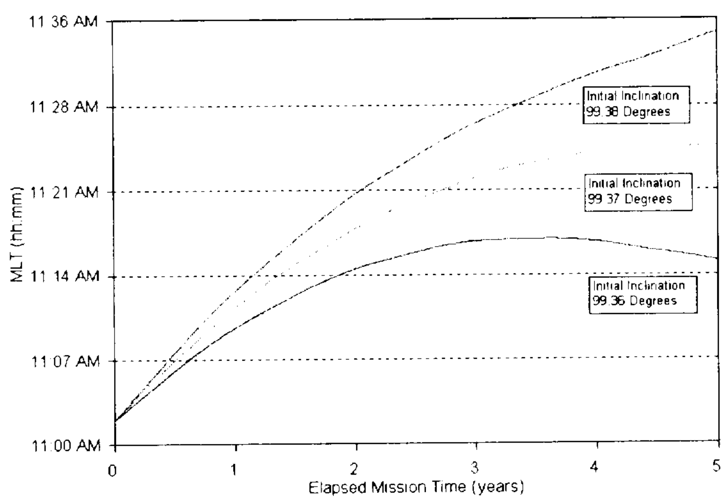

Figure 5. TOMS-EP Mission Orbit MLT Evolution for the 11:02 a.m. Initial MLT Case

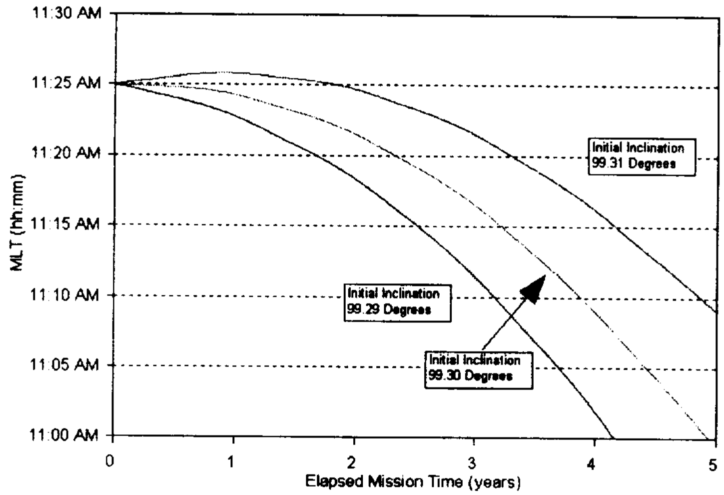

Figure 6. TOMS-EP Mission Orbit MLT Evolution for the 11:25 a.m. Initial MLT Case

Contingency ΔV Strategies for Correcting Out-of-the-Box MLT States

A contingency involving MLT will generally result from one of two things: either the MLT on arrival will be earlier than the 11:02 a.m. lower limit, or it will be later than the 11:25 a.m. upper limit. The goal in a contingency situation is to restore the spacecraft to as close to a nominal mission orbit as possible with as little interruption or delay of science data collection as possible. If the contingency is due to severely nonnominal launch vehicle performance, the insertion altitude may be significantly lower than expected, and extra fuel will be needed to bring the spacecraft up to the mission orbit. In such a case, fuel may be at a premium and the delta-V budget will also be a consideration .

For cases where the MLT will be too early, ascent maneuvers can be delayed to allow the MLT to drift noonward to an acceptable value. This is the most straightforward method of altering the MLT in a rapid manner. Figure 7 displays the MLT drift rate in minutes (min) per day relative to a Sun-synchronous orbit as a function of the semimajor axis in the low Earth regime. For TOMS-EP, the $+3\sigma$ semimajor axis of the parking orbit is 7071 km. This corresponds to an average altitude of approximately 693 km. Using this strategy, even in a very extreme case where the MLT on arrival at mission orbit would be 10 minutes too early and the semimajor axis of the parking orbit is at the $+3\sigma$ value, the delay would be slightly less than 3 weeks. Correction of the MLT in this manner would result in no sacrifice of available mission lifetime in the MLT box, but it could delay the start of science data collection.

However, it is possible in certain cases to avoid the delay incurred by postponing the ascent maneuver sequence. It may also be possible to avoid an interruption of science data collection. When the necessary change in MLT is small enough or the time before constraint violation would occur is long enough, it is possible to bias the inclination slightly and achieve the desired MLT drift rate. This would allow the spacecraft to drift up to the 11:02 a.m. boundary before the SVN angle constraint violation can occur. Without further correction of the nodal rate after the 11:02 a.m. boundary has been reached, the available mission lifetime in the MLT box may be impacted. To see how much the available lifetime would be impacted, the maximum possible lifetime in the MLT box was determined as a function of initial MLT. The maximum possible time in the box is, in this case, the time needed to drift noonward from the initial MLT to 11:25 a.m. and then down to 11:02 a.m. Figure 8 shows the maximum possible lifetime in the box as a function of the initial MLT in the 10:52 a.m. to 11:02 a.m. range. Using this information as a baseline, the degree to which lifetime in the MLT box will be affected can be determined.

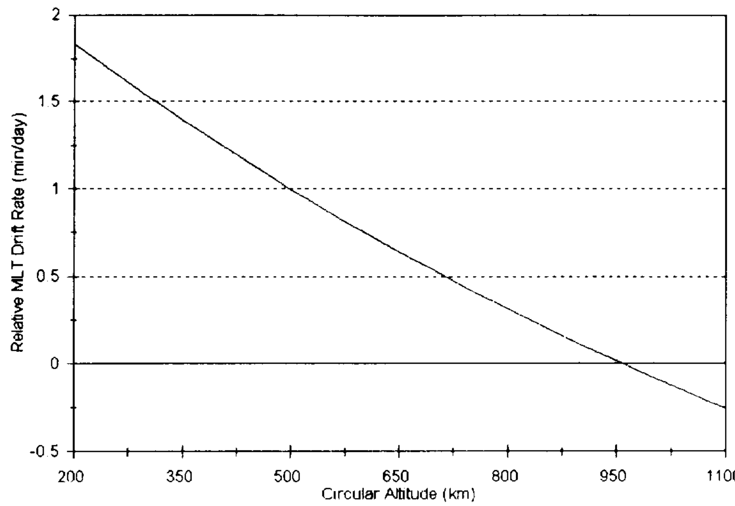

Figure 7. MLT Drift Rate Relative to a Sun-Synchronous Orbit as a Function of Circular Altitude at the 99.3- degree Inclination

Because the nodal rate is slowed by the action of solar gravity on the orbit, the MLT rate is at a maximum during the first year of the mission for orbits that must initially drift noonward. If the rate of MLT drift needed to avoid constraint violations is less than or equal to that of the maximum lifetime orbit, there will be no need to apply any correction maneuvers at all. The inclination of the initial mission orbit would merely be biased to provide the maximum lifetime in the MLT box, and no constraint violation would occur.

For an orbit with an initial MLT that is less than 11:02 a.m., the average MLT drift rate needed to avoid a constraint violation is given by

$$\frac{\mathrm{d}(MLT)}{\mathrm{d}t} = \left(\frac{\Delta MLT}{\tau}\right) \tag{2}$$

where ΔMLT = (11:02 a.m. – MLT on arrival)
τ = time between arrival and constraint violation

This is illustrated in Figure 9 where the first-year MLT drift rate in minutes (min) per year is plotted versus initial the MLT for the optimum lifetime orbits at initial MLTs in the 10:52 a.m. to 11:02 a.m. range. If the MLT drift rate falls on or under the curve for the initial MLT of the orbit, then the optimum lifetime can be achieved by a simple biasing of the inclination, and no contingency correction of the MLT rate is required.

However, if the necessary MLT drift rate is greater than the slope of the curve in Figure 9, then the available lifetime in the box will be affected. Faster than optimal initial drift rates will cause the MLT to reach a maximum above the 11:25 a.m. mark if left uncorrected. This effectively reduces the maximum lifetime to less than one-half of its optimal value. The reduction of lifetime is caused by the fact that at some point the MLT will exceed 11:25 a.m. However, since even one-half of the available mission lifetime in the MLT box is still several times greater than minimum lifetime of 2 years, the impact may be acceptable. The degree to which this will be a factor can be determined by considering the MLT drift rate necessary to avoid constraint violation and the degree to which this drift rate will affect the available mission life. Figure 10 shows the inclination bias needed to ensure maximum lifetime in the MLT box for mission orbits with initial MLTs in the 10:52 a.m. to 11:02 a.m. range. The inclination values displayed are those required to maximize the time spent between 11:02 and 11:25 a.m. In each case, the maximum MLT is 11:25 a.m., providing an upper bound on the available lifetime in the MLT box.

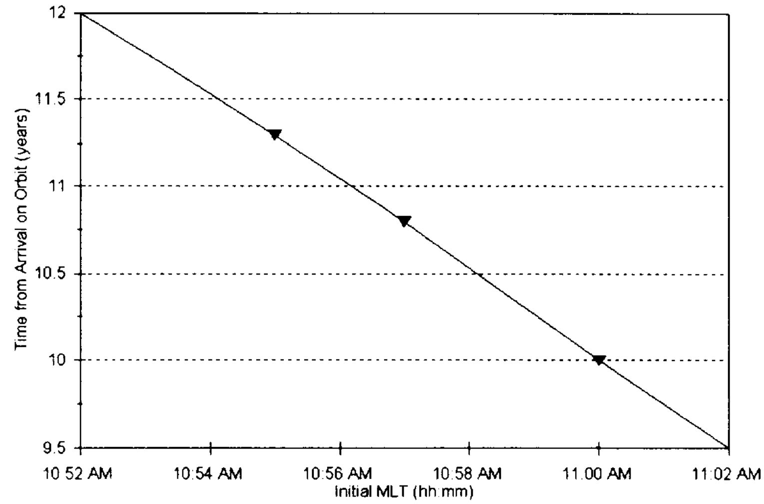

Figure 8. Maximum Possible Lifetime Versus Initial MLT on Arrival at Mission Orbit

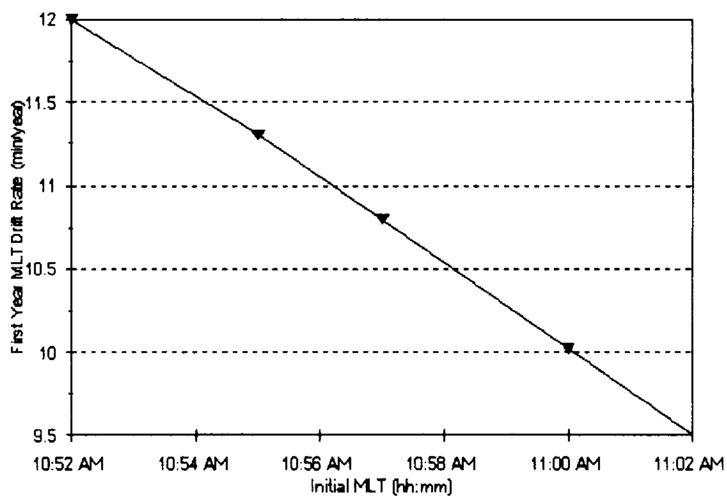

Figure 9. Average MLT Drift Rates for the First Year for Orbits With Maximum Time in the MLT Box

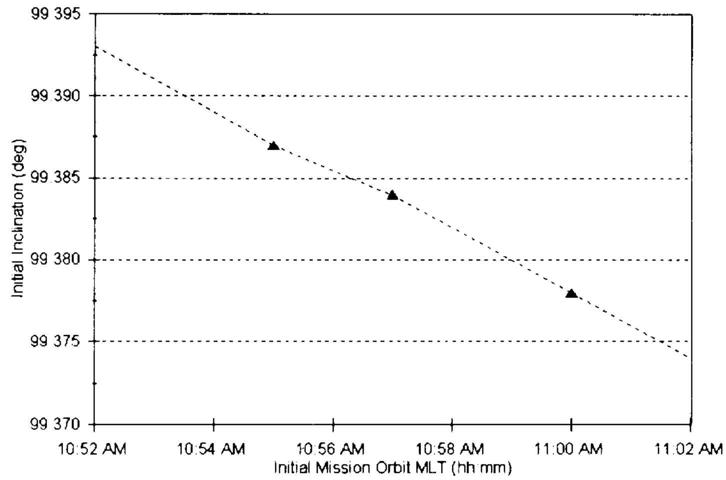

Figure 10. Inclinations Required for Maximum Lifetime Versus Initial MLT in the 10:52 a.m. to 11:02 a.m. Range

To quantitatively determine the impact of faster than optimum node rate on the available lifetime in the MLT box, consider a first-order Taylor series expansion of Equation (1) about the inclination. Neglecting the effects of drag on the orbit, the nodal rate as a function of elapsed mission time is given by

$$\dot{\Omega}(t) = \dot{\Omega}(0) + \left(\frac{\partial \dot{\Omega}}{\partial i}\right)\left(\frac{\mathrm{d}\,i}{\mathrm{d}\,t}\right)i \tag{3}$$

Evaluating the partial derivatives of Equation (1) with respect to i yields

$$\left(\frac{\partial \dot{\Omega}}{\partial i}\right) = \tan(i)\,\dot{\Omega} \tag{4}$$

The rate of change of inclination for TOMS-EP is approximately –0.02 degree per year, and t is the elapsed mission time. The average nodal rate, $\langle\dot{\Omega}\rangle$, and the time when the 11:25 a.m. boundary is reached, λ, can be estimated using recursion formulas based on Equation (3) as follows :

$$\lambda_n = \frac{\Delta\Omega}{\left[\left\langle\dot{\Omega}\right\rangle_{n-1} - 0.9856\,\frac{\text{deg}}{\text{day}}\right]} \tag{5}$$

$$\left\langle \dot{\Omega} \right\rangle_n = \frac{\left[\dot{\Omega}(0) + \dot{\Omega}(\lambda_n)\right]}{2} \tag{6}$$

where $\left\langle \dot{\Omega} \right\rangle_0 = \frac{\Delta MLT}{4\tau}$ and $\Delta\Omega = \frac{\Delta MLT}{4}$.

Obviously, as λ approaches the minimum acceptable lifetime, the value of interrupting science operations for additional maneuvers after the 11:02 a.m. boundary has been reached increases.

If the MLT is late upon reaching mission orbit, the available options and strategy are essentially the same as for the early MLT case. In an extreme situation, the altitude can be raised to a higher than mission orbit value and then restored to a nominal mission orbit value at a later time. Given the maximum altitude constraint of 1100 km, the best MLT drift rate that can be achieved in this manner is approximately 15 seconds per day, which is equivalent to over 90 minutes per year. For less serious cases, the strategy is similar to that of the too-early MLT case. However, there is less flexibility for MLT correction using an inclination bias for the cases where the MLT is too late. For contingency orbits with MLTs earlier than 11:02 a.m., the solar gravitational perturbation slows the MLT drift rate over time and, in effect, stretches out the time between arrival at the initial MLT and arrival at 11:25 a.m.. However, for orbits with MLTs later than 11:25 a.m., there is no noonward drift in the MLT. Therefore, the MLT rate will decrease steadily. In effect, the solar perturbation will act to shorten the time between arrival at the initial MLT greater than 11:25 a.m. and crossing of the 11:02 a.m. boundary. In other words, when the MLT is later than 11:25 a.m., the magnitude of the average nodal rate will tend to be larger and λ will be shorter for any given ΔMLT and τ. The strategy is essentially the same as for the early MLT case except that the shorter available mission lifetime can make it necessary to perform additional adjustment(s) to the orbit once the MLT has been restored to an acceptable value.

Relative Delta-V Costs of Using Inclination or Semimajor Axis To Control Nodal Rate

Equation (1) shows that a decrease in the nodal drift rate can be accomplished by either increasing the semimajor axis or by decreasing the inclination. (Since the eccentricity is of the order 10^{-3}, its effect can safely be ignored.) The choice of which parameter to adjust will depend upon the amount of time before violation of constraints and the amount of MLT that the orbit must drift through. Also of potential interest is the relative delta-V cost of adjusting each parameter under the constraint of desired nodal rate. This not only is of interest for contingency scenarios where fuel may be at a premium but also for stationkeeping scenarios. The relative delta-V cost of performing semimajor-axis-versus-inclination adjustment can be derived from Equation (1) using a first-order Taylor series approximation for the desired change in the nodal rate. If the rate of Ω is to be altered by a semimajor axis adjustment, the change in nodal rate will be given by

$$\delta\dot{\Omega} = \left(\frac{\partial\dot{\Omega}}{\partial a}\right)\Delta a \tag{7}$$

On the other hand, the change in the nodal rate produced by a change in inclination will be given by

$$\delta\dot{\Omega} = \left(\frac{\partial\dot{\Omega}}{\partial i}\right)\Delta i \tag{8}$$

Evaluating the partial derivatives of Equation (1) with respect to a and i yields

$$\left(\frac{\partial \dot{\Omega}}{\partial i}\right) = \tan(i)\,\dot{\Omega} \tag{9}$$

$$\left(\frac{\partial \dot{\Omega}}{\partial a}\right) = \left(\frac{-7}{2a}\right)\dot{\Omega} \tag{10}$$

The change in the semimajor axis for a given delta-V over a simple two-impulse Hohmann transfer (Reference 7) is given by

$$\Delta a \approx \frac{2a^2 V\ \Delta V_a}{\mu} = \frac{2a^{1.5}\Delta V_a}{\sqrt{\mu}} \tag{11}$$

where ΔV_a is the delta-V performed to change the semimajor axis. The change in inclination for a small plane change is given by

$$\Delta i \approx \frac{\Delta V_i}{V} = \frac{\Delta V_i\sqrt{a}}{\sqrt{\mu}} \tag{12}$$

where ΔV_a is the delta-V performed to change the inclination. Substituting Equations (9) and (10) into Equations (11) and (12) and solving for the ratio of ΔV_i to ΔV_a yields

$$\varepsilon \equiv \frac{\Delta Vi}{\Delta V_a} = \frac{-7}{\tan(i)} \tag{13}$$

Equation (12) provides a means of comparing the relative efficiencies of changing the drift rate through inclination adjustment and semimajor axis adjustment when the orbits are nearly circular. Figure 11 shows the value of this ratio, defined as ε, over the range of inclinations from 90 to 120 degrees. Note that at an inclination of 99.3 degrees, the ratio is approximately 1.15. This implies that it is approximately 15 percent more expensive in terms of delta-V to alter the nodal rate for TOMS-EP using the inclination as the control variable than it is using the semimajor axis. Of possible interest to future Sun-synchronous missions is the fact that ε is less than 1 for inclinations less than 98.13 degrees. In other words, it would be more efficient in terms of delta-V to use inclination as a control parameter for the MLT drift rate when affecting small changes to the inclination.

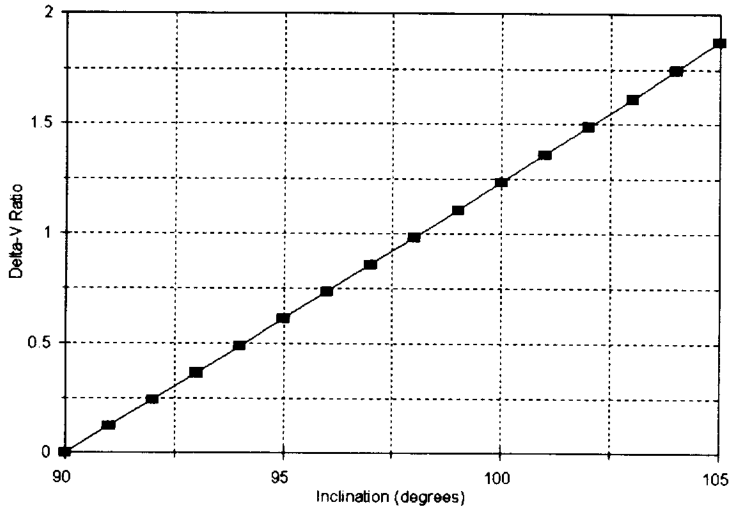

Figure 11. Delta-V Ratio as a Function of Inclination

Operational Concerns

Operational factors must be taken into account when considering the overall decision as to which control parameter to use,. To begin with, the spacecraft has a finite lifetime. Its performance, as well as that of the science instrumentation, will degrade over time. Performing maneuvers involves some measure of risk and can take time away from science operations. For example, at least four maneuvers must be executed to increase the semimajor axis, allow the node to drift down to its desired value, and then restore the semimajor axis to its nominal value. On the other hand, only half as many maneuvers are required to change the inclination, allow the node to drift back into the box, and then restore the inclination to its nominal value, provided that the adjustment to the inclination can be done in less time than the maximum maneuver duration. For TOMS-EP, the maximum maneuver duration is 35 minutes, with a nominal duty cycle of 82 percent This results in a maximum single maneuver inclination change of approximately 0.53 degree. The maximum single maneuver semimajor axis adjustment at a 955-km altitude is approximately 170 km, which would raise the circular altitude above the 1100-km limit. Since science operations cannot be conducted above 1100 km, the semimajor axis can be always be adjusted and restored to nominal in four maneuvers. If fuel is not at a premium and the necessary inclination change can be achieved in a single maneuver, it is clearly better to adjust the node rate using an inclination adjustment. This is less risky for the spacecraft and involves less operations cost and less interruption of science data collection.

Conclusions

Orbit adjustment strategies have been presented for the TOMS-EP mission for cases where the MLT of the mission orbit is outside the constraint boundaries. When the total delta-V cost is the overriding factor in the choice between the semimajor axis and the inclination as the control parameter for nodal rate adjustment, the decision can be made to first order using the ε function, which is the ratio of ΔV_i to ΔV_a. For nearly circular orbits, ε depends solely on the value of the inclination. For orbits whose inclinations are greater than 98.13 degrees, such as TOMS-EP, ε is greater than 1. However, in the case of TOMS-EP, this value is only 1.15, which is not significantly greater than 1, given the fuel budget of the mission. The choice of the semimajor axis versus the inclination as the control parameter is also dictated by operational concerns such as the maximum inclination change in a single maneuver and a desire to minimize the total number of maneuvers. Finally, it has also been shown that the size of the node rate adjustment, the available mission lifetime, and the duration prior to constraint violation are also factors in selecting a maneuver strategy.

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