# A MODERNIZED APPROACH TO MEET DIVERSIFIED EARTH OBSERVING SYSTEM (EOS) AM-1 MISSION REQUIREMENTS

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From a flight dynamics perspective, the EOS AM-1 mission design and maneuver operations present a number of interesting challenges. The mission design itself is relatively complex for a low Earth mission, requiring a frozen, Sun-synchronous, polar orbit with a repeating ground track. Beyond the need to design an orbit that meets these requirements, the recent focus on low-cost, "lights out" operations has encouraged a shift to more automated ground support. Flight dynamics activities previously performed in special facilities created solely for that purpose and staffed by personnel with years of design experience are now being shifted to the mission operations centers (MOCs) staffed by flight operations team (FOT) operators. These operators' responsibilities include flight dynamics as a small subset of their work; therefore, FOT personnel often do not have the experience to make critical maneuver design decisions. Thus, streamlining the analysis and planning work required for such a complicated orbit design and preparing FOT personnel to take on the routine operation of such a spacecraft both necessitated increasing the automation level of the flight dynamics functionality.

The *FreeFlyer*™ software developed by AI Solutions provides a means to achieve both of these goals. The graphic interface enables users to interactively perform analyses that previously required many parametric studies and much data reduction to achieve the same result. In addition, the fuzzy logic engine enables the simultaneous evaluation of multiple conflicting constraints, removing the analyst from the loop and allowing the FOT to perform more of the operations without much background in orbit design.

Modernized techniques were implemented for EOS AM-1 flight dynamics support in several areas, including launch window determination, orbit maintenance maneuver control strategies, and maneuver design and calibration automation. The benefits of implementing these techniques include increased fuel available for on-orbit maneuvering, a simplified orbit maintenance process to minimize science data downtime, and an automated routine maneuver planning process. This paper provides an examination of the modernized techniques implemented for EOS AM-1 to achieve these benefits.

## INTRODUCTION

The challenge in determining how best to support each mission is to not only look to the past to learn from successes and failures of previous missions, but to also look to the future to take advantage of new technologies. EOS AM-1 is no exception. In a similar fashion to the Landsat mission series, EOS AM-1 will fly in a Sun-synchronous, frozen orbit with a 16-day repeat cycle. This orbit necessitates frequent orbit maintenance maneuvers over the life of the mission. Modernized techniques were implemented for EOS AM-1 flight dynamics support in several areas, including launch window determination, orbit maintenance maneuver control strategies, and maneuver design and calibration automation. The benefits of implementing these techniques include increased fuel available for on-orbit maneuvering, a simplified orbit maintenance process to minimize science data downtime, and an automated routine maneuver planning process.

A cooperative effort with Lockheed Martin (the launch vehicle manufacturer) has resulted in an optimal use of the launch vehicle's capabilities that has enabled a greater than instantaneous launch window and has minimized the amount of corrective maneuvering required by the spacecraft. Once on orbit, analysis has shown that routine stationkeeping maneuvers executed as single burn maneuvers do not compromise orbital constraints. Additionally, in keeping with NASA's direction to reduce operations costs, the maneuver design process has been automated through the use of *FreeFlyer*™. This paper details these modernized approaches to meeting the AM-1 requirements described above, including updated analysis methods, simplified maneuver alternatives, and automated operations.

## MISSION OVERVIEW

The Earth Observing System AM-1 (EOS AM-1) spacecraft is an Earth Systems Science Program Office (ESSPO) initiative to explore global change and the Earth's environment. EOS AM-1 will be launched no earlier than October 6, 1998 aboard an Atlas IIAS expendable launch vehicle (ELV) from the Western Range of Vandenberg Air Force Base. After the ascent maneuvers are executed to place EOS AM-1 in its mission orbit at 705 km mean equatorial altitude, the five science instruments aboard the spacecraft will begin taking measurements of the Earth's environment. These data will later be correlated with data from related instruments on other spacecraft to provide scientists with a more in-depth view of the phenomena under study.

The EOS AM-1 mission orbit is both frozen and Sun-synchronous with a 16-day repeating ground track. The ground track must be maintained to ±20 km of the World Reference System (WRS). The frozen orbit condition must be maintained such that the altitude over a given latitude is within +10/-5 km of the nominal value at all times. In addition, the Mean Local Time (MLT) of descending node must remain between 10:15 am and 10:45 am throughout the duration of the mission to maintain constant lighting over the Earth's surface. Passive control of the 98.2 degree nominal Sun-synchronous inclination prevents the need for out-of-plane maneuvers while maintaining the constant lighting within these mission tolerances. The inclination will be biased above the

nominal value to achieve a 10:15 MLT at beginning of life, and the inclination drift with time will cause the MLT to vary slowly over the course of the mission towards 10:45 and back to 10:15, requiring no maneuver to adjust the inclination actively. For more details on this technique, see Ref. 1.


## METHODOLOGY IMPROVEMENTS

In preparing to support the launch and operation of EOS AM-1, flight dynamics analysts have incorporated several techniques into the mission plan that, while not new, have not previously been used in an optimized manner. The first of these techniques is the use of guided targeting to achieve optimal inclination targets determined on board using a polynomial to widen the launch window. The second technique involves using one burn instead of the traditional Hohmann transfer to accomplish the combined ground track and frozen orbit maintenance. Performing one burn instead of two minimizes instrument down times and periods of less-accurate data while simplifying operations. The paragraphs below describe the benefits and concern associated with the use of these techniques and provides analysis verifying the accuracy and reliability of these methods.

### Launch Window Widening

To achieve a Sun-synchronous orbit, the spacecraft must be launched at the time that the desired orbit plane passes through the launch site longitude. This time occurs once per day in the appropriate (ascending or descending) direction. Ideally, this constraint would imply an infinitely small launch window to accurately achieve the desired MLT. The length of the window may be widened around the exact launch time by making use of the permissible error range on the MLT requirement. However, this error box is often better used to eliminate inclination maintenance maneuvers. The MLT drift throughout the mission may be kept to within the MLT limits by choosing the optimum inclination for a given MLT. This strategy eliminates the need for out-of-plane inclination maintenance maneuvers. Figure 1 (Ref. 2) shows the effects on MLT drift of the optimum inclination choices for EOS AM-1 for 10:20 am and 10:40 am beginning of life MLTs. This maintenance method for Sun-synchronous orbits is described more fully in Ref. 1. When these considerations are incorporated into the analysis, the desired launch target still requires achieving the optimum combination of inclination and MLT. Therefore, a virtually instantaneous launch window is once again required.

A second option is to make use of guided targeting when available from the ELV for widening the launch window by altering the target orbit parameters during powered flight. Guided targeting is a feature often used by a vehicle to accommodate needs of various payloads, such as azimuth targeting for deep space missions and minimum parking orbit inclination targeting for geosynchronous spacecraft. The Atlas IIAS vehicle that will be used to launch EOS AM-1 is capable of guided targeting implemented though the use of a polynomial in the flight code. EOS AM-1 is taking advantage of this capability to change the inclination and MLT targets depending on the actual minute within the launch window that the ELV lifts off. Using this method, the EOS AM-1 window was widened from instantaneous to a 20 minute launch opportunity. Although the EOS AM-1 MLT limits are between 10:15 and 10:45 am indicating that a 30 minute

window would be possible, the launch vehicle is restricting its target orbits to those between 10:20 am and 10:40 am MLT. This conservative approach will to prevent exceeding the science requirements due to vehicle dispersions on the inclination, which would cause a high MLT drift rate at beginning of life. This high drift rate may cause an immediate violation of the MLT constraint.
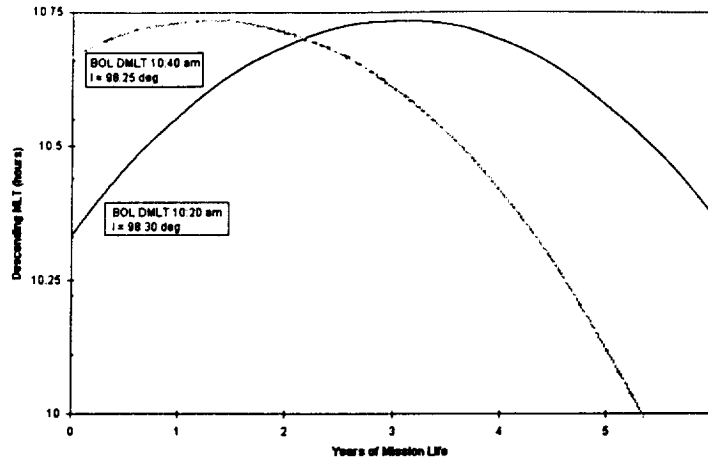


Figure 1: Optimum MLT and Inclination Targets for EOS AM-1

The Atlas flight code computes the inclination target in the following manner (Ref. 3). After launch occurs, the actual liftoff time is used to calculate the desired Greenwich Mean Time (GMT) of the descending node of the injection orbit from the equation:

$$GMT_{DN} = GMT_{LO} + \Delta t_1 + \Delta t_2 \qquad (1)$$

where:    $GMT_{LO}$ is the GMT of liftoff in seconds.
          $\Delta t_1$ is the nominal time of launch vehicle flight from liftoff to spacecraft separation (seconds)
          $\Delta t_2$ is the nominal time from spacecraft separation to the descending node (seconds)

Because the exact actual powered flight times are not known before completion of that flight segment, values must be used for $\Delta t_1$ and $\Delta t_2$ that are determined pre-launch. In addition, the flight code cannot accept multiple values for these variables based on launch time, so the same constant values of $\Delta t_1$ and $\Delta t_2$ must be hard coded for use at all points in the launch window. Since the launch will most likely occur at the beginning of the launch window, the 10:20 values for these times were computed based on simulated powered flight trajectories by Lockheed Martin and set as constants in the flight code. Then, the $GMT_{DN}$ computed in (1) may be used to compute $MLT_{DN}$, assuming a constant value for the longitude of descending node (LDN):

$$GMT_{DN} = \{MLT_{DN} - [LDN * (86400 \ sec/360 \ deg)]\}_{modulo\ 24} \qquad (2)$$

where:     LDN is the longitude of descending node (deg East). It is the angle
           measured east of the Greenwich meridian to the descending node at
           the time of the descending node crossing.

Finally, the target inclination may be computed from a polynomial of the form:

$$INC_{TARG} = C_0 + C_1(MLT_{DN}) + C_2(MLT_{DN})^2 \qquad (3)$$

where the $MLT_{DN}$ is measured in hours computed using (2), $INC_{TARG}$ is the target inclination in degrees, and the coefficients are computed before launch by fitting a curve to the optimal inclination and MLT targets for each minute of the launch window as shown in Figure 2 (Ref. 2). For the data in Figure 2, $C_0 = 80.987296$, $C_1 = 3.460392$, and $C_2 = -0.172758$. These values of inclination and $MLT_{DN}$ computed during flight augment the specified altitude target to fully determine the ELV target orbit.
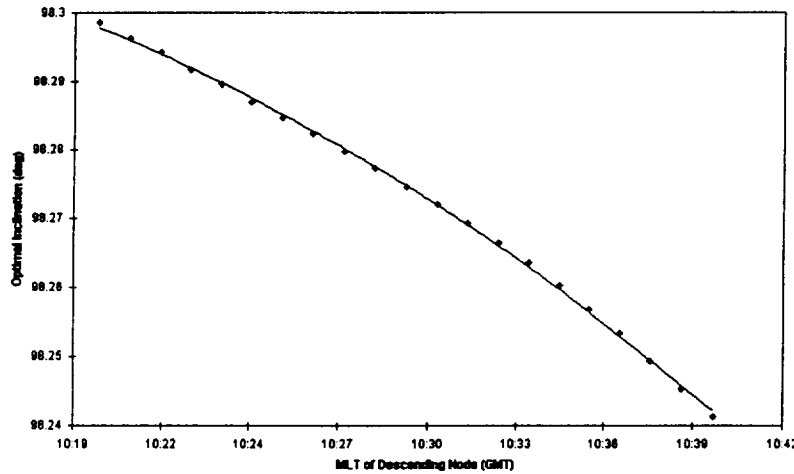


Figure 2:  Optimum MLT targets for EOS AM-1 Injection

        One issue raised about this technique is that when using a constant value for the $\Delta t$'s and the LDN in the above equations, the error caused by using one value over the whole launch window might outweigh the benefits of using the guided targeting. This concern arose because the inclination targets varied only 0.05° over the 20 minute launch window. It was eventually decided that holding the values constant did not cause a problem based on the analysis described below. Note that although the ELV is only contractually obligated to provide inclination accuracy within 0.1°, historical data has shown that Atlas vehicles routinely achieve inclination targets to within hundredths of a degree of the targeted value. Therefore, the targeted values are a reasonable goal for the mission. The closer the vehicle can place the spacecraft to its targeted inclination, the less fuel the spacecraft will have to spend on operationally complex out-of-plane inclination maneuvers to return to the optimum initial state.

        Lockheed Martin supplied optimized trajectory runs for 10:20, 10:30, and 10:40 optimum $MLT_{DN}$ and inclination targets. Flight Dynamics used these data and held the LDN and $\Delta t$'s from the 10:20 nominal trajectory constant over the whole launch window to compute the inclination target, as will be done in the flight code. The target

inclination was then computed using equations (1) - (3) for each minute of the window. Values for the beginning, middle, and end of the launch window are shown in Table 1.

Table 1
INCLINATION TARGETS USING BEGINNING OF WINDOW LAUNCH
CONSTANTS

| MLT Targeted | $GMT_{LO}$ | $\Delta t_1$ | $\Delta t_2$ | $GMT_{DN}$ | LDN | LMST (hours) | INC Target |
|---|---|---|---|---|---|---|---|
| 10:20 | 67065.8 | 820.3867 | 126.6371 | 68012.82 | 231.5716 | 10.33333384 | 98.29827 |
| 10:30 | 67665.8 | 820.3867 | 126.6371 | 68612.82 | 231.5716 | 10.50000051 | 98.27531 |
| 10:40 | 68265.8 | 820.3867 | 126.6371 | 69212.82 | 231.5716 | 10.66666717 | 98.24275 |

The worst case encountered in this analysis is a launch at the end of the window while achieving the $3\sigma$ LDN dispersions on the target state. If the 98.24275° target 10:40 state above is compared with the optimum inclination of 98.2413°, the difference is -0.001446309° in inclination, well within the inclination dispersion allowance of 0.1°. If non-constant values of LDN and $\Delta t$ had been used, the 10:40 target would be computed using the optimal 10:40 LDN and $\Delta t$'s, yielding 98.24115°, a difference of 0.00015° from the target computed using 10:20 constants.

The worst-case LDN dispersions computed by Lockheed Martin are +/-0.060525° for a 10:30 am target orbit. Applying these dispersions to the 10:20 data above (assuming similar dispersions regardless of when in the launch window liftoff occurs), the targets may be recomputed using the maximum ($LDN_{1020}$+0.060525°) and minimum ($LDN_{1020}$-0.060525°) LDNs. Results indicate that the maximum LDN dispersion case causes the 10:40 target to exceed the MLT box by **10.66792605**-10.66666666 = 0.00125939 min, well within the 0.5 min allowable dispersion. For the minimum LDN dispersion case, the 10:20 target exceeds the MLT box by 10.33333333-**10.32652272** = 0.00681061 min, also well within the 0.5 min allowable dispersion.

These analyses show that guided targeting as is used for the EOS AM-1 launch is a technique that works well for Sun-synchronous orbits. Thus a technique that is applied regularly to deep space and geosynchronous orbits has been shown to produce significant improvements in the low-Earth regime.

**Frozen Orbit Control**

Having thus improved the launch and ascent process, the maintenance of the mission orbit was also examined for possible improvements. In addition to maintaining the ground track control grid, the science instruments on EOS AM-1 dictate that only small altitude changes can occur over any given latitude. Consequently, a frozen orbit is implemented to constrain the mean argument of perigee near 90 degrees. Freezing the orbit requires a mean eccentricity of 0.00116 for the mission altitude and inclination. If no ground track control maneuvers were required, some infrequent frozen orbit maintenance maneuvers would be required over the life of the mission to reshape the orbit. However, since the mission requires frequent altitude maneuvers, these maneuvers can be used to simultaneously restore the frozen orbit while performing ground track control. The key to utilizing the altitude maneuvers to simultaneously meet the frozen

orbit constraints is to perform the burns at a location in the orbit that will restore the orbit shape rather than degrade it. The location of the single burn within the orbit should be chosen to place the post-maneuver mean eccentricity and argument of perigee as close as possible to nominal values (0.00116 and 90 degrees, respectively). The maneuvers are placed alternately in the two locations, separated by about 180° anomaly, that the Hohmann transfer maneuvers would normally be placed to restore the frozen orbit.

Because it is desirable for operational reasons (less downtime for instruments, less data interruption, less maneuver planning) to perform the least number of maneuvers possible and still maintain the orbit within the science requirements, the technique of using only one maneuver instead of the traditional Hohmann transfer pair to maintain the AM-1 ground track was designed into the AM-1 support. A single maneuver has the same total ΔV as the pair and is placed appropriately to maintain the frozen orbit condition. This technique was used with success to maintain the semi-frozen orbit of Landsat-5. AM-1 has a more stringent requirement to maintain its frozen altitude to within +10/-5 km mean altitude and ±20° mean argument of perigee. Therefore, analysis was required to investigate the effects of the location of single ground track correction maneuvers within the orbit on the frozen orbit condition.

An algorithm was developed for the Flight Dynamics Analysis Branch that determines the best location to perform a single burn to drive the orbit back to the optimal frozen conditions. This algorithm was easily integrated into AI Solutions' object-oriented *FreeFlyer*™ product and is used as part of the automated ground track maintenance maneuver planning process. The algorithm (Ref. 5) requires as input the initial mean semi-major axis, argument of perigee, and eccentricity, as well as the values of the ΔV and burn duration required for the ground track maintenance maneuver that will be accomplished in combination with the frozen orbit maintenance. First, the average orbit velocity is computed from the mean semi-major axis (a) as:

$$V_{avg} = 1000\sqrt{\frac{\mu_{Earth}}{a}} \text{ m/s} \tag{4}$$

Dividing the total desired ΔV for the ground track maneuver by the burn duration yields a ΔV per second, δv. Then the standard variations of Keplerian elements under this ΔV are given by:

$$\Delta e = \frac{2\delta v(e + \cos MA)}{V_{avg}} \tag{5}$$

$$\Delta \omega = \frac{2\delta v \sin MA}{eV_{avg}} \tag{6}$$

Applying these equations iteratively over the duration of the maneuver allows the initial Keplerian elements to be coarsely propagated. After each iteration, the mean anomaly (MA) is calculated using:

$$MA^{(n)} = MA^{(n-1)} - \Delta\omega + \sqrt{\frac{\mu_{Earth}}{a^3}}\Delta t \qquad (7)$$

The initial MA may then be varied parametrically to determine the value that best achieves the desired frozen orbit conditions. Figure 3 shows a scan over one orbit at 2° mean anomaly increments. The $\Delta V$ is applied at each step and the post-burn eccentricity and argument of perigee computed. The area highlighted by the circle in Figure 3 shows where the set of post-burn solution points most closely intersects the target point of 0.00116 and 90°. This intersection point corresponds to a mean anomaly of 49°, where the computed values are 90.22° and 0.0011689, respectively. The point of 0° MA and the direction of increasing MA are both indicated in the figure.



Scan of Burn Location to Restore Frozen Conditions
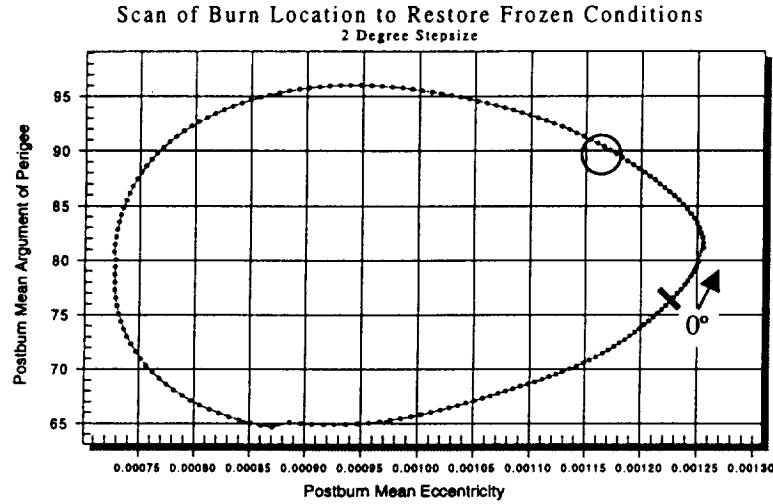2 Degree Stepsize

Figure 3: Optimum Mean Anomaly to Achieve EOS AM-1 Frozen Orbit

The frozen orbit evolution for an 18-month span with maneuvers determined using this algorithm is shown in Figure 4. The figure indicates that performing the single maneuver ground track corrections at the optimum frozen orbit restoration location achieved the maintenance of the mean argument of perigee to within the ±20° allowed by the mission requirement. The straight line portions of the plot indicate places at which the maneuvers were performed.

The radial position constraint of +10/-5 km in mean altitude is then met by default, since the argument of perigee requirement is the more stringent of the two as described in Reference 4. This result may be easily seen when examining Figures 5 and 6 from Reference 4, which show the frozen orbit evolution for eccentricities that are increments of 0.002 higher (Figure 5) and lower (Figure 6) than the nominal 0.00116 value. The center ellipse in each figure is the nominal eccentricity, and ellipses moving out from the center are incrementally higher or lower, respectively. Based on both figures, the eccentricity must not deviate more than ±0.004 from the nominal value. For an argument of perigee deviation of ±20°, keeping the eccentricity deviation within these bounds requires constraining the altitude to within approximately +3.7 km/-2.3 km of the 705 km mean nominal, as shown in Figure 7 (Ref. 4). Since these altitude restrictions are

tighter than the required +10/-5 km limits, maintaining the argument of perigee will ensure that the radial position requirement is not violated.
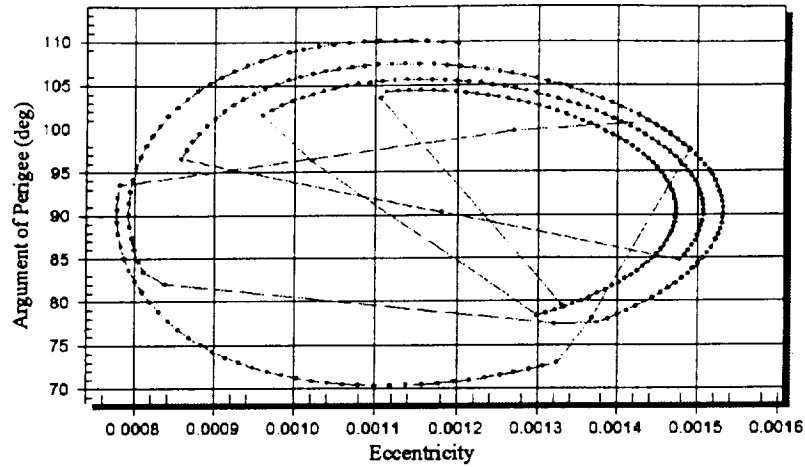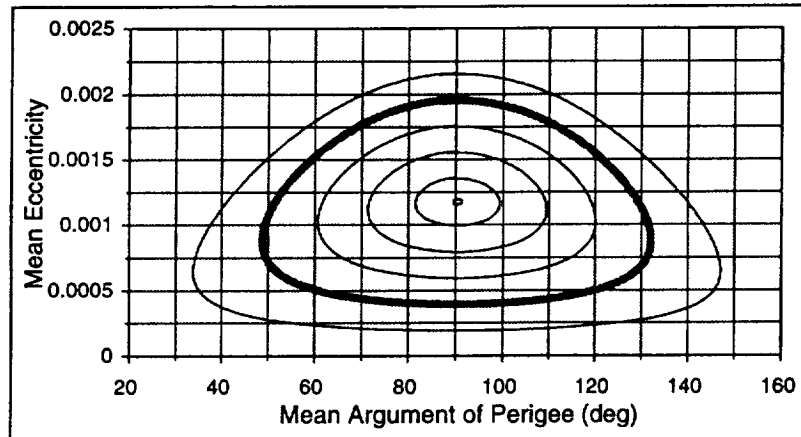


Figure 4: 18-Month Frozen Orbit Evolution



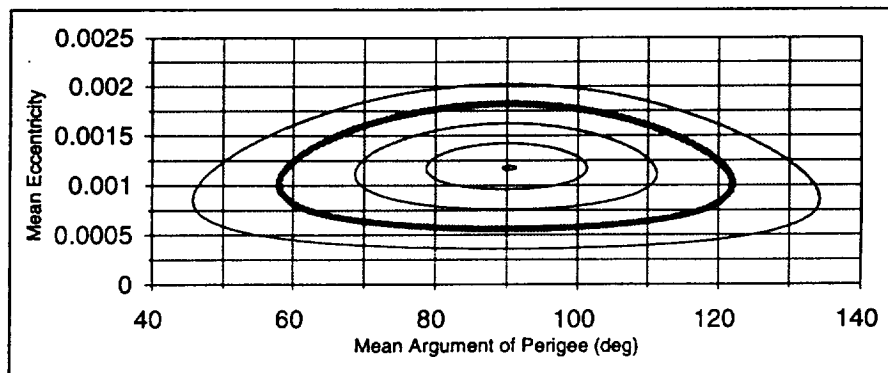Figure 5: Frozen Orbit Evolution for Eccentricities of 0.0002 Increments Above Nominal



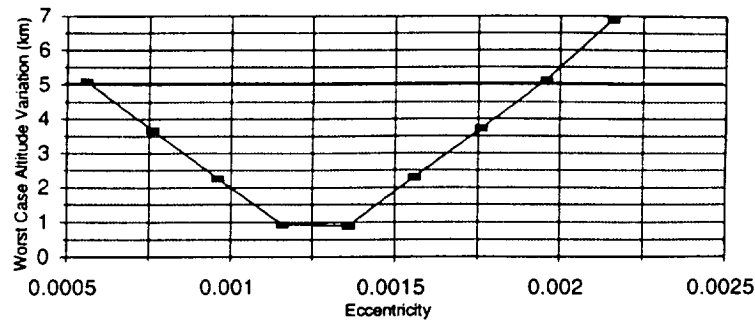Figure 6: Frozen Orbit Evolution for Eccentricities of 0.0002 Increments Below Nominal

Figure 7: EOS AM-1 Altitude Variation vs. Eccentricity

## ADVANCEMENTS IN OPERATIONS TECHNIQUES

Flying a spacecraft with multiple orbital and operational constraints such as EOS AM-1 traditionally requires experienced personnel to design, plan, and execute maneuver control strategies. Current directions in NASA are driving towards more streamlined, "lights-out" environments in which spacecraft operators are only present during the day shift. This change of approach forces operators to perform a variety of functions more efficiently. The *FreeFlyer*™ mission design and operations software, a commercial off-the-shelf (COTS) product developed by AI Solutions, Inc. under contract to NASA GSFC, provides the analyst with all the functionality required to design and test various control strategies. More importantly, this same strategy is then easily automated in the operations environment.

There are two factors that must be addressed in the mission design process. The first is examining the orbit mechanics to determine the best way to achieve and maintain an orbit that will meet the science requirements. The second, equally important factor is to address the real-world operational issues that must be included in any maneuver plan. For example, the basic physics behind the ground track control problem is to adjust the orbit period using altitude control. The operational constraints can include ground station viewing requirements and lighting constraints. *FreeFlyer*™ is designed to include both types of considerations in the design process.

### The Physics - Ground Track Control

As described earlier, the ground track pattern for EOS AM-1 must remain within ±20 km of the WRS grid. In order to use the full ±20 km ground track control box, the orbit must be raised above the nominal altitude, causing the period to be greater than that of the nominal altitude. In that case, the spacecraft takes longer than nominal to reach the descending node, the Earth turns farther under the orbit plane, and the ground track drifts westward. When the nominal altitude is reached, there is no drift. As the period of the orbit continues to decrease, the spacecraft to reaches the descending node earlier each orbit and the ground track error drifts eastward. The drift continues eastward to the edge of the control box. Consequently, periodic altitude raising maneuvers are required prior to reaching the eastern boundary to reset the ground track to the eastern edge of the box. After the maneuver, drag will again act on the orbit and will slow the westward drift rate

until it begins to drift eastward again. This repeated process of the ground track control problem appears as a scalloped-shaped plot as shown in Figure 8, where maneuvers are executed at the peaks and nominal altitude is reached in the troughs.
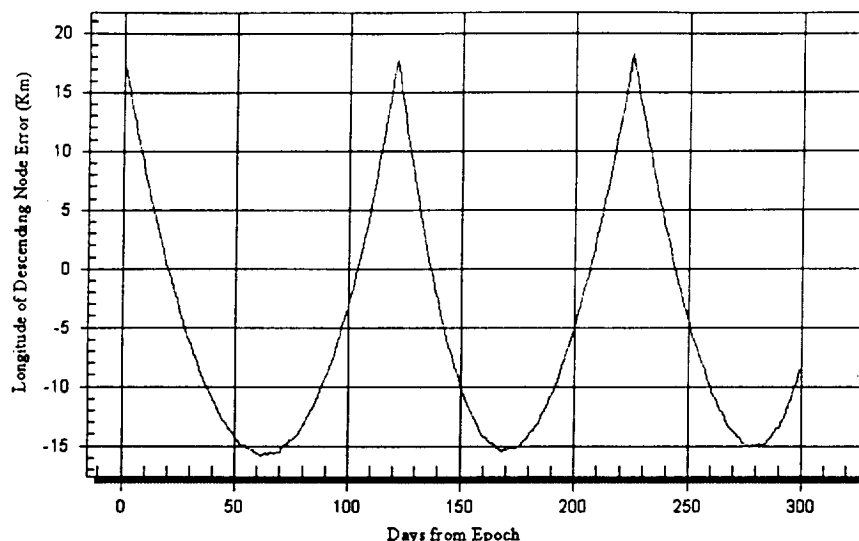


Figure 8: EOS AM-1 Ground Track Control for ±20 km Error Box

Since the ground track drift is due largely to atmospheric drag effects and since the EOS AM-1 mission will span periods of both low and high solar flux, the frequency of the maneuvers will vary greatly over the mission lifetime. Also, the magnitude of the maneuvers can vary by factors of up to four between the solar maximum and the solar minimum. This variability has been handled historically by sizing the ground track maneuvers by hand to see what size burn will turn the drift westward while not overshooting the westward boundary. Stated differently, the analyst would test burn sizes until the turnaround point was at an acceptable limit near the western edge. This requires analyst knowledge of acceptable limits, drift rates, and flux predictions.

In *FreeFlyer*™, this process has been automated by numerically implementing the same strategy. The burn size is determined using an internal targeting algorithm based on a differential corrector incorporated into *FreeFlyer*™. Each iteration is evaluated by checking the longitude error at the turnaround point. This point is numerically defined as the location where the derivative equals zero. Since the longitude error data points contain small oscillations as shown in Figure 5, a running average of the data is first computed to smooth the curve so that a derivative may be calculated accurately.

Figure 9 shows the results of a maneuver targeted with the method described above. In this figure, an initial guess is tested in the curve labeled (1), a perturbation is applied along (2), and then the first iteration (3) is computed, tested, and accepted. This strategy minimizes the analysts' time pre-launch and allows the FOT to perform functions operationally without prior understanding of the problem.
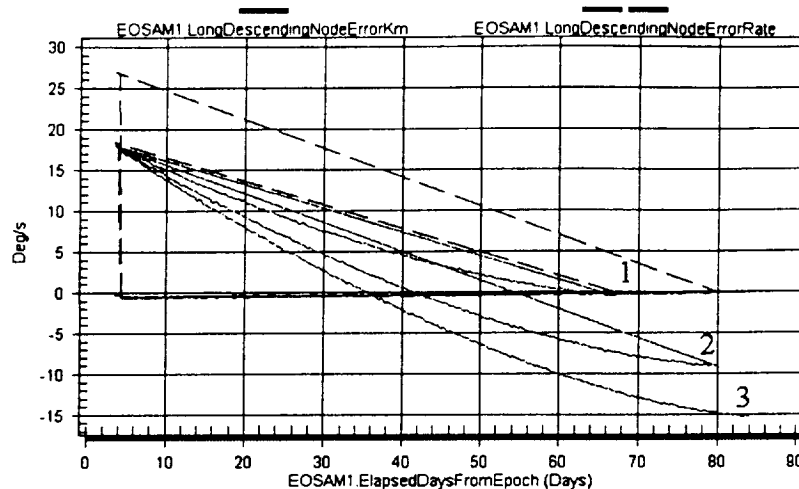
Figure 9: Ground Track Maneuver Targeting

In addition to designing and maintaining the orbit to meet science requirements, the operations environment places restrictions on the orbit design as well. These restrictions are often arbitrary and not related to the mechanics of the design itself.

*FreeFlyer*™ is designed to automate operations by addressing both the physics and these operational requirements. The control language in the program allows the user to require any number of conditions to be met before performing an action. Therefore the user can state that if the need for a maneuver is detected and the spacecraft is in view of a ground station and the spacecraft is not in shadow, then the software should plan and execute the required maneuver.

However, since a maneuver plan will not always be comprised of true/false conditions, *FreeFlyer*™ contains a fuzzy logic engine to resolve conflicting constraints or to allow constraint weighting. For example, if a soft boundary is reached, there may be time to wait for an ideal maneuver location. However, if the hard boundary is reached an immediate burn may be required. Some examples of these principles as they are being used for the EOS AM-1 mission are described in the remainder of this section.

## Operational Considerations – Calculable Parameters

A key component to automated maneuver planning is to include operational considerations, such as lighting conditions or maximum thruster on-times. While some constraints are either true or false, others may be approximate constraints. *FreeFlyer*™ provides a mechanism that allows mission constraints to be defined and evaluated in terms of approximations. For instance, a basic maneuver to raise perigee would not necessarily need to occur exactly at apogee, but rather near apogee to allow other constraints (such as acquiring a ground station) to be satisfied.

*FreeFlyer*™ contains a mechanism that allows combinations of constraints to be evaluated simultaneously and resolved into acceptable actions, even when these constraints appear to conflict. This mechanism is fuzzy logic. Fuzzy logic has been used

for control systems in cameras, subways, and automobiles to resolve conflicting control goals. *FreeFlyer*™ takes this technique and applies it in the orbit control regime.

Perhaps the least glamorous and yet most valuable example of an operational constraint utilizing fuzzy logic is time. With the staffing of the prime operations support shift during normal business hours, the scheduling of maneuver times is a key component of the EOS AM-1 control strategy. For AM-1 the FOT desired to restrict the maneuvers to occur mid-week during the late afternoon, allowing sufficient time to plan and execute the burn in a single shift. In *FreeFlyer*™, the day of the week and time of the day for maneuvers can be added easily into the control logic of the maneuver plan.


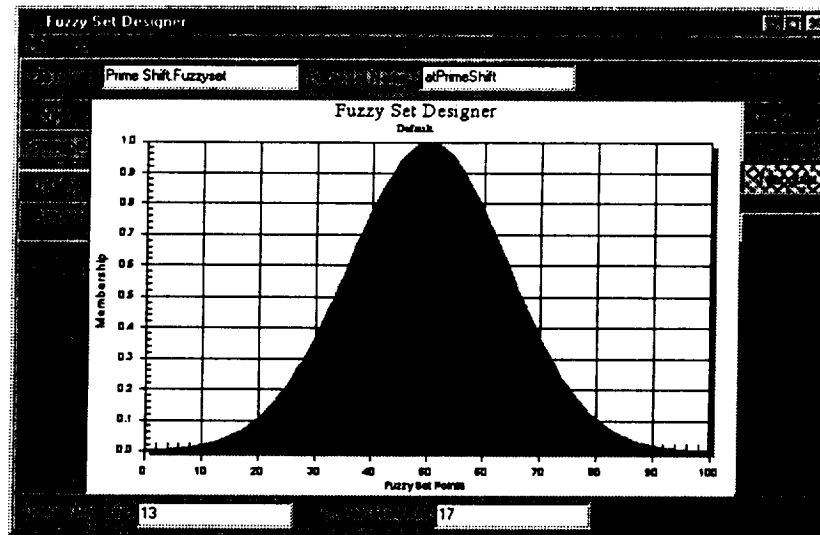
Figure 10: Fuzzy Set Utility in *FreeFlyer*™

A fuzzy set representing the time of day is shown in Figure 10. The set is defined over a domain ranging from 13 to 17, representing the Greenwich Mean Time (GMT) of a day measured in hours. This domain was chosen to correspond to midday local time/EST. The shape of the set is used to weight the importance of the maneuver time in the control logic. Higher values (i.e. higher "degrees of membership" in the fuzzy logic sense) represent more acceptable solutions. This fuzzy set can then be used in *FreeFlyer*™ as a component of the decision algorithm configured by the user. More specifically, the user controls the maneuver plan using the following syntax:

```
If   (AM1.LongitudeError  >  18   and  AM1.TimeOfDay   is
atPrimeShift) then Maneuver EOSAM1
```

This command line (taken literally from a *FreeFlyer*™ control script, with slight modification for clarity) evaluates the error in the EOS AM-1 ground track and the time of day at the operations center for a modeled spacecraft epoch, and plans a maneuver if the error in the ground track is approaching the control boundary at a time of day that is acceptable for maneuver execution.

**Operational Considerations – Non-Calculable Parameters**

The time of day, shadow conditions, or ground station coverage are events that can be readily computed in *FreeFlyer™*. EOS AM-1 also requires the interpretation of man-made constraints. The requirement on the ground track control maneuvers is that EOS AM-1 must be in view of one of the TDRS satellites. For long-range planning, the location of the maneuver is tested to determine if the spacecraft is outside the TDRS zone of exclusion. For final maneuver plans, however, this is not sufficient.

A contact schedule for EOS AM-1 is delivered electronically on a weekly basis. This schedule contains the allotted contact opportunities with the TDRS system, a subset of the geometrically possible contacts computed in *FreeFlyer™* . The contacts are approximately 10-minutes in duration and occur approximately twice per orbit. To ensure that the maneuver is planned within these scheduled passes, an ASCII file containing the weekly schedule is read by *FreeFlyer™*, and is converted to fuzzy sets based on the spacecraft epoch. These fuzzy sets are then incorporated into the control script in a manner similar to that discussed above for the time of day constraint. The new control logic takes the form (Ref. 6):

```
Load InTDRSContact from TDRS_Schedule using AM1.Epoch;
If (AM1.LongitudeError > 15 and AM1.Epoch is atPrimeShift
and AM1.Epoch is InTDRSContact) then Maneuver EOSAM1
```

The analyst literally sets the control logic using this kind of near-natural language technique. The shapes of the fuzzy sets can easily be modified using extensions to the control language.

The flexibility provided by *FreeFlyer™* for orbit control makes it an extremely powerful tool for mission analysis, planning and operations. The tool addresses needs in the user community that have been identified for a number of years, and moves the satellite control regime much closer to autonomous operations.


## CONCLUSION

EOS AM-1 has been able to realize cost savings in several areas. First, the expert flight dynamics personnel will only be required to support the mission post-launch in a consultation standing. FOT personnel will be able to include the routine flight dynamics activities into their daily schedule with a minimum of impact due to the high level of automation. Maneuvers will be restricted to the nominal work hours of the prime shift. In addition, time spent by the flight dynamics experts in planning special maneuvers, like the ascent sequence, has been drastically reduced by eliminating the need for running multiple pieces of software in parametric runs.


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