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PAPER AAS 94-165

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USING ANOMALOUS ALONG-TRACK FORCES TO CONTROL THE TOPEX/POSEIDON GROUND TRACK*†

Bruce E. Shapiro, Ramachandra S. Bhat, and Raymond B. Frauenholz**

The TOPEX/POSEIDON ground track maintenance maneuver targeting strategy was changed following launch due to the observation of unexpected, and hence anomalous, accelerations. These accelerations can cause changes in the ground track drift rate comparable to those produced by drag. They exhibit a body fixed character and can cause orbital decay or boost depending on the satellite and solar array attitude. In addition, the anomalous accelerations can sometimes provide a passive (i.e., not expendible) technique to apply a desired boost or decay to the orbit. Varying the times of transition between the satellite's yaw modes effectively implements *micro-maneuvers* equivalent to thrust maneuvers with $\Delta V < 1.0$ mm/sec. This activity, which considerably simplifies ground track maintenance, has been performed several times.

INTRODUCTION

TOPEX/POSEIDON was launched by an Ariane 42P on August 10, 1992 with injection occurring at 23:27:05 UTC, approximately 19 min. 57 sec after lift off. The joint US/French†† mission is designed to study global ocean circulation and its interaction with the atmosphere to better understand the Earth's climate.[1,2] This goal is accomplished utilizing a combination of satellite altimetry data and precision orbit determination to precisely determine ocean surface topography. To facilitate this process the satellite is maintained in a nearly circular, frozen orbit ($e \approx 0.000095$ and $\omega \approx 90°$) at an altitude of ≈1336 km and an inclination of $i \approx 66.04°$. This provides an exact repeat ground track every 127 revolutions (≈9.9 days) and overflies two altimeter verification sites: a NASA site off the coast of Point Conception, California (latitude 34.4691° N, longitude 120.68081° W), and a CNES site near the islands of Lampione and Lampedusa in the Mediterranean Sea (latitude 35.54649° N, longitude 12.32054°E)[3]. The operational orbit was acquired on September 21, 1992, some 42 days after launch, following a sequence of six orbital acquisition maneuvers.[4]

The Jet Propulsion Laboratory (JPL) is responsible for conducting all satellite mission operations including operational navigation. Operational orbit determination using radiometric data acquired via the NASA Tracking and Data Relay Satellite System (TDRSS) is provided by the Flight Dynamics Facility (FDF) of NASA's Goddard Space Flight Center (GSFC).[5]

Satellite fixed accelerations equivalent to continuous body-fixed forces on the order of several micro-newtons began to be observed shortly after launch.[6,7] Higher accelerations observed immediately after launch were attributed to "outgassing", a complex process of molecular release from satellite non-metallic components. These accelerations declined steadily

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and the presence of residual accelerations were observed after attaining the operational orbit. The residual accelerations exhibited a body fixed origin and caused orbital decay or boost depending on the satellite and solar array attitude. These residual forces are believed to arise due to a combination of solar array curling, thermal imbalances, radiation forces, and outgassing.[8] Although they are predictable and have been described using detailed thermal models, since the residual forces were not predicted by orbit analyses prior to launch they are referred to *en masse* as *anomalous forces*. Since the anomalous force demonstrates some characteristics resembling a signed drag force, it is sometimes referred to as a *boost force*.

Orbit maintenance maneuver design was originally expected to depend primarily on the effective prediction of atmospheric drag.[9,10] Reliable predictions of the anomalous forces are also necessary, since these are of the same order of magnitude as drag. These forces are determined in terms of an effective thrust parameter $(1+\tau)$ as a part of routine orbit determination. An empirical model was developed based on the observed thrust dependence on satellite attitude, solar array pitch bias angle, and β', the angle between the orbit plane and the sun line. This model has been continuously refined using observations of the thrust parameter and the prediction uncertainty has been reduced with time. By varying the times of transition between periods of fixed yaw and continuous yaw steering, extra boost or decay can be applied to the orbit, and hence used to modify the ground track drift. The result of these changes to the attitude control strategy is the effective implementation of *micro-maneuvers* with typical maneuver magnitudes of $\Delta V < 1.0$ mm/sec.

This paper discusses the use of the anomalous force to implement micro-maneuvers to prevent the ground track from leaving the control band. The circumstances which led us to implement micro-maneuvers are described. Modifications to the maneuver design strategy and error models necessitated by the existence of these forces are presented. The use of the anomalous forces to perform additional ground track maintenance and extend the time between maneuvers is described. Finally, our overall success at ground track maintenance under the influence of these forces during the TOPEX/POSEIDON mission is summarized.

ANOMALOUS FORCE

Pre-launch analysis indicated that central body gravity and drag were the principal perturbing forces acting on the ground track, even though the orbital altitude is relatively high at ≈1336 km. Luni-solar gravity produces periodic perturbations which are sometimes comparable in magnitude to drag; these perturbations can either accentuate or reduce the effects of drag. The extreme sensitivity to drag is a consequence of the stringent ±1km ground track control requirement.[9]

Analysis of tracking data obtained subsequent to launch indicated the existence of an unmodeled anomalous force acting upon the satellite.[6] The magnitude of this anomalous force is equivalent to that of a continuous thrust on the order of micro-newtons. The direction and magnitude are a function of the satellite attitude, solar array pitch offset angle, and β', the angle between the orbit plane and the Earth-sun line (Figure 1). The anomalous force is modeled in terms of a thrust parameter $(1+\tau)$ as part of the routine orbit determination performed by GSFC/FDF. An empirical model, shown in Figure 1(a), was developed by representing τ as a function of β'. The thrust is converted into an equivalent rate of change in the semi-major axis (da/dt). The model assumes that the anomalous force will repeat with the same characteristics as an explicit function of β' during subsequent β' cycles (≈56 days).

Nearly continuous yaw steering of the satellite about the local nadir and solar panel pitching are utilized to maintain the dominant 28 m^2 solar panel pointed toward the sun for power optimization. The actual pitch angle is offset from the true sun line to control the rate of battery charging, and is a function of solar-array degradation level. The pitch offset is changed only rarely (approximately annually). The satellite yaw is nominally held fixed whenever $|\beta'| < 15^\circ$.

Two different fixed yaw angles are used: yaw = 0° when $0° < \beta' < 15°$ *(flying forward)*, and yaw = 180° when $-15° < \beta' < 0°$ *(flying backward)*. When $|\beta'| > 15°$ the satellite is continuously yaw steered. When $\beta' > 0$ this is referred to as *positive yaw steering*, and when $\beta' < 0$ it is referred to as *negative yaw steering*. The anomalous force causes an orbital boost during negative yaw steering and causes decay during positive yaw steering. A larger boost is applied during fixed yaw flying forward then during negative yaw steering, and a larger decay is applied during fixed yaw flying backward than during positive yaw steering.

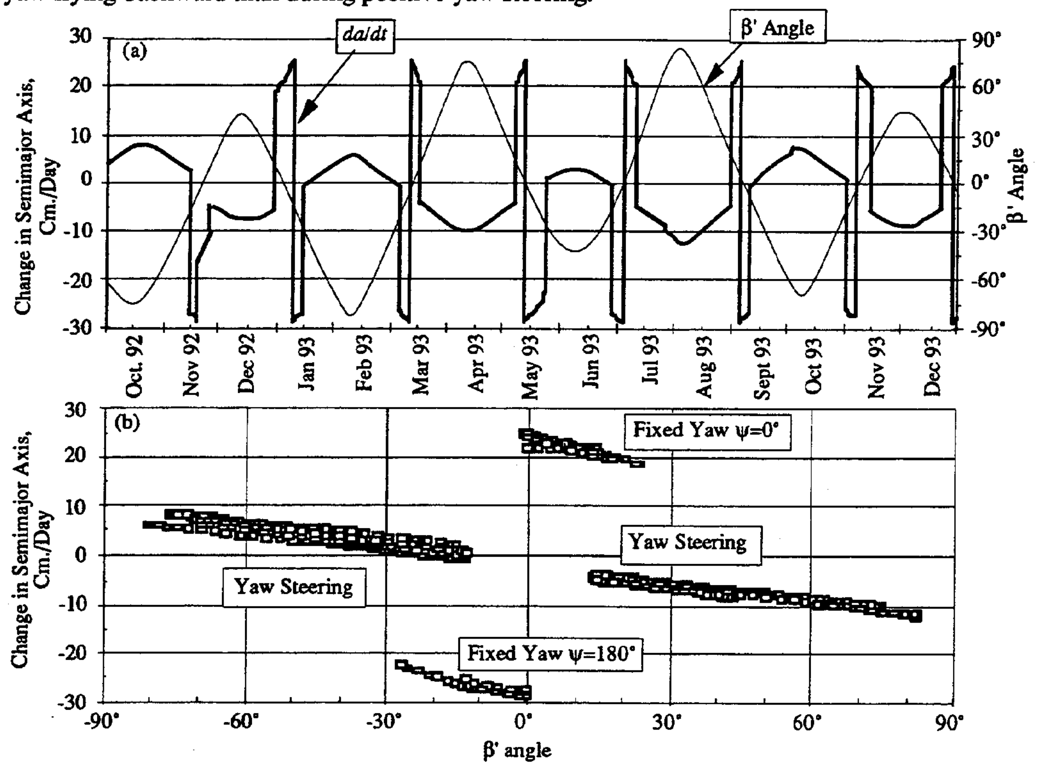

Figure 1. (a) The anomalous force and β' cycle; (b) repeatability as a function of β'.

The anomalous force results in a change of the semi-major axis of approximately of 3-10 cm/day during yaw steering and 25-30 cm/day during the fixed yaw periods after the effects of all other known forces, including drag, are taken into account. Drag produces a decay ≈ 5 – 15 cm/day, and hence the anomalous force has the same order of magnitude of effect upon the orbit as the largest orbital perturbation. However, the magnitude of the force does not repeat identically for similar β' conditions. Significant modeling improvements were realized by the time of the second orbit maintenance maneuver (OMM2, December 21, 1992). The uncertainty in the anomalous force prediction was $\sigma \approx 1.2$ cm / day during yaw steering and $\sigma \approx 4.5\, cm/day$ during fixed yaw.

GROUND TRACK MAINTENANCE REQUIREMENTS

Since achieving the operational orbit on September 21, 1992, periodic orbit adjustment maneuvers have been implemented to maintain the ground track and ensure that all verification site over flight requirements are met. Mission requirements limit the scheduling of maneuvers so that they occur on an interference-free basis with scientific data acquisition and precision orbit determination (POD). Specific requirements are summarized as follows:[1]

1. Maintain the operational orbit so that at least 95% of all equatorial crossings at each orbit node are contained within a 2 km band measured longitudinally.
2. Maintain the operational orbit during the initial verification phase so that it overflies designated locations at two verification sites within ±1 km on at least 95% of the planned over flights.
3. Maintain the eccentricity $e < 0.001$. This requirement is automatically met by utilization of the frozen orbit, which is not *per se* a mission requirement.
4. Perform the minimum practical number of orbit maintenance maneuvers during the initial verification phase, with a minimum of 30 days between maneuvers with 95% probability and whenever the 81-day mean 10.7 cm solar flux satisfies $\overline{F_{10.7}} \leq 225$.
5. Orbit maintenance maneuvers are to be performed as nearly as possible to the transition between 127-orbit repeat cycles (±1 rev).
6. The spacing between maneuvers shall be as large as practical during the observational phase of the mission.
7. Maintenance maneuvers are to be performed over land wherever possible.

In addition, maneuvers are generally scheduled to allow time for a backup one cycle (≈9.9 days) later without violating the ±1 km control band. This shortens the mean time between maneuvers. Furthermore, since the three-axis stabilized spacecraft utilizes nearly continuous sinusoidal yaw steering and solar array pitching for optimal solar-array pointing, maneuver execution entails performing a complex "turn-burn-turn sequence." Consequently, the scheduling of a maneuver is tightly constrained to prevent any compromise to satellite health and safety. Yaw steering must be temporarily suspended and the satellite slewed to the appropriate attitude to correctly orient the thrusters for maneuver execution; this yaw slew is subsequently "unwound" after the maneuver. The overall duration of this "turn-burn-turn" maneuver sequence varies depending upon the initial yaw rate and turn angle. Additional maneuver design requirements are derived from thermal, power, and satellite attitude control constraints and capabilities. Because of the constraints upon maneuver design it is preferable to extend the time between maneuvers as far as possible.

GROUND TRACK MAINTENANCE MANEUVER DESIGN

The principal maneuver design program is GTARG*, which utilizes an analytic mean-element propagator including all perturbations that are known to cause significant variations in the satellite ground track.[11] These include earth oblateness, luni-solar gravity, and drag, as well as the thrust due to impulsive maneuvers. Recursion relations are used for the Earth geopotential and luni-solar gravitational forces. Zonal harmonics to J_{20} are included. A satellite unique drag model is used which incorporates an approximate mean orbital[10] Jacchia-Roberts atmosphere[12,13] and a variable mean area (VMA) model.† Targeting strategies will either (a) maximize the time between maneuvers (*longitude targeting*) or (b) force control band exit to occur at specified intervals (*time targeting*). A runout mode allows for ground track propagation without targeting. Error models include uncertainties due to orbit determination, maneuver execution, and drag unpredictability. Maneuver Δv magnitudes are targeted to precisely maintain either the unbiased ground track itself, or a comfortable error envelope about the unbiased ground track. As will be

* GTARG was developed for the TOPEX/Poseidon mission and has been submitted to COSMIC.

† The VMA (Variable Mean Area) model[9] defines the mean drag area over an orbit as a tabular function of β'. This model is used by both GTARG and DPTRAJ since the calculation of a continuously variable area would be computationally intense. The true area is a rapid periodic function of orbit angle whose extrema are a slowly varying function of β'.

discussed below, GTARG was modified during mission operations to incorporate the effects of additional anomalous along-track forces and their errors.

Solar flux ($F_{10.7}$) and geomagnetic parameter (K_p) predictions are based on the daily SESC* 3-day and weekly 27-day outlook.[14] The latest outlooks are combined with observed data to generate a merged 27-day data set. Missing data are determined by linear interpolation. The solar flux is then extrapolated by repeating the merged data set as required for the prediction span. A slope describing the long term variation of the solar cycle is applied to the merged data set. The slope is derived from a fifth order polynomial fit to the SESC regression model prediction of $F_{10.7}$ for the remainder of the solar cycle. The geomagnetic data are extrapolated at a constant value equal to the average K_p over the first 27 days.

Earlier analysis[9] indicated that density estimation errors would strongly dominate the ground track prediction at all times except during the lowest period of solar flux ($\overline{F_{10.7}} \approx 70$). As such, a simple longitude targeting strategy incorporating the ±95% anticipated errors (±1.96σ) in all error sources would be satisfactory. This strategy biases the targeted ground track eastward so that the 95% envelope is made just tangent to the western edge of the control band (see Figure 2) The width of the error envelope $\sigma_{\Delta\lambda}$ at any time is calculated as

$$\sigma_{\Delta\lambda} = \sqrt{\sum_i k_i \sigma^2_{\Delta\lambda,i}} \tag{1}$$

where $\sigma_{\Delta\lambda,i}$ is the 1-σ error in the ground track due to error source i, the k_i are weight factors, and the sum ranges over all error sources.[11,15] The confidence level represented by the error envelope is determined by the size of the scale factors k_i , which give the contribution of error source i to the width of the envelope. By assuming that the error sources can be represented as normally distributed random variables, 1.96σ provides a 95% confidence envelope.

Once maneuvers have been successfully targeted with GTARG, the maneuver ΔV is validated with DPTRAJ. DPTRAJ utilizes a predictor-corrector integrator with automatic step size control[16,17] and has the capability of incorporating all relevant perturbing sources including finite maneuvers, anomalous force, Earth oblateness, luni-solar gravity, atmospheric drag, solar radiation pressure, solid earth tides, polar motion, precession, and nutation.

MODIFICATIONS TO GROUND TRACK MAINTENANCE STRATEGY

GTARG was modified to incorporate the along-track satellite-fixed force via a table look-up model, consisting of a list of daily *da/dt* values. In addition, the error model was modified. Error sources already incorporated were the uncertainties due to maneuver ΔV implementation, drag prediction, and orbit determination. An additional term was added to the summation of eq. (1) to model uncertainties in the prediction of the anomalous force, $\sigma_{\Delta\lambda,Boost}$. Starting from equation (12) of reference 10, $\partial\Delta\lambda/\partial a \approx 3\omega_e t/2a$, where $\Delta\lambda$ is the ground track, and introducing a boost of Δa once per orbit for N orbits, then after a time $t \approx NP$,

$$\sigma_{\Delta\lambda,Boost}(t) = \sum_{k=1}^{N-1} \frac{3}{2}\frac{\omega_e \Delta a}{a} kP = \frac{3}{4}\frac{\omega_e \Delta a}{a}\left[t\left(\frac{t}{P}-1\right)\right] \xrightarrow{t>>P} \cong 0.30\Delta a\left(\frac{t}{P}\right)^2 \tag{2}$$

where P is the period and ω_e is the earth rotation rate. The errors predicted in this way are root-sum-squared with the other error sources to produce the total error model for maneuver targeting (eq. (1)).

* The Space Environment Services Center of the National Oceanic and Atmospheric Administration.

Naively incorporating the error model of eq. (2) into longitude targeting leads to extremely conservative maneuver design, as it assumes that the errors on successive days are highly correlated with one another. If the errors are treated as independent random variables, the daily errors must be accumulated in quadrature and equation (2) is modified as

$$\sigma^2_{\Delta\lambda,boost}(t_N) = \left(\frac{3}{2}\frac{\omega_e \Delta a}{a}\right)^2 \sum_{k=1}^{N-1} (t_N - t_k)^2 = \left(\frac{3}{2}\frac{\omega_e P \Delta a}{a}\right)^2 \sum_{k=1}^{N-1} (N-k)^2 \tag{3}$$

where $t_k = kP$, and hence

$$\sigma_{\Delta\lambda,Boost}(t) = \frac{3}{2}\frac{\omega_e \Delta a}{a}\sqrt{\frac{(t-P)t(2t-P)}{P}} \xrightarrow{t>>P} \cong 0.86\Delta a\left(\frac{t}{P}\right)^{3/2} \tag{4}$$

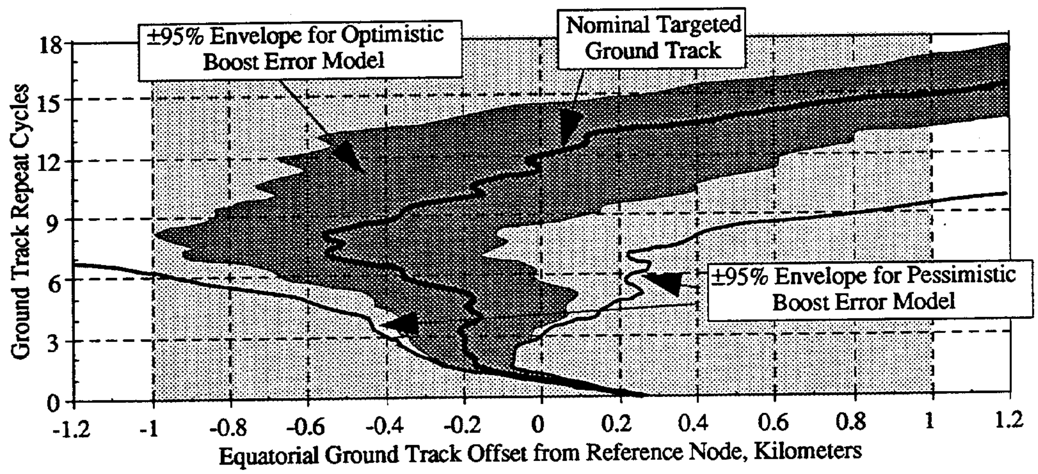

Figure 2. Comparison of optimistic and pessimistic targeting strategies for OMM4. The 95% envelope incorporating optimistic boost errors is longitude targeted.

When the anomalous force is not constant, the equations must be expressed iteratively. Let the propagation step size be M orbits, and use the notation $\sigma_N = \sigma_{\Delta\lambda,boost}(t_N)$, where $\sigma_1 = 0$. Define the auxiliary variables α_k, β_k, and γ_k where $\alpha_1 = \gamma_1 = 0$, and let $K = 3\omega_e/2a$. Then the error model[16] is

$$\left.\begin{aligned}
\beta_N &= \tfrac{4}{3}P^2(\Delta a_N)\left(M^2 - \tfrac{3}{8}M + \tfrac{1}{8}\right)^2 \\
\sigma_{N+M} &= \sqrt{\sigma_N^2 + K^2\left[\left(M^2+2M\right)\alpha_N + M\gamma_N + \beta_N\right]} \\
\alpha_{N+M} &= \alpha_N + MP^2(\Delta a_N)^2 \\
\gamma_{N+M} &= 2M\alpha_N + \gamma_N + M(M-1)P^2(\Delta a_N)^2
\end{aligned}\right\} \tag{5}$$

These more conservative errors more closely resemble the observed data. Since the result is to narrow the error envelope, larger ΔV's are produced by the targeting process. Consequently, the maneuver targeting process becomes more aggressive. An example is given in figure 2. The darkly shaded area shows the ±95% error envelope longitude targeted based upon the optimistic error accumulation algorithm of equation (5). The significantly larger errors which are generated using the pessimistic algorithm of equation (2) are also shown.

USING THE ANOMALOUS FORCE AS A MICRO-THRUSTER

Significant boost or decay may be applied using the anomalous force, by varying the times of transition between the satellite yaw modes. The satellite utilizes three distinct yaw attitude modes to maintain sunwards pointing of the solar array, based upon the magnitude of β'. When the sun is above or below the orbital plane by less than β_{LL}' (nominally 15°), the satellite X-axis is maintained in the orbital plane and aligned along the velocity (0° fixed yaw) or anti-velocity vector (180° fixed yaw). This ensures that the sun is kept on the solar-array side of the satellite and avoids shadowing of the solar array by the high gain antenna and prevents overheating of the modular power system. When b' is outside the $\pm\beta_{LL}'$ limit, sinusoidal yaw steering is implemented to keep the satellite Y-axis nearly perpendicular to the sun direction. Continuous pitching of the solar array provides two axis directional control and ensures sunward pointing of the solar array normal. The actual solar array pitch angle is offset from the optimal angle to limit the battery charging rate.

The anomalous force has a large along track component during fixed yaw periods. The force is continuous and acts like a "micro-thruster," slowly applying thrust along or opposite to the velocity vector. This causes a large boost (≈24 to ≈27 cm/day) during the fixed 0° yaw period (nominally $0° < \beta' < 15°$) and a large decay (≈26 to ≈30 cm/day) during the fixed 180° yaw period (nominally $-15° < \beta' < 0°$). The orbit may be boosted or decayed by varying the duration of the periods of fixed yaw. The maximum variation that is allowed is limited by satellite health and safety considerations to require a switch between fixed yaw and yaw steering (or vice-versa) when $12° < |\beta'| < 30°$ (Figure 3). The yaw flip (from yaw of 0° to 180° or vice-versa) must be performed at $\beta'=0°$ during all fixed yaw periods. Even with this constraint the orbit may be boosted or decayed up the order of ≈1.5 m. A boost may be applied by increasing the duration of fixed yaw at 0° and decreasing the duration of fixed yaw at 180°, and decay may be applied decreasing the duration of fixed yaw at 0° and increasing the duration of fixed yaw at 180°.

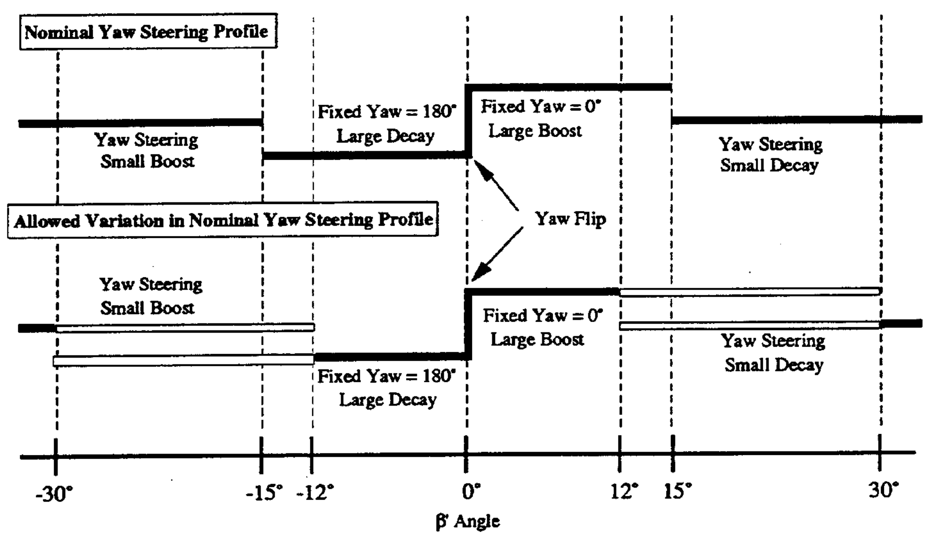

Figure 3. Nominal yaw steering timeline (solid bands) and allowed variation (clear bands). Note that the timeline may also be reversed, since β' is a cyclic function of time.

Maneuver design assumes nominal fixed yaw periods ($\beta_{LL}' = \pm 15°$) and targets on the ±95 percentile error envelope. However, the ±95 percentile envelope uses assumed error levels for solar flux,* anomalous force, maneuver execution,** and orbit determination.† The largest uncertainties are in the solar flux and anomalous force. It was demonstrated that such unexpected variations in the ground track can effectively be removed by taking advantage of the anomalous force during fixed yaw periods. A small maneuver which would have been required in May 1993 was thereby eliminated There are several advantages of using the anomalous force in place of a small maneuver ($\Delta V < 1.0$ mm/sec):

1. Maneuver design and implementation utilizes a dedicated effort from a large fraction of flight operations personnel for several days around the maneuver. The work required to determine the variation in the timing of the fixed yaw is significantly smaller. A substantial change in the on-board memory, nominal command sequence, and satellite monitoring activities are required to perform a maneuver. Implementing a change in the fixed yaw period requires the modification of only a single command word. Thus the work level of the operations personnel and the danger to satellite health and safety are significantly reduced by not performing a maneuver.

2. Science data is not acquired around the burn time of a maneuver.‡ No data is lost because of a change in fixed yaw periods.

3. Maneuvers disrupt precision orbit determination. Variations to fixed yaw periods do not.

4. Maneuvers are an active and expendable process. Use of the anomalous force is passive and a non-expendable process, thereby increasing the operational lifetime of the satellite.

5. Appropriate use of the anomalous force reduces the number of maneuvers required during the mission by increasing the time between maneuvers.

6. Small maneuvers ($\Delta V < 1$ mm/sec) may be totally eliminated by the use of the anomalous force.

7. The anomalous force may be used to schedule the maneuver at an operationally convenient time.

The disadvantage is that there is no complete physical model to confidently represent the anomalous force. Richter's current model[8] treats only the solar array, and is far too complex to implement directly within the targeting process (e.g., GTARG). The ground track prediction and the uncertainty in the prediction using the empirical model is one of the major sources of ground track prediction error. Nevertheless, the successful demonstration of ground track control using the anomalous force during May 93 by eliminating a maneuver showed that the anomalous force could be exploited as an effective tool. The anomalous force was used to bring the backup window for OMM4 (performed on August 6, 1993) within the control band, and to postpone OMM5.

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* The uncertainties assumed for maneuver targeting are based upon the statistical success of this method during recent periods of similar solar activity, i.e., during the past 13 weeks.

** Maneuver execution uncertainties for OMM3 targeting were taken as σ=0.44 mm/sec (fixed) and σ=1% (proportional).

† OD uncertainty for OMM3 targeting was taken as σ=0.33 m.

‡ Acutally, it is possible to avoid data loss during maneuvers by switch to "flex" telecommunications format. This was used on OMM-4 and and OMM-5.

IMPLEMENTATION OF MICROMANEUVER

The ground track is monitored regularly to ensure that mission requirements are met and to provide a minimum 30 day advance notice of any maneuvers. From the beginning of cycle one* (through OMM3), nearly 70% of all equatorial crossings were within ±500 meters of the reference track. Since the entire control band was not being utilized, a more aggressive targeting strategy involving optimistic error models was used to target OMM3, which was performed on March 30, 1993.

Although optimistic error models were incorporated, the maneuver design biased the 95 percentile western error envelope eastward some 100 meters (maximum western extent 900 meters west of the reference track) because there was some concern about meeting the verification site overflight requirement. The initial post-maneuver analysis, utilizing DPTRAJ, indicated that the nominal track would extend no more than 850 meters west prior to turning eastward. Later analyses, during the following weeks, indicated that the predicted ground track would extend progressively further westward before turning around. By the first week in May, DPTRAJ predicted that the nominal ground track would leave the control band on June 7 and remain outside for approximately 30 days, with a maximum displacement from the western edge of the control band of ≈180 meters (Fig 4).

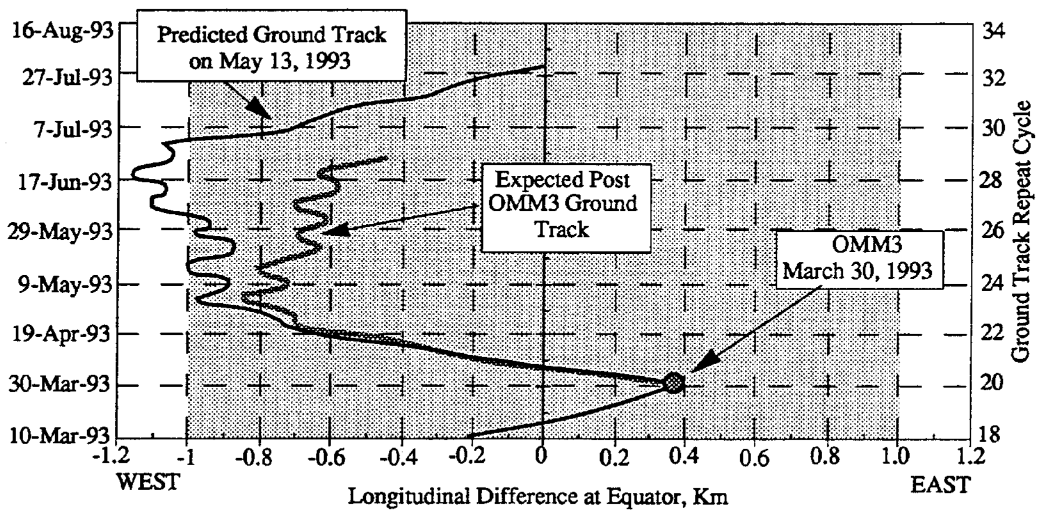

Figure 4. Predicted ground track at time of OMM3 and prior to implementation of micro-maneuver.

The changes in the characteristics of the ground track were principally due to large variations in the solar flux levels and anomalous force during April from those predicted at the time of OMM-3 maneuver design. Larger solar flux and higher boost were observed than expected. The expected average solar flux level was ≈136 solar force units,† while the observed average solar flux was ≈118 units (Figure 5d). Consequently, the actual decay due to atmospheric drag was significantly less than expected. In addition, the anomalous force, which varies as a function of β' and the attitude articulation strategy, did not behave as expected (Figure 5c). It was predicted that the anomalous force would cause from between ≈6 to ≈12 cm/day decay in the

* A cycle is defined as a complete geographical coverage set of the Earth with start and end points marked by successwssive overflights of the same geographical location. The cylces are numbered sequentially from zero (an incomplete cycle, starting with the acquisition of the observational orbit). A 127 orbit cycle begins at the southermost latitude of the orbit with ascending node longitude of 99.947° E.

† 1 SFU (Solar Flux Unit) $=10^{-22} Wm^{-2} Hz^{-1}$. Values quoted refer to the 10.7 cm (2800 MHz) full sun radio flux measured by the Dominion Radio Astrophysical Observatory at Penticton, B.C., Canada, and predicted by SESC.

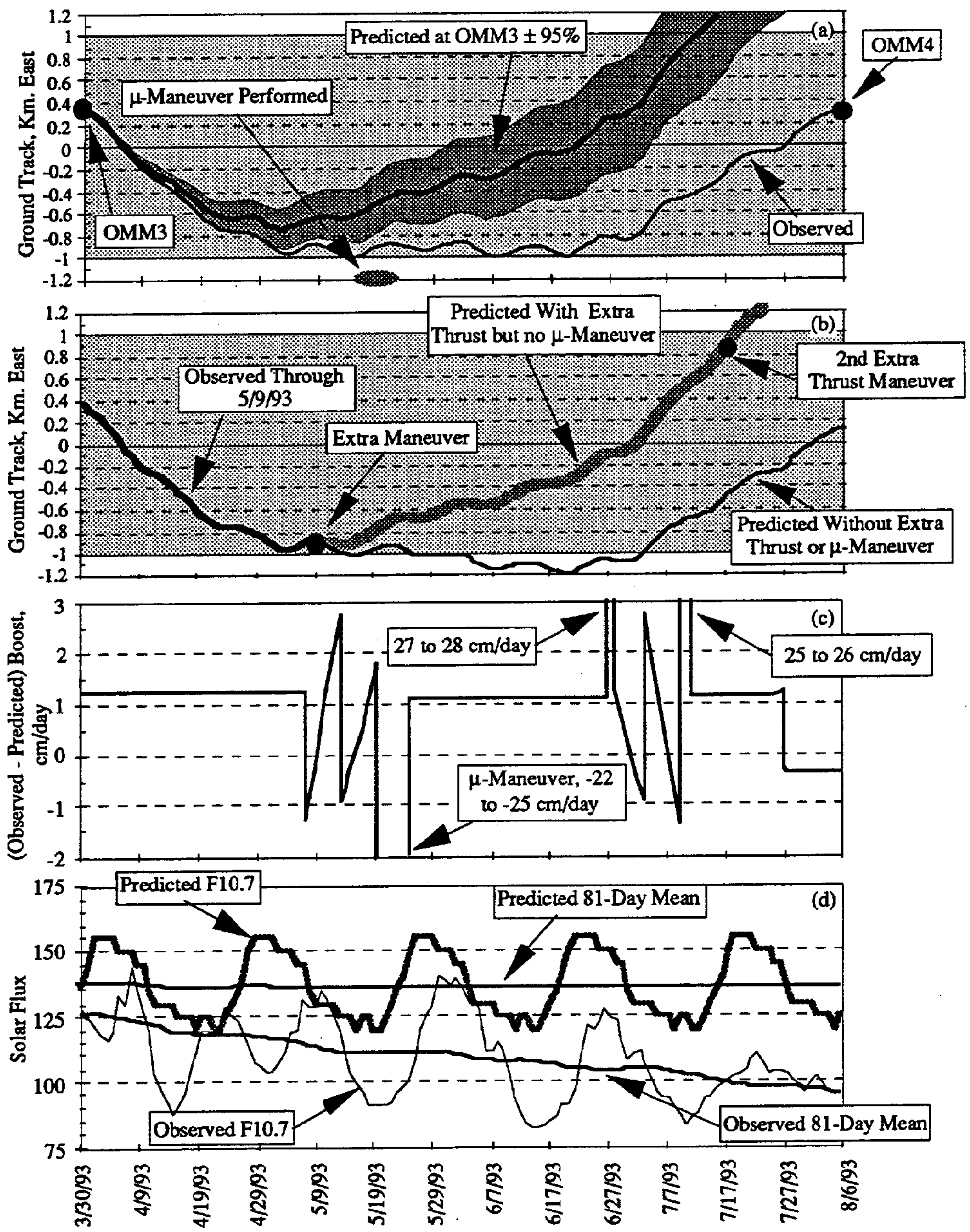

Figure 5. (a) Targeted and observed Post-OMM3 ground track; (b) Situation in early May, 1993, showing the extra maneuver which would have been required (projected with GTARG); (c) Error in predicting the semi-major axis change due to the anomalous force in OMM3 design; (d) Corresponding solar flux.

semi-major axis during the positive yaw steering phase immediately following OMM3. However, the actual decay ranged from ≈5 to ≈8 cm/day. The differences in these two results are too large to be explained by the change in the error model alone. The solar flux behaved beyond the ±95% expectations and the anomalous force did not repeat as before. Less decay occurred than predicted and the resulting semi-major axis was slightly above the referendce valueas the ground track reached the western boundary of the control band. Perturbations due to luni-solar gravity at that time were strong and added to the western movement of the ground track. Thus the ground track would have crossed the western boundary during June, 1993.

To prevent the ground track from the leaving the control band, two maneuvers would normally have been required (Figure 5b). The first one would be performed near the western boundary and would turn the ground track around by decreasing the semi-major axis. The second maneuver would be required six or seven cycles later (60 to 70 days), near the eastern boundary, and would have the characteristics of a typical orbit maintenance maneuver, increasing the semi-major axis. Rather than perform the additional maneuvers, an alternative strategy was suggested, which used the anomalous force to control the ground track. The 180° fixed yaw period was to be extended beyond the nominal β'=-15° in order to increase the decay period sufficiently that the ground track would not cross the boundary, in effect implementing a "micro-maneuver." The maximum extension could not go beyond β'=-*30*° due to satellite health and safety concerns. When the decision was made to consider extending the 180° fixed yaw period, the satellite was already in the 0° fixed yaw mode which immediately preceded it. At that time the anomalous force was causing ≈21 cm/day boost, ≈3 cm/day larger in magnitude than expected, further compounding the problem.

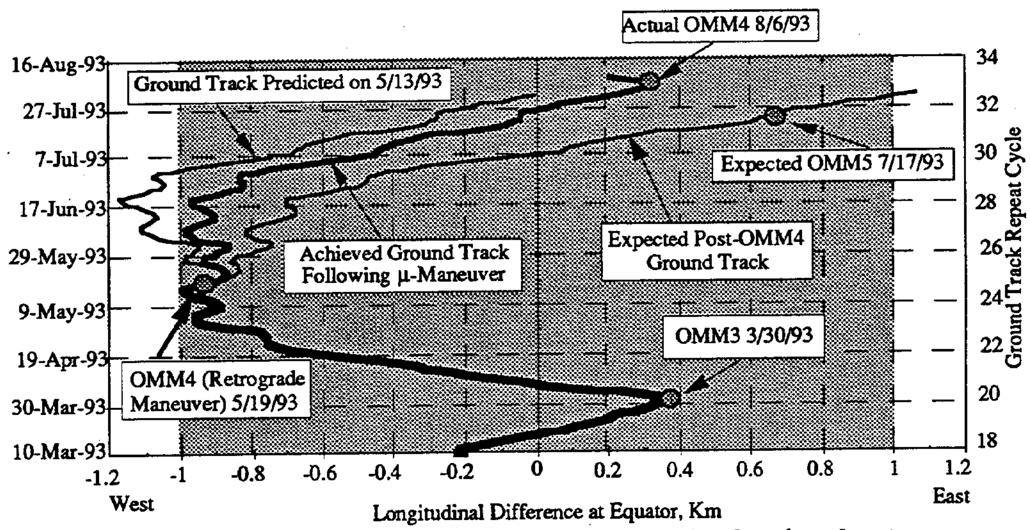

Figure 6. Design of retro-maneuver which was not implemented and projected post-maneuver ground track. The maneuver design was performed with DPTRAJ.

Nominally, a small retrograde (opposite to the velocity vector) maneuver (OMM4) would have been required on May 19, 1993 at the boundary of ground track repeat cycles 24 and 25 to prevent the ground track from leaving the control band, just 50 days after OMM3. This maneuver would have decreased the semi-major axis sufficiently to turn the predicted ground track eastward in the presence of strong luni-solar gravitational perturbations and the error sources. The maneuver design process (Figure 6) indicated that the maneuver magnitude would be around $\Delta V \approx 1$ mm/sec, smaller than the typical orbit maintenance maneuver magnitudes (from ≈ 3 mm/sec to ≈ 5 mm/sec). It would have been possible to implement this maneuver, as magnitudes as small as ≈0.04 mm/sec are possible with the on-board thruster configuration. The subsequent maneuver (OMM5) would have been expected on July 17, 1993, providing a maneuver spacing of 60 days between OMM4 and OMM5. This OMM5 would have been performed near the eastern boundary of the control band and have the typical characteristics of other orbit maintenance maneuvers which increase the semi-major axis.

The anomalous force during this fixed yaw period was expected to cause an orbit decay from ≈24 to ≈30 cm/day (±95%). Thus a five day extension would sklowly decrease the semi-major axis slightly more than one meter. The length of the extension was determined by performing a sensitivity analysis with GTARG (Figure 7), while DPTRAJ was used to study the precise ground track behavior under the extension implemented. Since the force was not well understood and was behaving differently from expected, the sensitivity analysis included 1 to 5 day extensions of the fixed yaw period with constant decay levels varying from 24 to 30 cm/day. The VMA model was updated to be consistent with the fixed yaw strategies being considered. The objective was to keep the 95 percentile western envelope of the ground track within the control band, taking into account the best known models of the solar flux and the anomalous force at the time. Results showed that the required length of extension of the fixed yaw period was proportional to the decay level. A minimum four day extension was required to keep the 95 percentile west track within the control band, assuming a decay level of 28 cm/day. The ground track prediction with DPTRAJ showed that the nominal track skirted the western boundary with a 4-day extension with very little margin for error.

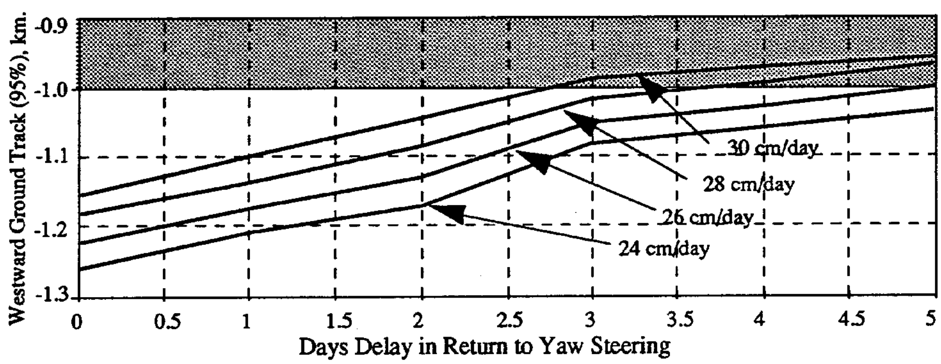

Figure 7. Ground Track Sensitivity Analysis.

The satellite had already been in the 180° fixed yaw mode for three days by the time this analysis was completed. The decay level was in the range of ≈24 to ≈26 cm/day, significantly smaller in magnitude than the expected level of ≈28 cm/day. Consequently, the earlier analysis was extended to include 5, 6, and 7 day extensions with decay levels in the range of 24 cm/day to 28 cm/day and utilizing updated solar flux predictions and anomalous force models. This further analysis indicated that the 95 percentile envelope would remain within the control band at a decay level of 24 cm/day with a 5-day extension. The corresponding DPTRAJ results indicated that four or five day extensions would not make much difference in the ground track behavior. The ground track would be held near the western boundary by the luni-solar gravitational attraction and tidal forces even though the orbit would decay below the reference orbit due to atmospheric drag. However, the margin with a 5-day extension to β'=-26.5° was slightly larger than with a 4-day extension. Thus the 5-day extension was implemented.

Although it had been expected that the decay rate due to the anomalous force would be constant throughout the fixed yaw period, the actual decay rate decreased from ≈26 cm/day to ≈21 cm/day by the end of 180° fixed yaw period.* This change indicated that the decay rate is also a function of β', even during the fixed yaw periods. The variation of the decay rate was found to be nearly linear in β'. The variation in β' leads to changes in the angle of incidence of solar radiation impinging on the solar panel and this causes a variation in the decay rate. There was concern whether the full objective was achieved by the 5-day extension because of the reduced decay rates. However, the nominal ground track did not cross the western boundary and it turned eastward around June 20, 1993 (Figure 5a). The subsequent orbit maintenance

* This decay was later explained by Richter's thermal analysis, which had not been completed at the time.

maneuver (OMM4) was performed on August 6, 1993 at the boundary between Cycles 32 and 33 extending the period between maneuvers to 130 days. Two earlier maneuvers, which would have been required at 40 and 60 day intervals, respectively, were eliminated.

The average decay rate during the fixed yaw period was ≈23 cm/day. The additional decay in semi-major axis due to the extension of 5.4 days was about 1.25 meters. Thus the semi-major axis was reduced by an amount equivalent to a maneuver with magnitude $\Delta V \approx 0.58$m mm/sec without disturbing science data acquisition. The anomalous force was effectively used to slowly perform a "micro-maneuver" to ensure that the ground track remained within ±1 km control band. The fixed yaw periods (≈21 cm/day boost during the fixed 0° period and ≈23 to ≈28 cm/day decay during the fixed 180° period) are particularly useful for implementing "micro-maneuvers" if required. The orbital boost maneuver is performed by extending the 0° fixed yaw period and the orbital deboost maneuver is performed by extending the 180° fixed yaw period

CONCLUSION

Anomalous forces produce a continuous thrust on the order of micro–newtons, and constitute the largest uncertainty to TOPEX/POSEIDON maneuver design. Maneuver targeting strategies were redesigned in flight to incorporate the effects of this unexpected perturbation. These new targeting strategies are currently being used to design and implement ground track maintenance maneuvers. Although the force is continuous, it causes significantly larger boost or decay levels during periods of fixed yaw (≈24 to ≈30 cm/day) than during yaw steering. The semi-major axis can be either increased or decreased by using the anomalous force to provide a boost equivalent to ≈1.0 mm/sec by suitably varying the timing of the periods of fixed yaw. This is exactly what was done in May, 1993, when the transition from fixed yaw to yaw steering was delayed to prevent the ground track from leaving the control band. The process eliminated a retrograde maneuver, effectively performing a "micro-maneuver" equivalent to a thrust ΔV of 0.58 mm/sec magnitude. Similar processes have been used more recently to delay the time of subsequent orbit maneuvers.

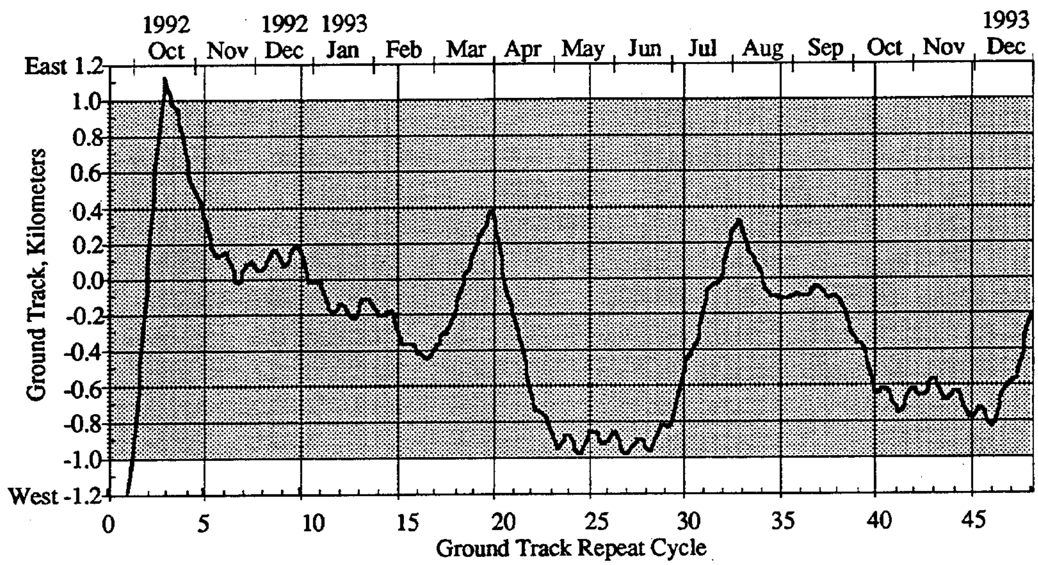

Figure 8. TOPEX/POSEIDON ground track. The control band is shaded.

This "harnessing" of the anomalous force has shown that it can be a useful tool to counter the uncertainty in ground track prediction, to place the maneuver at an operationally convenient time, to increase maneuver spacing, and to eliminate small maneuvers. It has also shown that an essentially passive technique can sometimes be used to control the ground track without performing a maneuver. There are numerous advantages to this technique over the conventional technique, which have been enumerated above. The incorporation of this technique into the nominal mission design has allowed us to maintain the ground track continuously within the control band since reaching the operational orbit (Figure 8). Over 98% of the more than 6000 nodal crossings which occurred during this time have been within the ± 1 km reference bandwidth, easily satisfying mission requirements.

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