USING ANOMAI .OUS ALONG-TRACK FORCES FOR TOPEX/POSEIDON GROUND TRACK CONTROL *I* *

Extended Abstract of a paper submitted to the. AIAA/AAS Space Flight Mechanics Meeting, Feb. 14-16, 1994, Cocoa Beach, Florida

Bruce Shapiro, Ram Bhat, and Ray Frauenholz
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

The TOPEX/POSEIDON satellite is maintained in a nearly circular, frozen mbit (c ≈ 0.030095, ω ≈ 90') at an altitude of ≈1336 km. and an inclination of i ≈ 66.04", which provide.s an exact repeal ground track every 127 revolutions (≈ 9.9 days) and overflies two altimetry verification sites. Orbit maintenance maneuvers are required to recover orbital decay due to drag and ground track drift duc to luni-solar **gravity. Since obtaining the operational orbit on** Sept. 2.5, 199?., the. ground track has bet.n maintained within a ±1 km control band of the desired reference track for over 97% of the more than 4000 orbits. Solar array curling, thermal imbalances, radiative forces, and outgassing combine. to produce a force equivalent to a continuous thrust on the. order of micro newtons, and constitute the largest uncertainty to maneuver design. Because these forces were not predicted by pre-launch orbital analyses they are called *anomalous forces*. 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 **mane.uvcrs.** Furthermore, it **is** possible **[o** exercise some, control over the, anomalous force to effect changes in the satellite ground track. In early May, 1993, it became clear that the ground track would cross the western boundary of [he. control bound (-1 km) during June for approximately three cycles (30 days) with a maximum western excursion of ≈ 180 meters. To prevent this from occurring, two maneuvers would normally be required. Rather than perform maneuvers, the attitude articulation strategy **was** modified 10 take advantage of the high rate of orbital decay caused by the anomalous force in fixed yaw at a fixed yaw, io effect performing a "micro-maneuver" of approximately 0.58 mm/sec magnitude. This simpler procedure, which made a maneuver unnecessary, more than doubledthe expected time. between mane.uvcrs from 6 Cyclers (≈60 days) to 13 cycles (=130 days).

INTRODUCTION

TOPEX/POSEIDON was launched by an Ariane 4?1' on August 1 0, 1992 with injection occurring at 23:27:05 UTC, approximately 19 min. 57 scc 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 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 (c ≈ 0.000095 and ω≈90°) at an altitude of ≈1336 km and an inclination of i ≈ **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

* The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the. National Aeronautics and Spare Administration.

** Extended abstract submitted to the AI AA/AAS Space Flight Mechanics Meeting, i'et). 14-16, 1994, Cocoa Beach, Florida.

†† The mission is jointly funded by the US National Aeronautics and Space Administration (NASA) and the French Centre National d'Etudes Spatiales (CNES).

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%).

Satellite fixed accelerations equivalent to continuous bociy-fixed forces on the order of several micro-Newtons began to be observed shortly after launch. These forces arise due to a combination of solar array curling, thermal imbalances, radiation forces, and outgassing. Although they are well determined and predictable, since the forces were not predicted by orbit anal yscs prior to launch (hey are referred to en *masse* as *anomalous forces*. These anomalous forces can be used to perform precise ground track corrections by modifying the satellite's attitude articulation strategy. The result of these changes to the attitude control strategy is the effective implementation of "micro-maneuvers" with typical maneuver magnitudes of AV < 1.0 mm/sec.

"l"his paper discusses the nature of the anomalous force in terms of its effect upon the satellite's orbital ground track, 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 anti extend the time between maneuvers is described. Finally, our overall success at ground track maintenance under the influence of these forces during the first year of the TOPEX/POSEIDON mission is summarized.

ANOMALOUS FORCE

Pre-launch analysis indicated that the central body gravity and drag were the principal perturbing forces acting on the ground track. Luni-solar gravity produces periodic perturbations comparable in magnitude to drag; these perturbations can either accentuate or decrease the effects of drag. Solar radiation forces were omitted in these earlier analyses because the resulting ground track variations were significantly smaller than those due to the other forces.

Analysis of tracking data obtained subsequent to launch indicated the existence of an unmodeled anomalous force acting upon the satellite [Frauenholz 1993]. 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 and β', the angle between the orbit plane and the Earth-sun line (Fig. 1).

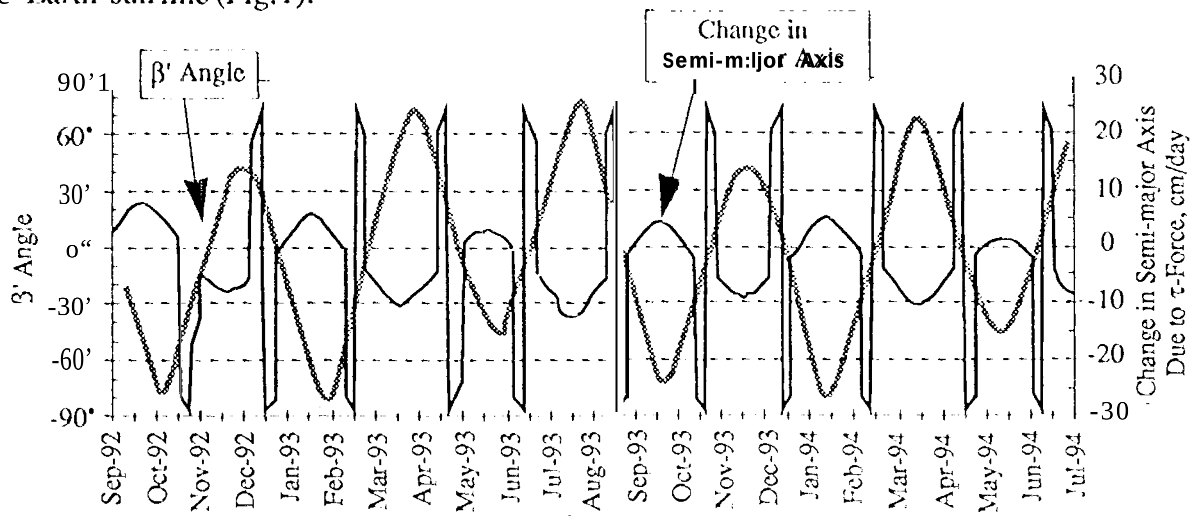

Figure 1
The anomalous force is strongly dependent on the yaw articulation strategy and hence the β' angle.

"l"he 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, arc taken into account. During yaw steering, the anomalous force produces a positive da/dt during periods of negative β' and a negative da/dt during periods of positive β'. The satellite is held at fixed yaw for a 10 to 15 day period around $\beta' \approx 0$; the yaw orientation is reversed by 180" at the zero point. These $\beta' = 0$ points occur at approximately 56 day intervals. The direction of da/dt has been observed to reverse at the yaw flip. Significant attenuation of the anomalous force during the fixed yaw period can be made by adjusting the solar array lead or lag angle (subject to satellite power and thermal constraints) to use thermal radiative and solar pressure forces to best advantage. Drag produces a decay ≈ 5- 15 cm/day, and hence the anomalous force has the same magnitude of effect upon the orbit as the largest orbital perturbation.

There are both +X and +-Y body fixed components to the anomalous force. During yaw steering periods, the +Y forces predominate. These forces arise from a combination of solar array deflection (curling) and a thermal imbalance between the +Y and -Y side of the satellite bus. A three degree deflection of the solar array has been calculated to cause approximately 1 μN force. During periods of fixed yaw, the along-track forces originate from the + X body-fixed components. These components are due to radiation forces which arise from solar array pitch biasing, and outgassing from the thermal blankets on the X-axis ends of the satellite. The effect of the anomalous force is described in much greater detail elsewhere. [Frauenholz 1993, Richter 1993].

GROUND TRACK MAINTENANCE REQUIREMENTS

Periodic orbit adjustment maneuvers are required to maintain the ground track and ensure that all verification site over flight requirements are met. They must occur on an interference-free basis with scientific data acquisition and precision orbit determination (POD). Specific requirements can be summarized as follows [MSRD 1989]:

1) Maintenance of the, operational orbit so that at least 95% of all equatorial crossings at each orbit node are contained within a 2 km longitude band,

2) Maintenance of the operational whit during the initial verification phases 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 arc to be performed as nearly as possible to the transition between 12,7-orbit repeat cycles (±1 rev).

6) The spacing between maneuvers shall be as large as possible during the observational phase of the mission.

7) Maintenance maneuvers are to be performed over land wherever possible.

In addition, maneuvers arc generally scheduled to allow time for a backup onc cycle (=10 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. Micro-maneuvers are performed by modifying the satellite articulation control strategy whenever this would extend the maneuver interval without compromising satellite safety constraints.

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 [Shapiro & Bhat, 1993]. 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 [Frauenholz & Shapiro 1991] Jacchia-Roberts atmosphere [Jacchia, GTDS] and a variable mean area (VMA) model [Bhat, Frauenholz & Cannell, 1989]. Targeting strategies will either (a) maximize the time between maneuvers (*longitude targeting*) or (b) for-cc 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 discussed below, GTARG was modified during mission operations to incorporate the effects of additional anomalous along-track forces.

Solar flux ($F_{10.7}$) and geomagnetic parameter (K_p) predictions are based on the daily SESC 3-day and weekly 27-allay outlook. 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. The 81-day centered average $\overline{F_{10.7}}$ is calculated from the extrapolated values of $F_{10.7}$. The geomagnetic data are extrapolated at a constant value equal to the average K_p over the first 27 days.

Earlier analysis [Bhat, Frauenholz and Cannell, 1989] indicated that density estimation errors would strongly dominate the ground track prediction at all times except during the lowest period of solar flux ($F_{10.7} \approx 70$). 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 bane] (see Fig. 3, below). The width of the error envelope $\sigma_{\Delta\lambda}$ at any time is calculated as

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

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. 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 [Spier, 1971; DPTRAJ, 1971] and has the capability of incorporating all relevant perturbing sources including finite maneuvers, 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. The table consists of a list of daily *da/dt* values. In addition, the error model was modified. Error sources already incorporated were the uncertainties due to thrust implementation, drag prediction, and orbit determination. An additional term was added to the summation to model the uncertainties in the prediction of the anomalous force, $\sigma_{\Delta\lambda,Boost}$. Starting from equation (12) of [Frauenholz and Shapiro 1991] $\partial\Delta\lambda/\partial a \approx 3\omega_e t/2a$, where $\Delta\lambda$ is the ground track, and introducing a boost of Δa once per orbit for N orbits, then after a time $t \approx NP$,

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

The errors predicted in this way are root-sum-squared with the. other error sources to produce the total error model for maneuver targeting (equation (1)).

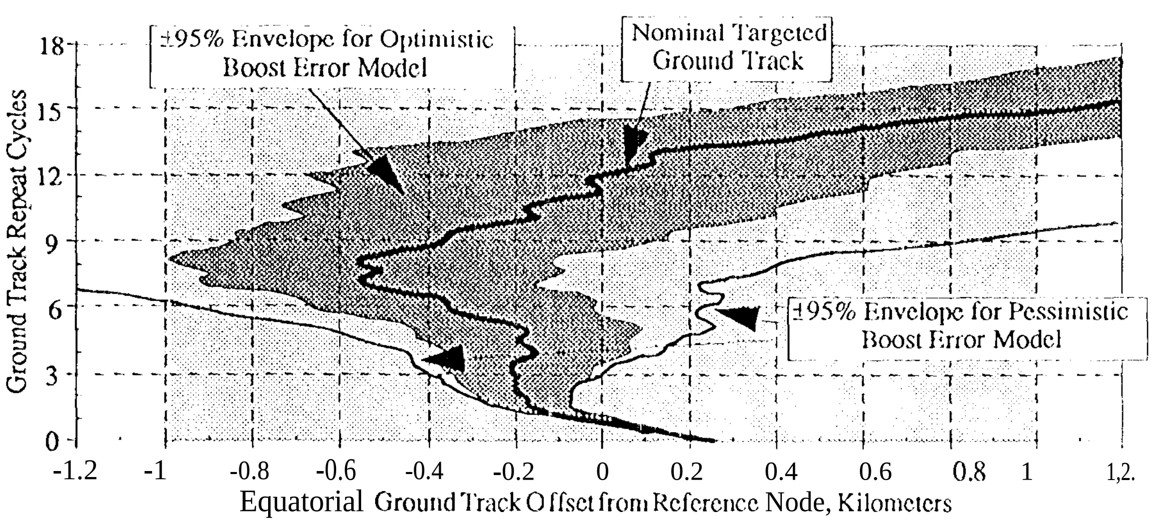

Figure 2
Comparison of Optimistic and Pessimistic Targeting Strategies for OMM4. The 95 % Envelope incorporating optimistic Boost Errors is longitude targeted.

Naively incorporating the error model of eq. (2) into longitude targeting leads m 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

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

where $t_k = kP$, and hence

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

When the anomalous force is not constant, the equations must be expressed iterative] y. 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 mode] is

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

These more conservative errors more closely resemble the observed data. S nce the result is m narrow the error envelope, larger AV'S are produced by the targeting process, Consequently, the maneuver targeting process becomes more aggressive. An example is give ı 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 arc generated using the pessimistic algorithm of equation (4) arc also shown. The paper will discuss the changes in the maneuver magnitude and maneuver interval which are accomplished by this more aggressive targeting strategy.

IMPLEMENTATION OF MICRO MANEUVER

The ground track is monitored regularly to ensure that mission requirements arc met and to provide a minimum 30 day advance notice of any maneuvers. Since the beginning of cycle onc (through OMM-3), 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 9S percentile western error envelope eastward some 100 meters (maximum western extent 900 meters west of the reference track) because then e 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 ground track would extend progressively further westward than predicted 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 3b).

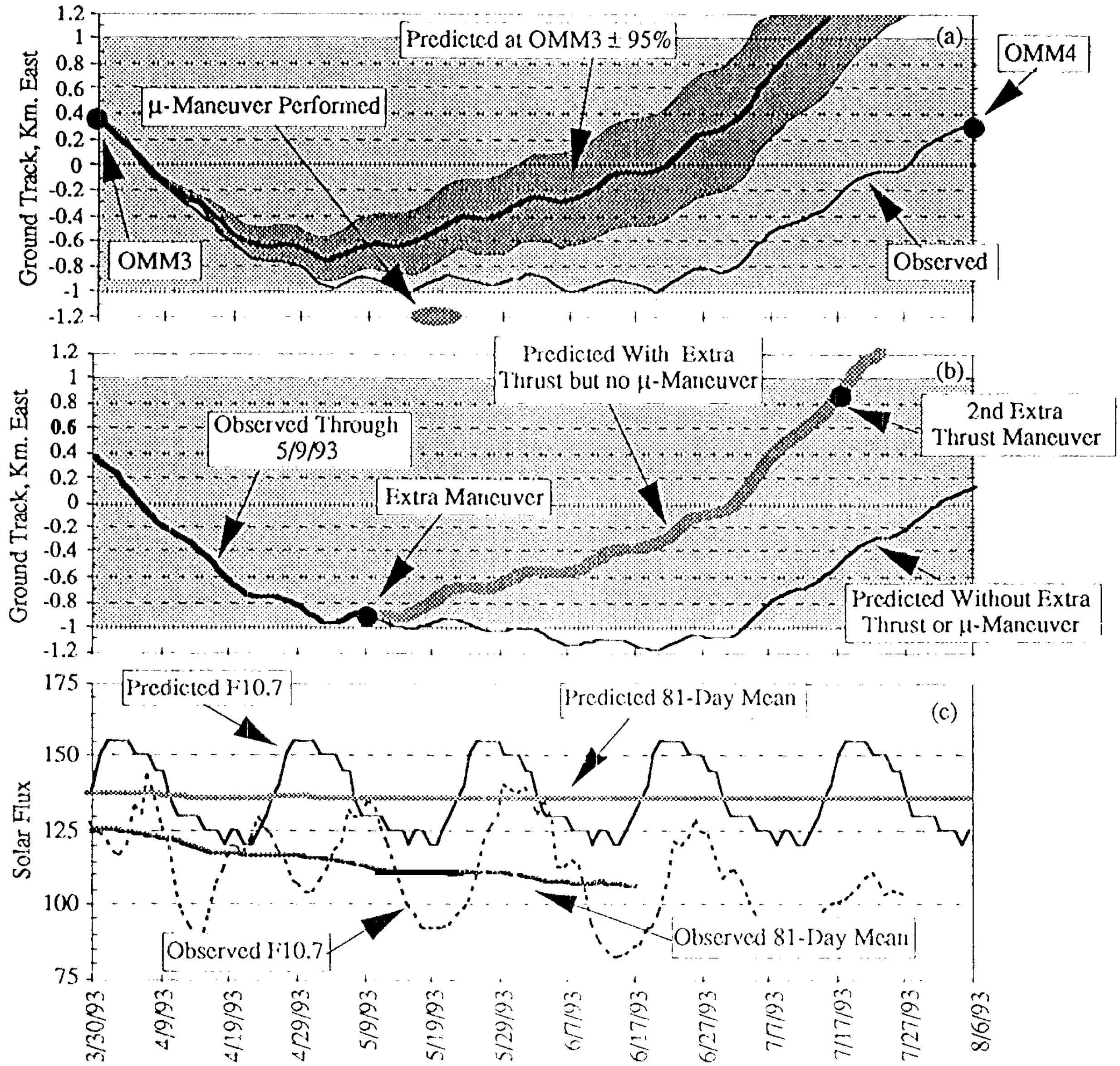

Figure 3

(a) Targeted and Observed Post-OMM3 ground track; (b) Situation in **early May, 1993, showing the extra maneuver which would have been required; (c) Corresponding predicted and observed solar flux.***

The changes in the characteristics of the ground track were principal}: due to large variations in the solar flux levels and anomalous force. during Apri] from those predicted at the time of OMM-

* The final paper will also include. the anomalous force in this analysis

3 maneuver design. The expected average solar flux level was ≈136 Solar Flux Units,* while the observed average solar flux was ≈118 Units (Fig. 3c) and predicted to decrease to ≈102 Units. 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 (Fig. 3d). Although the timing of boost and decay forces can be predicted with a high degree of accuracy, the magnitude of the force does not repeat identically for similar β′ conditions and the empirical model must be continuously adjusted based on observations. Some improvements have been made with the implementation of Richter's thermal model. Thus it was expected that the anomalous force would cause ≈6 to ≈12 cm/day decay in the semi-major axis during the positive yaw steering phase after OMM-3. However, the actual decay was ≈5 to ≈8 cm/day during this period. The differences in these two results are too large to be explained by the change in error models alone; the solar flux behaved beyond the 95% expectations and the anomalous force did not repeat in the manner expected. The semi-major axis did not decay as expected and the resulting orbit was actually higher than the reference orbit when it was near the western edge of the control band,

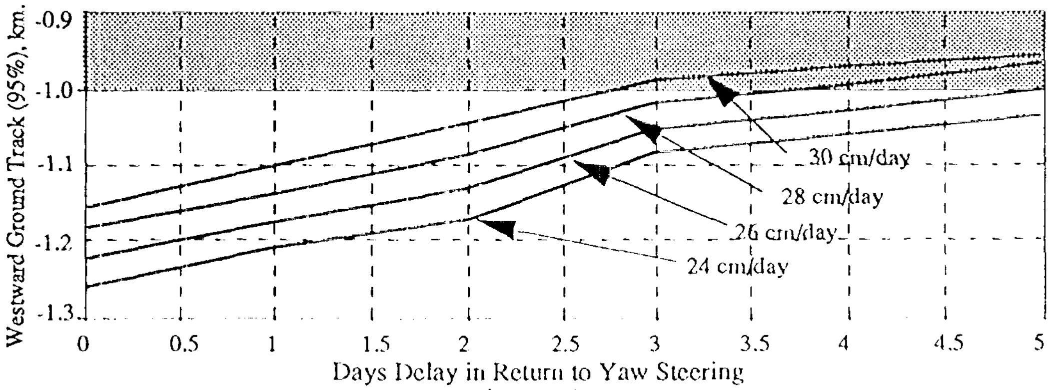

Figure 4
Ground Track Sensitivity Analysis.

To prevent the ground track from the leaving the control band, two maneuvers would normally be required (Fig. 3 b). The first one would be performed near the western boundary and would turn the ground track around by decreasing the semi-majol axis. The second maneuver would be required six or seven cycles later (60 to 70 days), would take place near tile 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 O" 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. For satellite safety concerns, it was too late to change the nominal yaw flip time, but them was still sufficient time to design command sequences which would extend the 180'0 fixed yaw. The length of the extension was determined by performing a sensitivity analysis with GTARG (Fig. 4), while DPTRAJ was used to study the in-ccisc. ground

* 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, 11, (.'.. Canada, and predicted by the NOAA Space. Environment Services Center (SESC) in Boulder, Colorado.

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 cm/day to 30 cm/day in a step size of 2 cm/day. The VMA model was updated to take into account 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 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.

The satellite had already been in the 1800 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 available with 5-day extension to $\beta' \approx -26.5°$ was slightly larger than the 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 pane] 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 2.(), 1993 (Fig. 3a). The subsequent orbit maintenance maneuver (OMM4) was performed on August 6, 1993 at the boundary between Cycles 32 and 33 (Table 1) 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 pm-form a "micro-maneuver" to ensure that the ground track remained within ± 1 km control band. The fixed yaw periods (≈21 cm/clay boost during the fixed 0° period and ≈23 to ≈28 cm/day decay during the fixed 180° period) arc particularly useful for implementing "micro-maneuvers" if required. The orbital boost maneuver is performed by extending the 0° fixed yaw period and the orbital de-boost maneuver is performed by extending the 180° fixed yaw period

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

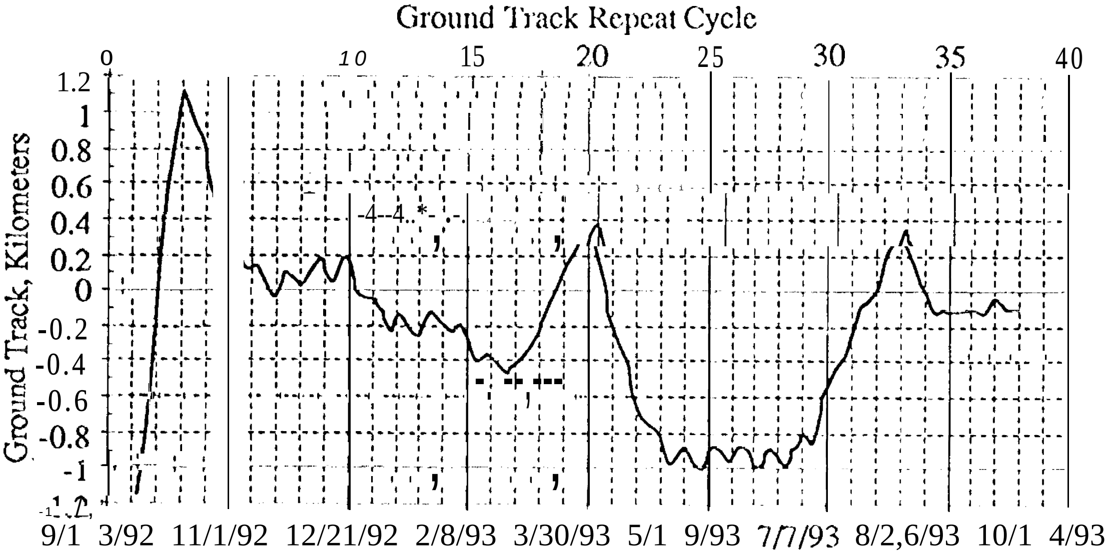

Figure S

TOPEX/POSEIDON ground track. The vertical grid lines correspond to cycle boundaries.

CONCLUSIONS

Anomalous forces produce a continuous thrust on the order of micro newtons, and constitute the largest uncertainty to 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. In May, 1993, the satellite attitude articulation strategy was modified by extended the period of fixed yaw to take advantage of these anomalous forces and prevent the ground track from leaving the control band. This strategy effectively performed a "n~icro-maneuver" of approximately 0.58 mm/sec magnitude. As a result, two additional orbit maintenance maneuvers which would have been required were prevented. Figure 5 shows the ground track maintenance since launch. Overall the ground track has been maintained within the control band since reaching the (operational orbit in Sept. 1992. Over 97% of the more than 4000 nodal crossings which occurred during this time have been within the ±1 km reference bandwidth, well exceeding mission requirements.

REFERENCES

[Bhat, 1991] Bhat R.. S., "TOPEX/POSEIDON Orbit Acquisition Maneuver Design," AAS 91-514, 1991 *AAS/AIAA Astrodynamics Specialist Conference,* Durango, Colorado, August 19-22, 1991,

[Bhat, 1992A] Bhat, R. S., *TOPEX/POSEIDON Ground Track Maintenance -3,* Jet Propulsion Laboratory IOM FOS 93-012, October 30, 1992 (Internal Document).

[Bhat, 1992B] Bhat, R. S., *TOPEX/POSEIDON Ground Track Maintenance -4,* Jet Propulsion Laboratory IOM FOS 93-016, October ?,0, 1992 (Internal Document).

[Bhat, Frauenholz, and Cannell, 1989] Bhat, R.S., Frauenholz, R. B., and Cannell, P. E., "TOPEX/POSEIDON Orbit Maintenance Maneuver Design," AAS 89-408, *AAS/AIAA Astrodynamics Specialists Conference*, Stowe, V-l', August 7-10, 1989.

[Bhat and Shapiro, 1993] Bhat, Ram and Shapiro, Bruce, *Use of the Anomalous Force in TOPEX/POSEIDON Ground Track Maintenance*, Jet Propulsion Laboratory IOM FOS 93-024, June 15, 1993 (Internal Document).

[Bhat, Shapiro, and Frauenholz, 1993] Bhat, R.S., Shapiro, B. E., and Frauenholz, R.B., "TOPEX/POSEIDON Orbit Acquisition Maneuver Sequence", *AAS/AIAA Astrodynamics Specialists Conference,* AAs-93-571, Victoria, BC, Canada, Aug. 16-19, 1993.

[Carlisle, 1991] Carlisle, George, A. DiCicco, H. Harris, A. Salama, M. Vincent, *TOPEX/Poseidon Project Mission Plan,* Jet Propulsion Laboratory, JPL D-6862, rev. C, Aug. 1991 (Internal Document).

[Ekelund, J, Sunseri, R. F., and Collier, J.B.] *DPTRAJ/ODP User's Reference Manual,* Jet Propulsion Laboratory, JPL D-263, Oct. 15, 1971 (Internal Document).

[Frauenholz and Shapiro 1991] Frauenholz, R. B., and Shapiro, B. E., "The Role of Predicted Solar Activity in TOPEX/POSEIDON Orbit Maintenance Maneuver Design," A AS 91-515, *AAS/AIAA Astrodynamics Specialists Conference,* Durango, CO, August 19-22, 1991.

[Frauenholz, Hamilton, Shapiro, and Bhat 1993] Frauenholz, R. B., Hamilton, T. W., Shapiro, B.E., and Bhat, R, S., 'The Role of Anomalous Satellite.-1~ixcd Accelerations in TOPEX/Poseidon Orbit Maintenance," *AAS/AIAA Astrodynamics Specialists Conference,* Paper AAS 93-570, Victoria, BC, Aug. 16-19, 1993.

[Guinn, 1991] Guinn, J. R., "Short Period Gravitational Perturbations for Conversion Between Osculating and Mean Orbital Elements,". AAS/*AIAA Astrodynamics Specialists Conference,* Durango, CO, August 19-2.2., 1991, Paper AAS 91-430.

[Hamilton, 1993] Hamilton, T.W., *Impact of Anomalous Forces on TOPEX/POSEIDON,* Jet Propulsion Laboratory 10M TPO 93-0311, February 1, 1993 (Internal Document).

[long, 1989] Long, A. C., Capellari, J. O., Velez, C.E., Fuchs, A. J., *Goddard Trajectory Determination System (GTDS) Mathematical Theory,* Rev. 1, GSFC Flight Dynamics Division FDD/552-89/01 and CSC Technical Report CSC/TR-89/6001, July 1989.

[Nelson, Gehred, Hirman, and Heckman, 1992] Nelson, I.(i., Gehred, P. A., Hirman, J.W., Heckman, G.R., "User's Guide to the Preliminary Report and Forecast of Solar Geophysical Data," *Preliminary Report and Forecast of Solar Geophysical Data,* NOAA Space Environment Services Center, SESC PRF 897, Nov. 1 0, 1992.

[Richter, 1993] Richter, Robert, *Radiation Forces Acting on the TOPEX/Poseidon Spacecraft Along the Velocity Vector due to the Solar Array - Initial Results,* Jet Propulsion Laboratory IOM 3544 -TOP-93-004, July 8, 1993 (Internal Document).

[Roberts, 1971] Roberts, C, "An analytical Model for Upper Atmospheric Density Base.ci Upon Jacchia's 1970 **Models",** *Celestial Mechanics ,4,* pp. *368-77, 1971.*

[Shapiro, 1993] Shapiro, B. E., *GTARG Error Models,* Jet Propulsion Laboratory IOM 314.5-1691, April 2.2, 1993 (Internal Document).

[Shapiro and Bhat, 1993] Shapiro, Bruce, and Bhat, Ramachandra, "GTARG - The TOPEX/POSEIDON Ground Track Maintenance Maneuver Targeting Program", Paper AIAA 93-1129, *AIAA Aerospace Design Conference,* Irvine, CA, Feb. :16-191993.

[Spier, 1971] Spier, Gerd W., *Design and Implementation of Models for the Double Precision Targeting Program (DPTRAJ),* Jet Propulsion Laboratory, Technical Memorandum 33-451, April 1 S, 1971 (Internal Document).

[TOPEX, 1989] *TOPEX/POSEIDON Project Mission and Systems Requirements,* Jet Propulsion Laboratory JPL D-5901, April 1989 (Internal Document).

[TOPEX, 1993] TOPEX/POSEIDON Project, *OMM3 Performance Report,* Meeting Minutes, April 2, 1993 (Internal Document).

Vincent, 1990A] Vincent, M. A., "The Inclusion of Higher Degree and Order Gravity Terms in the Design of a Repeat Ground Track," AIAA-90-2899-CP, *AIAA/AAS Astrodynamics Conference,* Portland, Oregon, August 1990.

Vincent 1990B] Vincent, M. A., *TOPEX/POSEIDON Orbit Characteristics,* Jet Propulsion Laboratory, JPL D-7511, June 1990 (Internal Document).