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THE ROLE OF ANOMALOUS SATELLITE–FIXED ACCELERATIONS IN TO PEX/POSEIDON ORBIT MAINTENANCE*

R. B. Frauenholz†, T.W. Hamilton‡, 11.1':. Shapiro††, and R. S. Bhat‡‡

Jet Propulsion Laboratory, Californ ia Institu te of Techn ology, Pasade na, Ca.

Abstract

Shortly after the launch of TOPEX/POSEIDON on 10 August 1992 orbit determination indicated orbit decay levels ~60 times larger than could be explained by atmospheric drag. Outgassing, a complex process of molecular releases from satellite non–metallic parts, was the most likely source of these early decay rates. The high decay levels steadily declined during the first six weeks while a planned sequence of six maneuvers placed the satellite in the operational orbit to precisely overfly a predetermined repeat ground track. At the same time, on- going orbit trend analysis revealed the presence of residual along- track forces comparable to atmospheric drag which clearly exhibit a body-fixed origin. These forces cause either orbit decay or boost, depending on the satellite attitude and solar array articulation strategies. As such, the anomalous along- track force can either add to, or oppose, the decay due to drag

Orbit maintenance maneuver design was expected to depend primarily on effective predictions of atmospheric drag, but now also depends equally on effective predictions of the anomalous along- track force This paper describes the empirical prediction model for the anomalous forces for comparison with an independent analytic method derived from planned attitude atriculation strategies, both illustrating their effect on the satellite ground track.

Introduction

TOPEX /POSEIDON was successfully launched by an Ariane 4'21' from French Guiana on 10 August 1992. The primary goals of this joint NASA/French mission are to study ocean circulation and its interaction with the atmosphere, to better understand climate change; to improve knowledge of heat transport in the ocean; to model ocean tides; and to study the marine gravity field. To accomplish these objectives requires determination of ocean surface height to a 3σ accuracy of 13 cm utilizing a combination of satellite altimetry and precision orbit determination based on laser ranging measurements. These objectives are to be accomplished over a primary mission lifetime of three years, with a possible two year extension.

The Jet Propulsion Laboratory (JPL) is responsible for TOPEX /POSEIDON mission operations, including operational navigation support. Major navigation functions include all maneuver design and evaluation and related trajectory analysis. Operational orbit determination support is provided to JPL by the Flight Dynamics Facility at the Goddard Space Flight Center (GSFC/FDF) using tracking data acquired via the NASA Tracking & Data Relay Satellite System (TDRSS). Detailed interfaces and procedures for exchanging trajectory and orbit determination data between JPL and the GSFC/FDF were established and thoroughly tested prior to launch to assure all performance requirements were satisfied.

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† Technical Manager, Member AIAA

‡ Senior Technical Manager, Member AIAA.

†† Member Technical Staff, Member AAS, Member AIAA

‡‡ Member Technical Staff.

Orbit Requirements

A planned sequence of six orbit adjust maneuvers[1,2] began soon after launch to precisely place the satellite in a near-circular frozen orbit with an inclination of ~66 deg at an altitude of ~1336 km. During the maneuvering process, the orbit ground track was aligned with a reference ground track which repeats every 127 revolutions over 10 sidereal days, while also overflying single NASA and CNES altimeter verification sites. This sequence was completed on 21 September 1992, 42 days after launch.

Maneuvers are periodically required to maintain the operational orbit and ground track. The specified control and scheduling constraints require that:

1) 95% of all equatorial crossings are contained within a 2-km longitude band at each orbit node,

2) 95% of all altimeter verification site overflights are within ±1 km during the initial verification phase (first six months),

3) maneuver spacings are at least 30 days, time phased to occur near the boundary of pre-determined 10-day orbit cycles to limit interference with precision orbit determination, and

4) the burn occurs over land to preclude interruption of altimetry.

In addition, satellite telecommunications, thermal, and power constraints affect the selection of the maneuver location within the orbit. These constraints have geometric origins arising from the satellite attitude articulation strategy.

Attitude Articulation Strategy

TOPEX/POSEIDON is a three axis stabilized satellite (Fig. 1) with the altimeter boresight always pointed along the local nadir. At the same time, near-continuous yaw steering about the local nadir and solar array pitching maintain the dominant 28 m^2 solar array pointed near the sun for power optimization. Shortly before launch, a plan was adopted to apply a solar array pitch offset, thereby reducing the projected area to limit battery charge rates for performance enhancements. While a pitch bias of 57.5 deg is currently providing very good battery performance, radiation forces normal to the solar array are not along the flight path as expected without the pitch bias. Resulting radial and along-track components of the solar force affect orbit and ground track differently, depending on the satellite attitude. Understanding these effects and developing a reliable prediction model become the primary challenges addressed by this paper.

The yaw steering strategy is used continuously except when $-15 \leq \beta' \leq 15$ deg, where β' is the angle between the orbit plane and the sunline (Fig. 2). When β' is near these angular limits a fixed yaw attitude is utilized to avoid excessive yaw rates. The satellite is positioned at a zero yaw angle when $0 \leq \beta' \leq 15$ deg, whereas a fixed yaw angle of 180 deg is utilized when $-15 \leq \beta' \leq 0$. Accordingly, a yaw flip maneuver is required near $\beta' \simeq 0$ to keep the solar array on the sunlight side of the satellite. The β' angle passes through zero once every ~56 days as the satellite orbit node regresses ~2.2 deg/day and the earth moves in its orbit ~1 deg/day. As a result, the fixed yaw and yaw flip events recur at this approximate frequency.

Atmospheric Drag

Prelaunch studies[3] established atmospheric drag as the major non-gravitational perturbation affecting the satellite ground track, even though the orbit altitude is relatively high at ~1336 km. This sensitivity to drag results from the stringent ±1-km ground track control requirement. Atmospheric drag causes a decay in the orbit semi-major axis, resulting in an eastward drift of the satellite ground track that will eventually travel outside the established control boundary. Periodic maneuvers are scheduled to maintain the ground track inside the control boundaries by removing the accumulated orbit decay with an increase in semi-major axis. The frequency of maneuvers depends on the accuracy of drag predictions. Effective drag prediction strategies become a necessary part of the maneuver design process, requiring long-term predictions of solar and geomagnetic activity[4] to estimate atmospheric density and a faithful representation of the average drag reference area which varies with β'. Use of the Jacchia-Roberts atmospheric density model effectively accounts for daily variations in solar and geomagnetic activity, although none of the currently available density models reflect flight data at the TOPEX/POSEIDON altitude.

To develop a trend in the overall drag behavior, the GSFC/FDF estimated a daily drag multiplier using tracking data acquired via the TDRSS. The daily drag multiplier is $(1+\rho_1)$, where $\rho_1 = 0$ indicates nominal drag. Here, all unmodelled along-track accelerations are arbitrarily absorbed into drag without necessarily declaring these effects are actually due to only drag. Fig. 3(a) shows the daily $(1+\rho_1)$ estimates from launch through the end of 1992, indicating an exponential decline from an initial post-launch value of ~60 times nominal drag to near-nominal levels by late September 1992 when operational orbit conditions were achieved. Fig. 3(b) shows the corresponding rate of change in semi-major axis varies between -150 and +25 cm/day, equivalent to along-track forces between ~3 and 20μN. Normal outgassing is the most likely explanation for the initial high orbit decay rates. More recently, the rate of change in semi-major axis has been observed to be much lower, but clearly exhibits sustained periods of only boost or decay, which have a body-fixed relationship to planned satellite attitude articulation strategies.

The orbit decay rates due to *observed* drag, isolated in Fig. 3(c), vary between 3 and 14 cm/day, which are equivalent to drag forces between ~0.3 and 1.8μN. This variability generally follows the known variations in the average satellite reference drag area with β', and also reflects the nominal atmospheric density based on *observed* solar and geomagnetic activity.

Estimates of residual orbit decay/boost rates, shown in Fig. 3(d), were obtained by removing the observed drag decay in Fig. 3(c) from the total decay/boost in Fig. 3(b). The residual, or anomalous, decay/boost rates exhibit the same general trend and order-of-magnitude behavior as the total rates. However, this evaluation technique assumes the anomalous forces are always proportional to the satellite drag area, which is not necessarily true. A separate estimate of an along-track force acting in the presence of nominal drag isolates the anomalous force and provides a convenient means of measuring the net effect on the satellite orbit and ground track.

Estimating the Anomalous Force

By 21 September 1992 the maneuver sequence designed to acquire operational orbit conditions had been successfully completed.[2] Each of the six maneuvers interrupted newly-stable orbit conditions, precluding opportunities to confidently establish a trend in an anomalous along-track force. Fortunately, this limitation had been acceptable, since orbit changes induced by maneuvers were much greater than the effects of the observed decay rates. Once in the operational orbit, effective maintenance maneuver planning would require estimates of the anomalous force, as the resulting decay/boost rates were now the same order-of-magnitude as those induced by atmospheric drag. Plans were made to begin estimating the anomalous force as part of future routine orbit determination. Only the anomalous force would be estimated, and not the drag multiplier $(1+\rho_1)$, since both along-track forces could not be estimated simultaneously without introducing conflict in the estimation process.

A strategy was adopted to estimate a constant along-track force acting over a seven-day tracking arc. This force was estimated in the presence of nominal drag, thereby establishing an average force referred to the center of the tracking data arc. A day-by-day moving average along-track force was obtained by advancing the seven-day tracking arc by a day and dropping off the first day, so adjacent solutions were always based on six days of common tracking data. This technique produced a reasonably smooth and consistent daily history of the anomalous forces which were then converted to equivalent acceleration and integrated to determine the rate of change in orbit semi-major axis. Finally, orbit determination solutions were grouped into families corresponding to one of the four basic satellite attitude articulation strategies: 1) yaw steering when $\beta' > 0$, 2) yaw steering when $\beta' < 0$, 3) fixed zero yaw angle, and 4) fixed 180-deg yaw angle.

A suitable period of orbit quiet first became available after achieving the operational orbit (21 September) and prior to the first orbit maintenance maneuver (OMM1) on 12 October, a yaw steering period when $\beta' < 0$ and increasing negatively (see Fig. 2). Estimates of the anomalous force indicated sustained orbit boost rates that varied between ~2 and 7 cm/day, as shown in Fig. 4. These results indicate the force was acting along the satellite +Y axis, varying linearly with the yaw amplitude and β'. A least-squares fit of the daily estimates with β' provided a time dependent model of the anomalous force useful for predicting future boost rates during yaw steering when $\beta' < 0$. This model matches estimated anomalous force behavior immediately following OMM1 (see Fig. 4).

The anomalous force was initially estimated during fixed yaw in November 1992, first for a zero yaw angle where the satellite +X axis is pointed in the direction of motion and is aligned with the satellite velocity. As such, estimates of an along-track force originate from the satellite X-axis; any originating from +Y are not observable as along-track perturbations. The solar array pitch bias assures a force component in the direction of motion, resulting in a net orbit decay level of ~28 cm/day that remains essentially constant during this fixed yaw period.

Following the yaw flip maneuver in mid-November, the satellite continued in a fixed-yaw configuration at a 180-deg yaw angle. In this attitude the -X axis opposes the satellite motion, so the anomalous force would be expected to cause an orbit boost of similar magnitude. However, a solar array pitch bias *lag* angle had been employed during all previous fixed-yaw periods (yaw = 180 deg) to maximize the solar array temperature. The use of a lag angle has been discontinued in favor of always using a lead angle, as the observed solar array temperature difference was only ~3° C. The lag geometry actually reduced the decay rate by ~50% from 28 to 14 cm/day, rather than providing a net boost (see Fig. 4).

After returning in early December 1992 to yaw steering and positive β' geometry, the anomalous along-track force induced a net orbit decay as expected. Once again these forces originated from the +Y axis and generally varied with yaw amplitude and β', as shown in Fig. 4. The +X forces observed during fixed yaw are no longer observable as along-track perturbations. However, these new estimates were far less consistent than those observed when $\beta' < 0$, for yet unknown reasons.

Repeat estimates of the anomalous force for the same satellite attitude conditions first became possible when the satellite returned to fixed yaw in early January 1993. The first use of a lead solar array pitch bias at a zero yaw angle resulted in a constant orbit boost estimated to be ~21 cm/day. For operational convenience during the holiday period in late December, the fixed yaw period purposely began early at a β' angle of ~24 deg, rather than the nominal value of 15 deg. As a result, the satellite was in this fixed yaw attitude for about 10 days, providing an extended period of orbit boost soon after OMM2 implementation on 21 December. This plan was reflected in OMM2 design.[5] The yaw flip maneuver followed near $\beta' \simeq 0$, placing the satellite in a 180-deg yaw attitude. Estimates of the anomalous force were very similar to those obtained during the last occurence of this attitude geometry in November 1992, resulting in constant decay rates of ~28 cm/day (Fig. 4).

Estimates of the anomalous force obtained to date have demonstrated near-repeatable decay/boost behavior that correlates reasonably well with the satellite attitude articulation strategies. This behavior has led to the development of an empirical prediction model indicated by the solid line in Fig. 4. This prototype model is now used in orbit maintenance maneuver design[5,6] together with other models that have a significant effect of the satellite ground track.

Effects on the Satellite Ground Track

An example of the relative influences of the anomalous along-track forces and atmospheric drag on the satellite orbit and ground track are compared in Fig. 5. The comparison period is the interval immediately following OMM1 (see Figs. 3,4). For illustration, the orbit is initially positioned exactly on the reference ground track with a semi-major axis which provides an exact repeat ground track when the orbit is propagated in the presence of only earth gravity. This means that the ground track offset depicted in Fig. 5 will always remain zero, regardless of the orbit propagation time. Luni-solar gravity has predictable and significant periodic effects on the TOPEX/POSEIDON ground track[3] that are routinely modelled as part of orbit maintenance maneuver design.[5] Here luni-solar effects have been purposely omitted to isolate the individual contributions of atmospheric drag and the anomalous along-track force, and to also characterize their combined effect.

Fig. 5 shows that the orbit steadily decays and the ground track drifts directly eastward when drag alone is applied during orbit propagation. This expected result reflects observed drag characterized by the decay rate history immediately following OMM1 (see Fig. 3c). Here, the orbit decay rate rapidly increases due to the combined effects of higher average drag area at lower β' and a sudden large increase in solar activity. The separate effects of the decay/boost model on the ground track have been estimated for the same time interval using the post-OMM1 model shown by the solid line in Fig. 4. Here, the ground track initially drifts westward because the model predicts orbit boost during the fixed yaw period immediately following OMM1. The ground track then reverses eastward when orbit decay predicted by the model begins to have influence. The combination of drag and the anomalous along-track forces causes the ground track to remain near the reference track early in the propagation period, as drag and anomalous boost effects are initially nearly balanced. Later, the combined forces reverse eastward as each force predicts orbit decay.

Summary

Understanding how the combined non-gravitational forces affect the satellite ground track is a primary objective of operational orbit maintenance for TOPEX/POSEIDON. Typical maneuver ΔV magnitudes are less than ~5 mm/sec,[3,5] correcting the semi-major axis by ~10 meters. This paper shows that the anomalous along-track forces change the semi-major axis by as much as 20-30 cm/day during periods of fixed yaw nominally lasting ~5 days. The resulting net change in semi-major axis becomes more than a meter, an effect equivalent to a maneuver of ~0.5 mm/sec. This effect is a significant percentage of a typical maneuver, and must be part of routine orbit maintenance to limit ground track prediction errors and to maximize the time between maneuvers.

The paper also presents a theoretical analytic model which describes the effect of anomalous body-fixed forces in terms of planned satellite attitude articulation strategies. Comparisons are made between results predicted by the theoretical model with those obtained through direct empirical means. Good agreement provides a closed-form method of confidently predicting the effects of the anomalous along-track forces on the satellite ground track, leading to improved maneuver planning and execution accuracy,

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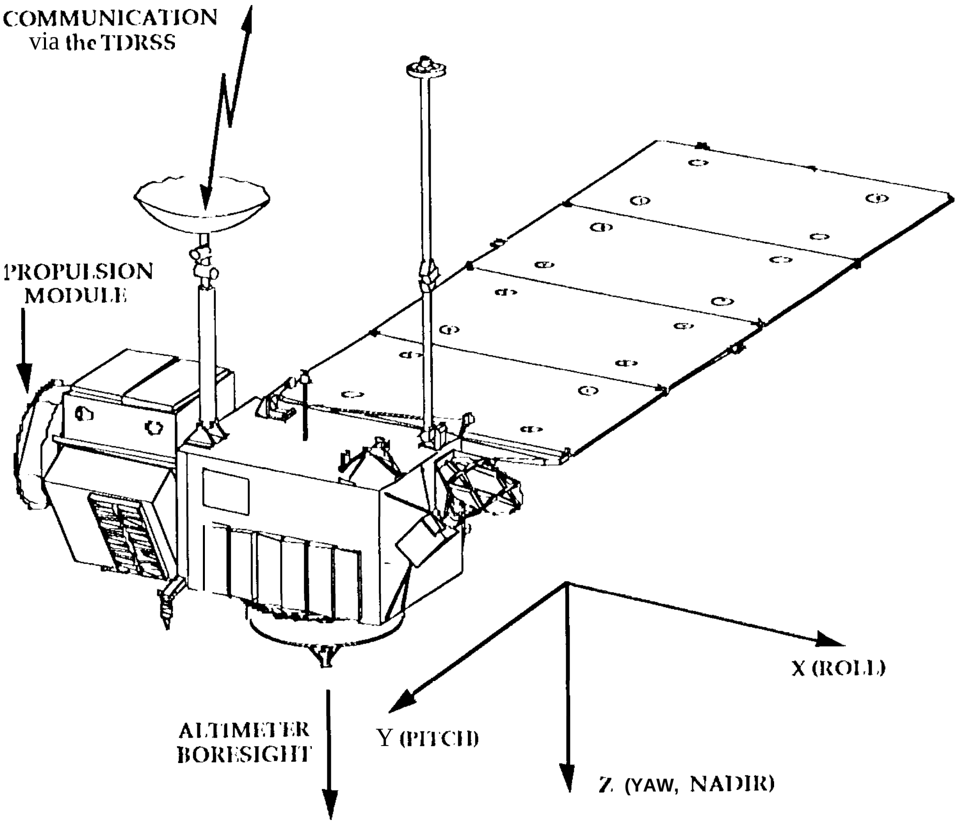

Fig. 1. TOPEX/POSEIDON Satellite.

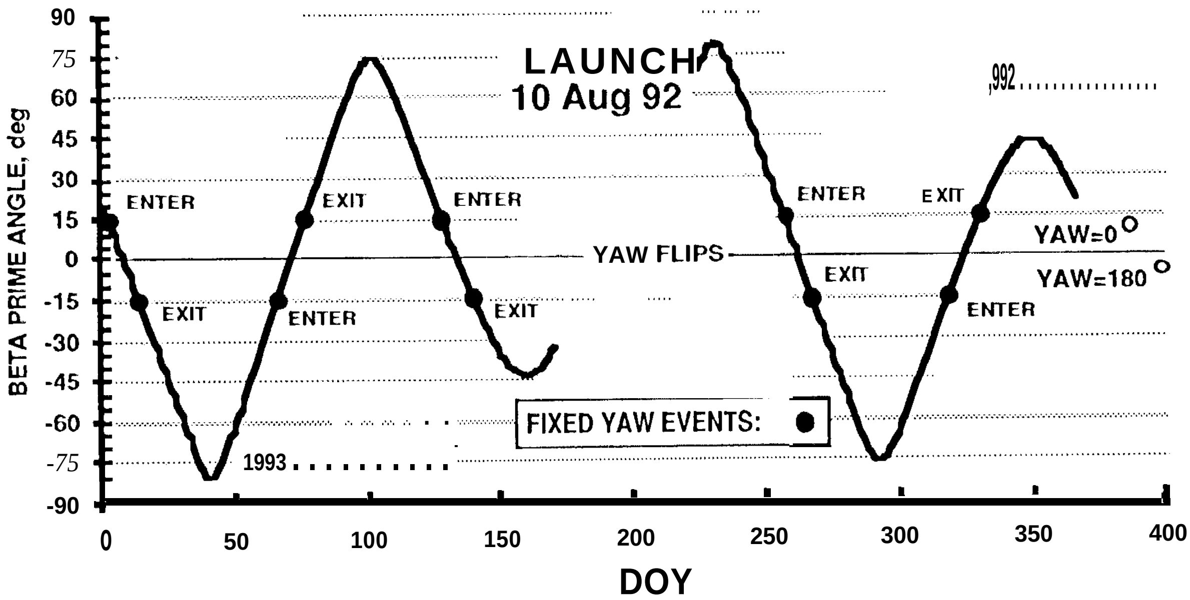

Fig. 2. History of β' Angle and Periods of Fixed Yaw.

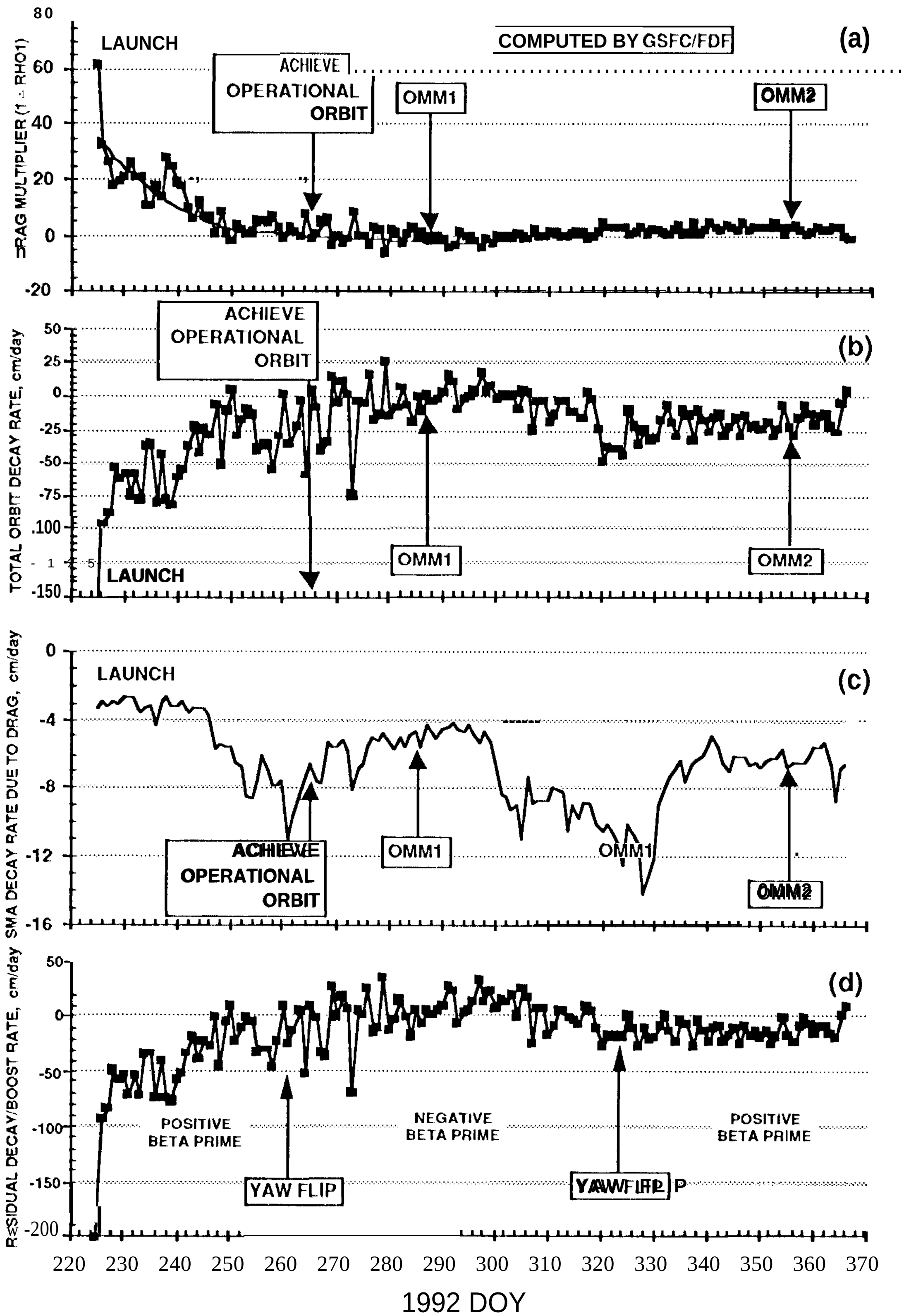

Fig. 3(a) Atmospheric Drag Multiplier (GSFC/FDF), (b) Equivalent Total Orbit Decay, (c) Orbit Decay Due to Observed Drag, and (d) Residual Decay/Boost Rates.

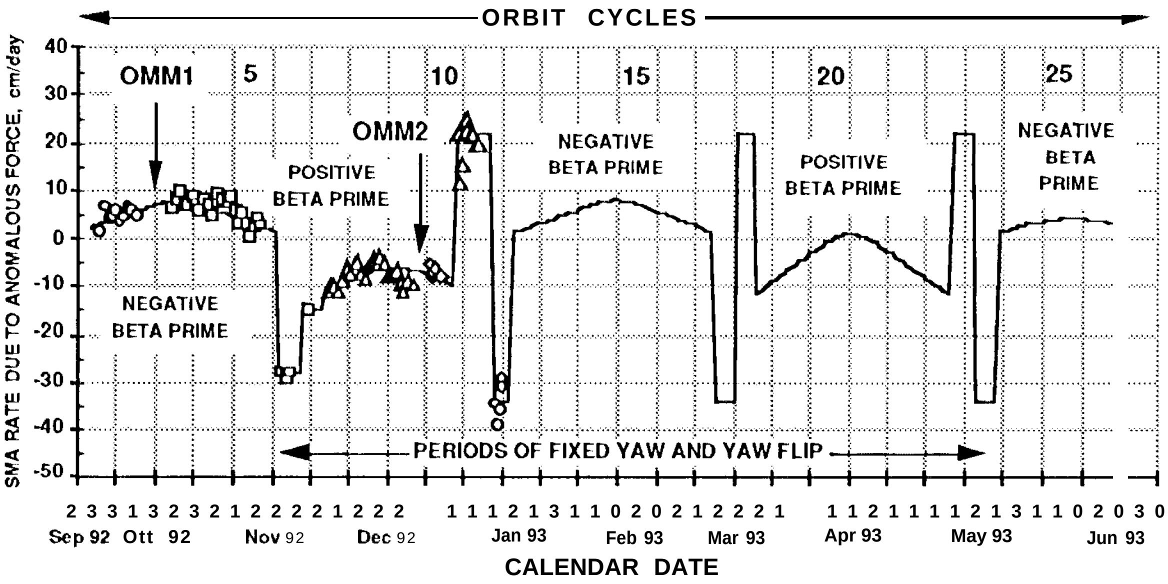

Fig. 4. **History & Prediction of Orbit lloost/Decay due to Anomalous Forces.**

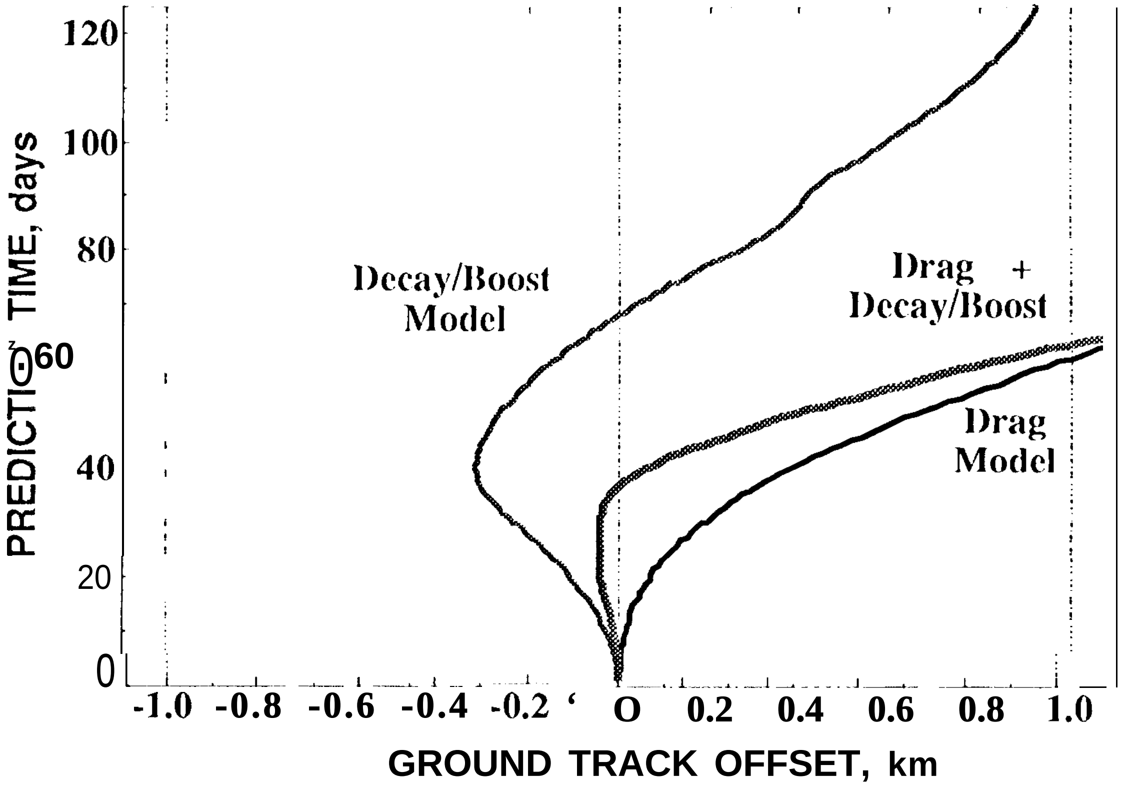

Fig. 5. Typical Effects of Drag & Decay/Boost on the satellite Ground Track.