TOPEX/POSEIDON NAVIGATIONAL AND ORBIT MAINTENANCE SUPPORT DURING SOLAR MAXIMUM CYCLE OF 1999 TO PRESENT

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ABSTRACT *– This paper presents orbit maintenance and navigational support of TOPEX/Poseidon from 1999 to present during the solar maximum cycle. A history of orbit maintenance maneuvers, streamlining the support during the fixed yaw flying forward periods and the role of solar panel pitch bias variations are presented. A sample analysis shows several scenarios regarding the particular use of the solar panel bias strategy and its effects on the semi-major axis and the ground track. Each option reflects the increase (or decrease) in the semi-major axis due to varying solar pitch bias angles and how the solar pitch bias strategy relates to the previous orbit maintenance maneuver (OMM) designs and overall OMM strategy.*

INTRODUCTION

The TOPEX/Poseidon satellite, launched on August 10, 1992, entered its 10th year of successful operation this year. The TOPEX/Poseidon mission, a joint US-French program, studies and gathers information about the world's oceans to better understand ocean circulation. Since mid 1999, spacecraft orbit maintenance and support has continued during the period of the solar maximum. About every 11 years the sun undergoes a period of heightened activity. The frequency and magnitude of solar flares and sunspots increase while the corona often expands to many times its average size.

TOPEX orbit maintenance depends on accurate and timely predictions of atmospheric drag, solar radiation pressure, and anomalous along track forces. Orbit Maintenance Maneuvers (OMMs) are designed to keep the TOPEX ground track within its ±1 km equatorial longitude control band. Heightened solar activity underlines the need for more OMMs. Compared to earlier in the mission (during solar minimum), more OMMs have been executed, averaging four every year since mid 1999.

When possible, the TOPEX Navigation team schedules the OMMs during fixed yaw and flying forward attitude modes. This overall OMM strategy standardizes maneuver opportunities, simplifies each OMM design including constraint checking, and eliminates large yaw turns prior to the actual maneuver burn. The strategy also reduces the manpower support needed for orbit maintenance and OMM events. A more detailed study discussed in this paper shows the specific advantages associated with performing OMMs during fixed yaw and flying forward attitude modes.

The current solar maximum and its effect on orbital decay (higher drag) results in a greater dependence on the passive technique of changing the TOPEX solar panel bias angle during fixed yaw periods (first demonstrated in 1993) to counter the effects of drag. A sample analysis shows several scenarios regarding the particular use of the solar panel bias strategy and its effects on the ground track. Each option reflects the increase (or decrease) in the semi-major axis due to varying solar pitch bias angles and how the solar pitch bias strategy relates to the previous OMM design and overall OMM strategy.

BRIEF DESCRIPTION OF TOPEX/POSEIDON SATELLITE

The TOPEX/Poseidon satellite, managed for NASA by Jet Propulsion Laboratory (JPL) was successfully launched into Earth orbit in August 1992. The mission objective is to study global ocean circulation and its interaction with the atmosphere to better understand the Earth's climate. TOPEX flies at an altitude of about 1336 km in a nearly circular orbit, with an inclination of 66.04 deg. This orbit provides for an exact repeat ground track every 127 revolutions (about ten days per cycle). Originally projected for a three-year primary mission with the possibility of a two-year extension, TOPEX is now orbiting the Earth in its tenth year of successful operation. It has orbited the Earth approximately 43,500 revolutions and has completed 339 cycles.

TOPEX is a three-axis stabilized, near-continuous sinusoidal yaw steering spacecraft (see Fig. 1). The solar array (SA) pitching strategy combined with yaw steering is used to maintain the SA pointed toward the Sun for power optimization. When the β' (the angle between the orbit plane and the sun line) is between ±30 degrees, a fixed yaw attitude is used to avoid excessive yaw rates. The satellite is in fixed yaw flying forward mode when $0 < \beta' < 30$, and is in fixed yaw flying backward mode when $-30 < \beta' < 0$. When β' is near 0 degree, a yaw flip maneuver is used to maintain the SA on the sunlight side of the satellite. The actual pitch angle of the SA is offset from the true sun line to control the rate of battery charging, and is a function of SA degradation level. Since the beginning of the mission there have been four pitch offset angle changes. Currently, the pitch bias angle is maintained at 40 degrees.

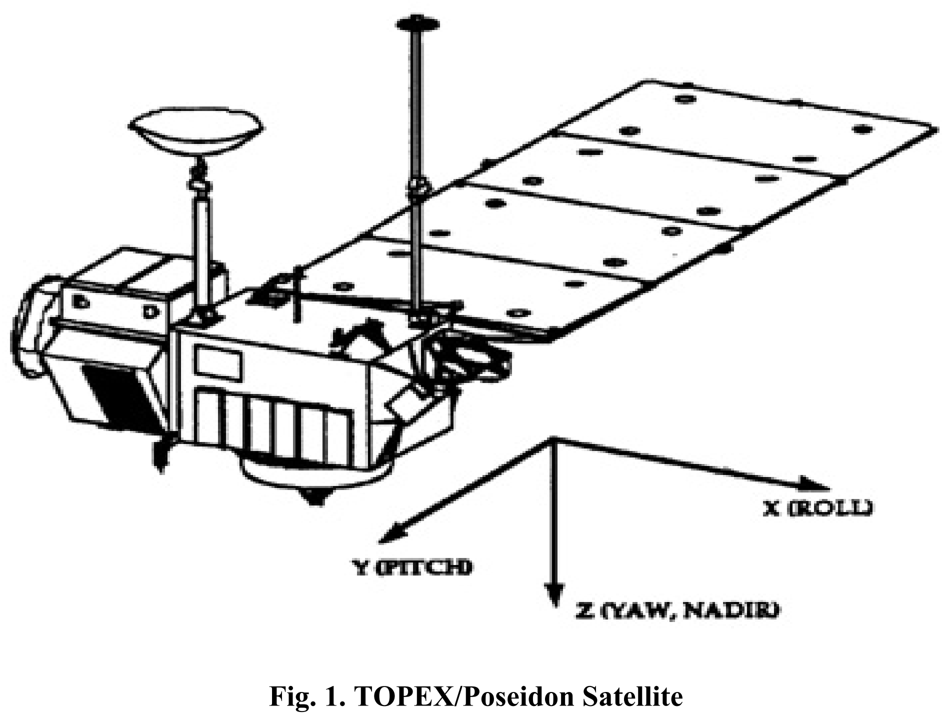

Fig. 1. TOPEX/Poseidon Satellite

Anomalous Force

The existence of an anomalous force was initially observed in 1993 from analysis of tracking data [Ref. 1]. The magnitude of this force is equivalent to a continuous thrust on the order of micro-Newtons. The direction and magnitude are a function of the satellite attitude mode. The anomalous force has a large along track component during fixed yaw periods. This force applies a rather slow thrust along or opposite to the velocity vector. During positive fixed yaw periods, it creates a boost and during negative fixed yaw it has a decay effect. Table 1 shows the characteristics of the anomalous force for TOPEX.

Table 1. Anomalous force characteristics for TOPEX

Attitude Mode	Solar Array Pitch Bias 40°	Solar Array Pitch Bias –40°
0 < β' < 30	Variable Boost: 15 –27 cm/day	Variable Decay
-30 < β' < 0	Variable Decay: 30 –40 cm/day	Variable Boost: 7 –17 cm/day
Yaw steering β' >30	Variable Decay 5 –15 cm/day	N/A (pitch bias always +40° during yaw steering)
Yaw steering β' < -30	Variable Boost 3 – 13 cm/day	N/A (pitch bias always +40° during yaw steering)

Solar Flux and Geomagnetic History

The TOPEX Navigation Team uses a Jacchia-Roberts Density Model that accepts as input the $F_{10.7}$ solar flux values, planetary geomagnetic indices K_p and A_p, and the 81-day mean solar flux values $F_{10.7}$. During the course of the solar cycle (cycle period seven to thirteen years, averaging eleven years), the solar flux values undergo a solar maximum and minimum that reflect the level of sunspot activity. During the solar maximum periods, the active growth and decay patterns of the Sun also cause large day-to-day fluctuations of the $F_{10.7}$ solar flux values. Along with an increase in both the magnitude and fluctuations of the solar flux, the solar maximum period also causes periods of high geomagnetic activity. Large coronal ejections or solar flares produce spikes and peaks in the geomagnetic K_p and A_p index values. These colossal flare-ups can last from a few minutes to few hours and can release huge amounts of energy. As the energy from the solar flares races away from the Sun, solar wind can create forces that cause decay in the TOPEX altitude and thus the semi-major axis (SMA). Solar wind forces consequently affect the TOPEX ground track, which must be maintained within a ±1 km control band.

Since the launch of TOPEX in 1992, solar flux and geomagnetic activity levels have varied considerably during the satellite on orbit support. Solar maximum was evident around the TOPEX launch. A new cycle started from minimum levels in 1994. Solar maximum levels reappeared from mid 1999 and are expected to last until 2002. Fig. 2 shows a plot of solar flux data for the past ten years.

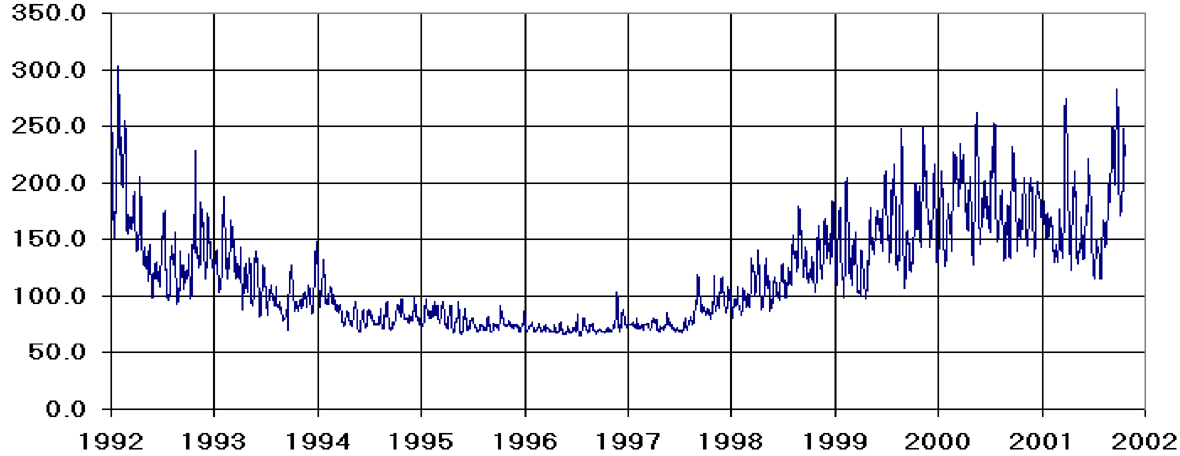

Fig. 2. $F_{10.7}$ Solar Flux Values

Notice the solar flux minimum around the years 1995 to 1998. The relatively smaller solar flux values during those years helped the Navigation team maximize the time in between maneuvers. OMM9 occurred on January 15, 1996 and OMM10 was not performed until December 1, 1998. With the return of the solar maximum, both the general magnitude of the solar flux and its day-to-day fluctuations has increased.

Fig. 3 shows a plot of A_p values for the past 10 years. Notice the relatively large spikes around the period corresponding to the solar maximum. As a result of the solar maximum period, TOPEX must maneuver approximately four times a year to stay within the $\pm$1 km control band.

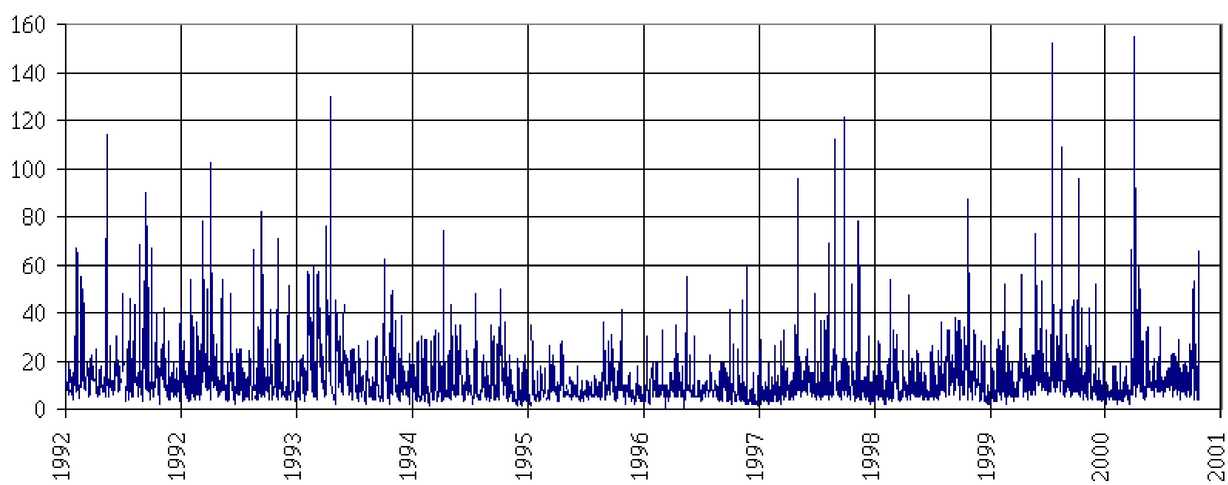

Fig. 3. Geomagnetic Ap Values

ORBIT MAINTENANCE MANEUVERS (OMM)

Since reaching the operational orbit in 1992, the TOPEX satellite has performed a total of nineteen OMMs. Since solar maximum levels reappeared in 1999, an average of four maneuvers per year have been performed to maintain the ground track within a ±1 km control band. Specific requirements for OMM are described in Ref. 2. One of the requirements specifies that the OMM be performed as nearly as possible to the transition between 127 orbit cycles (±1 revolution). Furthermore, since the spacecraft utilizes nearly continuous yaw steering and solar array pitching for optimal solar array pointing, maneuver executions in the early years entailed performing a complex "turn-burn-turn" sequence where yaw steering is temporarily suspended and the satellite slewed to the attitude where the thrusters are correctly oriented for burn execution. After the maneuver execution, the sequence is then "unwound" to yaw steering again.

Because of the complexity of this maneuver execution, reduction in manpower, and streamlining the OMM support, the navigation team proposed to perform the maneuvers at fixed yaw attitude mode, flying forward (yaw at 0 degree) periods, when possible. The project agreed to this proposal, but left available the option to perform the maneuvers at other attitude modes if necessary. Simulations regarding the number of maneuvers performed each year during the solar maximum show that TOPEX might perform one or two less maneuvers in a year if the time between maneuvers was maximized as opposed to targeting only fixed yaw flying forward periods for maneuvers. However, the benefits of performing maneuvers during fixed yaw periods outweigh the benefits of doing one less maneuver per year as a result of maximizing the time between maneuvers. OMM16, OMM17, and OMM19 were performed successfully with less complexity during fixed yaw mode, flying forward ($0 < \beta' < 30$). The results of the OMM16 and OMM17 are presented in the following sections.

Additional maneuver design requirements are derived from thermal, power, high or low solar flux conditions, and solar array lead/lag strategy using anomalous force as a micro-thruster. Table 2 illustrates the factors that affect the ground track variations during a typical maneuver.

Table 2. Factors affecting the ground track

Event	Duration (Days)	Effect	Approximate delta-V (mm/s)
Nominal OMM	-	Boost	+3.5
5% maneuver error	-	Boost/decay	±0.2
Solar Activity / Drag changes	1	Boost/decay	±0.03
Solar Activity / Drag changes	30	Boost/decay	±1.00
Switch from lead to lag (flying backward)	1	Boost	+0.25
Switch from lead to lag (flying backward)	12	Boost	+3.30
Advance the switch from flying forward to yaw steering	1	Decay	-0.13

OMM16 Planning and Performance

The ground track is monitored regularly to ensure that the ± 1 km control boundary requirement is met and to provide sufficient time for planning and execution of OMMs. Pre-maneuver analysis for OMM16 indicated that the ground track was predicted to cross the eastern boundary on October 15, 2000 (see Fig. 4).

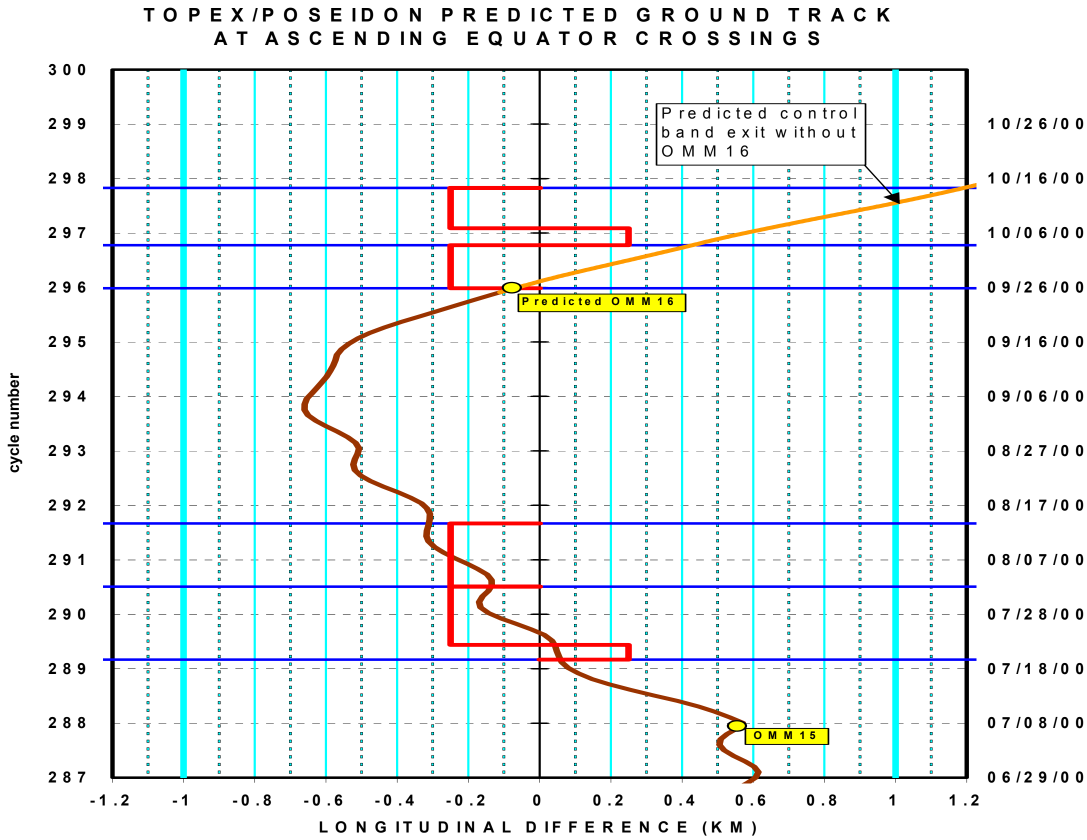

Fig. 4. Predicted Ground Track without OMM16

The upcoming fixed yaw period on September 24, 2000 was the opportunity to plan the maneuver. The new cycle boundary started on September 26, 2000. In order to have sufficient pre- and post- tracking time for orbit determination and post maneuver calibration analysis, it was agreed upon to stay in continuous yaw steering mode and switch to fixed yaw (yaw= 0^o) just before the start of the new cycle when $\beta'=22^o$ (see Fig. 5). Changing the fixed yaw period requires the modification of only a single command word, thus, the work required to implement the variation in the timing of the fixed yaw is relatively small.

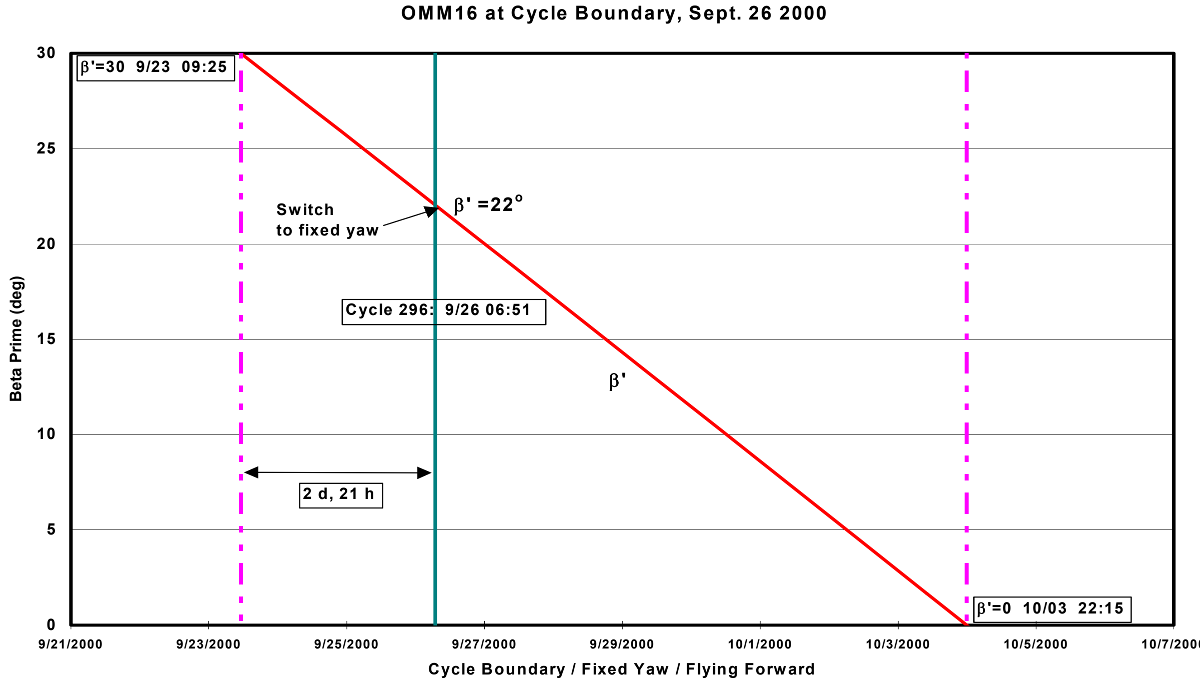

Fig. 5. OMM16 at Cycle Boundary

OMM16 occurred when the ground track at ascending node crossing was about 66 meters west of the reference longitude. The ideal delta-V value was selected at 4.5 mm/s, and an increase of 9.66 meters in SMA was expected. The changes in the characteristics of the ground track were principally due to variations in the solar flux levels and anomalous force during September. The designed maneuver was based on positioning the solar array to create boost for both fixed yaw flying forward and backward periods. Due to an achieved delta-V value of about 3% higher than expected, and lower solar flux conditions, more boost than was expected was observed. Consequently, the actual decay due to atmospheric drag was significantly less than expected. Larger boost resulted in SMA value somewhat above the reference value and the ground track was predicted to reach the western boundary of the control band, as illustrated in Fig. 6.

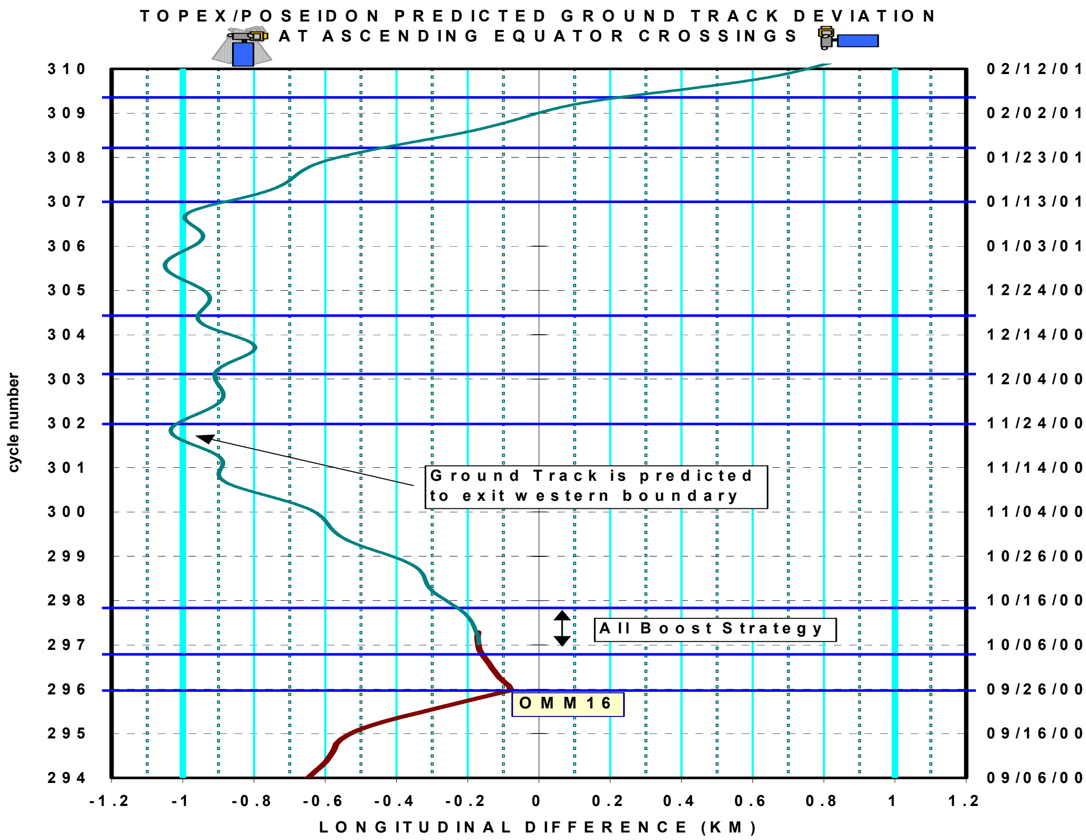

Fig. 6. Predicted Post-OMM16 Ground Track with All Boost Strategy

To prevent the ground track from crossing the western boundary and violating the control band requirement, a partial lead/lag strategy was applied to create some decay condition during the second half of the fixed yaw period in October 2000, thereby lowering the SMA value and keeping the ground track within the control band (see Fig. 7).

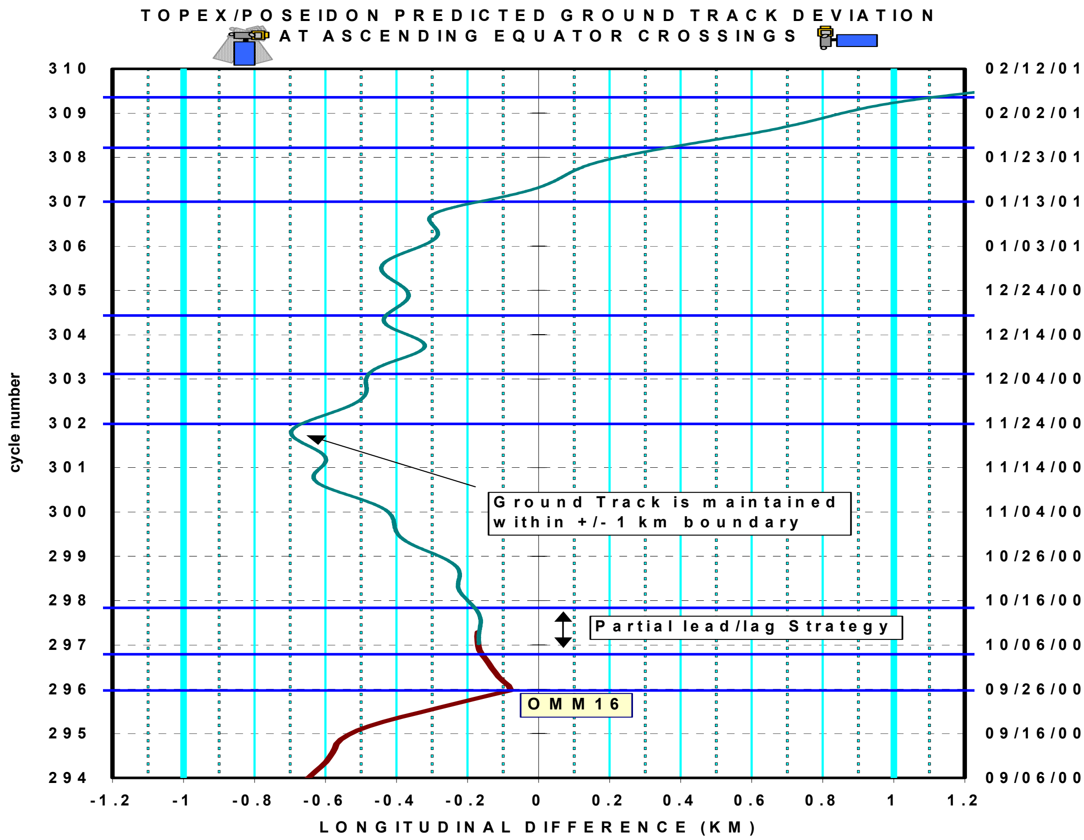

Fig. 7. Predicted Post-OMM16 Ground Track with Partial Lead/Lag Strategy

After the yaw flip at $\beta' = 0^o$ (yaw = 180^o) on October 4, 2000, the SA offset was kept at $+40^o$ (lead) for about 2.5 days to create a "micro maneuver" equivalent to a decay of approximately 1.2 meters in SMA value. Then, at the end of the 2.5 days, the SA was slewed back to lag position (SA=-40^o) to maintain a constant SMA decay rate (see Fig. 8) and to extend the maneuver spacing, while containing the ground track variation within the control boundary. This strategy helped to keep the ground track at the western boundary longer. Again, the work required to implement solar array bias offset changes is relatively small and can also be implemented in near real-time situations.

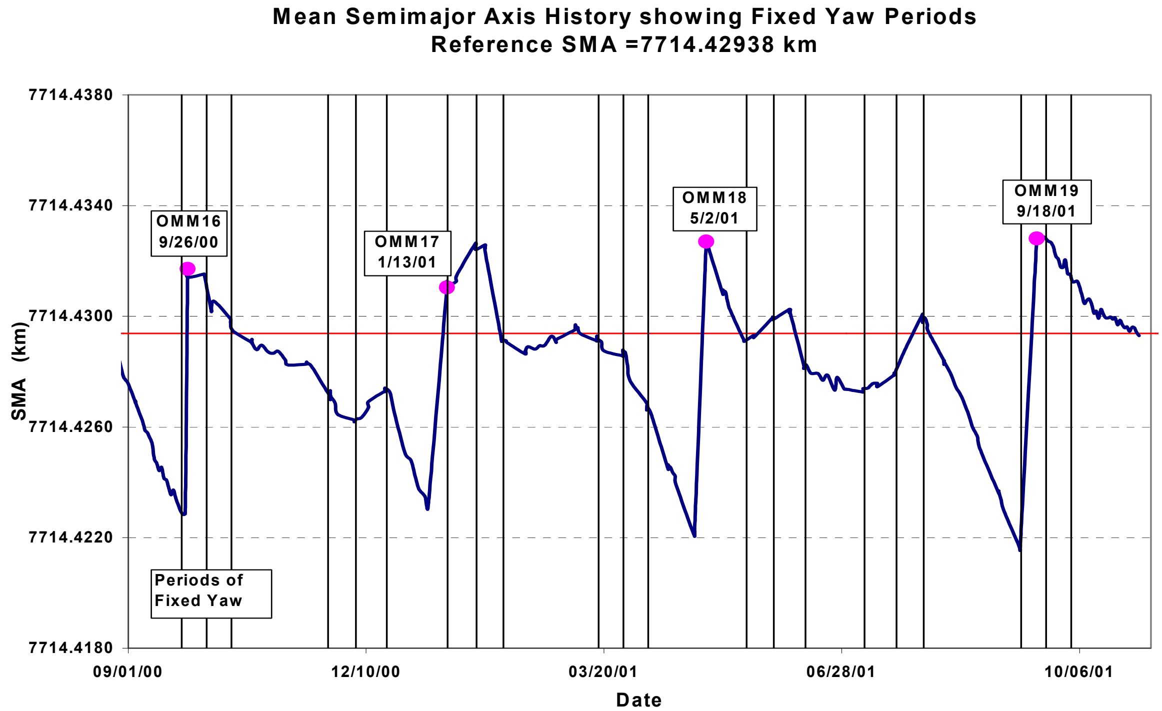

Fig. 8. Semi major Axis Maintenance History

Further analysis of trajectory runs showed that when the ground track started to turn eastward around mid-November, an all boost strategy during fixed yaw periods of November and December would help to extend the ground track maintenance near the western boundary. Therefore, at the start of fixed yaw on November 24, 2000, (yaw=180^o) the SA was again slewed to –40^o (lag position). After the yaw flip, the SA was switched to +40^o (lead position). Again, this strategy, along with somewhat lower than expected solar activity, helped create micro-thruster maneuver conditions and extend the ground track maintenance within the control band. The lead/lag strategy for OMM16 support during the solar activity conditions of September 2000 thru January 2001 extended the maneuver spacing to 109 days and OMM17 was planned to be executed at the start of cycle boundary and fixed yaw period of January 2001.

OMM17 Performance

OMM17 was performed successfully on January 13, 2001 under similar conditions as OMM16. The fixed yaw period was started at β'=27^o to coincide with the start of a new repeat cycle. Fig. 9 shows the maneuver performance of OMM17.

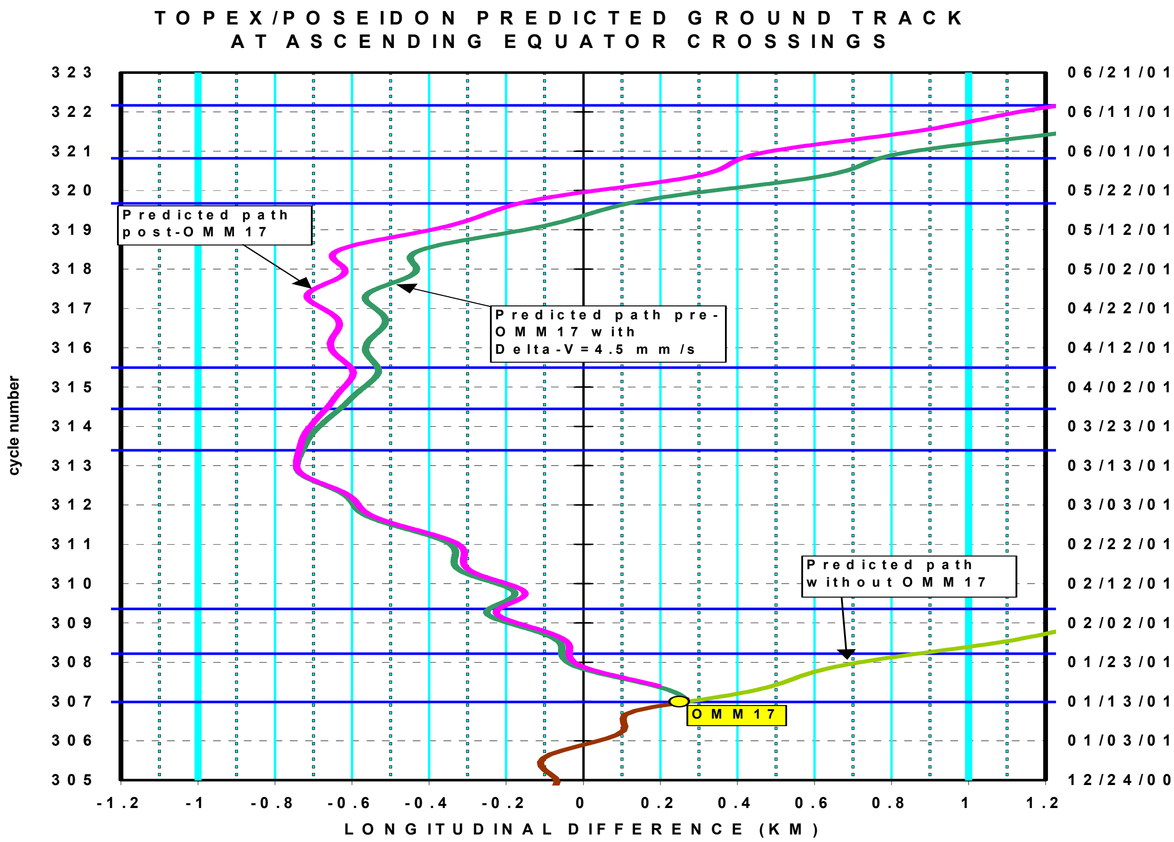

Fig. 9. OMM 17 Ground Track

Orbit Maintenance Maneuver Performance

Table 3 shows the performance of the last four maneuvers, which were executed during solar maximum.

Table 3. Maneuver Performance

Maneuver	Date	Pass Number	Attitude Mode	Ideal Delta-V (mm/s)	Achieved Delta-V (mm/s)	% Difference (Achieved-ideal)
OMM 16	09/26/2000	254	Fixed yaw, flying forward	4.50	4.633	+2.89
OMM 17	01/13/2001	254	Fixed yaw, flying forward	4.50	4.558	+1.11
OMM 18	05/02/2001	1	Yaw Steering	5.80	5.661	-2.40
OMM 19	9/18/2001	254	Fixed yaw, flying forward	5.30	5.000	-5.66

CONCLUSION

The results of the past OMM support indicate that an increase in the semi-major axis (from boost) will cause the ground track to shift westward, while a decrease moves the ground track eastward. By applying the solar array lead/lag strategy during the fixed yaw periods, the TOPEX Navigation team are able to maintain the ground track in the western portion of the boundary as long as possible, while extending the maneuver spacing during high and low solar activity and atmospheric drag conditions. Planning to perform the maneuvers at a cycle boundary and during fixed yaw flying forward periods, allows a standard way of supporting maneuvers. During these times, the procedures for maneuver support, expected delta-V values for SMA boost, power and battery concerns, attitude considerations, etc. will all be similar and routine processes. With the age of the TOPEX mission and the reduction in manpower, the advantages of this technique in streamlining the orbit support have been evident. The TOPEX ground track has been kept within the control band continuously and the number of orbit maintenance maneuvers executed has been between four and five per year, easily satisfying mission requirements.

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