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Clarence E. Doll
National Aeronautics and Space Administration
Goddard Space Flight Center (GSFC)
Greenbelt, Maryland 20771 U.S.A

Dipak H. Oza, David T. Bolvin, and John M. Lorah
Computer Sciences Corporation (CSC)
Lanham-Seabrook, Maryland 20706 U.S.A

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# TOPEX/POSEIDON ORBIT DETERMINATION USING TDRSS*

Clarence E. DOLL
*National Aeronautics and Space Administration (NASA)*
*Goddard Space Flight Center (GSFC)*
*Greenbelt, Maryland, 20771 U.S.A*

Dipak H. OZA, David T. BOLVIN, and John M. LORAH
*Computer Sciences Corporation (CSC)*
*Lanham-Seabrook, Maryland, 20706 U.S.A*

***ABSTRACT*** *- Orbit determination results are obtained for the Ocean Topography Experiment (TOPEX)/Poseidon spacecraft by the Goddard Space Flight Center Flight Dynamics Division (FDD) using the batch least-squares estimator available in the Goddard Trajectory Determination System to process Tracking and Data Relay Satellite (TDRS) System (TDRSS) tracking measurements. The first set of results describes the evaluation of a new and innovative FDD maneuver-related orbit determination technique designed to recover the change in along-track velocity, resulting from an impulsive TOPEX/Poseidon groundtrack maintenance maneuver, to an accuracy of 0.2 millimeter per second. The second set of results describes and assesses the accuracy of improved techniques for performing FDD free-flight TOPEX/Poseidon orbit determination. The results show that the root-mean-square radial component difference between the FDD TOPEX/Poseidon solution and the high-accuracy TOPEX/Poseidon precision orbit ephemeris is 24 centimeters.*

## 1 - INTRODUCTION

This study assesses a new constrained-maneuver orbit determination technique that was developed for evaluating and improving the recovery of the along-track velocity change resulting from an Ocean Topography Experiment (TOPEX)/Poseidon groundtrack maintenance maneuver. The paper also assesses the TOPEX/Poseidon free-flight orbit determination accuracy of the Tracking and Data Relay Satellite (TDRS) System (TDRSS)-based orbit solutions using the Goddard Space Flight Center (GSFC) Flight Dynamics Division (FDD) operational batch-least-squares system.

TDRSS is a geosynchronous relay satellite network; it currently consists of five geosynchronous spacecraft and a central command center called the White Sands Complex (WSC) at White Sands, New Mexico. Three of these TDRSs (TDRS-East, TDRS-West, and TDRS-Spare, located at 41 degrees, 174 degrees, and 171 degrees west longitude, respectively) actively support tracking of TDRSS-user spacecraft. Of the two remaining TDRSs, one (located at 275 degrees west longitude) is used only for spacecraft communications while the other (located at 46 degrees west longitude) is being reserved for future use. TDRSS can provide 85-percent to 100-percent coverage, depending on the spacecraft altitude.

The Bilateration Ranging Transponder System (BRTS) provides range and Doppler measurements for determining each TDRS orbit. The ground-based BRTS transponders are tracked as if they were TDRSS-user spacecraft. Since the positions of the BRTS transponders are known, their ranging data can be used to precisely determine the trajectory of the TDRSs.

The TOPEX/Poseidon spacecraft was launched on an Ariane 42P expendable launch vehicle in August 1992. In October 1992, maneuvers were completed that moved the spacecraft into its

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operational orbit, which is circular with an inclination of 66 degrees, an altitude of 1336 kilometers, a period of 112 minutes, and a 10-day ground track repeat period.

To fulfill the science goals of the TOPEX/Poseidon mission, the TOPEX/Poseidon spacecraft must be maintained within a precise predefined east-west groundtrack that is 2 kilometers wide at the equator and repeats itself every 10 days. However, due to small acceleration perturbations such as atmospheric drag, solar and lunar gravitational effects, observed but unexplained body forces, and Earth oblateness, the spacecraft will, over time, tend to drift out of this 2-kilometer groundtrack. To maintain the groundtrack, small along-track maneuvers are performed periodically to restore the semimajor axis to realign the TOPEX/Poseidon trajectory within the 2-kilometer band. Because the groundtrack requirements are strict and the perturbative forces are so small, only extremely small maneuvers (velocity change ($\Delta V$) less than 10 millimeters per second (mm/sec)) are necessary to maintain the groundtrack. To successfully execute such small maneuvers, thruster performance must be well characterized and understood. As an integral part of the thruster calibration goals, a comprehensive set of maneuver-related orbit determination requirements were levied on the FDD. These include determining the change in the radial and cross-track velocity resulting from a TOPEX/Poseidon groundtrack maintenance maneuver to 10 mm/sec ($3\sigma$). However, the most stringent of these required the FDD to determine the change in the along-track velocity ($\Delta V$), resulting from a groundtrack maintenance maneuver, to an accuracy of 0.2 mm/sec ($3\sigma$). The technique developed to meet this requirement is described in Section 2.1.

High-accuracy TDRSS-based free-flight orbit determination solutions are obtained for TOPEX/Poseidon using the batch-least-squares algorithm implemented in the Goddard Trajectory Determination System (GTDS). The TDRSS-based orbit solutions are compared with the high-precision orbit solutions obtained by the GSFC Space Geodesy Branch using laser and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) tracking measurements [Tapl 94]. The accuracy requirements on the Space Geodesy Branch orbit determination solutions, which are used to analyze the sea surface height measurements obtained by the TOPEX/Poseidon radar altimeter, are extremely stringent. The definitive orbit determination requirements for the TOPEX/Poseidon mission science data include a maximum 13-centimeter ($1\sigma$) radial position error. The availability of the high-accuracy independent precision orbit determination ephemerides (POEs) generated by the Space Geodesy Branch provides a unique opportunity to evaluate the accuracy of the orbit determination systems used by the FDD for operational navigation and analysis support. The orbit determination techniques and evaluation methods are given in Section 2.2.

Section 3 of this paper presents the maneuver solution results, and Section 4 presents the enhanced orbit solution results. The conclusions of this study are given in Section 5.

## 2 - ANALYSIS PROCEDURES

This section describes the analysis procedures used in this study and provides a description of the tracking measurements and orbit determination and modeling methods.

### 2.1 Orbit Maneuver Solutions

Preliminary FDD analysis results clearly indicated that new orbit determination procedures had to be developed to recover the TOPEX/Poseidon along-track $\Delta V$ change to an accuracy of 0.2 mm/sec. As a result, a new and innovative maneuver modeling technique, hereafter referred to as the constrained-maneuver technique, was proposed, developed, and analyzed by the FDD as a candidate procedure for supporting TOPEX/Poseidon groundtrack maintenance maneuvers. The steps for estimating the along-track velocity changes using this new technique are as follows:

1. Generate a premaneuver orbit determination solution, based only on premaneuver tracking measurements, to estimate the spacecraft position and velocity at the maneuver centroid time.

2. Generate a postmaneuver orbit determination solution, using only postmaneuver tracking measurements, to estimate the velocity at the maneuver centroid time while constraining the spacecraft position at the maneuver centroid time to be the same as the estimated premaneuver spacecraft position. The solution arcs and estimated parameters for the constrained-maneuver technique are schematically depicted in Fig. 1.

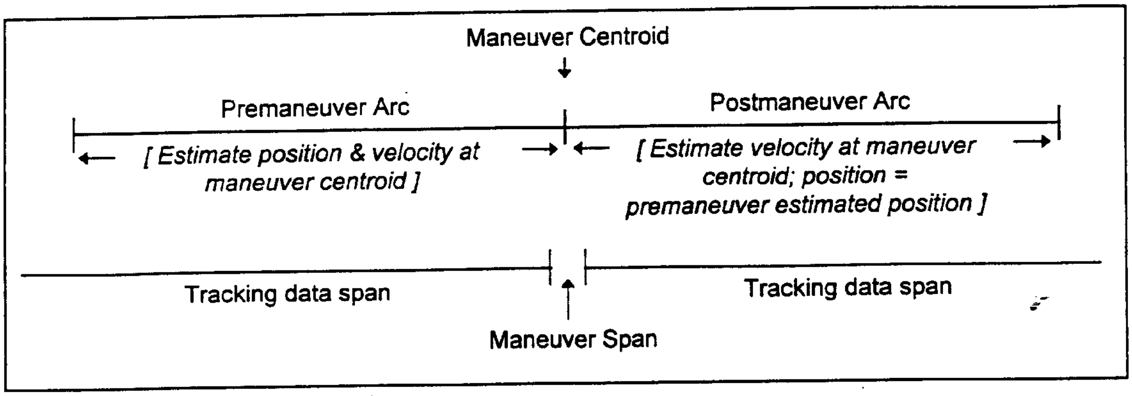


**Fig. 1:** Schematic diagram of the constrained-maneuver orbit determination arcs and estimated parameters

3. Determine the change in velocity using the differential form of the energy equation, which is derived below.

The *vis-viva* energy equation is given by

$$V^2 = GM\left(\frac{2}{r} - \frac{1}{a}\right) \quad (2.1)$$

where $V$ is the magnitude of the velocity of the spacecraft, $GM$ is the universal gravitational constant times the mass of the Earth, $r$ is the spacecraft radial position, and $a$ is the semimajor axis. Taking the partial derivatives of the energy equation yields

$$2V(\Delta V) = \frac{\partial V^2}{\partial a}(\Delta a) + \frac{\partial V^2}{\partial r}(\Delta r) \quad (2.2)$$

which becomes

$$\Delta V = \frac{GM}{2Va^2}(\Delta a) - \frac{GM}{Vr^2}(\Delta r) \quad (2.3)$$

Thus, the $\Delta V$ is a function of the change in the spacecraft radial position and the semimajor axis. The constrained-maneuver technique assumes that the maneuver is small enough to be considered instantaneous, which is approximately true for the TOPEX/Poseidon groundtrack maintenance maneuvers. In an instantaneous along-track maneuver, the semimajor axis (or period) is increased while the spacecraft position is assumed to be continuous and, therefore, does not change at the instant the maneuver occurs. Under these conditions, the $\Delta r$ term is zero, and the differential form of the energy equation becomes

$$\Delta V = \frac{GM}{2Va^2}(\Delta a) \quad (2.4)$$

By taking the difference between the determined postmaneuver and premaneuver semimajor axes at the maneuver centroid to compute $\Delta a$, and substituting typical values for $GM$, $V$, and $a$, an accurate estimate of $\Delta V$ can be obtained. This method for estimating the along-track $\Delta V$ change was developed and used because it realistically represents the velocity changes resulting from an impulsive maneuver. Alternatively, ΔV can be estimated by differencing the premaneuver and postmaneuver velocity magnitudes determined at the maneuver centroid time.

To evaluate the potential accuracy for estimating the along-track ΔV using the constrained-maneuver technique, comprehensive orbit determination analysis using GTDS and orbit determination covariance analysis using the Orbit Determination Error Analysis System (ODEAS) for the TDRSS-tracked Earth Radiation Budget Satellite (ERBS) was performed prior to the TOPEX/Poseidon launch. For ERBS, the theoretical accuracy limits of the constrained-maneuver technique were determined and assessed using tracking measurement spans where no maneuvers occurred, hereafter referred to as null-maneuver cases. In these null-maneuver cases, the constrained-maneuver technique was applied to spans of maneuver-free tracking measurements. Ideally, since no maneuver occurred, the estimated along-track ΔV at the null-maneuver centroid time should be zero. However, because the premaneuver and postmaneuver orbit determination arcs will be subject to different tracking measurement and dynamic effects from the same acceleration perturbations, the estimated along-track ΔV will not be zero. The goal of the ERBS analysis was to show that the estimated null-maneuver along-track ΔV, which represents the theoretical accuracy limit of the constrained-maneuver technique, will be less than 0.2 mm/sec. ERBS was considered a worst case relative to TOPEX/Poseidon since the errors would be attenuated at the TOPEX/Poseidon altitude. The results of this analysis are presented in Section 3. To complete the assessment of the constrained-maneuver technique, the maneuver evaluation results for the first seven TOPEX/Poseidon orbit maintenance maneuvers are also presented in Section 3.

## 2.2 Orbit Determination Methods and Modeling

The GTDS batch-least-squares estimation and the orbit determination procedure used in this study are described below.

### *2.2.1 GTDS Batch-Least-Squares Estimation*

The batch-least-squares estimation algorithm used by GTDS for this analysis is the same as that used for operational navigation support of the TOPEX/Poseidon mission by the GSFC FDD. The modeling and state estimation parameters used for this analysis were improved to provide more accurate results and to take advantage of techniques not currently in operational use. Specifically, the TOPEX/Poseidon state space was expanded to include estimation of the coefficient of solar radiation pressure and multiple along-track thrust parameters that were intended to compensate for an anomalous acceleration acting on the spacecraft. Analysis of the operational TOPEX/Poseidon orbit solutions indicated the presence of an unmodeled spacecraft body-fixed force with a day-to-day variability that occurred immediately after the mission orbit was achieved; this behavior became the subject of intense further analysis.

The solution arc for this study spans the 5-day period beginning 00 hours ($0^h$) coordinated universal time (UTC) on 4 November 1992 and ending at $0^h$ UTC on 9 November 1992, which corresponds to the middle of TOPEX/Poseidon Cycle 5. (A cycle is defined as a 10-day groundtrack repeat time for TOPEX/Poseidon.) The analysis started in the middle of Cycle 5 to avoid a TDRS-East maneuver early on 4 November 1992. The TOPEX/Poseidon POE is unaffected by TDRS events, since it is not produced using TDRSS tracking measurements. The main reasons for choosing this period are that it overlaps with a period for which sets of high-accuracy TDRS and TOPEX/Poseidon POEs are available and there was minimal TOPEX/Poseidon spacecraft activity during this period. Additionally, the accuracy of the enhanced GTDS TDRS orbits could be easily assessed [Oza 95].

Tracking measurements from TDRSS were used in GTDS to estimate the TOPEX/Poseidon and TDRS definitive orbits. The GTDS orbit solutions were obtained using range and one-way return and two-way Doppler measurements from TDRSS in addition to range measurements from BRTS.

The tracking consisted of an average of 10 passes of one-way return Doppler measurements and 11 passes of range and two-way Doppler measurements per day, with the average pass lasting 40 minutes.

### *2.2.2 Orbit Determination Procedure*

TDRS spacecraft trajectories were estimated simultaneously with TOPEX/Poseidon using both BRTS range and TOPEX/Poseidon range and two-way and one-way return Doppler measurements to determine the best possible TDRS trajectories for use in the TOPEX/Poseidon-only batch estimation. The modeling, tracking measurement types, and other orbit determination options used for the TDRSs and TOPEX/Poseidon in the simultaneous solution are presented in [Doll 94]. However, the current study uses a Joint Gravity Model-2 (JGM-2) 70×70 geopotential, an increase from the previous truncated JGM-2 50×50. Additionally, The GTDS solutions are derived using the ACB method described below. This ACB method is a slight refinement of the method used to produce the high-accuracy results presented in [Oza 94]. The data span chosen was 5 days, with one thrust correction factor estimated per day. The simultaneous TDRS-TOPEX/Poseidon solution arcs were selected to avoid all TDRS maneuvers and angular momentum unloads for TDRS, where possible, while maintaining the longest possible data spans. In addition, central angle editing was used to mitigate the effects of ionospheric refraction on the TDRS-to-TOPEX/Poseidon tracking link. The central angle chosen was designed to eliminate all data below the TOPEX/Poseidon local horizon.

The technique developed for obtaining more accurate TDRS orbit solutions using GTDS, referred to as the analytic calibration of biases (ACB) technique, involves performing a series of simultaneous TDRSs/TDRSS-user solutions to calibrate a set of relative range measurement biases for each source of TDRSS range measurement errors. The ACB technique estimates, in a methodical manner, a set of relative range measurement biases for each source of TDRSS range measurement error. In the standard ACB technique, a total of six solutions are generated. The first five solutions are simultaneous TDRSs/TDRSS-user solutions used to obtain the best possible TDRS trajectories. The final solution is a TDRSS-user-only solution that uses the best estimated TDRS trajectories determined from the previous simultaneous solutions. The details of this procedure are presented in [Oza 95]. Fig. 2 summarizes the ACB procedure schematically. After the TDRS trajectories were estimated in the simultaneous solution, they were used to compute a TOPEX/Poseidon-only solution based on the one-way and two-way Doppler data only. This was done to minimize the effect of TOPEX/Poseidon range measurement bias modeling errors on the TOPEX/Poseidon trajectory.

## 3 - MANEUVER SOLUTION RESULTS

This section gives the results of the ERBS and TOPEX/Poseidon along-track $\Delta V$ estimation using the constrained-maneuver technique. Section 3.1 presents the ERBS null-maneuver evaluation results that were performed prior to the TOPEX/Poseidon launch to verify and validate that the TOPEX/Poseidon accuracy requirement of 0.2 mm/sec along-track $\Delta V$ maneuver evaluation can be met. Section 3.2 presents real maneuver evaluation results for the first seven TOPEX/Poseidon orbit maintenance maneuvers (OMMs).

### 3.1 Prelaunch Null-Maneuver Results

Null-maneuver orbit determination analysis and orbit determination covariance analysis for the ERBS spacecraft were performed for the timespan beginning on 3 February 1988 and ending on 6 March 1988. The ERBS orbit is nearly circular and has a nominal altitude of 600 kilometers and an inclination of 57 degrees. Three null-maneuver cases were analyzed. The premaneuver and postmaneuver orbit determination arcs were 34 hours long to correspond to the FDD operational ERBS arc lengths during this period, and the modeling used was the same as that used for

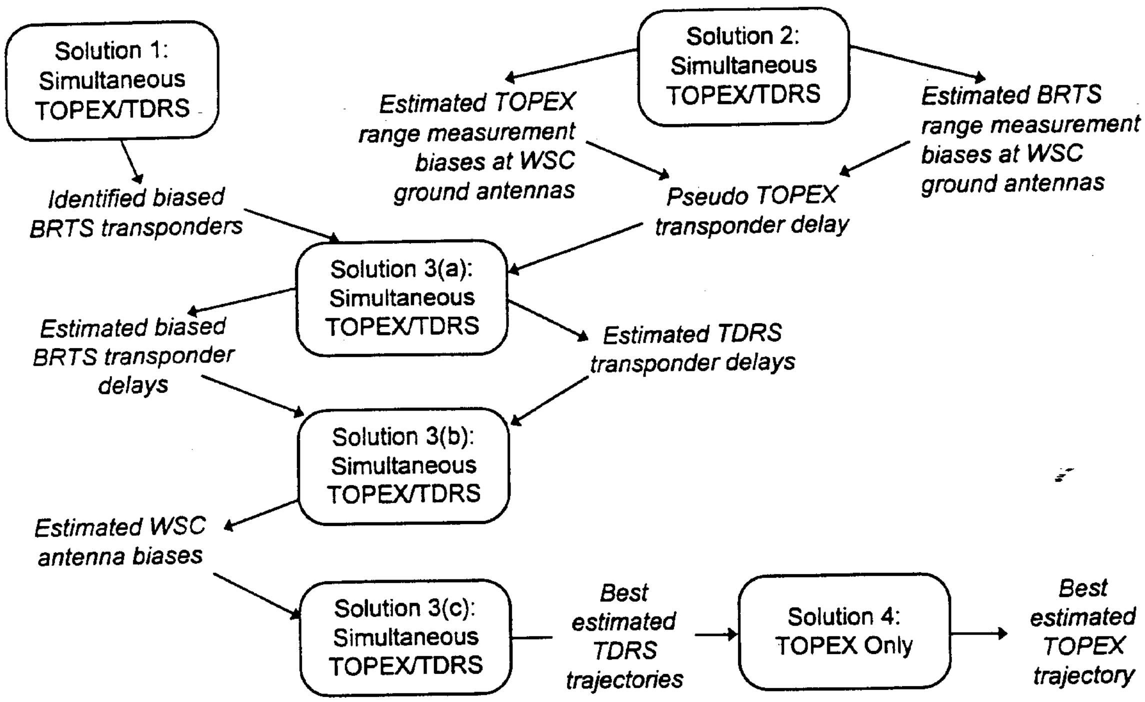


**Fig. 2:** Schematic of the ACB procedure

operational support during this period. The geopotential model used was the Goddard Earth Model-T2 (GEM-T2) truncated to 30×30, and the atmospheric density model used was the Harris-Priester model. The 34-hour TDRS-4 orbits for the ERBS solutions were pregenerated with the FDD operational modeling.

The three null-maneuver centroid times are 11:48 UTC on 1 March, 00:12 UTC on 3 March, and 14:14 UTC on 4 March. Under the planned orbit maintenance maneuver scenario, the TOPEX/Poseidon spacecraft would be tracked by TDRSS up to and immediately after the maneuver. To simulate this scenario, tracking measurements were omitted several minutes before and after the ERBS null-maneuver centroid time. The tracking measurement stop and start times, the centroid times, and the duration of the tracking measurement gap around each null maneuver are shown in Table 1.

**Table 1: ERBS Null-Maneuver Centroid and Tracking Measurement Start and Stop Times**

| Null Maneuver | Premaneuver Tracking Data Stop Time | Maneuver Centroid Time | Postmaneuver Tracking Data Start Time | Tracking Data Gap |
|---|---|---|---|---|
| 1 | 11:42 UTC March 1 | 11:48 UTC March 1 | 11:55 UTC March 1 | 13 minutes |
| 2 | 00:04 UTC March 3 | 00:12 UTC March 3 | 00:17 UTC March 3 | 13 minutes |
| 3 | 14:10 UTC March 4 | 14:14 UTC March 4 | 14:19 UTC March 4 | 9 minutes |

The results of the ERBS GTDS null-maneuver orbit determination and ODEAS 3σ orbit determination covariance analyses are shown in Table 2. For comparison purposes, additional postmaneuver solutions were generated in which the ERBS spacecraft position was not constrained to equal the premaneuver estimated position. The computed velocity differences at the maneuver centroid time for these unconstrained solutions are also shown in Table 2.

**Table 2: GTDS and ODEAS 3σ ERBS Constrained and Unconstrained Null-Maneuver Along-Track ΔV Estimation Results**

| Null Maneuver | Changes in Along-Track Component of Velocity (mm/sec) | | |
|---|---|---|---|
| | GTDS | | ODEAS |
| | Unconstrained | Constrained | Unconstrained |
| 1 | 2.50 | 0.13 | 3.38 |
| 2 | 1.27 | 0.54 | 2.10 |
| 3 | 2.65 | 0.21 | 5.84 |

The changes in the along-track velocity for the GTDS constrained-maneuver cases were computed from the premaneuver and postmaneuver orbit determination solutions using the differential form of the energy equation (Equation 2.4) derived in Section 2.1. Due to limitations in the software, ODEAS cannot adequately estimate the errors on the along-track velocity changes for the constrained-maneuver technique, so only unconstrained covariance analysis results are presented. The GTDS constrained-maneuver results show that the first null-maneuver solution meets the 0.2 mm/sec requirement, the third marginally exceeds the requirement, and the second exceeds the requirement. For the GTDS and ODEAS unconstrained solutions, the estimated along-track ΔVs, which were computed by differencing the premaneuver and postmaneuver along-track ΔV, exceed the 0.2 mm/sec requirement for all cases and are an order of magnitude larger than the constrained results. For all three unconstrained-maneuver cases, the geopotential uncertainty is the dominant error source. Additional covariance analysis was performed for TOPEX/Poseidon using the unconstrained technique, and the results indicated that the errors on the estimated along-track ΔV were comparable to those shown for ERBS in Table 2 [Scha 92]. This suggests that the constrained solution results for TOPEX/Poseidon and ERBS will also be the same order of magnitude. In fact, the TOPEX/Poseidon constrained-maneuver results will most likely improve over the ERBS results because the altitude of TOPEX/Poseidon is much higher than that of ERBS and is less likely to be affected by the perturbations resulting from atmospheric drag and geopotential errors. Furthermore, the analysis was performed using the GEM-T2 geopotential model, which is not the geopotential model used for TOPEX/Poseidon operational support. For TOPEX/Poseidon operational support, the more sophisticated GEM-T3 and JGM-2 geopotential models have been used. It should be noted that the covariance analysis results for the unconstrained solutions indicated that the radial and cross-track ΔV requirements are easily being met. The constrained- and unconstrained-maneuver analysis results for ERBS, in conjunction with the improved geopotential modeling for TOPEX/Poseidon, strongly suggest that the constrained-maneuver technique will meet the 0.2 mm/sec along-track velocity recovery accuracy requirement and will be used to support TOPEX/Poseidon operations.

### 3.2 TOPEX/Poseidon Orbit Maintenance Maneuver Results

As part of the operational support for TOPEX/Poseidon, Jet Propulsion Laboratory (JPL) TOPEX/Poseidon Navigation Team (NAVT) personnel monitor the trajectory of the TOPEX/Poseidon spacecraft to ensure that it stays within the prescribed 2-kilometer, 10-day repeating groundtrack. When periodic OMMs are required to move the spacecraft to within the groundtrack band, the NAVT determines the required along-track ΔV using TOPEX/Poseidon orbit predictions that are based on operational FDD orbit determination solutions. Since the launch of TOPEX/Poseidon in August 1992, seven OMMs have been successfully planned and executed. After the execution of each OMM, the NAVT evaluates the maneuver performance using special maneuver-related orbit determination solutions generated by the FDD with the constrained-maneuver technique. The premaneuver and postmaneuver orbit determination arc lengths for the constrained-maneuver solutions are both 4 days. Pregenerated 34-hour operational TDRS solutions were used for the TDRS trajectories in the TOPEX/Poseidon constrained-maneuver solutions.

After each OMM, the FDD provides the NAVT with an estimate of the achieved TOPEX/Poseidon ΔV by differencing the premaneuver and postmaneuver along-track velocities. The NAVT independently determines the maneuver ΔV using a modified, more sophisticated form of the differential energy equation [Bhat 93] described in Section 2.1. The FDD and NAVT along-track ΔV evaluation results for the first seven TOPEX/Poseidon OMM maneuvers using the constrained-maneuver technique are shown in Table 3.

**Table 3: FDD and NAVT TOPEX/Poseidon OMM Along-Track ΔV Evaluation Results Using the Constrained-Maneuver Technique**

| Maneuver | Date | Required ΔV (mm/sec) | FDD-Estimated ΔV (mm/sec) | Required ΔV – FDD ΔV (mm/sec) | NAVT-Derived ΔV (mm/sec) | FDD ΔV – NAVT ΔV (mm/sec) |
|---|---|---|---|---|---|---|
| OMM1 | 12 October 1992 | 9.100 | 9.425 | –0.325 | 9.431 | –0.006 |
| OMM2 | 21 December 1992 | 3.200 | 3.151 | 0.049 | 3.153 | –0.002 |
| OMM3 | 30 March 1993 | 4.640 | 4.688 | –0.048 | 4.692 | –0.004 |
| OMM4 | 06 August 1993 | 4.620 | 4.611 | 0.009 | 4.611 | 0.0 |
| OMM5 | 31 January 1994 | 4.000 | 4.065 | –0.065 | 4.089 | –0.024 |
| OMM6 | 20 May 1994 | 3.150 | 3.123 | 0.027 | 3.123 | 0.0 |
| OMM7 | 06 October 1994 | 3.150 | 3.162 | –0.012 | 3.146 | 0.016 |

For every OMM, the difference between the independently-derived FDD and NAVT along-track ΔVs is less than 0.2 mm/sec, suggesting that the accuracy requirement is being met. Furthermore, this not only clearly shows the strength and accuracy of the constrained-maneuver technique but also reflects the strength of the TDRSS tracking measurements to recover extremely subtle changes in TDRSS-user spacecraft orbits. This is especially true considering the relatively small magnitudes of the TOPEX/Poseidon OMMs.

## 4 - ENHANCED ORBIT SOLUTION RESULTS

This section presents some recent enhanced GTDS orbit solution results for the TOPEX/Poseidon spacecraft. The accuracy of these results is assessed by comparing the TOPEX/Poseidon ephemerides with the POEs described in Section 1.

The root-sum-square (RSS) comparison differences with the POE over the whole 5-day solution arc can be seen in Fig. 3. Here the root mean square (RMS) of the RSS differences is 1.07 meters with a maximum RSS difference (Diff) of 2.24 meters. The radial and along-track components have RMS values of 0.24 meter and 0.72 meter, respectively, while the cross-track component has an RMS value of 0.76 meter. The maximum differences are 0.43, 1.85, and 1.81 meters for the radial, along-track, and cross-track components, respectively. The radial, along-track and cross-track components of the differences between the final ACB TOPEX/Poseidon solution and the TOPEX/Poseidon POE can be seen in Fig. 4 for 1 day of the solution arc.

Some of the difference in the along-track component is probably due to differences in the modeling of the along-track accelerations. The POEs estimate a daily once-per-revolution along-track acceleration, consisting of two estimated parameters per day, and a daily constant along-track acceleration to accurately model the effects of the anomalous spacecraft forces as well as

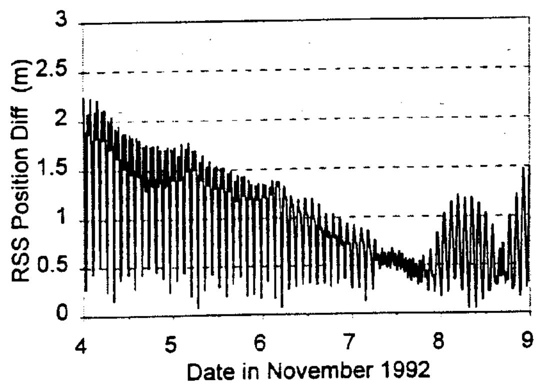


**Fig. 3:** RSS position difference between the POE and ACB ephemerides

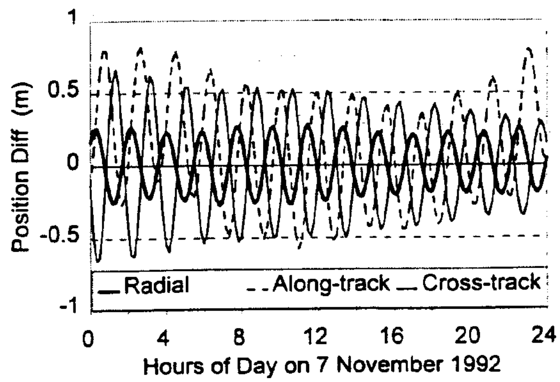


**Fig. 4:** Position differences by component between the POE and ACB ephemerides for 7 November 1992

atmospheric drag perturbations [Tapl 94]. The GTDS TOPEX/Poseidon-only solution, however, only estimates two thrust correction factors to characterize the along-track forces. Similarly, the POEs estimate a daily once-per-revolution cross-track acceleration, consisting of two solved-for parameters per day, to characterize the cross-track accelerations, while the GTDS solutions estimate no cross-track accelerations because of software limitations. Some differences can, in part, also be attributed to the differences in the modeling of the attitude changes resulting from the yaw-steering feature. These differences would affect both the measurement modeling and the atmospheric drag and solar radiation pressure force modeling. The POEs model the instantaneous changes in the spacecraft cross-sectional areas for drag and solar radiation pressure evaluation resulting from the yaw steering. The GTDS TOPEX/Poseidon solution uses the variable mean area model, which provides mean orbital values of the drag and solar radiation pressure cross-sectional areas.

The remaining differences between the GTDS trajectories and the POEs may be caused largely by differences in force modeling. A number of force modeling enhancements to GTDS should improve the GTDS solutions and narrow the differences with the POEs. These enhancements include improved spacecraft area models for both the TDRSs and the user spacecraft, dynamic polar motion, generalized acceleration models, an improved Earth shadow model, an Earth radiation pressure model, and an ocean tides model. The ability to estimate TDRS trajectories through maneuvers and momentum unloads should also improve the GTDS solutions.

It is important to note that TDRSS tracking does not have a requirement to yield orbit solutions with accuracy comparable to laser-tracked orbit solutions. However, a major objective of this work is to assess the achievable TDRSS orbit determination accuracy. It should also be noted that additional TOPEX/Poseidon cycles have been analyzed, and comparable POE comparison results were obtained.

## 5 - CONCLUSIONS

The constrained-maneuver technique was developed to accurately recover the along-track $\Delta V$ changes resulting from an orbit maintenance maneuver. The development of the null-maneuver technique was critical to assessing the capability of GTDS to meet the high-accuracy 0.2 mm/sec along-track velocity recovery requirement prior to the TOPEX/Poseidon launch. The development of the constrained-maneuver technique was instrumental in evaluating actual TOPEX/Poseidon OMMs, and to date has been successfully applied to seven OMMs. The along-track component of $\Delta V$ resulting from the OMM was obtained by two independent approaches, with errors significantly less than 0.2 mm/sec. The techniques developed and implemented here are general enough to be applied to any spacecraft for the evaluation of very stringent ΔV accuracy requirements for impulsive maneuvers.

This study also analyzed the TDRSS-user orbit determination accuracy using a batch least-squares estimation method. The estimated orbits were compared with the POEs. The radial component compared within 24 centimeters RMS, less than two times the 13-centimeter (1σ) POE accuracy requirement. These solutions compared with the POE within 1.1 meters RMS difference. Dynamical TOPEX/Poseidon modeling errors in GTDS caused a maximum of 1 meter of the observed error in the solutions. Given the observed residuals and the known level of dynamical mismodeling in the current GTDS solutions, it has been shown that the TDRSS tracking measurement data have sufficient quality to support orbit determination to levels better than 24 centimeters in radial accuracy and 2 meters in total position accuracy, provided issues of sufficient tracking coverage and accurate orbit determination force modeling are addressed.

The reduction of the differences, as compared with an earlier analysis, was the direct result of the use of the improved TDRS orbits obtained from the TOPEX/Poseidon/TDRS simultaneous solutions. This demonstrates that the treatment of the relay orbit determination has a significant impact on high-accuracy orbit determination in the TDRSS environment.

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