A Comparison of TOPEX/Poseidon TDRSS-based Operational Orbit Determination Results with the Precision Orbit Ephemeris[*]

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Since its' launch on August 10, 1992, the TOPEX/Poseidon satellite has successfully observed the earth's ocean circulation using a combination of precision orbit determination (POD) and dual-frequency radar altimetry. This mission is a joint effort of NASA and the French Space Agency CNES (Centre National d'Etudes Spatiales). The Jet Propulsion Laboratory (JPL) conducts mission operations for NASA with operational orbit determination (OOD) support from the Flight Dynamics Facility (FDF) at the NASA Goddard Space Flight Center (GSFC) and precision orbit determination support from the Space Geodesy Branch at GSFC.

The near-circular frozen orbit has a mean altitude of ~1336 km and an inclination of -66 deg, providing an exact repeat ground track every 127 orbits over -10 days. Orbit maintenance maneuvers (OMMs) keep the ground track within ±1 km of a fixed reference grid, while also assuring that other orbital parameters remain within required limits. Orbit monitoring and maintenance relies on **OOD using** primarily one-way Doppler acquired via the NASA Tracking and Data Relay Satellite System (TDRSS).

The POD process uses a combination of laser ranging, acquired via a world-wide laser network, and DORIS (Doppler Orbitography and Radiopositioning integrated by Satellite) data provided by CNES. Each POD solution provides a definitive precision orbit ephemeris (POE) covering a predetermined 10-day orbit repeat cycle. The POE provides geocentric radial position with an unprecedented accuracy of better than ~3 cm, serving as the reference standard for all other TOPEX/Poseidon orbit determination techniques. Much of this success is due to ongoing improvements in the geopotential model, presently defined by the third generation of the Joint Gravity Model (JGM-3), a 70x70 gravity field. Also, careful modeling of the satellite attitude and surface properties defines complex non-gravitational forces and their effects on the orbit.

This paper compares the orbit determination **results obtained by the TDRSS-based OOD** process **with the** reference **standard POE. This direct comparison establishes the** OOD **accuracy and** demonstrates **the** excellent long-term consistency of the OOD process during the more than five years since launch. Three types of comparisons are made: 1) position and velocity in orbit plane coordinates, 2) mean orbital elements, and 3) ground track position. The observed differences are explained in terms of key forces models and tracking strategies and data types.

TOPEX/Poseidon is a three-axis stabilized satellite; the attitude is controlled to ensure that the altimeter antenna and large solar array maintain accurate pointing. The satellite pitches at once per orbit rate to maintain nadir altimeter pointing, while "yaw steering" about the nadir keeps the solar array pointed near the sun for efective power management. In addition, the solar array continuously pitches to track the sun, while using a fixed pitch offset from the solar normal to limit peak battery charging currents.

A key parameter governing the attitude control algorithm is β', the sinusoidally-varying angle between the orbit plane and the sun. The satellite yaw steers when $|\beta| >$ ~15 deg. Near $\beta' \cong \pm 15$ deg, the satellite is commanded to a "fixed yaw" position to avoid excessive yaw angular rates. The satellite attitude is maintained at a zero yaw angle when $0 \leq \beta' \leq 15$ deg; in this attitude the satellite "flies forward" with the +X axis pointed along-track in the direction of motion. When $-15 < \beta' \leq 0$ deg, the satellite "flies backward" in a 180-deg yaw position with the -X axis pointed in the direction of motion. About every 60 days, a 180-deg yaw flip near $\beta' = 0$ keeps the solar array in sunlight.

The baseline OOD strategy uses a moving 7 day-10 hr tracking arc consisting primarily of single 40-min passes of one-way Doppler during each 112-min orbit. These passes are acquired via a TDRS-East or West satellite. This

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[*] 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 Space Administration.

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process uses a 20x20 truncation of the JGM-2 gravity field and variable mean area (VMA) models for atmospheric drag and direct solar radiation pressure. Each solution estimates the satellite cartesian state, the on-board oscillator frequency bias and drift rate, and a constant along-track "thrust" parameter. The thrust parameter compensates for mismodeling of attitude-dependent radiation forces caused by thermally-induced curling of the large solar array during yaw steering modes, and during fixed yaw modes, the presence of the solar array pitch offset. The magnitude of these pN-level radiation forces is equal to or greater than the effects of atmospheric drag, while the direction changes with the satellite yaw control mode. These along-track forces, while small, are quite important as they directly affect the orbit semimajor axis and the resulting satellite ground track. To properly account for these forces it is necessary to restart the OOD process whenever the yaw mode changes. A tracking arc of at least four days is required to confidently estimate a single along-track force applied over the entire tracking arc, so solutions for shorter tracking arcs are constrained by an apriori estimate.

The GSFC/FDF currently provides 00D solutions three times per week to facilitate ongoing orbit and ground track trend analyses. In the past, daily solutions were sometimes provided to support development and verification of empirical prediction models of the residual along-track radiation forces. Each solution is transmitted electronically to JPL as an Extended Precision Vector (EPV) message. The osculating state vector from the EPV serves as initial conditions for all ground track predictions, and for computing classical r-man elements used to monitor orbital behavior.

The cartesian position and velocity components from more than 600 OOD solutions spanning the mission lifetime are compared with the POE in orbit plane coordinates. During yaw steering, the mean errors in the radial, along-track, and cross-track position are 1.5, 7.8, and 2.5 m, with maximum errors of 6.4, 28.4, and 14.5 m, respectively. Orbit plane errors in the velocity components are 6.7, 1.4, and 2.4 mm/s, with maximum values of 24.1, 5.9, and 13.4 mm/s. These errors are primarily due to the use of a truncated geopotential field and by averaging non-gravitational forces over tracking arcs of several days. Most notable is the single along-track thrust parameter used to absorb mismodeling of complex radiation forces. The paper also shows that orbit solutions during fixed yaw modes are not as well-determined, as the necessarily-shorter tracking arcs have less information content. Histograms will show the distribution of all orbit plane errors, indicating the overall consistency of the 00D process.

TOPEX/Poseidon uses precision mean elements to effectively monitor the satellite orbit behavior. These elements are computed using a newly-developed osculating-to-mean conversion technique needed to meet the **stringent TOPEX/Poseidon accuracy requirements.** The **most important orbital parameter is mean** semimajor **axis,** with an orbit determination requirement of one meter (3σ), equivalent to an along-track velocity error of ~0.47 mm/s. For the mean elements to be useful, the magnitude of the computational errors should be no more than the the orbit determination errors.

Periodic perturbations due to earth, lunar, and solar gravity harmonics are averaged over 10 days to obtain stable mean elements from the osculating elements. With this technique, computational errors in mean semimajor axis are -40 cm (3σ), while the orbit determination error is -45 cm (3σ). The orbit determination error was established by comparing mean elements separately computed from the 00D and POD. The overall 3σ accuracy in mean semimajor axis is -60 cm due to the combined effects of orbit determination and computational errors, compared to the one-meter accuracy requirement. The paper presents similar results for orbit inclination, eccentricity, and the argument of perigee. Histograms describing the distribution of orbit determination errors are provided for all orbital parameters.

As of September 11, 1997, TOPEX/Poseidon had completed 183 ground track repeat cycles. Only 95 of the 23,241 equator crossing longitudes were outside the ±1 km control band. These voluntary violations occurred during the first two repeat cycles while preparing for the first OMM on October 12, 1992. The definitive equator crossings measured by the OOD process have been directly compared with those obtained from the POE. The mean longitude error is -2.2 m, with an observed maximum error of ~13 m. The paper also provides statistics for equator crossing timing errors. Histograms show the distribution of the equator crossing position and timing errors.

Using the POE as a reference, the paper will show that the TDRSS-based 00D processes satisfy all operational orbit accuracy requirements and has been very consistent throughout the mission. Differences in force models are summarized, indicating the major contributors to measured errors in orbital plane parameters, mean elements, and ground track position. Also, the influences of tracking data types used by the two distinctly different orbit determination techniques are summarized to identify their effects on the achieved orbit and ground track accuracies.