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Precision orbit determination for TOPEX/POSEIDON

B. D. Tapley, J. C. Ries, G. W. Davis, R. J. Eanes, B. E. Schutz, C. K. Shum, and M. M. Watkins[1]
Center for Space Research, University of Texas at Austin

J. A. Marshall, R. S. Nerem, and B. H. Putney
Space Geodesy Branch, NASA Goddard Space Flight Center, Greenbelt, Maryland

S. M. Klosko, S. B. Luthcke, D. Pavlis, R. G. Williamson, and N. P. Zelensky
Hughes STX Corporation, Greenbelt, Maryland

Abstract. The TOPEX/POSEIDON mission objective requires that the radial position of the spacecraft be determined with an accuracy better than 13 cm RMS (root mean square). This stringent requirement is an order of magnitude below the accuracy achieved for any altimeter mission prior to the definition of the TOPEX/POSEIDON mission. To satisfy this objective, the TOPEX Precision Orbit Determination (POD) Team was established as a joint effort between the NASA Goddard Space Flight Center and the University of Texas at Austin, with collaboration from the University of Colorado and the Jet Propulsion Laboratory. During the prelaunch development and the postlaunch verification phases, the POD team improved, calibrated, and validated the precision orbit determination computer software systems. The accomplishments include (1) increased accuracy of the gravity and surface force models and (2) improved performance of both the laser ranging and Doppler tracking systems. The result of these efforts led to orbit accuracies for TOPEX/POSEIDON which are significantly better than the original mission requirement. Tests based on data fits, covariance analysis, and orbit comparisons indicate that the radial component of the TOPEX/ POSEIDON spacecraft is determined, relative to the Earth's mass center, with an RMS error in the range of 3 to 4 cm RMS. This orbit accuracy, together with the near continuous dual-frequency altimetry from this mission, provides the means to determine the ocean's dynamic topography with an unprecedented accuracy.

Introduction

With the ability to yield precise, globally distributed, and temporally dense observations of the ocean surface, satellite altimetry has spurred the evolution of satellite oceanography. The altimeter observations can be combined with knowledge of the marine geoid to study the major geostrophic currents [*Wunsch and Gaposchkin*, 1980] and to monitor the rise in mean sea level [*Tapley et al.*, 1992]. The accurate determination of the satellite geocentric position is a fundamental requirement for accurate monitoring of sea surface topography. The ability to determine the radial component of the satellite orbit with sufficient accuracy to fully exploit the centimeter level precision of contemporary radar altimeters requires both high fidelity force models to describe the satellite motion and accurate tracking data which are well distributed temporally and geographically. The TOPEX/POSEIDON mission, a joint effort between the U.S. National Aeronautics and Space Administration (NASA) and the French Centre National d'Etudes Spatiales (CNES), contains significant advances in both of these areas. As planned, the TOPEX/POSEIDON mission will provide measurements of the sea surface topography during a nominal mission period of 3 years, with the expectation of an additional 2-year extension [*Stewart et al.*, 1986; *Fu et al.*, this issue]. To achieve the fundamental objective of monitoring the large-scale ocean general circulation patterns, a radial orbit accuracy of better than 13 cm RMS was adopted as a mission goal.

At the inception of the TOPEX/POSEIDON mission in the early 1980s, achieving 13-cm radial orbit accuracies required an order of magnitude improvement over existing capabilities for precise orbit determination computations. The orbit accuracy for the Seasat geophysical data records was estimated to be 1.5 m [*Marsh and Williamson*, 1980; *Schutz and Tapley*, 1980]. Initial requirements of the oceanographic community were for an orbit with a global radial orbit accuracy of 5 cm RMS or better. Since this was viewed as overly ambitious, a global RMS requirement of 13 cm, with the assertion that the nonaveraging geographically correlated height errors over ocean basins should be no more than 5 cm, was accepted by the oceanographic community as the mission goal [*Stewart et al.*, 1986]. The elements of the height error budget at mission start are shown in Table 1 [*Tapley et al.*, 1990]. It is clear that the orbit error is the dominant component, and the gravity model error dominates the contributions to the orbit error. To attain even the 13-cm orbit accuracy required significant

[1]Now at Jet Propulsion Laboratory, Pasadena, California.

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Table 1. Error Budget For TOPEX/POSEIDON Measurements of Sea Level

Error Source	Uncertainty, cm	Decorrelation Distance, km
	Altimeter	
Instrument noise	2.0	20
Bias drift	2.0	(many days)
	Media	
Electromagnetic bias	2.0	20–1000
Skewness	1.0	20–1000
Troposphere, dry	0.7	1000
Troposphere, wet	1.2	50
Ionosphere	1.3 (2.0*)	20
	Orbit	
Gravity	10.0	10,000
Radiation pressure	6.0	>10,000
Atmospheric drag	3.0	>10,000
GM (gravitational mass)	2.0	10,000
Earth and ocean tides	3.0	10,000
Troposphere	1.0	10,000
Station location	2.0	10,000
rss absolute error	13.3	

Assumptions: Dual-frequency altimeter; dual-frequency radiometer; SLR tracking, 15 station network; altimeter data averaged over 3 s; $H_{1/3}=2$ m, wave skewness=0.1; tabular corrections based on limited waveform-tracker comparisons; 1300 km altitude; no anomalous data, no rain; improved gravity model ; 13-mbar surface pressure; 100-ms spacecraft clock.

*For the one-frequency POSEIDON altimeter; inferred from models using DORIS data.

advances in the satellite force models and in the precision of the tracking systems.

The TOPEX/POSEIDON satellite, depicted in Figure 1, is a large satellite with a 25.5 m^2 solar panel and a mass of 2400 kg. It carries a dual-frequency radar altimeter (TOPEX) developed by NASA, a low-power single-frequency solid-state altimeter (POSEIDON) developed by CNES, and a microwave radiometer to obtain the altimeter height correction for the effects of atmospheric water vapor. The TOPEX/POSEIDON altimeters can measure the distance from the spacecraft to the instantaneous sea

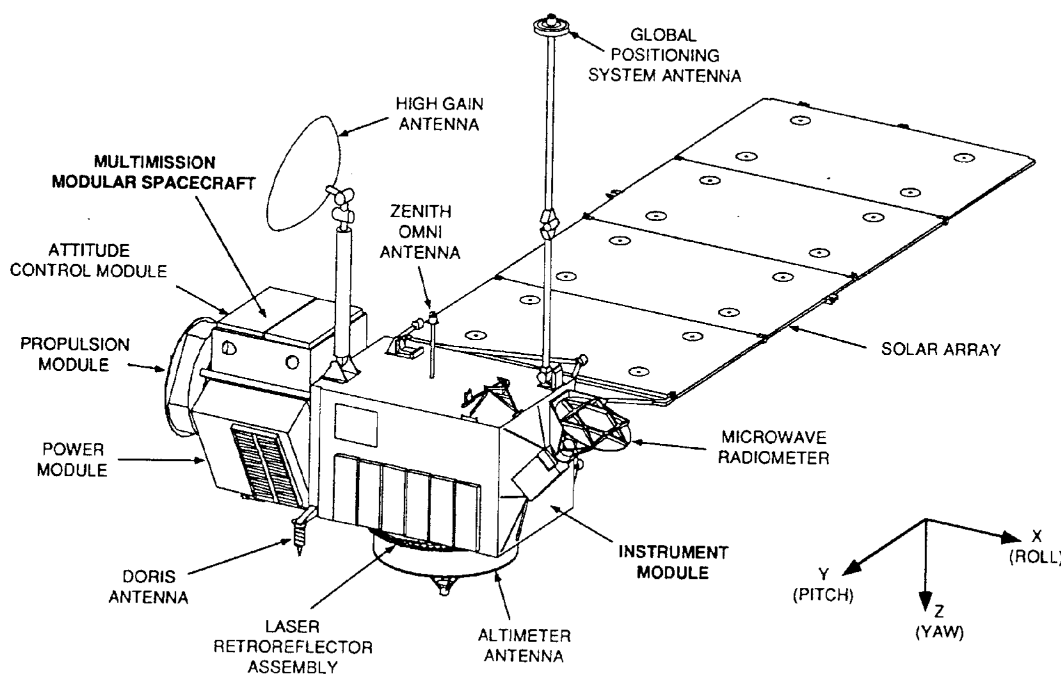

Figure 1. The TOPEX/POSEIDON spacecraft geometry and instrument location.

Table 2. TOPEX/POSEIDON Tracking Systems

Instrument	Purpose	Frequency	Precision
Laser retroreflector	reflects ground-based laser ranges for precision orbit and altimeter calibration	optical	0.5 – 5 cm
DORIS receiver	receives Doppler-shifted signals from ground beacons	401.25 MHz, 2036.25 MHz	0.5 mm/s
GPS receiver	receives pseudorange and phase signals from GPS satellites	1227.6 MHz, 1575.4 MHz	50 cm (pseudorange), 5 mm (phase)
TDRSS	data transmission, but carrier signal can be used as tracking	S band, K band	60 cm (range), 0.3 mm/s (range-rate)

surface with a precision of about 2 cm. To separate variations in the satellite height from variations in the ocean surface and to determine the absolute ocean surface height in the rigorously defined terrestrial reference system, an accurate determination of the satellite's orbit with respect to a network of accurately located ground-based tracking systems is required.

The demanding orbit accuracy requirement for TOPEX/POSEIDON initiated an associated requirement for accurate, temporally dense and globally distributed tracking. Several tracking systems were used to satisfy this requirement. A laser retroreflector array supports the baseline tracking system, satellite laser ranging (SLR) [*Degnan*, 1985], and a DORIS (Doppler orbitography and radiopositioning integrated by satellite) receiver enables important additional tracking from a geographically distributed set of Doppler transponders [*Nouël et al.*, 1988; *Dorrer et al.*, 1991]. An experimental Global Positioning System (GPS) receiver was also flown to demonstrate that GPS satellite-to-satellite tracking could provide subdecimeter level orbit determination [*Yunck et al.*, 1990; *Wu et al.*, 1991]. The Tracking and Data Relay Satellite System (TDRSS), which handles the telemetry data, can also be used as a tracking system [*Teles et al.*, 1980; *Schanzle et al.*, 1992]. Table 2 summarizes the characteristics and nominal precision of the tracking systems carried by TOPEX/POSEIDON. As an adjunct to the fundamental mission objectives, the multiple tracking systems on TOPEX/POSEIDON offer an unprecedented opportunity to compare and calibrate the orbit accuracy that can be obtained with different tracking data and orbit determination strategies.

Table 3. TOPEX/POSEIDON Orbit Parameters

Parameter	Description
Launch date	August 10, 1992
Altitude, km	1336
Eccentricity	0.0006
Inclination, deg	66.0
Period, min	112
Ground track equatorial spacing, km	316
Ground track repeat period, days	9.915625
Longitude of equator crossing, deg	99.947
Cycle 1 start date	September 23, 1992 (3:38 UTC)

The TOPEX/POSEIDON spacecraft was launched on August 10, 1992, and was maneuvered into an orbit with the parameters listed in Table 3. The inclination was selected as a compromise between a number of requirements: to provide large values for the intersection angles between ascending and descending ground tracks at midlatitudes, to maximize coverage of the world's oceans, and to minimize aliasing of ocean tide model error into the measured ocean surface topography [*Parke et al.*, 1987]. The semimajor axis and inclination are constrained to satisfy the condition that the orbit's surface ground track repeat itself to within 1 km every 9.9 days. The relatively high orbit altitude, when compared with earlier satellite altimeter missions, was selected to attenuate the influence of gravity model errors and to minimize the effects of atmospheric drag; both of which were judged to be necessary factors in achieving the required orbit accuracy. Even with the higher altitude, significant model improvement was required to achieve the error levels listed in Table 1.

Force Model Improvement

To address the force model limitations, an intensive effort was required to improve the satellite force models, with particular emphasis on the geopotential and radiation pressure models, and to develop computation and data analysis techniques to meet the TOPEX/POSEIDON accuracy requirements.

Gravity Model Improvement

Error analysis of the best general gravity model available at mission conception, which was GEM-10B [*Lerch et al.*, 1981], predicted radial errors exceeding 50 cm for the TOPEX/POSEIDON orbit. A collaboration effort was initiated for a sustained and concentrated effort to improve the prelaunch geopotential model [*Nerem et al.*, this issue]. The activity involved the reprocessing of the historical satellite tracking data, supplemented by surface gravity information and satellite altimetry data from recent missions. Since the gravity model development required reduction of a large and inhomogeneous database, encompassing over 30 satellites and millions of observations, an effort spanning nearly a decade was required. To achieve the TOPEX/POSEIDON goals, ancillary improvement in data treatment, nongravitational force modeling, and reference system modeling have been required to better isolate the gravitational signal from other sources of orbit perturbations.

Based upon the best geodetic constants, improved models and reference frame definition, and the software capabilities which were available in the mid-1980s, a series of preliminary solutions were produced [*Marsh et al.*, 1988, 1990; *Tapley et al.*, 1988, 1991; *Shum et al.*, 1990a; *Lerch et al.*, 1994]. Instituting the modeling improvements required a complete reanalysis of all orbits and regeneration of all of the information equations whose combination forms the gravity solution. Improved methods for obtaining optimal relative data weights and a calibrated error covariance were also developed [*Lerch*, 1991; *Lerch et al.*, 1991; *Yuan*, 1991]. Upon the completion of the GEM-T3 model [*Lerch et al.*, 1994], a reiteration of the solution process was undertaken. This reiteration introduced a refined set of constants and ancillary models, allowed better data editing using the improved models, and was designed to take advantage of the experience acquired in the previous gravity solutions. The constants used for the final iteration were based on the values adopted for TOPEX/POSEIDON precision orbit determination. The resulting model, the Joint Gravity Model (JGM-1), was completed at the time of the launch of the TOPEX/POSEIDON spacecraft in August 1992 [*Nerem et al.*, this issue].

During the 6-month verification phase, TOPEX/POSEIDON tracking data were used to improve the coefficients for the resonant orders 12, 25 and 38, as well as the orders 1 and 2 which lead to diurnal and semidiurnal perturbations [*Kaula*, 1966; *Nerem et al.*, this issue]. The improvement in the order 1 coefficients is especially critical, since errors in these coefficients give rise to diurnal orbit errors and are responsible for much of the geographically correlated errors discussed below. This improved model is referred to as the JGM-2 model. The TOPEX/POSEIDON altimeter data were excluded from this improvement process to ensure that no oceanographic signal was aliased into the gravity parameters.

A significant part of the gravity model development effort is involved in verifying that the covariance matrix of the gravity solution yields realistic error estimates. Various tests indicate that the JGM-2 covariance is well calibrated, and it can be used to predict accurately the contribution of the gravity model to the orbit error [*Rosborough and Tapley*, 1987; *Schrama*, 1992]. For TOPEX/POSEIDON, the global RMS radial orbit error due to errors in JGM-2 is estimated to be about 2 cm. The nonaveraging, or mean, geographically correlated component, illustrated in Figure 2, is of special concern. The mean correlated orbit error, which is the same for all tracks in a region and cannot be reduced by averaging altimeter data in that region, will corrupt the determination of the sea surface topography. The global RMS of the geographically correlated radial orbit error shown in Figure 2 is about 1.6 cm for JGM-2, with a maximum value of only 2 cm. These values are well below the 5-cm mission requirement and are insignificant when compared to the estimated 25-cm error still remaining in the JGM-2 geoid over the ocean [*Nerem et al.*, this issue]. The maximum mean correlated error for JGM-1 is 3.3 cm and also satisfies the mission requirement, but this value indicates that there is a significant improvement in the JGM-2 model. The largest errors tend to be associated with areas where satellite tracking data have historically been sparse, but from a geographical perspective, the radial orbit uncertainty due to the JGM-2

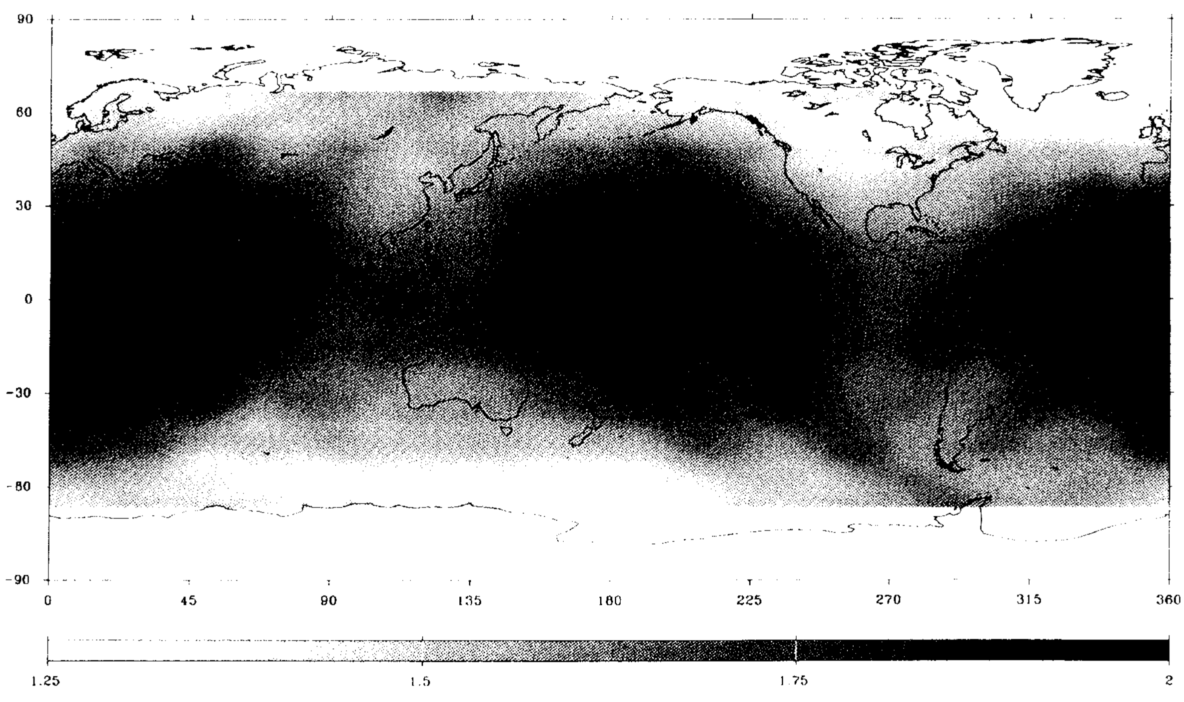

Figure 2. Non-averaging geographically correlated radial orbit error predicted by JGM-2 geopotential solution covariance (minimum, 1.2 cm; RMS, 1.6 cm; maximum, 2.0 cm).

gravity model is uniform over the oceans, varying only between 1 and 2 cm.

Nongravitational Forces

At the TOPEX/POSEIDON altitude the dominant surface force effects are due to solar, terrestrial and thermal radiation pressure, with secondary effects due to atmospheric drag [*Milani et al.*, 1987; *Ries et al.*, 1992]. To meet the TOPEX/POSEIDON surface force error budget, models were developed to account for the satellite's complex geometry and attitude variations, and its thermal and radiative surface properties [*Marshall and Luthcke*, 1994a, b]. The "macromodel," a relatively simple and computationally efficient model suitable for precise orbit computations, represents the spacecraft as an eight surface box-wing composite, i.e., the combination of flat plates arranged in the shape of a box and an attached solar panel. All plate interaction effects, such as shadowing, multiple reflections, and conduction are ignored. The nongravitational forces acting on each surface are computed as separate vector accelerations and summed to obtain the resulting acceleration of the satellite center of mass. The attitude of the spacecraft is modeled to account for the area variations that result from the yaw steering employed to maintain proper orientation of the solar panel with respect to the Sun [*Antreasian and Rosborough*, 1992]. The attitude modeling is based on the nominal attitude profile and may be modified to account for off-nominal events. The spacecraft attitude is especially critical for correcting the SLR and DORIS measurements to the satellite center of mass.

Standard finite element thermal radiation programs were modified to enable computation of the detailed surface forces due to solar and terrestrial radiation pressure as well as spacecraft thermal emission [*Antreasian and Rosborough*, 1992]. The macromodel was developed as an approximation to the detailed model, that is, "micromodel," to overcome the excessive computation requirements associated with the micromodel. The parameters of the macromodel (area, specular and diffuse reflectivity, emissivity, and a set of five temperature terms for each of the eight plates) were determined by making it match, through a least squares adjustment, the acceleration histories generated by the micromodel for various orbital configurations [*Marshall and Luthcke*, 1994a; *Nerem et al.*, 1993a]. A subset of the macromodel parameters were adjusted in the postlaunch model improvement effort. A prelaunch assessment of this procedure demonstrated that the radial orbit errors resulting from a tuned macromodel would be within the error budget requirement [*Luthcke and Marshall*, 1992].

In light of the robust tracking produced by the combination of SLR and DORIS tracking systems, the strategy of estimating a set of empirical accelerations to absorb the remaining surface force model error was adopted. The nominal set of parameters estimated for the precision orbit determination production, for each 10-day interval, are the initial conditions, a constant along-track acceleration for each day (i.e., daily subarcs), and daily sinusoidal along-track and cross-track accelerations with a period equal to the orbital period (i.e., one cycle per revolution or 1 cpr). Previous analyses indicate that the 1-cpr along-track acceleration is very effective in removing secular errors in the orbital eccentricity, which maps directly into the radial orbit error [*Ries et al.*, 1993]. The estimation of empirical 1-cpr cross-track accelerations is effective in removing secular errors in the orbital node and inclination, which, although not critical for the orbit height, is important for the high-quality fits required for reliable data editing. As noted previously, the large solar array leads to a large cross-sectional area, and changes in the yaw-steering program have a significant effect on the surface force variations. Consequently, the subarcs for the empirical accelerations are adjusted so that the breaks between subarcs occur at the yaw-steering transition epochs (yaw ramps and flips).

Shortly before launch, a concern was raised about the effect of the rate of charge on the operational lifespan of the spacecraft batteries. To reduce the peak charge rates that occur when the satellite enters sunlight after being shadowed by the Earth, the solar panel was pitched away from the Sun by an angle of about 60 degrees [*Frauenholz et al.*, 1993]. This influences the accuracy of the surface force model in several ways: (1) the dominate surface force, which is the solar radiation pressure on the solar panel, is no longer along the Sun-satellite line, (2) the difference between the specular and diffuse reflectivity of the solar panel becomes more important since their forcing vectors are no longer parallel, and (3) the solar panel temperature profile differs from the profile generated by the original finite element analysis. The impact of this change is minimized by accounting for the solar array orientation and reducing the temperature gradient across the solar array in the model. As the solar panel efficiency degrades, it is expected that the pitch angle offset will be decreased to maintain sufficient battery charge, but these changes can be accommodated in the surface force model.

Figure 3 shows the daily average of the along-track accelerations predicted by the a priori (JGM-1) box-wing model and the actual along-track accelerations inferred from the tracking data. The observed accelerations are based on 1-day SLR orbits computed as part of the quick-look verification activities at the Center for Space Research (CSR), so there tends to be greater scatter in the values. The differences between the two sets of points arise principally from unknown or "anomalous" nongravitational effects. Since this signal was not present in the prelaunch model development, it is not predicted by the macromodel.

The apparent exponential decay of the initially large accelerations suggests that they are attributable to outgassing. The large accelerations during fixed yaw are an expected result of the approximately 60° tilt in the solar array, but the modeling is not exact. Examination reveals that the force behavior is consistent with a body-fixed force directed along both the positive X and Y spacecraft axes (see Figure 1). In fixed yaw, the spacecraft's positive X axis is aligned with the velocity vector in positive β' (the angle between the orbit plane and the Sun) and with the antivelocity vector in negative β', changing direction at $\beta'=0$ (yaw flip) and resulting in a sudden symmetrical jump in the accelerations. At all other times, the spacecraft is in sinusoidal yaw and the Y axis crosses back and forth over the velocity vector, and a constant acceleration along the X axis has a negligible effect in the along-track direction. In the high β' regimes, the Y axis is oriented predominately along track. Additional details are given by *Frauenholz et al.* [1993].

Although the anomalous force behaves like a body-fixed X and Y acceleration, its source remains elusive. Several theories have been presented, including material outgassing, a propulsion system gas leak, solar array reflections onto the spacecraft body, small warping or deployment errors of the solar array [*Kar and Ries*, 1993], and thermal imbalance mismodeling. Unfortunately, no single hypothesis can explain all of the observed characteristics, but the force is persistent, routinely accounted for, and even exploited, in the orbit maintenance activities [*Frauenholz et al.*, 1993]. For the precision orbit determination purposes, however, it is not necessary to explain the anomalous force. It is only neces-

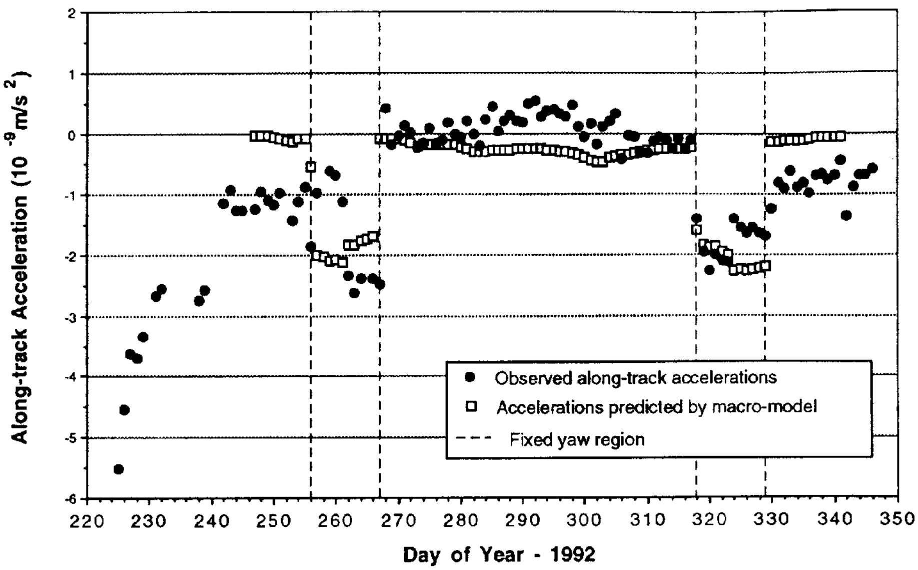

Figure 3. Daily averages of observed along-track accelerations for the TOPEX/POSEIDON spacecraft compared to prelaunch macromodel predictions. Day 224 corresponds to launch date of August 10, 1992. Cycle 1 began on day 267.

sary to account for it in the force model. This requirement can be satisfied since the acceleration appears to be roughly repeatable given the same spacecraft-Sun-Earth geometry.

Data from the first 15 cycles were used to estimate simultaneously the drag coefficients, box-wing parameters, and the gravity model coefficients to better represent the observed accelerations [*Marshall and Luthcke*, 1994a; *Nerem et al.*, this issue]. During the model improvement process, it became apparent that the box-wing parameters could not totally accommodate a constant body-fixed force. Consequently, body-fixed X and Y bias accelerations were introduced into the model to account for the anomalous force. Since estimates of these quantities were correlated with many of the box-wing parameters, the values for the X and Y bias accelerations were determined independently and were not adjusted as part of the JGM-2 solution. The values determined for these biases were $X_b = 0.39 \times 10^{-9}$ m/s^2 and $Y_b = 0.20 \times 10^{-9}$ m/s^2.

Figure 4 shows that the residual constant along-track accelerations, that is, the accelerations not accounted for by the model but absorbed instead by the estimation of a constant along-track acceleration for each day, have been reduced substantially after the model adjustment. Similarly, there is a significant reduction in the magnitude of the daily 1-cpr along-track accelerations which, as described above, are part of the nominal set of estimated parameters. The residual 1-cpr along-track accelerations are

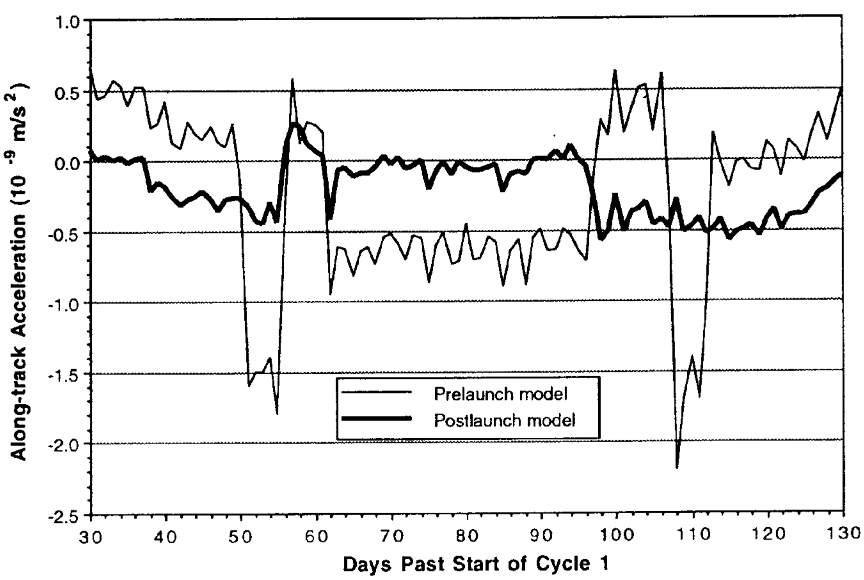

Figure 4. Daily average residual along-track accelerations before and after postlaunch tuning.

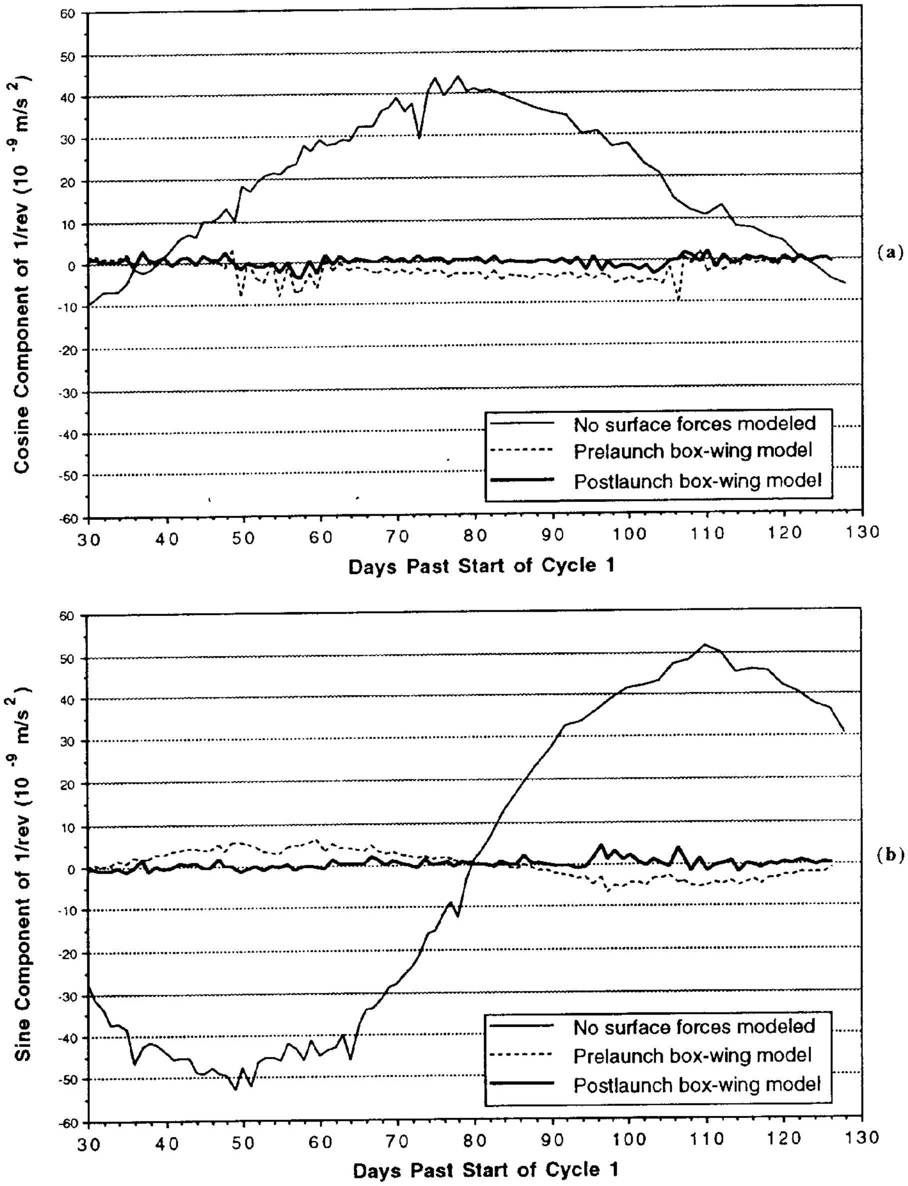

Figure 5. Estimated residual accelerations from TOPEX/POSEIDON surface force models. Daily averages of the (a) cosine and (b) sine components of a 1-cpr along-track acceleration.

displayed in Figure 5 and compared to the daily estimated average of the 1-cpr accelerations due to all surface forces. It can be seen that the JGM-2 solution has improved the accuracy of the surface force modeling. Further, the improved macromodel appears to account for more than 95% of the total along-track surface forces acting at the critical 1-cpr frequency.

The postlaunch model improvements outlined above have reduced the SLR fits by a factor of 2. Using the nominal 10-day arc, the fits with the prelaunch gravity and surface force models were 8–12 cm for the SLR data, while the improved models produce fits of 3–5 cm. The DORIS fits improved from about 0.62 mm/s to 0.56 mm/s. Activities are currently underway to further improve both the gravity field and nongravitational force modeling for TOPEX/POSEIDON.

Orbit Determination Systems

A fundamental requirement for the orbit determination effort is that tracking data should yield the same, or very nearly the same, solution when they are processed at either analysis center. To achieve the same orbit when tracking data are processed in two different software systems, it is essential that the force model description and the model parameters be the same. The software intercomparison and model standardization effort provides the standards by which this requirement is achieved and ensures that the TOPEX/POSEIDON satellite ephemeris will be determined in the appropriate terrestrial reference system. These two efforts, software intercomparison and model standardization, are described in the following sections.

Table 4. Phase 1 Software Intercomparison Results

Case	Radial,* mm	Along Track,* mm	Cross Track,* mm
Integration and all coordinates systems	2	17	3
J_2	2	20	3
N-body+ indirect J_2	2	23	3
J_2 with rotational deformation	2	23	3
Full GEM-T1 geopotential	2	30	1
Linear along-track acceleration	2	14	3
Solar radiation pressure	2	17	4
Frequency independent tides	2	26	3
Frequency dependent tides	10	150	90
Atmospheric drag	2	13	4
Relativity	2	11	4
Earth radiation pressure	1	33	4
All cases combined	10	178	84

*Maximum difference for 10-day integration for TOPEX/POSEIDON orbit; no parameters adjusted.

Software Intercomparison

A substantial effort was made to standardize and evaluate the accuracy of the Goddard Space Flight Center (GSFC) and CSR software systems. The software intercomparison was initiated with the objective of achieving millimeter-level agreement in the software used to compute the TOPEX/POSEIDON orbits. With this level of agreement, the final models could be used with comparable accuracy in either system.

Initially, a series of comparisons were made in which the basic force models, reference systems and measurement models were tested and verified to be in agreement [*Ries and Pavlis*, 1992]. Several minor errors, which were not detected in the normal testing process, were found in both systems, indicating the value of the intercomparison. As a result of this phase, the reference systems and measurement models were shown to agree at the millimeter level, and the combination of all the basic force model differences required for the TOPEX/POSEIDON orbit determination did not differ by more than 1 cm radially over a 10-day integration (Table 4). A second phase compared the data preprocessing (data editing and normal point formation) and the orbit determination procedure by using laser ranging to the Ajisai satellite. This phase established that both systems could process the same raw data set and obtain trajectories whose RMS radial component differences were at the subcentimeter level (Table 5). A third phase established that there was satisfactory agreement in the models peculiar to the TOPEX/POSEIDON satellite.

Orbit Determination Standards

To complete the intercomparison effort, a detailed description of the standard models for the reference system, the force models and the measurement models to be used for TOPEX/POSEIDON orbit determination was required. This ensures that the orbits produced by different institutions, using these standards, will be in a consistent reference system. The standards for the TOPEX/POSEIDON ephemeris evolved from the International Earth Rotation Service (IERS) standards [*McCarthy*, 1992] and the recommendations by *Wakker* [1990]. They have been revised to account for more accurate determination of many of the quantities described in these standards and expanded to account for TOPEX/POSEIDON peculiar values. The complete set of TOPEX/POSEIDON POD standards are described in Table 6.

Tracking System Performance and Station Positioning

A fundamental requirement for determining orbits, with the requisite accuracy for the TOPEX/POSEIDON mission, is a set of accurate, globally distributed tracking data. For continuous POD production, the level of SLR tracking data available for a satellite is influenced by periods of data outages due to weather, operator scheduling, and an increased workload associated with tracking an increasing number of satellites. The original concept of using the Department of Defense tracking network, TRANET, to augment SLR with temporally dense Doppler data was abandoned due to the system's high noise and systematic error characteristics [*Dunnell*, 1967; *Black*, 1980]. As part of the French payload, the DORIS Doppler system was developed and deployed by CNES, the Institut Geographic National (IGN), and the Groupe de Recherches de Geodesie Spatiale (GRGS) to support 10-cm level orbit determination for low-altitude Earth satellites, particularly TOPEX/POSEIDON [*Nouël et al.*, 1988; *Dorrer et al.*, 1991].

Table 5. Phase 2 Software Intercomparison Results

Case	Radial RMS, mm	Along Track RMS, mm	Cross Track RMS, mm
Fit edited Ajisai tracking data set* prepared by CSR	4	93	18
Fit individually prepared and edited Ajisai normal points	6	94	19

*Ten-day arc; epoch December 12, 1991.

Table 6. Precision Orbit Determination Standards for TOPEX/POSEIDON

Model	IERS Standard	TOPEX/POSEIDON Standard	Reference
		Reference Frame	
Conventional inertial system	J2000	IERS	*McCarthy* [1992]
Precession	1976 IAU	IERS	
Nutation	1980 IAU	IERS	
Planetary ephemerides	JPL DE-200	IERS	
Polar motion	IERS	UT rapid service	*Eanes and Watkins* [1993]
UT1-TAI	IERS	UT rapid service	
Station coordinates		CSR93L01, epoch: 1988.0	*Eanes and Watkins* [1993]
		DORIS stations from survey ties to SLR and from SPOT 2 tracking	*Watkins et al.* [1992]
Plate motion	Nuvel (NNR)	IERS+LAGEOS-derived corrections	*Eanes and Watkins* [1993]
Reference ellipsoid	a_e = 6378136.3 m $1/f$ = 298.257	IERS	
		Force Models	
GM	398600.4415 km^3/s^2	IERS	*Ries et al.* [1992]
Geopotential	GEM-T1; zero frequency tide applied to J_2	JGM-2	*Nerem et al.* [this issue]
$\bar{C}_{21}, \bar{S}_{21}$ – mean values	$\bar{C}_{2,1} = -0.17 \times 10^{-9}$ $\bar{S}_{2,1} = 1.19 \times 10^{-9}$	$\bar{C}_{2,1} = -0.187 \times 10^{-9}$ $\bar{S}_{2,1} = +1.195 \times 10^{-9}$	
$\bar{C}_{21}, \bar{S}_{21}$ – rates	none	$\dot{\bar{C}}_{2,1} = -1.3 \times 10^{-11}$/yr $\dot{\bar{S}}_{2,1} = +1.1 \times 10^{-11}$/yr, epoch 1986.0	(see rotational deformation)
Zonal rates	none (no epoch)	$\dot{J}_2 = -2.6 \times 10^{-11}/yr$, epoch 1986.0	*Nerem et al.* [1993b]
N body	JPL DE200/LE200	IERS	
Indirect oblateness		point mass Moon on Earth J_2	
Solid Earth tides	$k_2 = 0.3$	IERS plus	*Wahr* [1981]
Frequency independent	$\delta = 0°$, zero frequency tide not included	$k_3 = 0.093$	
Frequency dependent	Wahr's theory	IERS	
Ocean tides	11 constituents, 55 coefficients, maximum degree = 6, one order per species	JGM-2	*Nerem et al.* [this issue]
Rotational deformation	$\Delta\bar{C}_{21} = -1.3 \times 10^9 (x_p - \bar{x}_p)$ $\Delta\bar{S}_{21} = +1.3 \times 10^9 (y_p - \bar{y}_p)$ based on $k_2/k_0 = 0.319$ $\bar{x}_p = 0.''042, \bar{y}_p = 0.''293$	IERS with $\bar{x}_p = 0.''046, \bar{y}_p = 0.''294$ $\dot{\bar{x}}_p = 0.''0033$/yr $\dot{\bar{y}}_p = 0.''0026$/yr epoch 1986.0	*Nerem et al.* [this issue]
Relativity	central body (Earth) perturbation	all geocentric effects	*Ries et al.* [1991]
Solar radiation	solar constant $= 14.560 \times 10^{-6}$ N/m^2 at 1 AU, conical shadow model for Earth and Moon, R_e = 6402 km, R_m = 1738 km, R_s = 696,000 km	IERS	

Table 6. (continued)

Model	IERS Standard	TOPEX/POSEIDON Standard	Reference
Atmospheric drag		density temperature model, daily flux and 3-hour constant k_p, 3-hour lag for k_p; 1-day lag for $f_{10.7}$, $\bar{f}_{10.7}$ average of previous 81 days	*Barlier et al.* [1978]
Earth radiation pressure		Albedo and infrared second-degree zonal model, R_e = 6,378,136.3	*Knocke et al.* [1988]
Satellite parameters	cross-sectional area for some satellites	TOPEX/POSEIDON models; variable cross-sectional area for drag; "box and wing" for solar, Earth, and thermal radiation	*Marshall and Luthcke* [1994]
		Measurement Models	
Laser range			
Troposphere	Marini & Murray	IERS	
Relativistic correction	applied	IERS	
Center of mass/phase center		TOPEX/POSEIDON model	J. J. Degnan et al. (unpublished manuscript, 1994)
Doppler (DORIS)			
Troposphere		applied	
Relativistic corrections		applied	
Ionosphere (first order)		applied	
Center of mass/phase center	applied	TOPEX/POSEIDON model	
Site displacement			
Induced permanent tide	not removed	IERS	
Geometric tides			
Frequency independent	$h_2 = 0.6090$, $l_2 = 0.0852$, $\delta = 0°$	IERS	
Frequency dependent	K_1	IERS	
Ocean loading	table of values for some stations	IERS and updates	
Rotational deformation	$h_2 = 0.6090$, $l_2 = 0.085$	IERS with $\bar{x}_p = 0\text{''}.046$, $\bar{y}_p = 0\text{''}.294$, $\dot{\bar{x}}_p = 0\text{''}.0033$/yr, $\dot{\bar{y}}_p = 0\text{''}.0026$/yr, epoch 1986.0	

The TOPEX/POSEIDON standards are based largely on the IERS standards, which are also listed for comparison.

The combination of the SLR and DORIS tracking data sets for TOPEX/POSEIDON provides high precision tracking with nearly continuous geographic coverage. The uniform level of orbit accuracy being achieved attests to the fidelity and complementary nature of the DORIS and SLR systems.

The Satellite Laser Ranging System

The SLR system serves as the baseline tracking system for the TOPEX/POSEIDON mission. The SLR measurements represent the state of the art in satellite tracking, having demonstrated the capability of determining orbits with a precision of 1–2 cm in the radial direction for the LAGEOS satellites [e.g., *Tapley et al.*, 1993]. These systems have evolved to the current state by undergoing nearly a threefold improvement in the system precision every 5 years since the late 1970s. Today, the precision of SLR measurements is less than 1 cm for the best instruments. In addition, the optical wavelengths are not influenced by ionospheric refraction, and the effect of water vapor is much smaller than for radiometric tracking systems. Because SLR observations provide a precise, direct measurement of the absolute range from the tracking station to a satellite, they provide good resolution of all three components of the spacecraft position with respect to the tracking network.

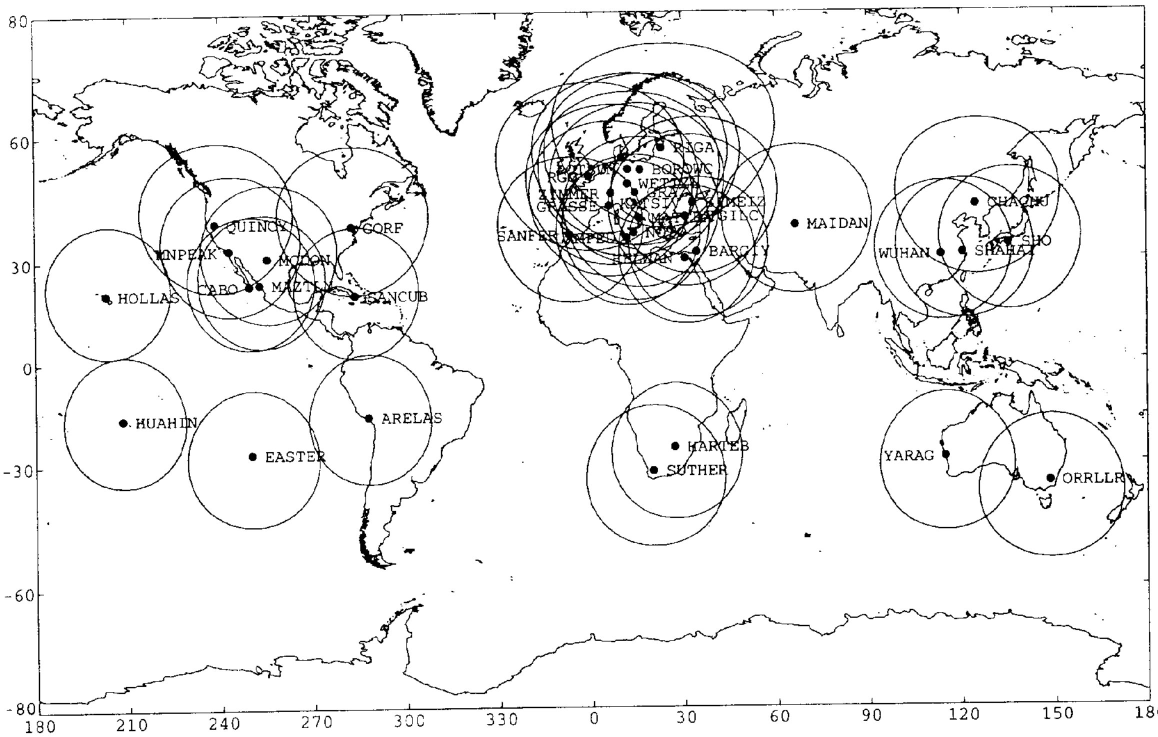

Figure 6. SLR tracking station distribution with 20-degree elevation visibility masks for TOPEX/POSEIDON altitude.

The NASA SLR systems are supported and managed by the NASA Dynamics of the Solid Earth Program [Degnan, 1985]. Coordination of the European laser sites is provided by the EUROLAS organization. There are as many as 30 laser tracking stations (both NASA and foreign sites cooperating with NASA) which are available to track TOPEX/POSEIDON at a given time. Figure 6 illustrates the distribution of the stations which have contributed tracking during the TOPEX/POSEIDON mission. Of these, a subset of NASA sites are tracking for two 8-hour shifts which are staggered over the 5-day work week to ensure good data coverage on a continuous basis. The NASA tracking stations along with a subset of the foreign stations constitute the primary tracking network and provide the baseline configuration required for mission support. Data are electronically transferred to NASA GSFC and are available within 2 days of their field acquisition through the Crustal Dynamics Data and Information System at GSFC [*Noll*, 1993].

To further improve the quality of the SLR data, the NASA Laser Network has assisted the TOPEX/POSEIDON project in the evaluation of the laser retro-reflector array (LRA) design flown on TOPEX/POSEIDON and performed the analysis to account for the far field diffraction and velocity aberration effects in the return signal (J. J. Degnan et al., unpublished manuscript, 1994). Many of the cubes in the large LRA ring return a signal, thereby smearing the return pulse and requiring detailed station-dependent modeling of the SLR reception hardware. Also, to mitigate the large dynamic range of the return signal for optimal ranging accuracy, an automatic neutral density filter to stabilize the intensity of the return signal is now being employed by many of the sites [*Eichinger et al.*, 1992].

Terrestrial Reference System

An important consideration in the success of the TOPEX/POSEIDON mission is the ability to define and maintain the terrestrial reference frame throughout the duration of the mission. The international network of satellite laser ranging systems has provided the backbone for the satellite geodesy effort during the past two decades [*Degnan*, 1985]. Laser tracking is crucial to the TOPEX/POSEIDON reference frame definition and provides the precise height control required to ensure the utility of the TOPEX/POSEIDON results for decadal studies of ocean surface change [*Smith et al.*, 1985, 1990; *Tapley et al.*, 1993; *Himwich et al.*, 1993]. The positions of the stations tracking the satellite define the orbit reference frame, and consequently, the ability to precisely determine their locations within a coordinate system whose origin is located at the Earth's mass center is of considerable importance. The SLR system provides the necessary reference frame through the precise station positioning obtained through ranging to the LAGEOS satellites.

The accuracy of the positions of the SLR sites, with respect to the Earth's center of mass, is estimated to be at the centimeter level, both in a relative sense and in an absolute sense. Recent comparisons of the relative positions of well-determined sites with those obtained from very long baseline interferometry indicate RMS differences at the subcentimeter level horizontally and 1–2 cm in height [*Ray et al.*, 1991; *Boucher et al.*, 1992; *Watkins et al.*, 1994]. The SLR set used in the *Watkins et al.* [1994] comparison was the SSC(CSR)93L01 solution of CSR submitted to the IERS. The operational set of station coordinates, SSC(CSR)93L02, differs from the L01 solution by only a very small rotation which maintains consistency with the International

Terrestrial Reference Frame. Since the polar motion series utilized is based on LAGEOS 1 solutions at CSR using the L02 station coordinates, it is the set used for operational processing of TOPEX/POSEIDON data. The relative accuracy of the DORIS site positions has recently been assessed at the 2- to 4-cm level from analyses of data from the SPOT 2 satellite, and better results have been obtained using TOPEX/POSEIDON tracking data [*Watkins et al.*, 1992, 1993; *Dufour et al.*, 1993].

The accuracy of the absolute positioning with respect to the Earth's center of mass is more difficult to assess, since SLR is currently superior to other techniques in realizing such a frame [Watkins and Eanes, 1993]. Sensitivity analyses and internal precision, however, coupled with comparisons between LAGEOS 1 and LAGEOS 2 values indicate that the mean SLR-derived geocenter is accurate to the few millimeters level. Limited comparisons with monthly averages from GPS as well as DORIS tracking of SPOT 2 and TOPEX/POSEIDON indicate agreement at the few centimeters level at worst [Vigue et al., 1992; Watkins et al., 1992, 1993].

The DORIS Tracking System

DORIS is a one-way, ascending Doppler system which utilizes a set of ground beacons that broadcast continuously and omnidirectionally on two frequencies of 2036.25 and 401.25 MHz. A receiver on board the satellite receives this signal and measures the Doppler shift, from which the average range rate of the satellite with respect to the beacon can be inferred. Average range rate is defined as the range change over a finite count interval, usually 7 to 10 s for DORIS. The relatively large frequency separation allows for removal of most of the ionospheric refraction. With the excellent short-period stability of the beacon oscillators and the in situ meteorological data provided by beacon sensors, the DORIS system produces range rate observations every 10 s with an average precision over the network of 0.5 mm/s [*Davis et al.*, 1993]. This is very close to the design precision of 0.3 mm/s, which is occasionally attained by the best stations.

The first DORIS beacon was installed in 1986, and the network was subsequently expanded to about 30 beacons by the launch of SPOT 2 in 1990. SPOT 2 carried an experimental DORIS receiver for testing and validation of the system. The SPOT 2 satellite altitude is about 840 km, and consequently, atmospheric drag is a major source of force modeling error. SPOT 2 data from 1990 and 1992 were successfully used for both gravity model improvement [*Tapley et al.*, 1991; *Nerem et al.*, 1993b] and for precise positioning [*Cazenave et al.*, 1992; *Watkins et al.*, 1992].

Doppler observations are inherently less sensitive to the geocenter location than SLR observations and are less capable of resolving the spacecraft position, particularly the component normal to the satellite plane. However, the temporal density and precision of the DORIS data provide the frequent, accurate observations of the satellite motion necessary to mitigate the effects of radiation pressure and drag forces. Thus the DORIS system is an excellent complement to the high-precision SLR system and plays an essential role in meeting the rigorous tracking demands of the TOPEX/POSEIDON mission. Figure 7 illustrates the geographic distribution of the DORIS network for those stations which are currently tracking TOPEX/POSEIDON. The DORIS network currently consists of about 50 beacons operationally supporting the TOPEX/POSEIDON mission, typically producing an excess of 100 usable passes per day. Note the uniform distribution of the

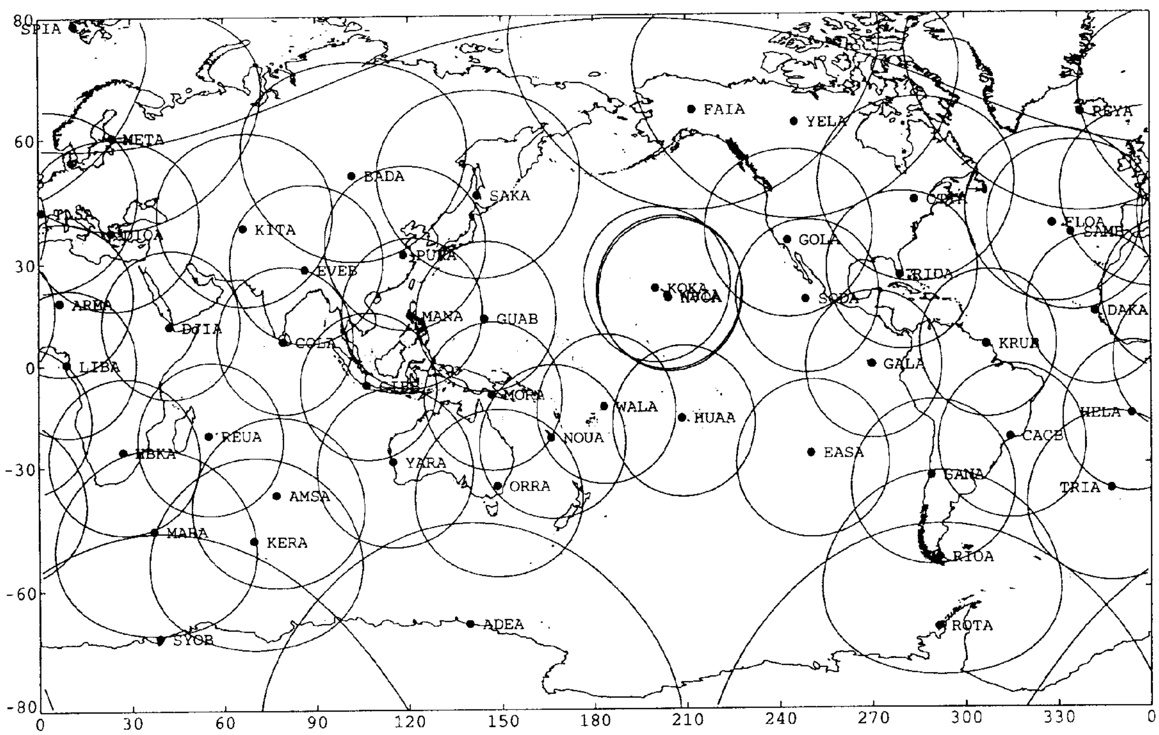

Figure 7. DORIS tracking beacon distribution with 15-degree elevation visibility masks for TOPEX/POSEIDON altitude.

DORIS network, particularly in the southern hemisphere and oceanic areas.

The DORIS system is conceptually similar to the U.S. Navy TRANSIT System in operation since the late 1960s with many significant advancements [*Black*, 1980]. There are three notable improvements implemented within the DORIS system design: (1) the ultrastable quartz oscillators used by the DORIS beacons yield a frequency stability of a few parts in 10^{13} over the Doppler count interval and represent a factor of 5–10 improvement over that provided by TRANSIT, (2) the frequencies selected for DORIS are higher than for TRANSIT and thus much better for the cancellation of ionospheric refraction effects, and (3) the system is configured as ground transmitted to satellite received, which enables all the tracking data to be collected on board the satellite and downlinked to a master control center. As with all radiometric tracking systems operating in this frequency range, the correction for the wet component of the tropospheric refraction is a difficult correction to model accurately [*Hopfield*, 1971; *Black and Eisner*, 1984]. However, given the robust data set provided by these systems, a pass dependent zenith scaling parameter to account for tropospheric refraction model error can be determined as part of the orbit determination process.

A complete globally distributed set of data is routinely collected using the standard procedures adopted by the DORIS network. Preliminary data quality assessments are performed at CNES, and the data are made available for supporting the POD production for TOPEX/POSEIDON. Early in the TOPEX/POSEIDON mission, there was a timing offset in the DORIS data. The advantage of an additional tracking system on TOPEX/POSEIDON was demonstrated by the fact that this timing bias (of the order of tens of microseconds) was clearly observed in the SLR analysis of the DORIS orbits. The initial timing problems have been corrected, and the DORIS data now appear to be generally free of significant timing errors.

Tracking Data Acquired

Both SLR and DORIS data sets are made available to the NASA and CNES POD centers in a timely fashion for the precision orbit calculations, and orbits from both centers are routinely compared. The station coordinates for new SLR stations are determined promptly by ranging to the LAGEOS satellites, but as stations are added to the DORIS network which were not included in the SPOT 2 station solution, their coordinates must be deter-

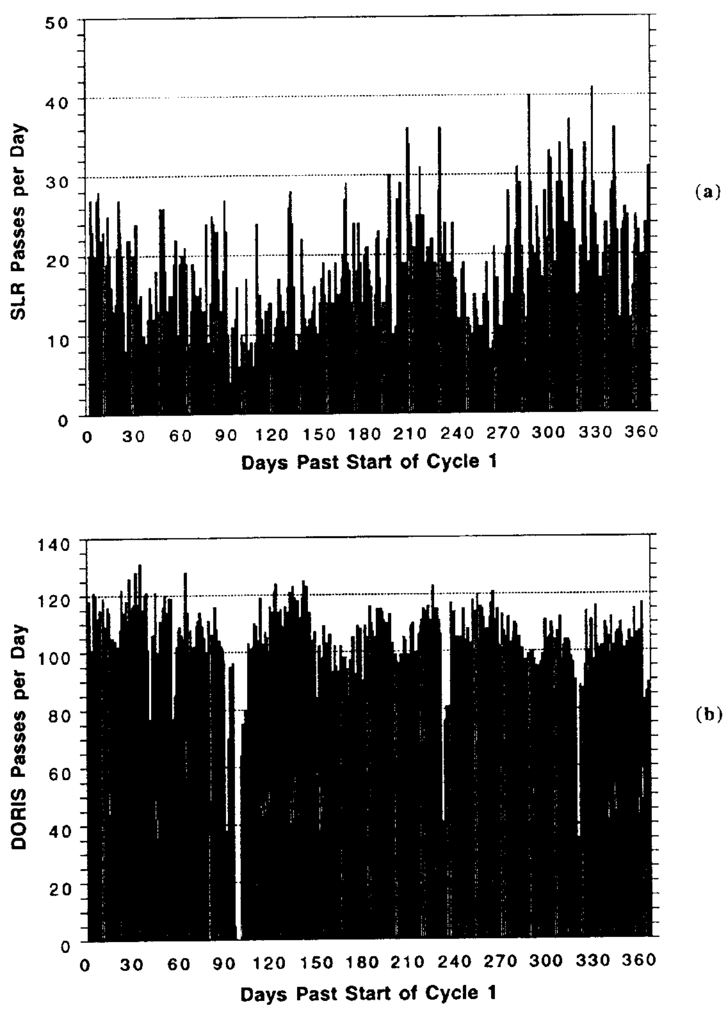

Figure 8. Histogram of (a) SLR and (b) DORIS passes acquired per day for cycles 1–37.

mined from TOPEX/POSEIDON DORIS data in order to include their tracking in the operational orbit determination [*Watkins et al.*, 1992, 1993; *Cazenave et al.*, 1994].

The daily passes collected by the SLR and DORIS tracking systems for the first year of the mission are shown in Figure 8. It is observed that the DORIS tracking system routinely provides about 100 passes per day and that the SLR system provides roughly 15–20 passes per day. The few days with weak or missing tracking for DORIS are primarily due to hardware upsets caused by unusually high radiation levels or from problems associated with the master beacon's ability to upload the daily work program. The days with weak tracking for SLR result from seasonal weather effects and from operator scheduling associated with holidays and weekends. However, as a result of the extra shifts and the high priority given to TOPEX/POSEIDON in the tracking scheduling, the data quantity is generally sufficient even during the low production periods, and not a single day of the operational orbit has gone unobserved by the SLR system. The consistency of the DORIS tracking relative to the SLR tracking highlights one of its primary advantages, while the strength of the SLR data and the fidelity of the force models is illustrated by the fact that an order of magnitude fewer SLR passes yields orbits with virtually the same accuracy as the DORIS data [*Davis et al.*, 1993].

Altimeter Measurements

The altimeter data are not used in the determination of the satellite orbit, but they can provide a global, independent measurement of the satellite height. To remove the dominant signal in the altimeter residuals, which is error in the model for the marine geoid and the quasi-stationary sea surface topography, altimeter crossovers can be formed [*Shum et al.*, 1990b]. The altimeter crossover measurement is formed by differencing two interpolated altimeter measurements at the crossing point of an ascending and descending track. In addition to the constant sea surface signal, static errors such as the altimeter height bias and the constant component of the orbit error are also eliminated in the crossover residual. However, the effect of temporally varying errors, such as media, tides, inverted barometer, instrument noise, and sea surface changes may be increased due to the differencing. In the case of TOPEX/POSEIDON the errors in these corrections now appear to overwhelm the orbit error signal, thus providing only minimal information about the orbit quality at each crossover location. Nevertheless, the crossover residuals are routinely monitored to provide an independent assurance that no serious mistakes have been made in the orbit determination process.

POD Production and Verification Performance

The TOPEX/POSEIDON Precision Orbit Determination Production System (PODPS), developed at NASA GSFC, was designed to produce a precise orbit ephemeris (POE) in an accurate, consistent, and timely fashion. Each POE is 10 days in length and is computed within 25 working days of the cycle end. The satellite orbit is computed through a least squares minimization of the tracking residuals using a precise model for the satellite orbit and the satellite tracking data. The PODPS is a menu-driven, highly automated system which strictly manages the functions necessary for routine determination of precise orbits, including data import, data processing, orbit generation and evaluation, and information archive, to ensure delivery of a high-quality, consistent product in a timely fashion. The essential aspects of the POD process are summarized below, and additional detail is given by *Putney et al.* [1993].

The POE is determined from SLR and DORIS tracking data imported from GSFC and CNES, respectively. The procedure requires near real-time ancillary data including polar motion from CSR and solar and magnetic flux from the National Oceanic and Atmospheric Administration Solar Geophysical Data Center in Colorado. All imported data and subsequent orbit ephemeris products are subjected to quality/sufficiency checks. In a sequence of tests, tracking data are evaluated and edited based on the misclosure between the actual observations and the calculated orbit. The editing process is iterated until data quality acceptance criteria are met. Once converged, the candidate orbit is then subjected to a number of orbit quality tests.

A high-elevation pass (HEP) test deletes all SLR passes that have data above a certain elevation, nominally 60 degrees, and computes a second orbit. The two orbits are then compared and the omitted data residuals from the high-elevation passes are used to project radial orbit error at the times of these independent data. The overlap test compares the candidate orbit and an overlapping 10-day orbit offset by 5 days to verify consistency in the solution. The altimeter crossovers residuals are computed from the converged POE orbit and are evaluated both globally and regionally. The altimeter data serve as an independent check of the orbit accuracy, although these residuals are now dominated by nonorbit errors. No one of these tests is sufficient for proving orbit accuracy, but as an ensemble, these tests provide a good measure of orbit quality.

Once the candidate orbit passes acceptance criteria for all tests, a POE file is generated and checked, and the results of the tests are summarized in a quality assurance report. Both products are sent to the Jet Propulsion Laboratory (JPL), CSR, and other users. Within a few days, comparisons are performed at CSR with orbits produced at CSR employing the standard TOPEX/POSEIDON models. The data editing, however, is independent, and other minor model differences are usually present. This test verifies the consistency, rather than the accuracy, of the POE, and represents a last chance to detect possible blunders. The verification system at CSR also performs an ongoing assessment of the overall orbit accuracy and its sensitivity to the methodology used to be sure that the mission requirements are continuing to be met. In addition, CNES produces precise orbits independently which are compared to the POE on a routine basis [*Nouël et al.*, this issue].

Orbit Accuracy Assessment

At the current accuracy level being achieved in the POD production, assigning an absolute accuracy is difficult. At the few centimeters radial orbit error level, no single test will quantify the error remaining in the orbits produced by the POE production system. The assessment must be gathered from a number of tests which measure various aspects of the orbit error. Internal accuracy tests, such as the data fits, comparisons of orbits generated with subsets of the tracking data, and comparisons of orbits from independent institutions but using the same models provide confidence in the quality and consistency of the orbit, but not necessarily the absolute error. A better test for accuracy is comparison with independent data if those data are sufficiently accurate. At present, the altimeter crossover residuals, which are influenced by time-varying oceanography, are not sensitive enough to perform the accuracy assessment. The precise orbits determined from the tracking data collected by the GPS demonstration receiver, processed using a different orbit recovery approach, provide an independent accuracy assessment that has not previously been available.

Table 7. Summary of Tracking Data Fits for Cycles 1–15

Cycle	SLR RMS of Fit, cm	DORIS RMS of Fit, mm/s	Number of SLR Passes	Number of DORIS Passes
1	4.4	0.55	213	985
2	3.4	0.58	164	1097
3	3.6	0.53	181	1160
4	5.0	0.53	134	1290
5	4.8	0.54	151	1065
6	4.8	0.55	158	1188
7	4.9	0.58	148	1257
8	4.5	0.56	146	1447
9	4.8	0.55	161	1289
10	4.0	0.58	118	556
11	4.6	0.52	76	931
12	5.5	0.56	110	1353
13	4.4	0.56	112	1369
14	4.6	0.56	139	1341
15	4.6	0.56	121	1302

Internal Orbit Quality Assessment

One measure of the quality of an orbit is how well it fits the tracking data. The overall residual RMS is indicative both of the model accuracy and of the data quality since large residuals, relative to the theoretical noise of the data, indicate either model deficiencies or systematic data problems. Table 7 indicates the fit obtained to the tracking data for cycles 1–15, and Table 8 summarizes the fits to the tracking data for the first year of the TOPEX/POSEIDON mission. The uniformity of the fits provided by each of the tracking networks is striking, even with the variability in the amount of available SLR data. Whereas the DORIS data is fitting close to the measurement noise level, the SLR data do not fit at the centimeter level, indicating the possibility of additional improvement. Nevertheless, these SLR data fits for 10-day orbits have only been exceeded by those now obtained on the LAGEOS and Etalon satellites, which are at much higher altitudes and have spherical shapes.

In the analysis of the SLR residuals, a timing and a range bias is estimated for each pass, effectively removing all orbit error signal from the residuals. Given the extremely accurate time tagging of the SLR data (generally less than a microsecond), the inferred timing bias can be used to estimate the along-track orbit error, and the range bias indicates the combined level of radial and cross-track orbit error in the pass at the point of closest approach to the station. The range biases from the high-elevation pass test, described earlier, yields a precise measure of the radial orbit error, but one which has limited geographic and temporal coverage. As shown in Table 8, the RMS of the range biases for the high-elevation passes is typically 3 cm and has not exceeded 4 cm.

The TOPEX/POSEIDON satellite follows a variety of attitude profiles depending upon the orbital geometry, and the POE accuracy is sensitive to errors in modeling the attitude as manifested in both the force and measurement models. To detect these occurrences and to evaluate the consistency across arcs, two intermediate 10-day orbits are computed. Each are offset from the original by 5 days, one overlapping with the first 5 days, and the other with the last 5 days, except where an orbit maintenance maneuver occurs. The overlap radial delta is the radial RMS difference between the POE and the overlapping solutions. Differencing two overlapping orbits eliminates the mean component of the geographically correlated errors and leaves only the difference of the time-varying error components, so this test is much more of a consistency test, particularly of the orbit errors due to the surface force model deficiencies. The results of this test, shown in Table 8, demonstrate that the empirical acceleration parameterization is very effective in containing the effects of any unmodeled accelerations. The maximum radial deviation from any one orbit overlapped with another was found to be under 6 cm.

Table 8. Summary of POE Quality Tests for Cycles 1–37

Test	Minimum	Mean	Maximum
SLR fit RMS, cm	3.0	4.3	5.3
DORIS fit RMS, mm/s	0.51	0.55	0.59
High elevation pass range bias RMS, cm	2.1	3.0	4.0
Overlap radial delta RMS, cm	0.3	1.0	1.3
Radial orbit error function RMS, cm	0.8	2.2	3.7
Altimeter crossover RMS, cm	9.1	10.2	12.4*

*Cycle 1 altimeter data may have been more affected by early off-pointing problems than later cycles.

Altimeter Data Analyses

The altimeter range and crossover data are not used in the orbit determination, but their residuals are calculated and examined, both globally and regionally, for inconsistencies. These data provide an independent and direct measurement of the satellite's radial position over the entire arc length. For these data to be used in an accuracy assessment, however, orbit error must be differentiated from other more dominant signals, particularly those due to the geoid, tides, mesoscale ocean variability, and sea state effects. The orbit dynamics act as a strong filter on the influence that nongravitational perturbing forces have on the trajectory and largely affect the amplitude and modulation of the satellite's orbit error at the 1-cpr frequency. Thus the major part of the orbit error signal is expected to exhibit the same 1-cpr form. To estimate the "radial orbit error function," the altimeter residuals are postprocessed and fit to extract the probable orbit error signal at the dominant 1-cpr frequency and its modulation over the 10-day cycle. Since the radial orbit error will have components which are constant, random or at frequencies other than 1 cpr, the radial orbit error function is not going to fully represent the total orbit error power. On the other hand, errors in the models for the geoid and sea surface topography can also introduce signals at 1 cpr [*Francis and Bergé*, 1993], resulting in the magnitude of the 1-cpr component of the orbit error being overestimated. In light of these two facts, the radial error function shown in Table 8 represents a reasonable, if slightly optimistic, estimate of the total error.

The altimeter crossover residuals, summarized in Table 8, have an RMS of 9–10 cm, but this value includes a number of ocean surface variations whose effect on the crossovers can only be estimated. These ocean surface effects include all time-varying components of the sea surface topography but are dominated by ocean tides, inverted barometer, and mesoscale variability. However, analysis of geophysical data record (GDR) altimeter range residuals over the Great Lakes, where most of these effects are not present, indicates a height RMS of 3 cm [*Morris and Gill*, this issue]. Since this value includes effects due to the ionosphere, troposphere, instrument noise and lake level measurement errors, the contribution of the nonconstant orbit error over the Great Lakes must be less than 3 cm RMS. Assuming that 3 cm is representative of the nonconstant orbit error globally and combining it in a root-sum-squared (RSS) sense with the prediction of 1.6 cm RMS for the constant correlated orbit error for JGM-2, the total RMS radial orbit error can be estimated to be about 3.4 cm.

Independent Orbit Comparisons

In Table 9 it is shown that the agreement between the POEs and independently determined orbits at CSR is typically about 2 cm radial RMS. As described above, the results of the software validation effort predicted this level of agreement for consistent data sets but demonstrated also the sensitivity of the POD results to data editing and other processing decisions. By adopting minor implementation differences and independent data editing and weighting decisions, this comparison should be able to detect any serious processing errors in the POE production.

Variations on some of the POE quality assurance tests are performed at CSR on the orbits produced at CSR. Since these orbits use the same models and have been shown to be essentially equivalent to the POEs in accuracy, tests on the CSR orbits can be expected to represent the quality of the POEs as well. One such test is the comparisons of the differences between the ends and the beginnings of adjacent orbital arcs. For GDR production, the POE orbits usually extend beyond the cycle start and stop times, but the CSR orbits are exactly one repeat cycle in length and do not overlap. Endpoint comparisons indicate how much the orbit shifts from one arc to the next to accommodate the force and measurement model errors. This is a very demanding test, since no data or estimated parameters are common to the two arcs, and the comparison is performed at the ends of the fit interval where the orbit is generally less well determined. Another test of the orbit quality is the RMS of the range biases obtained from post-processing high-elevation SLR passes. As the pass elevation angle increases, the mean error in the station-to-satellite range approaches the radial orbit error, assuming that the actual station biases are small enough to be negligible. This differs from the HEP test on the POE in that a new orbit is not fitted and, to separate more fully the radial orbit errors from the cross-track errors, only passes exceeding 75 degrees in maximum elevation are examined. Although the high-elevation passes give limited representation of the radial orbit error, their statistical significance is increased as more and more passes are processed. As indicated in Table 8, the endpoint overlaps and the high-elevation range biases are typically of the order of a few centimeters.

A unique and exceptionally valuable measure of the orbit quality is obtained by comparing orbits determined with SLR and DORIS tracking data to the orbits produced independently by JPL from GPS tracking data using the "reduced dynamic" orbit determination technique [*Yunck et al.*, 1994; *Bertiger et al.*, this issue]. This technique uses a sequential filtering procedure to reduce the residuals from an accurate dynamic long-arc solution. The approach reduces sensitivity to dynamic model errors by introducing process noise accelerations parameters into the estimated state, but it is more sensitive to measurement model errors. In contrast, the SLR/DORIS orbits are determined using a fully dynamic least squares batch estimator. Given the different modeling, tracking data, and estimation techniques, the level of agreement between orbits derived independently from these approaches provides an excellent measure of the orbit accuracy.

The POE orbits for seven cycles were compared with the

Table 9. Summary of Independent Orbit Accuracy Tests for Cycles 1–37

Test	Minimum	Mean	Maximum
POE–CSR radial delta RMS, cm	1.4	2.0	3.5*
CSR orbit endpoint overlaps, cm	0.6	3.2	8.7
CSR high elevation pass range bias RMS, cm	1.1	2.5	4.2
POE–JPL radial delta RMS,† cm	3.4	3.6	4.2
POE–JPL radial delta RMS with z bias removed,† cm	2.9	3.1	3.3

*Cycle 10 had unusually low tracking from DORIS and an early entry into fixed yaw-steering.
†Comparison to JPL "reduced dynamic" orbits for Cycles 14, 15, 17, 18, 19, 20 and 21.

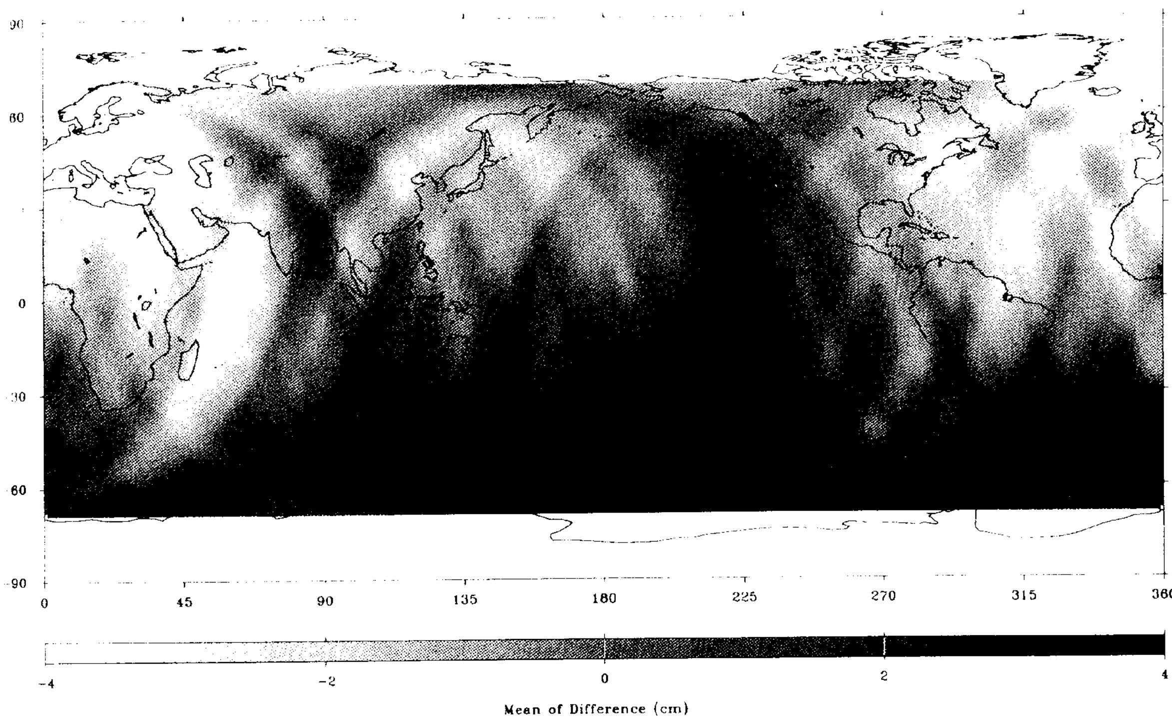

Figure 9. Mean radial orbit differences between POE and JPL reduced dynamic orbit for cycle 21.

"reduced dynamic" orbits produced by JPL, with the results shown in Table 9. The JPL "reduced dynamic" orbits have been determined with the estimation of a radial bias, approximately 6 cm in magnitude, in the GPS tracking data [*Bertiger et al.*, this issue]. This bias is thought to be due to an error in the position of the GPS antenna relative to the spacecraft mass center. Figure 9 shows the geographical distribution of the mean radial orbit differences for a typical cycle. In addition to the obvious large scale differences, there is an apparent north-south asymmetry which is the result of a bias of 2 to 3 cm along the Earth's spin axis between the two orbits. This "z bias," although not completely understood at this time, seems to be a characteristic of the JPL trajectories used in this comparison, since it does not appear in the comparison of the TOPEX/POSEIDON orbits with respect to the LAGEOS-derived center of mass of the Earth. Geocenter determinations from GPS in the z direction have typically been limited to about the decimeter level [*Vigue et al.*, 1992], although recent analyses have indicated improvement. The z bias must be removed to see the true nature of the geographically correlated errors in the JGM-2 orbits, assuming that the "reduced dynamic" orbit does not suffer from long-wavelength gravity-induced orbit error. The existence of the z bias indicates that accuracy assessments below the few centimeters level are very difficult.

In Figure 10 the same orbit differences as Figure 9 are displayed but with a z bias of 2.2 cm removed. The areas with the largest differences are the same areas where the JGM-2 covariance predicts the greatest uncertainty (see also *Christensen et al.* [1994]). Interpretation of actual orbit differences must be done with caution, since the location and weighting of the tracking data can affect the actual distribution of the orbit errors. However, as long as no gravity parameters are being estimated, the global power of the gravity model errors tends to be preserved in the dynamic orbits. With the z bias removed, the POE and JPL orbits agree to about 3 cm RMS radially (Table 9). The RMS of the mean radial orbit differences in Figure 10 is about 1.7 cm, matching very well the 1.6-cm RMS of mean correlated error predicted by the JGM-2 covariance. This indicates that the JGM-2 gravity solution covariance matrix is well calibrated and the correlated orbit errors in the POE can be assessed confidently to be 2 cm or less over the oceans.

Orbit Error Spectrum

For previous altimetry missions, the only independent measure of the orbit error was provided by the altimeter data itself, and efforts to estimate the level of orbit error attempted to filter from the altimeter residuals the frequencies which could be attributed to the orbit error. As discussed above, the dominant signal due to orbit error will occur around 1 cpr. Errors in the order 1 spherical harmonics of the geopotential model will cause a daily modulation in the 1-cpr term, order 2 terms will cause a twice-per-day modulation, and so on [*Kaula*, 1966]. In addition, errors in the degree 2 terms, especially the second-degree harmonic, will cause signals around 2 cpr to appear, the third-degree harmonics will cause 3-cpr signals, and so on. However, errors in the models for the geoid and sea surface topography heights will also cause signals at these frequencies in the altimeter residuals, and these effects are now comparable to the orbit error for TOPEX/POSEIDON. *Francis and Bergé* [1993] conclude that the main part of modulations at 2 and 3 cpr in the altimeter residuals can be accredited to the sea surface. If the sea surface model is not precisely centered along the Earth's z axis, which is equivalent to an error in the degree 1 zonal harmonic of the sea surface model, then a signal at exactly 1 cpr will be induced [*Schrama*, 1992]. Similarly, an error in the x or y coordinate directions for positioning the sea surface model relative to the Earth's mass center is equivalent to errors in the degree and order

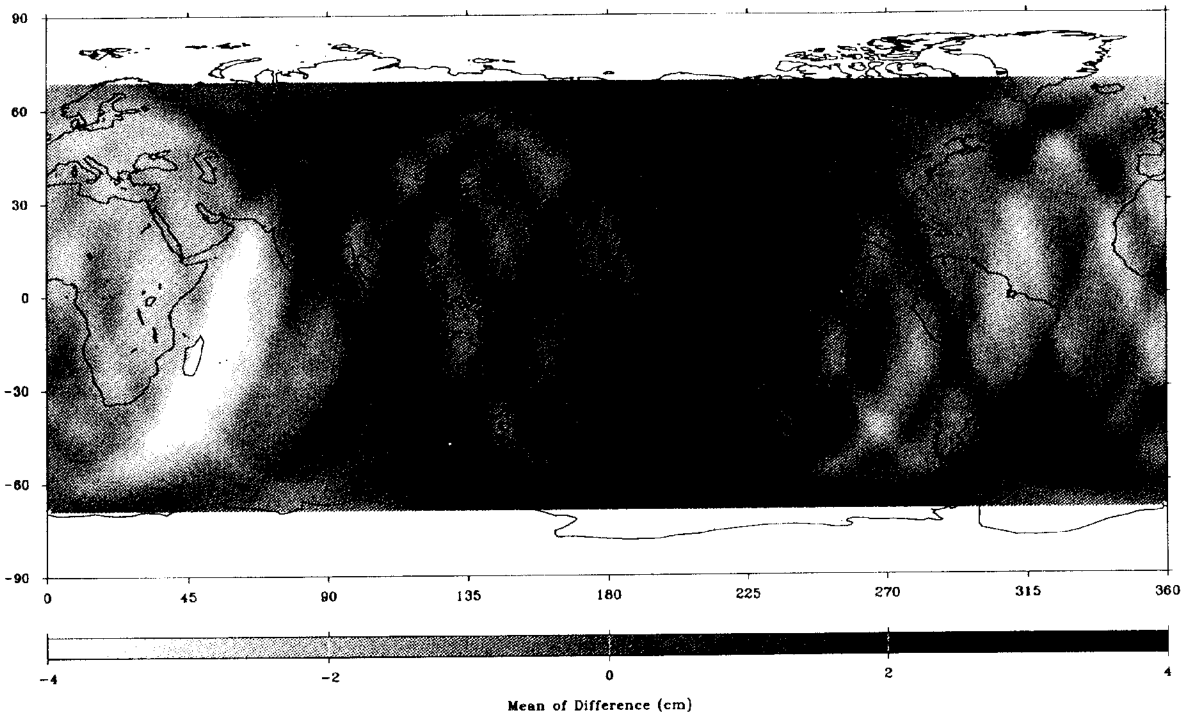

Figure 10. Mean radial orbit differences between POE and JPL reduced dynamic orbit for cycle 21 after removal of z bias.

1 terms and induces a daily modulation of the 1-cpr signal (and thus not at exactly 1 cpr). Tide modeling errors can also be expected to introduce signals at some of these frequencies, so using altimeter crossovers does not entirely remove the nonorbit signals, and there are additional complications in the analysis of crossover differences [*Schrama*, 1992]. The result is that spectral analysis of altimeter residual is not a definitive measure for calibrating the residual orbit errors for TOPEX/POSEIDON.

The independent JPL orbits, as discussed above, should be less sensitive to the correlated gravity model errors. In addition, even though the JPL orbits are not entirely without error, it is unlikely that the remaining errors are identical to the errors in the POE orbits. Thus spectral analysis of the differences between the POE and the JPL orbits should be representative of the errors in the POEs. Analysis reveals that the only significant power in the orbit differences is at 1 cpr, mainly from the z bias, and a daily modulation of 1 cpr. There is very little power at 2 cpr and nothing significant at any other frequency. When the z bias is removed, the power at 1 cpr exactly is essentially eliminated (Figure 11), and the remaining daily modulations of the 1 cpr are mainly the result of the 1–2 cm of geographically correlated orbit error due to the low-order terms of JGM-2 and the tide model. The remaining orbit errors are relatively random and thus subject to further reduction through averaging of multiple cycles.

The analyses discussed above do not address orbit errors which may have periodicities longer than the 10-day ground track repeat cycle. Some investigations using the GDRs have noted the presence of an approximately 60-day periodicity in the altimeter residuals [e.g., *Morris and Gill*, this issue]. The concern is whether there could be some dependence of the orbit errors at that period. Since the orbit plane completes a full revolution with respect to the Sun every 120 days, a period of low β' is encountered every 60 days. The associated satellite attitude changes cause significant variations in the nature of the surface forces, which are more difficult to accommodate. However, comparisons with the GPS "reduced dynamic" orbits show that the orbit accuracy is not significantly worse for the most demanding periods, for example, the fixed yaw cycles. This indicates that the empirical acceleration parameterization with suitable break points for the subarcs is effective in keeping the surface force modeling errors at the few centimeters level even during the more difficult cycles. If there is a slight increase in the level of orbit error, it is likely to manifest itself in the variable part of the orbit error, which would appear as a slight increase in the differences between ascending and descending arcs. In any case, the estimation of the initial position and velocity for each arc, combined with the daily empirical accelerations, is expected to break the correlation between the orbit error from cycle to cycle, and no significant long-period orbit error should be present. To explain the 60-day periodicities in the altimeter residuals, the altimeter corrections which may have some dependence on the solar position should be examined.

It is also possible for a part of the short-period perturbations due to nonresonant tide effects on the orbit to alias into long-period errors when sampled geographically. The magnitude of these tide modeling errors is estimated to be about 1 cm RMS for the 10 largest tides [*Bettadpur and Eanes*, this issue].

SLR/DORIS and GPS

The complementary nature of the two orbit determination strategies (SLR/DORIS dynamic and GPS "reduced dynamic") has proven to be valuable in several regards. The intercomparison described above provides a strong check on the calibration of the JGM-2 gravity covariance as well as on the SLR/DORIS orbit determination accuracy as a whole. In the case of the z bias it would be very difficult to distinguish the signal due to the z bias in the orbit from the identical signal in the altimeter residuals generated by a miscentering of the sea surface model [*Schrama*, 1992]. Another example is the early discovery, after comparison

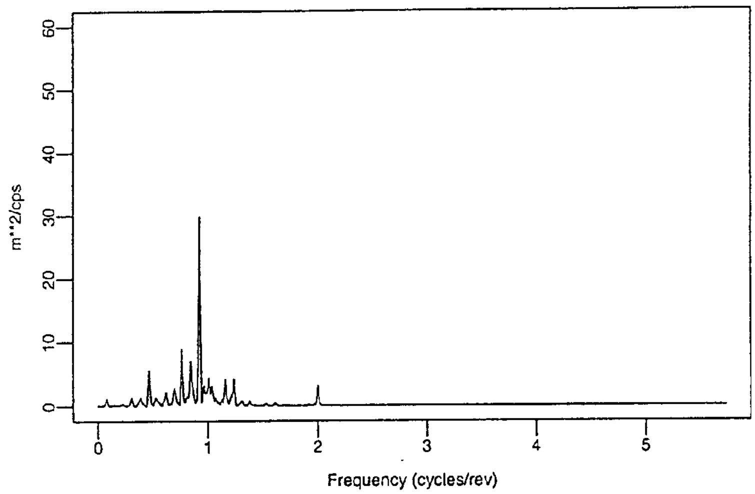

Figure 11. Spectrum of radial orbit differences between POE and JPL reduced dynamic orbit for cycle 21 after removal of z bias.

with the SLR/DORIS orbits, of an apparent 6-cm error in the TOPEX/POSEIDON GPS antenna location with respect to the spacecraft's center of mass along the direction of the yaw axis. This offset is now typically estimated in the TOPEX/POSEIDON GPS orbits [*Bertiger et al.*, this issue], and perhaps at some point a permanent correction will be determined. Finally, the GPS data offer the opportunity for additional gravity model improvement due to its global coverage [*Schutz et al.*, 1994]. Preliminary experiments with gravity models tuned with GPS tracking of TOPEX/POSEIDON indicate a reduction of the mean correlated radial orbit error to the subcentimeter level and an overall agreement of about 2.3 cm radial RMS in comparisons to the GPS "reduced dynamic" orbits. The actual orbit errors may be slightly larger than this since both orbits depend on the same a priori geopotential model, with the result that some part of the orbit error may still be common. At this level it is difficult to determine with confidence which orbit technique is more accurate, since both techniques are expected to be limited to about the 2- to 3-cm level [*Yunck et al.*, 1994; *Melbourne et al.*, 1994].

Orbit Error Budget

The evidence supporting the conclusion that the POE radial orbit accuracy is in the range of 3 to 4 cm RMS can be summarized as follows:

1. A significant effort was directed toward the gravity model development, with the result that the long-wavelength component of the gravity model for the TOPEX/POSEIDON mission is far more accurate than the mission specification. Covariance analysis of the improved gravity model, JGM-2, predicts that the total radial RMS orbit error induced by commission error is about 2 cm for TOPEX/POSEIDON, with omission error at the TOPEX/POSEIDON altitude being negligible. Independent tests indicate that the calibration of the covariance matrix is unlikely to be significantly in error, and the comparisons with the GPS orbits using the "reduced dynamic" technique indicate that the magnitude of the observed geographically correlated orbit differences is in very good agreement with that predicted by the covariance matrix.

2. Analyses have demonstrated that surface force model errors which generate radial orbit errors as large as 15 cm RMS, the level believed to be associated with the prelaunch macromodel, can be reduced to the 1-cm level by the combination of good tracking and appropriate parameterization. The parameterization currently used, that is, the estimation of daily constant and once-per-revolution along-track accelerations, has been shown to be very effective in reducing the residual radial orbit error. This parameterization is feasible because of the significant quantity of precise tracking provided by the DORIS system and the quality of the macromodel after postlaunch improvement. The estimation of the parameters for the periodic cross-track acceleration does not improve the radial component of the orbit directly, but it does remove the residual orbit errors in the cross-track direction so that there is more confidence in the tracking data editing. This same parameterization also tends to reduce the effect of the long-period ocean tide modeling errors. Thus it is reasonable to conclude that the contributions of the surface forces and ocean tides have each been reduced to the 1–2 cm level.

3. Endpoint overlap comparisons have been found to be a reliable indicator of the level of orbit error remaining. Since the orbits at the common time are determined over two independent spans of data and the least squares process tends to minimize the orbit errors at the middle of the arc, this test tends to place bounds on the time variable radial error. To have 2- to 4-cm RMS agreement in the radial direction at the endpoints of adjacent 10-day arcs suggests remarkable fidelity in the models and tracking data.

4. The fits to the tracking data, particularly the SLR data, is one of the best indications of the orbit accuracy, as long as the orbit errors are not too heavily parameterized. At this point the SLR data are usually fit to the 3- to 5- cm RMS level, and this number includes the contribution of the along-track and cross-track orbit errors as well as measurement modeling errors (i.e., errors in translating the range to the spacecraft center of mass which are sensitive to small attitude errors, complicated laser reflector array modeling errors, atmospheric refraction errors, and any SLR tracking anomalies). When only high-elevation SLR passes are evaluated, the RMS of the range biases, which are close to being dominated by the radial orbit error relative to the tracking stations, is usually about 3 cm. Intercomparisons indicate that the SLR stations as a whole are determined with respect to the geocenter at the centimeter level.

5. The RMS of the altimeter crossover data, which are not used

Table 10. TOPEX/POSEIDON Orbit Error Budget

Error Source	Mission Specification, cm	POE Estimate, cm
Gravity	10	2
Radiation pressure (solar, terrestrial and thermal)	6	2
Atmospheric drag	3	1
GM (Earth's gravitational mass)	2	1
Earth and ocean tides	3	1–2
Troposphere	1	< 1
Station locations	2	1
RSS Absolute Error	12.8	3–4

to determine the orbit, are about 9–10 cm, but this value includes a number of important atmospheric and ocean surface signals whose exact magnitude can only be estimated. However, analysis of the altimeter residuals over the Great Lakes, where most of the ocean surface effects are not present, indicates a height RMS of 3 cm [*Morris and Gill*, this issue]. Since this value includes residual error due to the ionosphere, troposphere, and instrument noise, the contribution of the nonconstant orbit error must be less than 3 cm RMS.

6. Intercomparisons of the POEs with orbits produced by CSR indicate a consistent agreement at the 2-cm level. While GSFC and CSR are using well-calibrated systems, there is some independence in each orbit determination procedure (different editing and data weighting, for example), and this level of agreement indicates that no significant errors are being made. Comparisons of these orbits with independent orbits, for example, those produced by JPL using the "reduced dynamic" technique to process the GPS tracking data, indicate that the radial differences are less than 4 cm RMS. After removing the z bias of a few centimeters which appears in most of the GPS orbits used for this comparison, the RMS differences are typically closer to 3 cm. This is very consistent with the high-elevation SLR tests and the Great Lakes test.

The combined evidence indicates that the overall radial RMS orbit error is 3-4 cm in an absolute sense (with respect to the center of mass of the Earth), with less than 2 cm attributable to long-wavelength, nonaveraging geographically correlated error. The revised orbit error budget, given in Table 10, indicates that the primary improvement has been in the gravity model. The effects of the surface forces, and to a lesser degree, the ocean tides, have been reduced by improvements in the models [*Casotto*, 1989] and by the estimation of the empirical accelerations. The current uncertainty in the gravitational mass of the Earth (GM) of about 2 ppb [*Ries et al.*, 1992] is equivalent to about 1 cm in satellite and station height and reflects the absolute uncertainty in the time invariant scale for TOPEX/POSEIDON orbits. The station coordinates of the higher quality SLR sites are known with respect to the Earth's mass center to about the same accuracy.

At this point the altimeter crossover residuals are clearly being dominated by nonorbit signals such as ocean tides, inverted barometer, and ocean variability. This should make the TOPEX/POSEIDON altimeter data tremendously valuable in the task of separating and understanding these effects.

Summary

To satisfy the objective of determining the basin-scale general ocean circulation, the requirement for the precise ephemerides was specified to have a global RMS radial orbit error of 13 cm. Achieving this unparalleled accuracy placed extensive demands on the tracking data, the software systems that process the data, and the knowledge of the force models which govern the satellite's motion. Intensive effort before and after launch to improve the models for the geopotential and the surface forces, combined with the precise SLR tracking data and the nearly global tracking provided by the DORIS system, has resulted in orbit accuracies significantly better than the original mission requirement. Tests based on data fits, covariance analysis, and orbit comparisons indicate that the overall radial RMS error is only 3–4 cm. Nonaveraging geographically correlated errors over ocean basins are not expected to exceed 2 cm. As indicated in Table 10, the mission orbit accuracy objectives have been exceeded by a significant margin. The robustness of the POD process, which produces orbits of this accuracy despite variations in orbital geometry, spacecraft attitude, and the amount of tracking data available from cycle to cycle, is of equal importance. The sequence of GDRs produced with these orbits should allow the determination of global ocean surface topography with unprecedented accuracy.

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References

Antreasian, P. G., and G. W. Rosborough, Prediction of radiant energy forces on the TOPEX/POSEIDON spacecraft, *J. Spacecr. Rockets, 29*, 81–90, 1992.

Barlier, F., C. Berger, J. Falin, G. Kockarts, and G. Thuillier, Atmospheric model based on satellite drag data, *Ann. Geophys., 34*, 9–24, 1978.

Bertiger, W. I., et. al., GPS precise tracking of TOPEX/POSEIDON: Results and implications, *J. Geophys. Res.*, this issue.

Bettadpur, S., and R. J. Eanes, Geographical representation of radial orbit perturbations due to ocean tides: Implications for satellite altimetry, *J. Geophys. Res.*, this issue.

Black, H. D., The TRANSIT system, 1977: Performance, plans and potential, *Philos. Trans. R. Soc. London, A, 294*, 217–236, 1980.

Black, H. D., and A. Eisner, Correcting satellite Doppler data for tropospheric effects, *J. Geophys. Res., 89*, 2616–2626, 1984.

Boucher, C., Z. Altamimi, and L. Duhem, ITRF 91 and its associated velocity field, *IERS Tech. Note 12*, Int. Earth Rotation Serv., Obs. de Paris, 1992.

Casotto, S., Ocean tide models for TOPEX precision orbit determination, *Rep. CSR-89-4*, Cent. for Space Res., Univ. of Tex. at Austin, December 1989.

Cazenave, A., J. J. Valette, and C. Boucher, Positioning results with DORIS on SPOT 2 after first year of mission, *J. Geophys. Res., 97*, 7109–7119, 1992.

Cazenave, A., L. Soudarin, and P. Gegout, Geodetic parameters derived from DORIS on TOPEX/POSEIDON, *Eos Trans. AGU, 75*, Spring Meeting suppl., 115, 1994.

Christensen, E. J., B. J. Haines, K. C. McColl, and R. S. Nerem, Observations of geographically correlated orbit errors for TOPEX/POSEIDON using the Global Positioning System, *Geophys. Res. Lett., 21*, 2175–2178, 1994.

Davis, G. W., J. C. Ries, and B. D. Tapley, Preliminary accuracy assessment of the DORIS tracking system on TOPEX/POSEIDON, paper presented at AAS/AIAA Astrodynamics Specialist Conference, Am. Astron. Soc. and Am. Inst. Aeron. Astronaut., Victoria, B. C., Canada, August 1993.

Degnan, J. J., Satellite laser ranging: Current status and future prospects, *IEEE Trans. Geosci. Remote Sens., GE-32*, 398–413, 1985.

Dorrer, M., B. Laborde, and P. Deschamps, DORIS (Doppler Orbitography and Radiopositioning Integrated from Space) system assessment results with DORIS on SPOT 2, *Acta Astronaut., 25*, 497–504, 1991.

Dufour, J. P., C. Boucher, and P. Willis, Comparisons between ITRF91 and recent DORIS solutions, paper presented at IERS Workshop, Int. Earth Rotation Serv., Paris, May 1993.

Dunnell, C. A., TRANET Doppler tracking system, *APL Tech. Dig., 6*, 17–23, 1967.

Eanes, R. J., and M. M. Watkins, The CSR93L01 solution, IERS Annual Report for 1992, Int. Earth Rotation Serv., Obs. de Paris, 1993.

Eichinger, R., T. Johnson, P. Malitson, T. Oldham, and L. Stewart, Optical attenuation mechanism upgrades, MOBLAS and TLRS systems, in Eighth International Workshop on Laser Ranging Instrumentation, *NASA Conf. Publ., 3214*, 14.2–14.13, 1992.

Francis, O., and M. Bergé, Estimate of the radial orbit error by complex demodulation, *J. Geophys. Res., 98*, 16083–16094, 1993.

Frauenholz, R. B., T. W. Hamilton, B. E. Shapiro, and R. S. Bhat, The role of anomalous satellite-fixed accelerations in TOPEX/POSEIDON orbit maintenance, paper presented at AAS/AIAA Astrodynamics Specialist Conference, Am. Astron. Soc. and Am. Inst. Aeron. Astronaut., Victoria, B. C., Canada, August 1993.

Fu, L. L., E. J. Christensen, C. A. Yamarone Jr., M. Lefebvre, Y. Menard, M. Dorrer, and P. Escudier, TOPEX/POSEIDON mission overview, *J. Geophys. Res.*, this issue.

Himwich, W. E., M. M. Watkins, C. Ma, D. S. MacMillan, T. A. Clark, R. J. Eanes, J. W. Ryan, B. E. Schutz, and B. D. Tapley, The consistency of the scale of the terrestrial reference frames estimated from SLR and VLBI data, in *Contributions of Space Geodesy to Geodynamics: Earth Dynamics, Geodyn. Ser.*, vol. 24, edited by D. E. Smith and D. L. Turcotte, pp. 113–120, AGU, Washington, D. C., 1993.

Hopfield, H. S., Tropospheric effect on electromagnetically measured range: Prediction from surface weather data, *Radio Sci., 6*, 357–367, 1971.

Kar, S., and J. C. Ries, The effect of solar array warping on TOPEX orbit determination, *Rep. CSR-TM-93-02*, Cent. for Space Res., The Univ. of Tex. at Austin, April 1993.

Kaula, W., *Theory of Satellite Geodesy*, Blaisdell Press, Waltham, Mass., 1966.

Knocke, P. J., J. C. Ries, and B. D. Tapley, Earth radiation pressure effects on satellites, in *Proceedings of the AIAA/AAS Astrodynamics Conference*, pp. 577–587, Am. Inst. Aeron. Astronaut., Washington, D. C., 1988.

Lerch, F. J., Optimum data weighting and error calibration for estimation of gravitational parameters, *Bull. Geod., 65*, 44–52, 1991.

Lerch, F. J., C. A. Wagner, S. M. Klosko, and B. H. Putney, Goddard Earth models for oceanographic applications (GEM 10B and 10C), *Mar. Geod., 5*, 2–43, 1981.

Lerch, F. J., J. G. Marsh, S.M. Klosko, G. B. Patel, D. S. Chinn, E. C. Pavlis, and C. A. Wagner, An improved error assessment for the GEM-T1 gravitational model, *J. Geophys. Res., 96*, 20023–20040, 1991.

Lerch, F. J., et al., A geopotential model from satellite tracking, altimeter, and surface gravity data: GEM-T3, *J. Geophys. Res., 99*, 2815–2839, 1994.

Luthcke, S. B., and J. A. Marshall, Nonconservative force model parameter estimation strategy for TOPEX/POSEIDON precision orbit determination, *NASA Tech. Memo., 104575*, November 1992.

Marsh, J. G., and R. G. Williamson, Precision orbit analyses in support of the Seasat altimeter experiment, *J. Astronaut. Sci., 28*(4), 345–369, 1980.

Marsh, J. G., et al., A new gravitational model for the Earth from satellite tracking data: GEM-T1, *J. Geophys. Res., 93*, 6169–6215, 1988.

Marsh, J. G., et al., The GEM-T2 gravitational model, *J. Geophys. Res., 95*, 22043–22071, 1990.

Marshall, J. A., and S. B. Luthcke, Modeling radiation forces acting on TOPEX/POSEIDON for precision orbit determination, J. Spacecr. Rockets, 31(1), 89–105, 1994a.

Marshall, J. A., and S. B. Luthcke, Radiative force model performance for TOPEX/POSEIDON orbit determination, *J. Astronaut. Sci., 41*(2), in press, 1994b.

McCarthy, D. D. (Ed.), IERS Standards 1992, *IERS Tech. Note 13*, Obs. de Paris, November 1992.

Melbourne, W. G., B. D. Tapley, and T. P. Yunck, The GPS flight experiment on TOPEX/POSEIDON, *Geophys. Res. Lett., 21*, 2171–2174, 1994.

Milani, A., A. M. Nobili, and P. Farinella, *Non-gravitational Perturbations and Satellite Geodesy*, 125 pp., Adam Hilger, Bristol, England, 1987.

Morris, C. S., and S. K. Gill, Evaluation of the TOPEX/POSEIDON altimeter system over the Great Lakes, *J. Geophys. Res.*, this issue.

Nerem, R. S., B. H. Putney, J. A. Marshall, F. J. Lerch, E. C. Pavlis, S. M. Klosko, S. B. Luthcke, G. B. Patel, R. G. Williamson, and N. P. Zelensky, Expected orbit determination performance for the TOPEX/POSEIDON mission, *IEEE Trans. Geosci. Remote Sens., 31*, 333–354, 1993a.

Nerem, R. S., B. F. Chao, A. Y. Au, J. C. Chan, S. M. Klosko, N. K. Pavlis, and R. G. Williamson, Time variations of the Earth's gravitational field from satellite laser ranging to LAGEOS, *Geophys. Res. Lett., 20*, 595–598, 1993b.

Nerem, R. S., F. J. Lerch, R. G. Williamson, S. M. Klosko, J. W. Robbins, and G. B. Patel, Gravity model improvement using the DORIS tracking system on the SPOT 2 satellite, *J. Geophys. Res., 99*, 2791–2813, 1994.

Nerem, R. S., et al., Gravity model development for TOPEX/POSEIDON: Joint Gravity Models 1 and 2, *J. Geophys. Res.*, this issue.

Noll, C. E., Data archiving and distribution for the Crustal Dynamics Project: The CDDIS, in *Contribution of Space Geodesy to Geodynamics: Technology, Geodyn. Ser.*, vol. 25, edited by D. E. Smith and D. L. Turcotte, 27–46, AGU, Washington, D. C. 1993.

Nouël, F., J. Bardina, C. Jayles, Y. Labrune, and B. Troung, DORIS: A precise satellite positioning Doppler system, in Astrodynamics 1987, edited by J. K. Solder et al., *Adv. Astronaut. Sci., 65*, 311–320, 1988.

Nouël, F., et al., Precise Centre National d'Etudes Spatiales orbits for TOPEX/POSEIDON: Is reaching 2 cm still a challenge?, *J. Geophys. Res.*, this issue.

Parke, M. E., R. H. Stewart, D. L. Farless, and D. E. Cartwright, On the choice of orbits for an altimetric satellite to study ocean circulation and tides, *J. Geophys. Res., 92*, 11693–11707, 1987.

Putney, B. H., et al., Precise orbit determination for the TOPEX/POSEIDON mission, paper presented at AAS/AIAA Astrodynamics Specialist Conference, Am. Astron. Soc. and Am. Inst. Aeron. Astronaut., Victoria, B. C., Canada, August 1993.

Ray, J. R., C. Ma, J. W. Ryan, T. A. Clark, R. J. Eanes, M. M. Watkins, B. E. Schutz, and B. D. Tapley, Comparison of VLBI and SLR geocentric site coordinates, *Geophys. Res. Lett., 18*, 231–234, 1991.

Ries, J. C., and D. Pavlis, Software intercomparison results: Phase 1 and phase 2, Cent. for Space Res., Univ. of Tex. at Austin, March 1992.

Ries, J. C., C. Huang, M. M. Watkins, and B. D. Tapley, Orbit determination in the relativistic geocentric reference frame, *J. Astronaut. Sci., 39*(2), 173–181, 1991.

Ries, J. C., R. J. Eanes, C. K. Shum, and M. M. Watkins, Progress in the determination of the gravitational coefficient of the Earth, *Geophys. Res. Lett., 19*, 529–531, 1992.

Ries, J. C., C. K. Shum, and B. D. Tapley, Surface force modeling for precision orbit determination, in *Environmental Effects on Spacecraft Positioning and Trajectories, Geophys. Monogr. Ser.*, vol. 73, edited by A. V. Jones, pp. 111–124, AGU, Washington, D. C., 1993.

Rosborough, G. W., and B. D. Tapley, Radial, transverse and normal orbit perturbations due to the geopotential, *Celest. Mech., 40*(3–4), 409–421, 1987.

Schanzle, A. F., J. E. Rovnak, D. T. Bolvin, and C. E. Doll, Orbit determination support of the Ocean Topography Experiment (TOPEX)/POSEIDON operational orbit, paper presented at NASA GSFC Flight Mechanics/Estimation Theory Symposium, NASA Goddard Space Flight Center, Greenbelt, Md., May 1992.

Schrama, E. J. O., Some remarks on several definitions of geographically correlated orbit errors: Consequences for satellite altimetry, *Manuscr. Geod., 17*, 282–294, 1992.

Schutz, B. E., and B. D. Tapley, Orbit accuracy assessment for Seasat, *J. Astronaut. Sci., 28*(4), 371–390, 1980.

Schutz, B. E., B. D. Tapley, P.A.M. Abusali, and H. J. Rim, Dynamic orbit determination using GPS measurements from TOPEX/POSEIDON, *Geophys. Res. Lett., 21*, 2179–2182, 1994.

Shum, C. K., B. D. Tapley, D. N. Yuan, J. C. Ries, and B. E. Schutz, An improved model for the Earth's gravity field, in *Proceedings of the IAG Symposium 103, Gravity, Gradiometry and Gravimetry*, pp. 97–108, Springer-Verlag, New York, 1990a.

Shum, C. K., B. H. Zhang, B. E. Schutz, and B. D. Tapley, Altimeter crossover methods for precision orbit determination, *J. Astronaut. Sci., 38*(3), 335–368, 1990b.

Smith, D. E., R. Kolenkiewicz, P. J. Dunn, J. W. Robbins, M. H. Torrence, S. K. Fricke, and S. Blackwell, A global reference frame from LAGEOS ranging (SL5.1AP), *J. Geophys. Res., 90*, 9221–9233, 1985.

Smith, D. E., R. Kolenkiewicz, P. J. Dunn, J. W. Robbins, M. H. Torrence, S. M. Klosko, R. G. Williamson, E. C. Pavlis, N. B. Douglas, and S. K. Fricke, Tectonic motion and deformation from satellite laser ranging to LAGEOS, *J. Geophys. Res., 95*, 22013–22041, 1990.

Stewart, R. H., L. L. Fu, and M. Lefebvre, Science opportunities from the TOPEX/POSEIDON mission, *JPL Publ. 86-18*, Jet Propuls. Lab., Pasadena, Calif., 1986.

Tapley, B. D., C. K. Shum, D. N. Yuan, J. C. Ries, and B. E. Schutz, An improved model for the Earth's gravity field, in Progress in the Determination of the Earth's Gravity Field, edited by R. H. Rapp, *Rep. 397*, pp. 8–11, Dep. Geod. Sci. and Surv., Ohio State Univ., Columbus, June 1989.

Tapley, B. D., B. E. Schutz, J. C. Ries, and C. K. Shum, Precision orbit determination for TOPEX, *Adv. Space Res., 10*, 239–247, 1990.

Tapley, B. D., C. K. Shum, D. N. Yuan, J. C. Ries, R. J. Eanes, M. M. Watkins, and B. E. Schutz, The University of Texas Earth gravitational model, paper presented at XX General Assembly, Int. Union of Geod. and Geophys., Vienna, August 1991.

Tapley, B. D., C. K. Shum, J. C. Ries, R. Suter, and B. E. Schutz, Monitoring of changes in global mean sea level using Geosat altimeter, in *Sea Level Changes: Determination and Effects, Geophys. Monogr. Ser.*, vol. 69, edited by P. L. Woodworth et al., pp. 167–180, AGU, Washington, D. C., 1992.

Tapley, B. D., B. E. Schutz, R. J. Eanes, J. C. Ries, and M. M. Watkins, Lageos laser ranging contributions to geodynamics, geodesy, and orbital dynamics, in *Contributions of Space Geodesy to Geodynamics: Earth Dynamics, Geodyn. Ser.*, vol. 24, edited by D. E. Smith and D. L. Turcotte, pp. 147–174, AGU, Washington, D. C., 1993.

Teles, J., P. B. Pheung, and V. S. Guedeney, Tracking and data relay satellite system range and Doppler tracking system observation measurements and modeling, *NASA Tech. Memo., X-572-80-26*, 1980.

Vigue, Y., S. M. Lichten, G. Blewitt, M. B. Heflin, and R. P. Malla, Precise determination of Earth's center of mass using measurements from the Global Positioning System, *Geophys. Res. Lett., 19*, 1487–1490, 1992.

Wahr, J. M., Body tides on an elliptical, rotating, elastic and oceanless Earth, *Geophys. J. R. Astron. Soc., 64*, 677–703, 1981.

Wakker, K. F., Report to the subcommittee on intercomparison and merging of geodetic data, *Rep. LR-638*, Delft Univ. of Technol., May 1990.

Watkins, M. M., and R. J. Eanes, Long-term changes in the Earth's shape, rotation, and geocenter, *Adv. Space Res., 13*, 251–255, 1993.

Watkins, M. M., J. C. Ries and G. W. Davis, Absolute positioning using DORIS tracking of the Spot-2 satellite, *Geophys. Res. Lett., 19*, 2039–2042, 1992.

Watkins, M. M., G. W. Davis, and J. C. Ries, Precise station coordinate determination from DORIS tracking of the TOPEX/POSEIDON satellite, paper presented at AAS/AIAA Astrodynamics Specialist Conference, Am. Astron. Soc. and Am. Inst. Aeron. Astronaut., Victoria, B. C., Canada, August 1993.

Watkins, M. M., R. J. Eanes, and C. Ma, Comparison of terrestrial reference frame velocities determined from SLR and VLBI, *Geophys. Res. Lett., 21*, 169–172, 1994.

Wu, S. C., T. P. Yunck, and C. L. Thornton, Reduced-dynamic technique for precise orbit determination of low earth satellites, *J. Guid. Control Dyn., 14*, 24–30, 1991.

Wunsch, C., and E. M. Gaposchkin, On using satellite altimetry to determine the general circulation of the ocean with application to geoid improvement, *Rev. Geophys., 18*, 725–745, 1980.

Yuan, D. N., The determination and error assessment of the Earth's gravity field model, *Rep. CSR-91-1*, Cent. for Space Res., Univ. of Tex. at Austin, 1991.

Yunck, T. P., S. C. Wu, J. T. Wu, and C. L. Thornton, Precise tracking of remote sensing satellites with the Global Positioning System, *IEEE Trans. Geosci. Remote Sens., 28*(1), 108–116, 1990.

Yunck, T. P., W. I Bertiger, S. C. Wu, Y. Bar-Sever, E. J. Christensen, B. J. Haines, S. M. Lichten, R. J. Muellerschoen, Y. Vigue, and P. Willis, First assessment of GPS-based reduced dynamic orbit determination on TOPEX/POSEIDON, *Geophys. Res. Lett., 21*, 541–544, 1994.

G. W. Davis, R. J. Eanes, J. C. Ries, B. E. Schutz, C. K. Shum, and B. D. Tapley, The University of Texas at Austin, Center for Space Research C0605, Austin, TX 78712. (e-mail: tapley@utcsr.ae.utexas.edu).

M. M. Watkins, Jet Propulsion Laboratory, Mail Stop 238-600, 4800 Oak Grove Drive, Pasadena, CA 91109-8099.

S. M. Klosko, S. B. Luthcke, D. Pavlis, R. G. Williamson, and N. P. Zelensky, Hughes STX Corporation, 7701 Greenbelt Road, Suite 400, Greenbelt, MD 20770.

J. A. Marshall, R. S. Nerem, and B. H. Putney, NASA Goddard Space Flight Center, Space Geodesy Branch, Code 926, Greenbelt, MD 20771.

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