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PRECISE ORBIT DETERMINATION FOR THE TOPEX/POSEIDON MISSION

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The TOPEX/Poseidon spacecraft was launched on August 10, 1992 to measure the Earth's ocean surface topography using radar altimetry. To achieve maximum benefit from the altimetric data, mission requirements dictate that the spacecraft's orbit must be computed to within 13 cm RMS radially. This necessitates highly accurate, globally distributed tracking data as well as extremely precise models for both the gravitational and non-gravitational forces acting on the satellite. The Space Geodesy Branch at Goddard Space Flight Center (GSFC) has the responsibility within NASA for the precision orbit determination for TOPEX/Poseidon. During the mission verification phase which extended into early March 1993, GSFC refined and assessed its precision orbit determination computer software, Earth gravitational models, and non-conservative force models, as well as evaluated the performance of both the satellite laser ranging (SLR) and DORIS Doppler tracking systems. Since March, GSFC has been distributing a 10 day precision orbit ephemeris (POE) to be put on the mission geophysical data records (GDR's) at regular twenty-two working day intervals. Radial orbit errors are consistently at the 5 cm RMS level. This paper reviews the model development and tuning and summarizes the achieved orbit determination accuracies for TOPEX/Poseidon.

INTRODUCTION

The joint U.S./French TOPEX/Poseidon (T/P) Mission requires unprecedented orbit modeling to achieve its ocean science goals. The satellite orbit must be determined with an RMS radial accuracy of 13 centimeters. This is an extremely stringent accuracy requirement for a satellite of this shape and altitude. T/P is in a circular orbit at 1340 km altitude. It is inclined with respect to the equator by 66 degrees. It is a large satellite with a 28 m^2 single solar panel and weighs nearly 2500 kg. T/P carries a total of five tracking systems including Satellite Laser Ranging (SLR)[1], DORIS Doppler[2], GPS[3], TDRSS[4], and the

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satellite altimetry itself. SLR and DORIS data types are used directly in the GSFC Precision Orbit Determination Production System (PODPS). SLR provides tracking from over 30 worldwide stations while DORIS, a one-way ground-to-satellite dual frequency Doppler tracking system developed in France, supplies data from a worldwide network of over 45 ground beacons. The DORIS systems are unaffected by weather and provide nearly continuous monitoring of the T/P orbit. The altimeter data (which directly measures the height of the satellite above the ocean surface) is used within PODPS as an independent reference for radial orbit accuracy assessment.

To meet the orbit accuracy requirements for T/P, GSFC, in collaboration with the POD teams at the Center for Space Research at the University of Texas at Austin (UT/CSR), the Colorado Center for Astrodynamic Research (CCAR), Centre National d'Etudes Spatiales (CNES, the French space agency), and the Jet Propulsion Laboratory (JPL), has produced improved gravitational models[5,6,7] and developed appropriate non-conservative force models taking into account the complex form of the T/P spacecraft[8,9,10]. There has been a great deal of progress made in both areas as verified by orbit analyses using the first year of the T/P data now available. In fact, the POD team has been able to significantly reduce its error budget, as shown in Table 1[11].

Table 1. TOPEX/Poseidon Orbit ERROR Budget

Error Source	Mission Spec. (cm)	Current Estimate (cm)
Gravity	10.0	2.2
Radiation Pressure (Solar, Earth, and thermal)	6.0	<3.0
Atmospheric Drag	3.0	1.0
GM (gravitational constant for mass of Earth)	2.0	1.0
Earth and Ocean Tides	3.0	2.0
Troposphere	1.0	<1.0
Station Location	2.0	1.0
RSS Absolute Error	12.8	<4.7

The routine and expedient determination of orbits (22 working days after the completion of each 10 day repeat cycle of the satellite) which consistently have the accuracy described in Table 1 necessitated the development of a POD production system. This PODPS system routinely performs the production task, under strict configuration controls, and has an expert evaluation component to insure that the required accuracy is achieved. A Quality Assurance (QA) report is produced and delivered with each Precision Orbit Ephemeris (POE). It contains a summary of all the attributes and results of the testing of the POE. This paper will describe the model development and results to date of the precision orbit determination for the TOPEX/Poseidon satellite being performed at Goddard Space Flight Center's Space Geodesy Branch.

MODEL IMPROVEMENT ACTIVITIES

Gravity Model Improvement

The T/P orbit serves as the reference frame for the altimeter measurements. Therefore, the dominant, long wavelength orbit errors associated with geopotential field mismodeling can alias directly into the altimeter measurements and corrupt the ocean circulation signal. Improving the gravitational model represented the greatest challenge for T/P POD. At the start of planning for T/P during the early 1980's, error analysis of the then best available gravity field, GEM-L2[12] predicted meter level radial errors for the T/P orbit. Since gravity field development required reduction of a large and diverse data base encompassing over thirty satellites and millions of observations, several years were devoted to this effort. The goal was to produce a long wavelength gravity field model capable of representing the radial position of T/P at the ± 10 cm RMS level with minimal geographically correlated error. Meeting these goals has focused on improvements in data treatment and ancillary force modeling to better isolate the gravitational signal from other sources of orbit perturbations.

In overview, an investigation transpired having three phases to produce gravitational solutions capable of meeting T/P goals:

(Phase I) Based upon the best geodetic constants, reference frame definitions and supporting software capabilities which were available in the 1984-1985 time frame, the GEM-T1, T2, and T3 series of solutions were produced. To advance beyond GEM-L2, the major changes which were instituted at this time were to:

(a) take advantage of super-computer capabilities and expand the truncation limits of the models well beyond the degree and order 22 limits of GEM-L2
(b) improve and expand the solid earth and ocean tidal models,
(c) adopt the improved DTM atmospheric drag model[13],
(d) improve the geocentric location of the station positions,
(e) update all geodetic constants to a consistent set;
(f) use a better polar motion and earth rotation time series and improve the definition of the reference frame; and
(g) incorporate new satellite tracking data.

Instituting these modeling gains required a complete reanalysis of all orbits and regeneration of all of the normal equations whose sum forms the gravity solution. Improved methods for obtaining optimal relative data weights and a calibrated error covariance were also developed. Resulting gravity modeling improvements were achieved incrementally. GEM–T1[5] is a model based exclusively on satellite tracking data and was the first model published as a result of these T/P efforts. GEM-T2[6] extended GEM-T1 to include data from 31 satellites, doubled the number of orbital arcs to nearly 1200, and utilized over 2.4 million tracking observations. GEM-T3[7] combined orbital tracking data with surface gravimetry and satellite altimetry and was complete to degree and order 50 in spherical harmonics.

(Phase II) Upon the completion of GEM-T3 and the near-exhaustion of available data sets suitable for gravitational field recovery, a reiteration of the fields was undertaken. This reiteration introduced a refined set of constants and ancillary models and was designed to take advantage of the extensive experience acquired in producing GEM-T1 through T3. The constants which were adopted for the reiteration have also been adopted for subsequent T/P precision orbit determination (see *Wakker [1990]*[14] for a detailed description of the T/P Reference System). This effort again required reanalysis of all data, and regeneration of all of the normal equations in order to produce the final pre-launch T/P gravitational field. The resulting gravity model, created in collaboration with UT/CSR, was called Joint Gravity Model (JGM-1)[15]. Highlights of the improvements instituted at this time included:

(a) use of an expanded ocean tide model which represents over 90 tide lines,
(b) implementing a new reference frame for the solution. The IERS Reference Frame was adopted replacing the so-called "zero-mean" system used for GEM-T1, T2, and T3. This was made possible in JGM-1 given complete modeling of rotational deformation effects (cf. *Marsh et al., [1988]*[5] for modeling requirements),
(c) expanding the JGM-1 solution to degree and order 70,
(d) use of ocean altimeter data from the region below 60° South latitude, the Mediterranean Sea, and from shallower ocean regions which were not included in GEM-T3,
(e) advancing the surface gravimetry data set through isostatic anomaly predictions to provide complete global coverage. This allowed the elimination of the Kaula's "power law" for *a priori* field conditioning,
(f) use of precise DORIS tracking of the SPOT-2 satellite from its global 40 station network (see *Nerem, et al.[1992]*[16] for discussion of DORIS' contribution to gravity field recovery),
(g) modeling of linear tracking station tectonic motions throughout the thirty year time period encompassed by the data,
(h) use of general relativistic effects in a geocentric frame[17]. This included light time corrections, the Lense-Thirring dragging of a satellite due to the rotating mass of the earth, central body effects, station coordinate corrections and various forms of measurement corrections.
(i) use of an Earth albedo force model

The JGM-1 model was ready at the time of the August 1992 launch of T/P.

(Phase III) Satellite orbits are significantly perturbed by their shallow resonance with the tesseral harmonics of the gravitational field. Also, "frozen" orbits like T/P are especially sensitive to errors in the zonal harmonics which cause them to drift away from an exactly repeating groundtrack. Therefore, T/P tracking data acquired during the first 6-month Verification Phase of the mission was incorporated to improve the T/P-sensitive portion of the JGM-1 field. This "tuning" produced the final JGM-2 model and was a collaborative effort between GSFC, UT/CSR and CNES. The first fifteen ten-day cycles of T/P SLR and DORIS Doppler average-range-rate data were used in combination with JGM-1. Table 2 summarizes the data set of JGM-2. Based on recommendations of the T/P Science Working Team, altimeter data from T/P was excluded from this tuning process to keep separate the T/P sensed oceanographic signal from the gravity parameters.

We presently use several methods to assess the orbit modeling capabilities of our gravitational fields. These approaches all rely on the veracity of the calibrated error covariance of the solutions. This requires extensive assessment of the calibration process to produce a reliable error model. The calibration for GEM-T2 is described in[6,18,19] based on methods described in[20]; and for GEM-T3 in[21]. From these analyses and tests, a reasonably comprehensive knowledge of the characteristics of the geopotential errors is obtained.

The calibrated error covariance matrix can be used to project the gravitational modeling error onto any orbital configuration. This projection uses the first-order analytical perturbation theory developed by *Kaula (1966)*[22] and gives a harmonic estimate of modeling error. This estimate does not take into account the distribution of tracking data nor does it consider the additional error arising from the erroneous estimation of the orbital state (epoch) position which propagates with the well-known one-cycle-per-revolution (1cpr) frequency commonly seen in data analyses. However, with the distribution and performance of the various

T/P tracking systems, we have found that these first-order projections are quite reliable in mapping a given gravity error into overall orbit error.

Table 2. Summary of Observations Utilized in the JGM-2 Geopotential Solution

Data Description	No. of Obs.
Tracking Data from 31 Satellites	2,601,000
Altimeter Range from SEASAT, GEOSAT and GEOS-3	569,000
Surface Gravimetry (1° grid)	64,000
TOPEX laser ranges	49,000
TOPEX DORIS avg-range-rate	748,000

Table 3 presents the projected orbit uncertainties for T/P in all components obtained using this method. It compares the projected performance of GEM-T3, JGM-1 and JGM-2. These estimates indicate that we have significantly exceeded the modeling goals established in the early 1980's. Confirmation of this level of geopotential performance will be established in the subsequent sections.

Table 3. Projected Orbit Error from Gravity Modeling for a 10-Day TOPEX Orbit
(Long period errors omitted)

Gravity Model	Radial RMS (cm)	Along Track RMS (cm)	Cross Track RMS (cm)	Total Position RMS (cm)
GEM-L2	65.4	262.5	73.5	280.3
GEM-T1	25.8	222.1	31.0	225.7
GEM-T2	10.4	145.7	15.5	146.9
GEM-T3	6.8	122.0	12.2	122.8
JGM-1	3.4	65.4	6.0	65.8
JGM-2	2.2	35.9	4.0	36.2

Nonconservative Force Modeling

As the results of the previous section demonstrate, gravity field mismodeling is no longer the major error source in precision orbit determination. Accurate modeling of the nonconservative forces on T/P has now become the significant concern[23]. To achieve the T/P orbit error requirements, a model which accounts for the satellites's complex geometry, attitude, and surface properties has been developed[9]. This "box-wing" representation treats the spacecraft as the combination of flat plates arranged in the shape of a box and a connected solar array. The nonconservative forces acting on each of the eight surfaces are computed independently, yielding vector accelerations which are summed to obtain the total aggregate effect on the satellite center-of-mass. *A priori* parameters values associated with each flat plate, which include area, specular and diffuse reflectivity, emissivity, and a set of 5 temperature related terms, were derived from a least squares fit to acceleration histories generated through a finite element analysis of the spacecraft[8,9].

However, both the finite element analysis ("micro-model") and the pre-launch box-wing model were based on a nominal mission profile and theoretical spacecraft performance. Therefore, parameters which can be inferred from the tracking data have been adjusted to obtain a better representation of the actual satellite acceleration history.

Before launch we learned that assumptions about the spacecraft's attitude used in the micro-model were obsolete. In order to reduce battery strain the T/P Project decided to bias the solar array away from maximum sun to limit the rapid changes in charging current that the spacecraft experiences upon entering and exiting the Earth's shadow. T/P is now flying with a 57.5° offset in the solar array pitch angle. Consequently, the magnitude and direction of the finite element analysis acceleration histories were not representative of the actual spacecraft accelerations. However, the impact on the box-wing model was minimized through properly orienting the solar array and reducing the temperature gradient across the solar array. Also, the spacecraft team altered the time of the transition between sinusoidal and fixed yaw regimes from the pre-launch values. This served to modify the micro-model thermal acceleration profile in this regime. Nonetheless, the pre-launch box-wing model performs remarkably well, modeling over 95% of the observed spacecraft accelerations[10].

The daily residual along track accelerations determined from orbital fits to the T/P SLR and DORIS tracking data are shown in Figure 1. These values represent the daily average difference between both the *a priori* (JGM-1) and tuned (JGM-2) predicted box-wing alongtrack accelerations and the actual T/P along track accelerations. These differences arise principally from unknown non-conservative effects. Since this signal was not observed in the pre-launch analysis, it is not predicted by the micro-model. Thus, the force is termed "anomalistic". Note that the force is usually less than 1 nm/s^2 in magnitude and that the pre-launch box-wing model accounts for over 95% of the observed acceleration. Examination reveals the magnitude of the anomalistic force is nearly the same at recurring spacecraft-Sun-Earth geometries. Furthermore, the force behavior is consistent with a body-fixed force directed along both the positive X and Y spacecraft axes. In fixed yaw the spacecraft's positive X axis is aligned with the velocity vector in positive β' and with the anti-velocity vector in negative β', changing direction at $\beta'=0$. At all other times T/P is in sinusoidal yaw and the Y axis crosses back and forth over the velocity vector. The Y axis is predominately oriented along track in the higher β' regimes. Although the anomalistic 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 s/c body, small warping or deployment errors of the solar array[24], and thermal imbalance mismodeling. Unfortunately, no single hypothesis can explain all of the observed characteristics at this time.

However, for the purposes of precision orbit determination, we do not have to explain the anomalistic force. We only have to model it accurately. This is possible if the acceleration is, as mentioned previously, repeatable given the same spacecraft-Sun-Earth geometry. Through July of 1993, the characteristics of the anomalistic force have remained virtually unchanged. Consequently, the following modelling approach remains valid.

The T/P tracking data is processed in 10 day arcs or cycles. The first cycle began after the spacecraft achieved its operational orbit on September 22, 1992. Data from the first 15 cycles was used to tune the drag coefficients, box-wing parameters, and the gravity field simultaneously to better represent the observed accelerations. After simulations and on-orbit studies, the following adjusted box-wing parameter set was chosen:

1) SPECULAR REFLECTIVITY ▸ X-, Z+, Z-, SA+, SA-
2) DIFFUSE REFLECTIVITY ▸ Y-
3) EMISSIVITY ▸ X-, Y+, SA+
4) AREA ▸ X, Y, Z.

During the tuning process, it became apparent that no box-wing parameter was defined in a manner to totally accommodate a constant body-fixed force and, therefore, the anomalistic force still crept into the other parameter solutions. Consequently, body-fixed X and Y parameters were introduced into the model in an attempt to properly account for the anomalistic force. However, these terms were highly correlated with many of the box-wing parameters. Also, the deep resonant orders of the geopotential experienced large changes in this tuning process since they absorb all of the 1cpr non-conservative force modeling errors not accommodated by the body-fixed accelerations. Consequently, the values for the X and Y accelerations were determined independently of the box-wing, gravity, and drag terms, resulting in realistic values of X= 0.39 nm/s^2 and Y= 0.20 nm/s^2. These accelerations were used as *a priori* terms and the gravity field and box-wing models were tuned appropriately. Figure 1 shows that the resulting residual alongtrack accelerations have been substantially reduced. The spikes during the spacecraft flips in Cycles 6 (Day 57) and 11 (Day 106) have been virtually eliminated. Even more telling, however, is the reduction in the recovered amplitude of the 1cpr acceleration parameters over the same period, displayed in Figure 2. These give a more independent measure of the macro-model performance since they are not as correlated with the applied X and Y constant body-fixed accelerations.

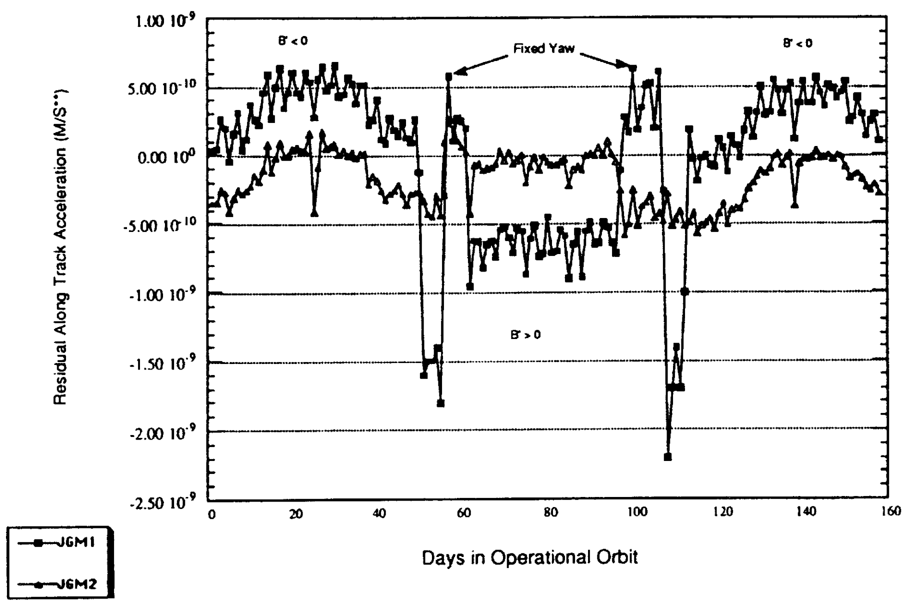

Figure 1. Residual Alongtrack Accelerations

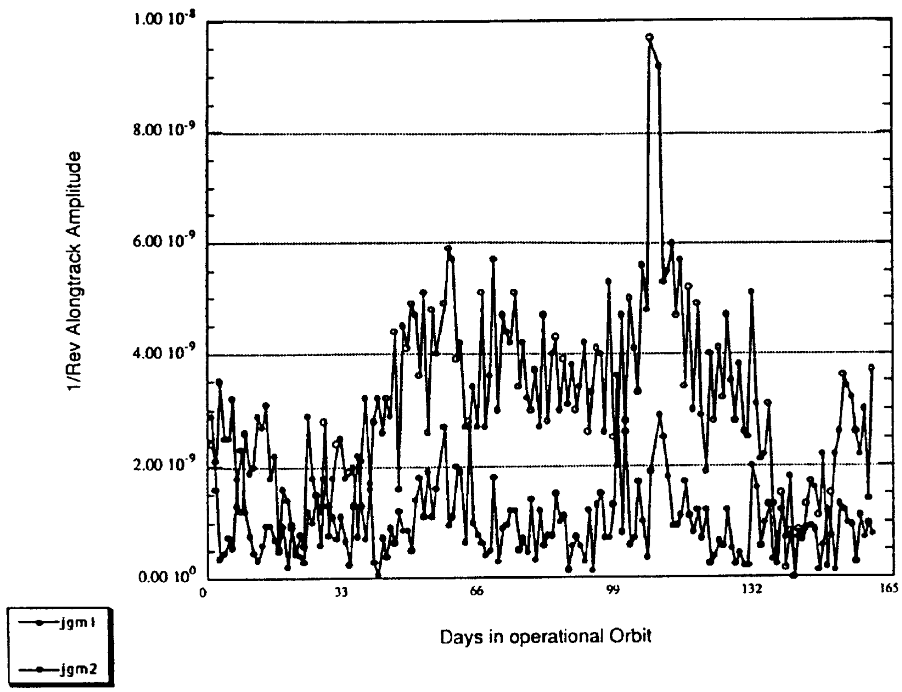

Figure 2. Alongtrack Once-per-Rev Accelerations

Table 4 displays the orbit improvement resulting from the model improvements outlined in this section for selected arcs. Clearly, the efforts have been successful. Activities are currently underway to further improve both the gravity field and non-conservative force modeling for T/P.

Table 4. Pre-Launch vs. "Tuned" Model Performance

Cycle	SLR Data Fit RMS (cm)		DORIS Data Fit RMS (cm)	
	OLD	NEW	OLD	NEW
1	8	4	0.58	0.55
2	9	3	0.62	0.58
9	9	5	0.58	0.58
11	12	5	0.68	0.52
12	8	5	0.63	0.56
13	11	4	0.61	0.56
RSS Total	10	5	0.62	0.56

PODPS PERFORMANCE

System Description

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 (approximately the groundtrack repeat cycle of the T/P orbit), and is computed within 25 working days of the cycle end. JPL combines the POE with altimeter measurements and other ancillary data on the Geophysical Data Record (GDR) for distribution to the science community. The PODPS has been built around GSFC's GEODYN II state-of-the-art orbit determination program[25]. The GEODYN program computes the satellite orbit using a least squares minimization of the difference of a precise model for the satellite orbit and the satellite tracking data.

The PODPS is a menu driven, highly automated system which strictly manages those 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 timely fashion. In anticipation of the rapid advances in hardware technologies, the PODPS system was designed to be portable across a wide range of computer environments. Currently it operates on an HP 735 workstation and CRAY YMP super-computer, and has previously run in an IBM MVS environment. Should any one computer system go down, backup capabilities and procedures will allow POE production to continue.

The POE is determined from SLR and DORIS tracking data imported from the Crustal Dynamics Data and Information System (CDDIS) at GSFC and from CNES, respectively. The procedure requires near real time ancillary data including polar motion from UT/CSR and solar and magnetic flux from the NOAA Solar Geophysical Data Center in Colorado. All imported data and subsequent orbit ephemeris products are subjected to quality/sufficiency checks. In a sequential ordering of tests (Figure 3), 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 subject to a battery of orbit quality tests. The high elevation 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 adjacent orbit offset by 5 days to verify consistency in the solution. The altimeter data residuals and altimeter crossovers are computed from the converged POE orbit and are evaluated both spatially and temporally. The altimeter data serves as an independent check of the orbit accuracy. Alone, no one of these tests is sufficient for proving orbit accuracy. However, 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, checked, and the results of the tests are summarized in a Quality Assurance (QA) report. Both products are sent to JPL, and other users.

The operator's decision as to the quality of the tracking data and candidate orbit ephemeris, and choice to proceed to the next level of testing, are guided by the "Expert System". Over 200 quantifiable criteria related to orbit performance have been identified in all of the tests described above. The current system applies the most important 108 of the criteria to evaluate the orbit quality. A pass/fail threshold value determined from pre-launch simulations is assigned to each of these criteria. Since the criteria vary in significance, a weight has also been assigned so that an overall score for the orbit accuracy can be determined. The scores for each test, and for the ensemble of tests are included in the QA report. The choice of criteria, criteria pass/fail values, and criteria weight values are expected to evolve as experience is gained processing T/P data. Nevertheless this extensive automated testing process ensures uniform processing of the T/P tracking data and detailed scrutiny of each of the resulting orbits.

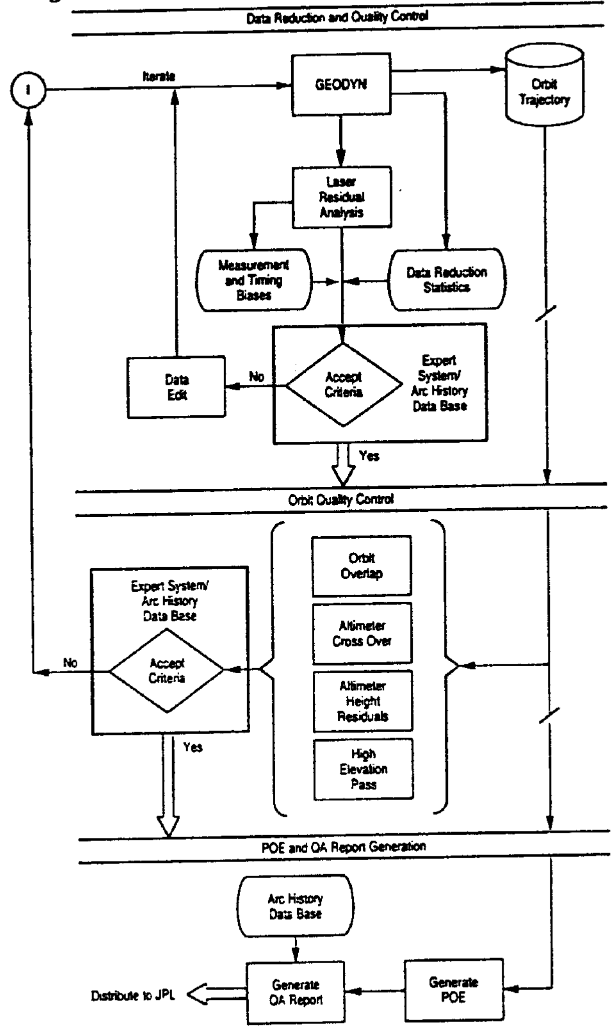

Figure 3. TOPEX/Poseidon POE Quality Assurance Process

Tracking System Performance

TOPEX/Poseidon is supported by three of the most precise satellite tracking systems which have ever been developed. SLR and DORIS data from worldwide networks are used for the generation of precision orbits. T/P also flies a GPS receiver, and is in constant view of four or more of the high altitude GPS satellites. The GPS observations provide excellent geometric coverage around the T/P orbit. These data are being processed as part of a GPS Experiment, conducted at JPL[26], and are currently withheld from the precision orbit activities discussed herein and analyzed independently. Nevertheless, the SLR and DORIS tracking data being obtained on T/P is extraordinary in its strong geographic coverage and precision. The uniform levels of orbit accuracy being routinely achieved, attests to the fidelity and complementary nature of the DORIS and SLR systems.

The NASA SLR systems are supported and managed by the NASA Dynamics of the Solid Earth Program. There are as many as 30 laser tracking stations (both NASA and foreign sites cooperating with NASA) which are operational and available to track T/P at a given time. Of these, a subset of NASA sites are tracking for two eight-hour shifts which are staggered over the week to ensure good data coverage on a continuous basis. All NASA and a select subset of foreign stations, numbering 16 in total, constitute the primary tracking network and were the baseline configuration required for mission support. However, many other sites acquire data and all available observations are used in the precision orbit computations. Data are electronically transferred to NASA/GSFC and are available within two days of their field acquisition on the CDDIS at GSFC.

Laser systems are currently the most accurate and advanced means of precision satellite tracking. These ranging systems have substantially evolved, undergoing nearly a threefold improvement in system precision every five years since the late 1970's. Today the precision of SLR measurements is less than a cm for the best instruments. This evolution has spurred the development of the improved orbit models discussed in previous sections.

To further improve the quality of the SLR data, the NASA Laser Network has assisted the T/P project in the evaluation of the laser retro-reflector array design flown on T/P, and has performed the analysis to design algorithms to account for the far field diffraction and velocity aberration effects seen in the return signal from this satellite. Also, to mitigate the large dynamic range of return signal for optimal ranging accuracy, an automatic introduction of a neutral density filter to stabilize the size of the return signal is being employed by many of the sites.

The Doppler Orbitography and Radio-positioning Integrated by Satellite system (DORIS) is a French developed high precision radiometric tracking system for precision orbit determination in support of geodetic, geodynamic, and oceanographic applications[27]. DORIS provides tracking support for the French portion of the T/P Mission. CNES developed DORIS and first flew the system on the SPOT-2 satellite.

The DORIS system is conceptually similar to the U.S. Navy TRANSIT System in operation since the late-1960's with many significant advancements. Essentially, there are three notable improvements implemented within the DORIS system design:

(1) The ultra-stable quartz oscillators used by the DORIS beacons yield frequency stability at a few parts in 10^{-13} over the Doppler count interval. The nominal precision of this tracking data, 0.3-0.4 mm/s for a 9 second destruct count interval, represents a factor of 5-10 improvement over that available from TRANSIT.

(2) The frequencies selected for DORIS are much better for the cancellation of ionospheric refraction effects. DORIS uses 2 Ghz and 400 Mhz frequencies instead of the 400 Mhz and 150 Mhz used by TRANSIT.

(3) The system is configured as ground transmitted-to-satellite received, which enables the tracking data to be collected onboard the satellite and downlinked to a master control center now located in Toulouse, France. With TRANSIT, the data are collected by global ground receivers requiring a significant data staging activity. This scheme permits data volume to be low and the data to be available immediately after acquisition. These data presently are transmitted to the master ground station every 12 hours.

The DORIS on-board package records one-way averaged Doppler range-rate measurements computed from the dual frequency signals from each ground beacon. The widely separated frequencies permit complete elimination of first order ionospheric refraction effects, with higher order effects being barely detectable even in the most extreme solar activity. The DORIS ground beacons record and transmit meteorological data continuously. As with all radiometric tracking systems operating in this frequency range, the correction for wet tropospheric refraction effects is the most difficult of the data corrections which are required. However, given the robust data set provided by these systems, solution for tropospheric refraction zenith scaling parameters are routinely made and well resolved within the orbit recovery. This significantly reduces these errors.

A well distributed global network of DORIS transmitting beacons has been established and continues to expand over time. The 45 station network in place to support T/P produces in excess of 100 passes per day and represents one of the most geographically extensive network ever configured. A complete geographic sampling of data is routinely collected using the standard procedures adopted by the DORIS network. The efficiency of the data collection process is that anticipated by the DORIS Project with few exceptions, like infrequent "single event upsets" which cause the on-board receiver to need resetting. Preliminary data quality assessments are performed at CNES. The large volume of "clean" data which passed this initial screening and the absence of significant data problems detected within the GSFC analysis attests to the fidelity of the DORIS technology.

Because of its relationship to the TOPEX/POSEIDON Mission, the analysis of DORIS data has been a high priority activity at NASA/GSFC[16]. 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.

Table 5 summarizes the orbit fit and data accumulation obtained for the first 25 ten-day cycles of the TOPEX Mission. The uniformity of orbital fits provided by each of the tracking networks, even with the extreme variability in the amount of available SLR data, is most striking. Whereas the DORIS data is fitting quite close to their inherent noise level, the SLR data is not able to fit at the cm level. Nevertheless, these SLR data fits for 10-day orbits have only been exceeded by those now obtained on the LAGEOS 1/2 and ETALON 1/2 satellites, which are at much higher altitudes than T/P. The T/P results shown in Table 5 are viewed as quite unprecedented and represent the state-of-the-art in both tracking system and data analysis performance.

Product Testing

Each POE is subject to a series of tests resulting in the evaluation of 108 criteria. The results for 7 of the more important criteria are summarized in Table 6, giving the mean, standard deviation about the mean, maximum, and minimum values over 23 processed cycles (cycles 1-4, 9-27). The fit to the tracking data is a good indication of the total orbit accuracy and consistency. Simulations have shown that the RMS total T/P error is about twice the RMS of the SLR fit given the T/P baseline network. Therefore, the SLR fit of 4.4 ± 0.6 cm implies a total orbit error of approximately 10 cm. In the analysis of the SLR residual ranges (i.e. misclosure between observed and calculated ranges), a timing and offset bias is estimated for each pass, effectively removing all orbit error from each pass. The timing bias implies along-track orbit error, and for range data, the offset 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 High Elevation Pass (HEP) test yields a precise limit of the radial orbit error, but one which has extremely limited geographic and temporal coverage. A subset of SLR passes whose maximum elevation exceeds 60 degrees are selected and down-weighted in a solution. Then, an offset and timing bias is computed for each HEP pass of residuals, and the HEP radial error estimate is formed by taking the RMS of these offset biases. The higher the elevation of

Table 5. Summary of Tracking Data Fits and Quantities for TOPEX/Poseidon Cycles 1 through 25

Cycle	SLR RMS of Fit (cm)	DORIS RMS of Fit (mm/s)	# of SLR Passes	# of DORIS Passes	DORIS Time Tag Offset (μsec)
1	4.4	0.55	213	985	-19
2	3.4	0.58	164	1097	-16
3	3.6	0.53	181	1160	-15
4	5.0	0.53	134	1290	-19
5	4.8	0.54	151	1065	-14
6	4.8	0.55	158	1188	-13
7	4.9	0.58	148	1257	-17
8	4.5	0.56	146	1447	-16
9	4.8	0.55	161	1289	-21
10	4.0	0.58	118	556	-12
11	4.6	0.52	76	931	3
12	5.5	0.56	110	1353	-5
13	4.4	0.56	112	1369	-6
14	4.6	0.56	139	1341	-9
15	4.6	0.56	121	1302	-9
16	5.2	0.56	130	1276	-10
17	4.0	0.55	151	1264	-8
18	5.2	0.57	189	1257	5
19	4.6	0.56	138	1288	5
20	4.7	0.56	189	1274	5
21	3.8	0.54	161	1259	1
22	3.8	0.54	238	1251	8
23	3.9	0.56	174	1236	8
24	4.8	0.51	190	831	7
25	3.9	0.54	143	1216	9

a pass, the more an offset bias estimate will represent radial orbit error. This estimate shows that the radial error varies between 2 - 4 cm, averaging 3 cm.

TABLE 6. Current Estimate of T/P Orbit Accuracies

Test Criteria	**Mean**	**Std Dev**	**Max**	**Min**
SLR fit RMS (cm)	4.4	0.6	5.3	3.0
DORIS fit RMS (mm/s)	0.55	0.02	0.58	0.51
Radial Error Function RMS (cm)	2.0	0.7	3.5	0.8
Overlap Radial Delta RMS (cm)	0.9	0.3	1.6	0.5
Altimeter range fit RMS (cm)	20.3	0.6	22.5	19.2
Altimeter Crossover fit RMS (cm)	10.4	0.6	12.4	9.3
HEP Radial Error Estimate RMS (cm)	3.1	0.5	4.0	2.2
UT/CSR Radial Delta RMS (cm)	2.0	0.5	3.5	1.4

The T/P satellite follows a variety of attitude profiles depending upon the orbital geometry. The POE accuracy is extremely 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 five days, and the other with the last five days. Taking the difference between two overlapping orbits removes the highly structured geographically correlated error resulting from imperfections in the gravity model, leaving the difference of the time-varying error components. The Overlap Radial Delta is the radial RMS difference between the POE and the overlapping solutions. This test demonstrates that the empirical acceleration parameterization is extremely effective in containing the effects of any unmodelled accelerations, keeping the orbits consistent to within 1 cm radially and in total to within 5 cm. The maximum radial deviation from any one orbit overlapped with another was found to be under 6 cm.

The altimeter data for T/P is an important resource for the accuracy assessment of the POE. This data is withheld from the orbital solution and provides an independent and direct global measurement of the satellites radial position over the entire arc length. First, the IGDR altimeter range data is corrected for sea state and filtered for steep geoid. The data is then passed through the orbit determination software while holding the POE orbit fixed and adjusting one bias to form the altimeter range residual. The altimeter crossover measurement is formed by taking the difference between two interpolated sea surface height altimeter observations at the crossing point of a descending and an ascending track. The crossover residuals are computed from the altimetric range residuals using linear interpolation. Before these data can be used in the accuracy assessment, however, orbit error must first be differentiated from other more dominant signals, particularly those due to the geoid, mesoscale ocean variability, and tides. Similarly, the crossover residual contains the effects of time-varying orbit error, and time varying ocean and media signals.

The magnitude of radial orbit error is small compared to the other signals found in the altimeter residuals. Table 7 provides a likely error budget for the altimeter residual signals. The geoid and tide errors shown in Table 7 have been scaled down from global estimates, since the altimeter data is masked, as mentioned above, over some regions where the geoid and tide models have a greater uncertainty. The crossover error magnitude is the RSS combination of the time varying error from the descending pass and time varying error from the ascending pass. Since the geographically-correlated orbit error is eliminated in forming the crossover, and this component is considered to be equal to the time varying component, the magnitude of the crossover orbit error equals the magnitude of the altimeter range orbit error.

Table 7. Altimeter Residual Signal Error Budget

ERROR SOURCE	ALTIMETER RANGE (cm)	CROSSOVER (cm)
orbit error	5	3.5
geoid height	11-19	0
ocean tides	4-8	6-11
mesoscale variability	4-6	0
ocean "stationary" dynamic topography	5	0
significant wave height correction	2	2.8
troposphere diffraction	2	2
altimeter measurement	1	1.4
RSS total	14.6-22.8	8.9-12.8

Orbit dynamics act as a strong filter on the influence that nonconservative perturbing forces have on the orbit trajectory, and largely affect the amplitude and modulation of the satellite's 1cpr signal. Thus, the orbit error signal is expected to largely exhibit the same 1cpr form. The altimeter residuals have been decomposed spectrally using a least-squares package to estimate the sine + cosine amplitudes at discrete frequency intervals. Typically less than 25% of the total 10 cm RMS variance can be attributed to orbit error using this method.

The altimeter residuals are post-processed and fit to extract the probable orbit error signal at the dominant 1cpr frequency and its modulation over the 10-day cycle ("bow-tie" effect). The Radial Error Function has the form:

$$\Delta H_t = a + b(t) + c\cos(\omega_t) + d\sin(\omega_t) + e(t-t_{mid})\cos(\omega_t) + f(t-t_{mid})\sin(\omega_t)$$

where a represents a bias, b represents a tilt, c and d are associated with the 1cpr terms, and e and f are coefficients of the modulation of the 1cpr signal over the arc. Among other limitations, the function does not accommodate the complex orbit errors, and assumes that the "bow-tie" signal is symmetric and always smallest at the mid-point of the arc (t_{mid}). Consequently, the Error Function result is slightly smaller than the HEP radial error estimate.

To get a more independent assessment of the accuracy of the POE's, one can look at results of orbit determination activities underway at other POD centers. UT/CSR acts as the verification center for the POE's before they are placed on the GDR's, producing their own T/P ephemeris from SLR and DORIS data. The resulting orbit comparisons show agreement to the 2 cm level (Table 6). Also, T/P carries an experimental GPS receiver which is being used to study new techniques for precision orbit determination[26]. The GPS constellation provides nearly continuous three-dimensional tracking of the spacecraft, allowing a more "geometric" approach to orbit estimation than is possible using the more sparsely distributed SLR/DORIS data. By modeling many of the error sources as stochastic processes, GPS-based orbits are much less sensitive (although not completely independent) to dynamic modeling errors arising from the gravity field and nonconservative force models. GPS-based orbits computed at the Jet Propulsion Laboratory have an estimated radial accuracy of 3 cm RMS[26]. Since the GPS network is independent of the SLR/DORIS network, and since the orbit determination techniques are quite different, a comparison of orbits computed using the two data sets/methods should provide a realistic estimate of the orbit errors. Table 8 shows a comparison of TOPEX/Poseidon orbits computed using SLR/DORIS tracking data at GSFC (the T/P POE) versus orbits computed by JPL using only the GPS data. The comparisons are computed over 10 day intervals. Both the GSFC and the JPL orbits used the JGM-2 gravity model and the tuned T/P macro model. However the JPL orbit includes the stochastic adjustment of constant radial, transverse, and normal accelerations over 15 minute intervals[28]. JPL refers to this procedure as the "reduced-dynamic" estimation technique.

As shown in Table 8, the differences between the GSFC and JPL orbits averages 3.5 cm RMS in the radial direction. Therefore the radial orbit errors in either orbit are almost certainly less than 5 cm RMS. This is a considerable achievement for both research teams given that the original goal for TOPEX/Poseidon orbits was 13 cm RMS radially. In addition, the average crosstrack and alongtrack differences of 5 cm and 10 cm, respectively, show that all components of the spacecraft position are being well determined.

Table 8. RMS Orbit Differences (cm) GSFC SLR/DORIS POE versus JPL GPS Reduced-Dynamic

Cycle Number	Radial	Crosstrack	Alongtrack
Cycle 14	3.42	7.27	10.50
Cycle 15	3.49	6.52	9.66
Cycle 17	3.73	5.20	11.40
Cycle 18	3.29	5.33	10.46
Cycle 19	3.74	4.97	11.80
Cycle 20	4.20	5.08	15.14
Cycle 21	3.40	5.81	9.27

Although there is no one test sufficient for assessing the absolute accuracy of the orbit, the resulting combination of these results strongly suggest that the radial accuracy of these orbits is good to 5 cm or better. Furthermore the orbits are highly consistent, showing an internal consistency of 1 cm, and 2 cm when compared to an independently determined orbit. With these unprecedented orbit accuracies, enormous insight will be gained over the T/P mission lifetime for understanding basin-wide ocean circulation, the primary science goal of this mission.

SUMMARY

This paper has summarized the current TOPEX/Poseidon precision orbit determination results generated by the PODPS system at NASA/GSFC. Through remarkable improvements in both the gravitation and non-conservative force modeling, the POD team has not only met orbit error mission criteria, but has been able to substantially reduced the orbit errors in the precision orbit ephemeris (POE). The consistent quality of the POE, despite the variations in orbital geometry, spacecraft attitude, and the amount available tracking data from cycle to cycle, is of equal importance to the scientific community. The PODPS system has played a significant role in ensuring this consistency and quality and, also, a timely delivery of the product. The cooperative and diligent efforts of all members of the POD at NASA/GSFC, UT/CSR, CNES, and JPL have made this achievement possible.

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