# The First Low Earth Orbiter with Precise GPS Positioning: Topex/Poseidon

Willy Bertiger, P. Abusali, Yoaz Bar-Sever, Bruce Haines, Rodrigo Ibanez-Meier, Ron Muellerschoen, Tim Munson, H. J. Rim, Bob Schutz, Pascal Willis, Sien Wu and Tom Yunck

**This paper was presented at ION GPS 93 in Salt Lake City Utah, September 1993 and will appear in the proceedings of that meeting.**

**BIOGRAPHIES**

*Willy Bertiger* received Ph.D. in Mathematics from the University of California, Berkeley, in 1976, specializing in Partial Differential Equations. Following his Ph.D., he continued research in maximum principles for systems of partial differential equations while teaching at Texas A&M University. In 1981, he went to work for Chevron Oil Field Research. At Chevron, he worked on numerical models of oil fields and optimization of those models for Super Computers. In 1985, he began work at JPL as a Member of the Technical Staff in the Earth Orbiter Systems Group. His work at JPL has been focused on the use of GPS for high precision orbit determination . GPS studies have included: high precision geodetic baseline determination, software development and analysis for the Topex/Poseidon-GPS orbit determination experiment, and filter software and algorithm development for gravity field determination.

*P.A.M. Abusali* is with the Center for Space Research, University of Texas and has been involved in research related to GPS applications and satellite orbit analysis since 1984. He received his M.S. and Ph.D. from the same University.

*Yoaz Bar-Sever* received his Ph.D. in Applied Mathematics from the Technion - Israel Institute of technology, in 1987, specializing in Geophysical Fluid Dynamics. From 1987 to 1989 he was a post-doctoral fellow at the Department of Applied Mathematics at Caltech. In 1989 he joined the Earth Orbiter Systems Group at JPL as a Member of the Technical Staff. In 1993 he received a M.S.E.E. degree from the University of Southern California, specilaizing in Signal Processing. His main interests are in modeling of spacecraft dynamics and in geophysical applications of precise orbit determination.

*Bruce Haines* received his Ph.D. in Aerospace Engineering Sciences from the University of Colorado in 1991, after which he joined the Earth Orbiter Systems Group at JPL. He is a member of the Topex/Poseidon Joint Verification and Precision Orbit Determination Teams, and specializes in precise orbit and geodetic analyses using GPS and in oceanographic applications of satellite altimetry.

*Rodrigo Ibanez-Meier* received his Ph.D. in high-energy physics from Rice Univ. in 1992, and joined JPL's Tracking and Applications Section the same year. He is now working in POD and several applications of GPS/LEO systems, including Earth orientation, crustal motion, atmospheric and ionospheric observations.

*Ron Muellerschoen* received a B.S. degree in physics at Rensselaer Polytechnic Institute and a M.S. degree in applied math at the University of Southern California. He is currently a member of the technical staff with the Earth Orbiter Systems at the Jet Propulsion Laboratory.

*Timothy N. Munson* is a member of the technical staff at Jet Propulsion Laboratory.

*H. J. Rim* received his Ph.D. from The University of Texas at Austin in 1992.He is a Research Engineer/Scientist at the Center for Space Research, with primary research interests in GPS.

*Bob Schutz* received a Ph.D. in 1969. Currently, he is Professor of Aerospace Engineering and Engineering Mechanics at the University of Texas-Austin, and holds the Gulf Oil Foundation Centennial Fellowship in Engineering. He is also Associate Director of the Center for Space Research and a member of the Applied Research Laboratory staff, both of which are components of the University of Texas-Austin.

*Sien Wu* received his B.S.E.E. degree from the National Taiwan University, Taipei, Taiwan; and Ph.D. degree from the University of Waterloo, Ontario, Canada. He joined the Jet Propulsion Laboratory in 1975 and is currently a Technical Group Leader in the Tracking Systems and Applications Section. He has been involved with the development of various tracking systems for deep-space as well as near-earth space vehicles, and their applications to precision geodesy. His current interest is in the precision applications of the NAVSTAR Global Positioning System.

*Tom Yunck* received his B.S.E.E. from Princeton University, and his Ph.D. in Systems & Information Science from Yale University. He is currently Deputy Manager of the Tracking Systems and Applications Section at JPL, where he is involved in the application of GPS to precise orbit determination and geodesy.

*Pascal Willis* received his Ph.D. from Ecole Polytechnique, Paris in 1983.and is head of the Geodetic Research Lab at IGN. His principal interests are GPS and DORIS.

## ABSTRACT

The Topex/Poseidon oceanographic satellite was launched in August 1992 carrying a high performance GPS receiver. The purpose of the receiver is to evaluate GPS for precise orbit determination of low orbiting Earth satellites. Using GPS, we have obtained an estimated radial orbit accuracy of 3 cm RMS for Topex/Poseidon, and estimated cross track and along track accuracies of better than 10 cm.

To obtain this accuracy, we have used specialized filtering strategies that take advantage of the global 3-dimensional coverage provided by the GPS constellation. The particular family of filtering strategies used has come to be known as reduced dynamic tracking. In this technique a small adjustment to an arbitrary 3-dimensional acceleration is made at each measurement time to correct for mismodeled dynamics using the strength of the GPS measurement system. Since each adjustment is essentially local, the information needed to compute the adjustment must come primarily from the instantaneous measurement geometry rather than satellite dynamics.

Orbit accuracy has been evaluated through such techniques as postfit measurement residuals, orbit differences between overlapping data arcs, orbit differences with traditional dynamic orbit solutions derived from different measurement systems (laser ranging and DORIS doppler) and different analysis software, and altimeter crossover statistics.

## INTRODUCTION

TOPEX/Poseidon, a US/French oceanographic mission launched in August 1992, carries two independent tracking systems to provide the operational precise orbit determination needed to meet the mission scientific requirements. These include a French-built one-way Doppler system known as DORIS (Doppler Orbitogaphy and Radio positioning Integrated by Satellite) and an SLR (satellite laser ranging) reflector arrary than canbe used by ground-based SLR systems. In addition to these operational tracking systems, TOPEX/Poseidon carries a six-channel GPS receiver capable of making dual-frequency P-code pseudorange and continuous carrier phase measurements—the first of its kind to be placed in Earth orbit. The GPS receiver was placed onboard as a flight experiment to demonstrate the potential of differential GPS tracking for very high precision orbit determination. GPS is the only tracking system capable of providing continuous 3-dimensional tracking of Earth satellites.

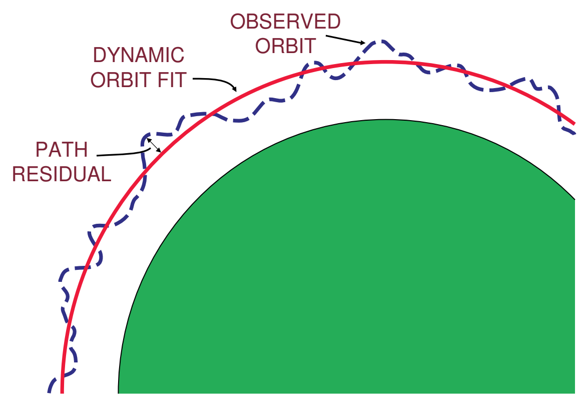



**Fig. 1 Reduced Dynamic Tracking**

The GPS experiment on TOPEX/Poseidon (Ref 1) presents the first opportunity to apply the reduced dynamic technique for precise orbit determination of earth satellites (Ref. 2,3). The technique exploits the great observing strength of GPS to make local geometric corrections to the satellite orbit obtained in a conventional dynamic solution. This reduces orbit errors arising from the mismodeling of forces acting on the satellite, while increasing somewhat the effects of measurement error. The principle is illustrated in Fig. 1. The solid line represents a dynamic orbit solution in which the solution trajectory is described by a set of physical and empirical force models, which may have been adjusted in the solution. The dashed line represents the observed orbit embodied in the GPS data. The dynamic orbit solution yields a set of postfit data residuals reflecting the difference between the solution orbit and the measurements. The size of that difference depends in part on the accuracy of the force models used in the dynamic solution. Because the flight receiver typically tracks five or six GPS satellites simultaneously, at each time step there is sufficient residual information to construct geometrically the 3D vector between the dynamic solution and the observed orbit. Thus the observed orbit can be fully recovered to replace the model orbit as the orbit solution.

This concept offers a continuum of possible solution strategies. At one extreme we can give no weight to the geometric corrections and retain the dynamic solution. At the other extreme we can fully apply the geometric corrections to obtain an essentially kinematic solution. In that case the underlying dynamic solution serves as a point of departure but has little influence on the geometrically determined orbit, and the effects of force model errors are greatly reduced. In between we can give arbitrary relative weight to dynamic and geometric information by constraining the geometric correction with respect to both the dynamic solution and the previous correction, partially reducing dynamic model error. An “optimal” weighting will tend to balance dynamic, geometric, and measurement errors.

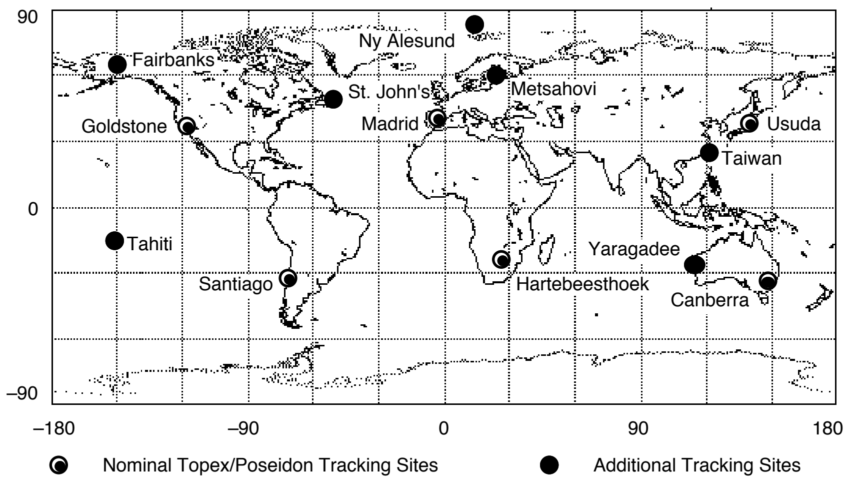



**Fig. 2 GPS Ground Tracking Network**

The success of this experiment was made possible through the interaction of a large team which included groups at the Jet Propulsion Laboratory (JPL) and the Center for Space Research (CSR) of the University of Texas at Austin, and a scientist visiting JPL from the Institut Geographique National (IGN, France). The JPL team focused on refining the reduced dynamic solution strategy, while CSR, which has a long history of precise dynamic tracking with satellite laser ranging, adapted their software for dynamic orbit determination (Ref. 4) and tuning the Earth’s gravity with TOPEX/Poseidon GPS data. The JPL and CSR analysis systems were developed independently (Ref. 5,6), though they share a number of common models. Comparisons between orbits produced with each system serve as an important test of orbit accuracy and precision. IGN has expertise in the DORIS system as well as GPS. IGN and JPL worked closely together to adapt JPL's GPS software to process DORIS data as well. In addition to the efforts of our team, there is a large complementary effort underway at Goddard Space Flight Center and CNES (Centre National d’Etudes Spatiale, in Toulouse) to determine precise orbits with SLR and DORIS.

## DATA

Signals from up to six GPS satellites can be received simultaneously by the GPS Demonstration Receiver (GPSDR) on TOPEX/Poseidon. For data taken before Jan. ‘93, at least 5 GPS satellites are observed 80% of the time and at least 4 are observed 96% of the time. With more GPS satellites now in orbit, these statistics are currently somewhat higher. Note that with 4 GPS being observed, if no other parameters were adjusted one could determine the satellite position and clock offset at each measurement time. Of course this is not the optimal strategy, but it gives an idea of the basic power of GPS compared to both SLR and DORIS which do not have continuous coverage or observations in many directions at one time.

In addition to the flight receiver, there is a global network (Fig. 2) of Rogue and TurboRogue receivers on the ground that establish the precise reference frame and that serve to reduce a number of important errors. Each ground receiver (Ref. 7,8) can track up to 8 GPS satellites simultaneously. For data taken before Jan. ‘93, each ground receiver typically observed 5 or more GPS satellites 90% of the time and 6 or more 72% of the time. Dual frequency carrier phase measurements on TOPEX/Poseidon are recorded every second, while pseudorange measurements are smoothed and recorded every 10 seconds. Carrier phase and pseudorange data are collected simultaneously by the ground receivers at 30 second intervals.

## DATA PROCESSING SOFTWARE AND MODELS

*GIPSY-OASIS II, Dynamic, Reduced Dynamic Processing*

Data processing at JPL for both dynamic and reduced dynamic solutions was performed with the GIPSY-OASIS II analysis software (Refs. 5,6). The main components of the analysis software are a GPS data editor, orbit integrator, measurement model generator, and filter/smoother. The data editor operates on a combined set of dual frequency GPS phase and pseudorange measurements and detects outliers and carrier phase discontinuities(Ref. 11). A highly automated expert system ties all the modules together producing daily orbit solutions unattended (Ref. 12). This system can produce a reduced dynamic solution for TOPEX/Poseidon within two days of on-board data acquisition with less than 6 hours CPU time on a desktop workstation.

The orbit integrator performs a numerical integration of the satellite orbit using a nominal initial state and a set of high accuracy models of the forces acting on the satellite. It also computes partial derivatives of the current state of the spacecraft with respect to the dynamical and epoch state parameters. The initial trajectory and partial derivatives are written to a file to be read by the measurement model program.

The force models for TOPEX/Poseidon include the JGM-2 gravity model developed at the Goddard Space Flight Center and the University of Texas at Austin specifically for TOPEX/Poseidon (Ref. 13), and models of atmospheric drag, Earth albedo, solar radiation pressure, and thermal radiation emitted by the satellite (Ref. 14). In addition to these forces, there is an empirical acceleration parameter, $\vec{a}$, of the form

$$\vec{a} = \vec{C} + \sum_{i=1}^{2} \vec{A}_i \cos \omega_i t + \vec{B}_i \sin \omega_i t \qquad [1]$$

where $\vec{C}$, $\vec{A}_i$, and $\vec{B}_i$ are constant vectors in the coordinate system oriented in the nominal spacecraft along track and cross track directions. The frequencies $\omega_i$ are once and twice per revolution of TOPEX/Poseidon and $t$ is time past an epoch. Partial derivatives of the current state with respect to the coefficients $\vec{C}$, $\vec{A}_i$, and $\vec{B}_i$ are computed. In addition, partial derivatives of the GPS satellite current states with respect to their epoch states and the Rock 4 solar pressure model (Refs. 15,16) are computed.

After editing, the data are compressed to 5-min normal points and the dual frequency ionosphere free combinations of phase and pseudorange are formed. In the compression step the pseudorange data are smoothed against the carrier over the entire 5-min interval, while the phase is simply sampled at the appropriate times. The nominal trajectory is then used to compute model GPS observables and partial derivatives of those observables with respect to the adjusted parameters. The observable model program reads spacecraft positions and partials with respect to dynamical and epoch state parameters from the file written by the integrator. In addition to partials of the observables with respect to dynamical parameters, partial derivatives of the observables are computed with respect to ground station position, zenith troposphere delay, earth orientation, the geocenter, GPS clocks, and receiver clocks. The model includes relativistic effects, solid-earth tides, pole tides, phase windup due to antenna rotation (Ref. 22), and antenna phase-center variation as a function of azimuth and elevation.

Following the modeling step, the filter/smoother is executed to estimate a large set of parameters (specified by the user), adjusting them to minimize the mean squared difference between the GPS observations and the computed model. In its simplest form the filter/smoother would produce a conventional least squares solution; but to obtain a more accurate orbit some parameters are treated as stochastic processes using a Square Root Information Filter (SRIF) formulation (Ref. 17). The parameters adjusted in our standard solution strategy are summarized in Table 1.

In these solutions, all clocks in the system are modeled as white noise processes with no apriori constraint, except for one which is held fixed as a reference clock (hydrogen maser at Fairbanks). The zenith troposphere delay at each ground station is modeled as a random walk which in 1 hour adds 1 cm uncertainty in the zenith delay. For the 30-hour data arcs, the parameters of the Rock 4 solar pressure model are treated as loosely-constrained constants plus colored process noise with a 4 hour correlation time and sigma of 10% at each batch time.

Prior to generating the reduced dynamic solution, the TOPEX/Poseidon state and the empirical constant and once- and twice-per-revolution accelerations (Eq. 1) are first adjusted to convergence in a dynamic solution, which takes two passes through the filter. This iteration of the dynamic solution brings the final adjustment of stochastic accelerations within (or very close to) the linear regime. In the last (reduced dynamic) step, a final adjustment is made of the TOPEX/Poseidon state and all other previously adjusted parameters, except for the empirical once- and twice-per-rev parameters, which are held fixed, and the constant accelerations ($\vec{C}$, Eq. 1), which are

**TABLE 1. ESTIMATION SCENARIO FOR DYNAMIC FILTERING OF TOPEX/POSEIDON ORBIT, GIPSY-OASIS II**

| Data Type | Data Weight |
|---|---|
| Ground Carrier Phase | 1 cm |
| Ground Pseudorange | 1 m |
| T/P Carrier Phase | 2 cm |
| T/P Pseudorange | 3 m |

(all parameters are treated as constants unless otherwise specified)

| Estimated Parameters | Parameterization | constraint |
|---|---|---|
| T/P Epoch State | 3-D epoch position | 1 km |
| | 3-D epoch velocity | 10 cm/s |
| T/P Empirical forces | constant | 1 mm/s$^2$ |
| (cross track & along track) | 1- & 2-cycle-per-rev | 1 mm/s$^2$ |
| T/P Antenna Phase Center Offset | radial | 5 m |
| GPS States | 3-D epoch position | 1 km |
| | 3-D epoch velocity | 1 cm/s |
| GPS Solar Radiation Pressure | *constant:* | |
| | solar pressure scale factor | 100 % |
| | Y-bias | 2x10$^{-3}$ $\mu$m/s$^2$ |
| | *process-noise:* | 1 1 hrs batch; 4 hrs correlation |
| | X and Z scaling factor | 10 % |
| | Y-bias | 10$^{-4}$ $\mu$m/s$^2$ |
| Non-Fiducial Station Location | ECEF rectangular coordinates | 1 km |
| Tropospheric delay | random-walk zenith delay | 50 cm; 0.17 mm/s$^{1/2}$ |
| Pole Position | X and Y pole | 5 m |
| Pole Position Rate | X and Y pole rate | 1 m/day |
| UT1 – UTC Rate | constant | 100 s/day |
| Carrier Phase Biases | constant over a continuous pass | 3x10$^5$ km |
| GPS and Receiver Clocks | white-noise | 1 sec |

treated as process-noise paramerters. The latter are given a correlation time of 15 min with steady-state sigmas of 10 nanometers/sec$^2$ in the radial and 20 nm/s$^2$ in the cross and along track directions for the 30 hour arcs. It is the geometric strength of the GPS observations that allows these final stochastic adjustments to be made with high accuracy.

*MSODP1 Dynamic Solution with GPS and UTOPIA SLR/DORIS Solutions*

MSODP1 is an independent orbit determination software package developed by CSR, with its heritage in the high precision single satellite analysis package, UTOPIA. MSODP1 was used to produce GPS-based orbits while UTOPIA was used to produce SLR/DORIS-based orbits for TOPEX/Poseidon. The force modeling is essentially the same as GIPSY-OASIS II, but filtering and data editing are vastly different (Refs. 4,18).

In the CSR analysis, GPS pseudorange data are used to correct the phase time tags and 30-sec double differenced iononsphere free phase measurements are formed. The L1 and L2 phase data are interpolated to account for time tag offsets between the TOPEX and the ground-stations to facilitate the removal of Selective Availability in the differencing mode. Only double differenced data beteween TOPEX/Poseidon and one of the six nominal ground stations were used in 24-hour arcs. The estimation procedure employs a batch least squares filter, augmented with a square-root-free Givens solutions algortihm (Ref. 19). The TOPEX/Poseidon radiation pressure model includes thermal forces (Ref. 14). Table 2 summarizes the adjusted parameters in MSODP1.

SLR/DORIS solutions have been performed using UTOPIA, which has significant commonality at the subroutine level with MSODP1, especially in the force modeling and numerical techniques. Extensive tests between UTOPIA and MSODP1 have been performed that show agreement at the mm-level between the two programs. Although MSODP1 can process SLR data, the regular processing has been done with UTOPIA. The TOPEX/Poseidon estimated parameters are the same as those given in Table 2 for the epoch state and the once/revolution empirical parameters. The pre-flight nominal values for SLR and DORIS reference points on T/P have been used, adjusted only for the changes in spacecraft center of mass.

**TABLE 2. ESTIMATION SCENARIO FOR DYNAMIC FILTERING OF TOPEX/POSEIDON ORBIT, MSODP1**

| Data Type | Data Weight | |
|---|---|---|
| Ionosphere-free phase double differences | 2 cm | |
| | (all parameters are treated as constants) | |
| **Estimated Parameters** | **Parameterization** | **constraint** |
| T/P Epoch State | 3-D epoch position | none |
| | 3-D epoch velocity | none |
| T/P Empirical forces (cross track & along track) | constant amplitude and phase of 1-cycle-per-rev | none |
| T/P Antenna Phase Center Offset | radial | none |
| GPS States | 3-D epoch position | none |
| | 3-D epoch velocity | none |
| GPS Solar Radiation Pressure | solar pressure scale factor | none |
| | Y-bias | none |
| Non-Fiducial Station Location | ECEF rectangular coordinates | none |
| Tropospheric delay | New Constant every 2.5 hrs | none |
| Double Difference Biases | Constant over a pass | none |

## ORBIT QUALITY ASSESSMENT

First we examine internal tests within the GIPSY-OASIS II processing system. Then we will make comparisons to the solutions produced by MSODP1 and UTOPIA, and to the precise orbit ephemeris (POE) produced for the altimeter geophysical data records which are released to the science community. The POE is computed by NASA's Goddard Space Flight Center with SLR/DORIS data.

*Reduced Dynamic Internal Tests*

Postfit Residuals

As one of the quality checks, the postfit reduced dynamic residuals on the ionospherically calibrated carrier phase and pseudorange measurements over the full arc are examined. Anomalous data points are automatically detected and removed. In general, the phase residuals have an RMS value of less than 5 mm; and the pseudorange residuals have an RMS value of less than 70 cm. These values are nearly equal to, respectively, the phase data noise and the combined pseudorange data noise and multipath error. This implies no substantial mismodeling in the estimation process. The GPS data are in general of high quality; only 0.01% of data are detected as anomalous and automatically removed from the filtered solution.

Orbit Overlap

TOPEX/Poseidon data are processed in 30-hr arcs centered on noon (Fig. 3). This yields adjacent orbits with 6 hrs of overlap. Although part of the data used are common in yielding the two orbit solutions in this overlap period, they are only partially correlated due to the largely independent determination of GPS dynamic orbits and ground station locations for each arc. The orbit agreement in the overlap is therefore a rough (and somewhat optimistic) indication of the orbit quality.

To avoid the “edge effects” commonly encountered with reduced dynamic orbit determination, 45-min segments from each end of the two solutions are omitted. Forty-five minutes corresponds to three times the time constant used for the stochastic accelerations. This leaves a 4.5-hr overlap between two consecutive days for agreement analysis. A sample of the orbit difference during the 4.5-hour overlap is shown in Fig. 4. The RMS difference is 0.88 cm in altitude, 5.70 cm cross track and 3.44 cm along track. Fig. 5 shows the RMS overlap agreement in altitude for twelve complete 10-day cycles. The RMS agreement is consistently below 2 cm, with an average of about 1 cm. The overlaps with reduced dynamic filtering are consistently better than those with dynamic filtering, which have an altitude overlap difference as high as 5 cm with an average RMS of about 3 cm.

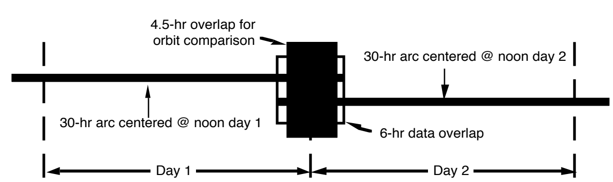



**Fig. 3. Overlapping data arcs and orbit solutions**

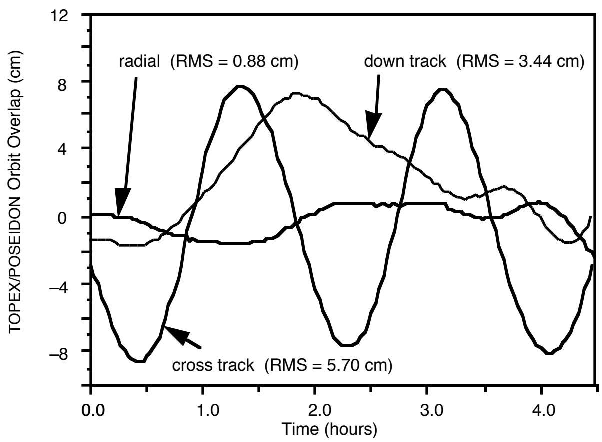



**Fig. 4. Comparison of overlapping TOPEX/Poseidon reduced dynamic orbit solutions**

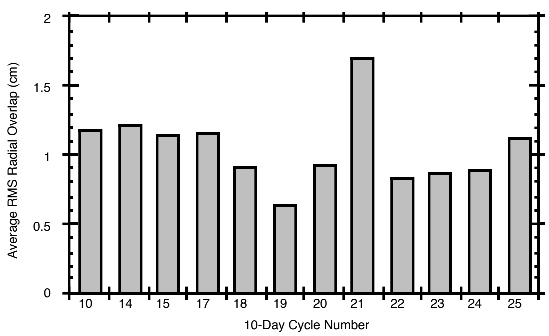



**Fig. 5. TOPEX/Poseidon radial reduced dynamic orbit overlaps for twelve complete 10-day cycles**

*External Tests*

Comparison with MSODP1 GPS and UTOPIA SLR/DORIS

GPS orbits were generated with MSODP1 for Feb 8-18, 1993 (cycle 15) using JGM-2 and an experimental gravity field designated JGM-2/TX-F. JGM-2/TX-F was produced by the CSR group using TOPEX/Poseidon GPS data from Cycles 10, 15, and 17 in a procedure similar to the derivation of JGM-2; data from 150 days of SLR and DORIS were also added to the JGM-1 normal equations to obtain the experimental gravity field. In addition to the GPS determined orbit for TOPEX/Poseidon, UTOPIA was used to compute SLR/DORIS orbits with both JGM-2 and JGM-2/TX-F. The differences between these four orbits and the reduced dynamic orbit are shown in Fig. 6. The experimental gravity field moves the radial component closer to the GPS reduced dynamic solution in all cases. The SLR/DORIS solution is 1.8 cm closer in 3-D to the reduced dynamic solution with the experimental field while the GPS dynamic solution moves about 1.8 cm away due mostly to the cross track component. The reasons for these cross track differences are under investigation.

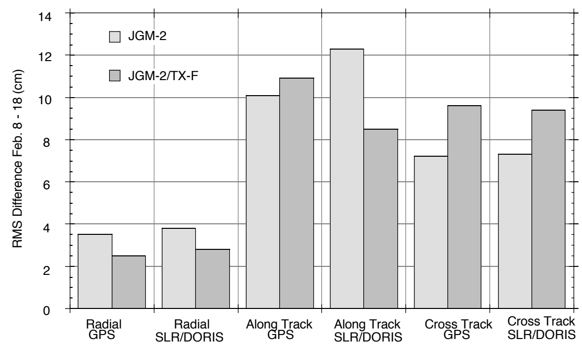



**Fig. 6 RMS difference between dynamic orbits, with JGM-2 and JGM-2/TX-F with the GPS reduced dynamic orbits**

Comparison with NASA Precise Orbit Ephemeris (POE)

The NASA POE is computed by Goddard Space Flight Center for inclusion on the geophysical data records containing the altimeter data. These orbits are produced by yet another software package, Geodyn, although extensive intercomparisons were performed between both Geodyn and UTOPIA. Fig. 7 shows the RMS differences between reduced dynamic orbit solutions from GPS data and GSFC's dynamic solutions from combined laser ranging and DORIS data over eight 10-day TOPEX/Poseidon repeat cycles. The RMS altitude agreements are all better than 4 cm, implying a 3 to 4 cm accuracy for TOPEX/Poseidon altitude solutions for both

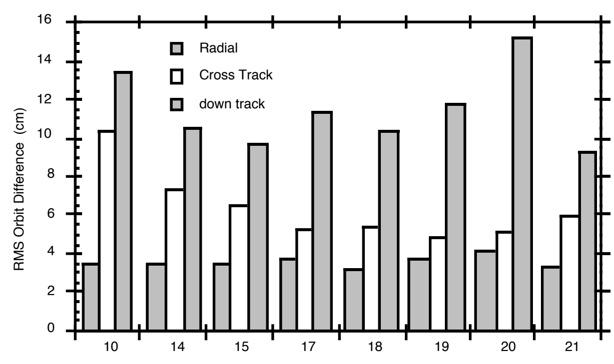



**Fig. 7. Comparison of TOPEX/Poseidon reduced dynamic orbit solutions with GPS against Goddard Space Flight Center SLR/DORIS orbits**

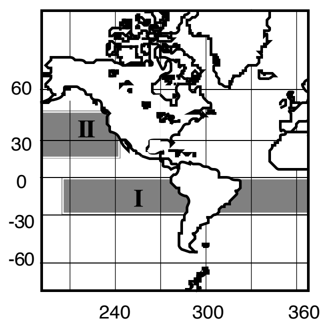
the GPS and SLR/DORIS data types. The other two components are slightly worse: 5-10 cm cross track and 9-16 cm along track.

<u>Altimeter Crossover Statistics</u>

An additional method for assessing the radial orbit accuracy relies on altimeter data collected by the spacecraft. TOPEX/Poseidon carries two nadir-pointing radar altimeter systems that can measure the range to the sea surface with an uncertainty of less than 4 cm rms (Ref. 20). These range measurements can be used together with the precise radial ephemeris to determine the geocentric height of the sea surface. At the points in the ocean where the satellite ground tracks intersect on ascending and descending passes, two such determinations of sea height can be made. In the absence of errors in the orbit and in the media corrections to the altimeter range, the height difference at the crossing point location is a measure of the true variability of the ocean surface.

Crossover observations from seven separate 10-day repeat cycles of the TOPEX/Poseidon ground track were used for this analysis (Ref. 21). We used only the data from the U.S. dual-frequency altimeter in order to avoid contending with any uncalibrated range bias between the two altimeter systems. As crossovers may occur days apart, corrections for certain surface variations, such as those attributable to tides and atmospheric pressure loading were applied. A confounding factor is the unmodeled sea height variation from changes in ocean currents. Most of the important changes in ocean circulation evolve over time periods exceeding a few days. We thus restricted our analysis to crossovers occurring within the individual cycles. We also identified two ocean regions where the current variation over short periods is known to be relatively low. Figure 8 gives the crossover statistics in these regions, as well as globally, for the GPS reduced-dynamic orbits and the NASA precise orbit (described in the previous section). Over 30,000 individual crossovers occurring in the period from January 30 to April 29, 1993, are represented in the global statistic.

The actual radial orbit error is difficult to quantify based on these statistics since the residuals also contain errors in the media corrections, and unmodeled oceanographic effects. A large portion of the tidal and atmospheric pressure signal has been removed using global models, but a sizable signal remains. Moreover, certain correlated errors in the orbit are not observable in crossover differences. These observations nonetheless provide a powerful and independent tool for measuring orbit consistency and for gauging improvement. In this context, we note that the GPS-based reduced dynamic orbits yield lower crossover residuals, suggesting that they represent an improvement in the modeling of the TOPEX/Poseidon orbit. The 4 mm reduction in the global rms crossover residual suggests an improvement of about 2–3 cm in orbit height repeatability for the reduced dynamic orbits.




**RMS Crossover Difference (cm)**

| **Region** | **No.** | **NASA POE** | **GPS R.D.** |
|---|---|---|---|
| Global | 31618 | 11.0 | 10.6 |
| Region I | 1192 | 7.6 | 7.2 |
| Region II | 765 | 10.4 | 9.2 |

**Fig. 8. Summary of RMS altimeter crossover difference with NASA POE (SLR/Doris) and GPS reduced-dynamic solutions.**

## CONCLUSIONS

The TOPEX/Poseidon GPS experiment has demonstrated the accuracy and utility of the reduced dynamic technique. Reduced dynamic tracking with GPS allows one to tradeoff model accurracy for measurement precision and geometric strength. We have shown an accuracy of approximately 3 cm in the radial direction through comparison with external orbits determined with SLR/DORIS. Altimeter crossover statistics suggest greater overall accuracy for the GPS reduced dynamic orbits.

## ACKNOWLEDGEMENT

The work described in this paper was carried out in part by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

We would like to aknowledge Steve Nerem for his help in comparing to the precise orbit emphemeris (POE) produced by Goddard Space Flight center and John Ries of the University of Texas for his many helpful comments.

## REFERENCES

[1] Melbourne, W. G., B. D. Tapley and T. P. Yunck, The GPS flight experiment on TOPEX/Poseidon, *Geophys. Res. Lett.*, submitted August 1993.

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

[3] 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. & Rem. Sensing, GE-23*, 450–457, 1990.

[4] Rim, H., *TOPEX orbit determination using GPS tracking system*, Ph.D. dissertation, The University of Texas at Austin, Austin TX, december 1992.

[5] *An Introduction to GIPSY/OASIS II*, JPL Course Notes, Boulder Colorado, July 19–23, 1993, edited by F. H. Webb and J. F. Zumberge.

[6] Wu, S. C., Y. Bar-Sever, S. Bassiri, W. I. Bertiger, G. A. Hajj, S. M. Lichten, R. P. Malla, B. K. Trinkle and J. T. Wu, *Topex/Poseidon Project: Global Positioning System (GPS) Precision Orbit Determination (POD) Software Design*, JPL D-7275, March 9, 1990.

[7] Thomas, J. B., *Functional Description of Signal Processing in the Rogue GPS Receiver*, JPL Publication 88-15, June 1988.

[8] Meehan, T.,T. N. Munson, J. B. Thomas, J. M. Srinivasan, D. J. Spitzmesser, L. E. Young, R. E. Neilan, “Rogue: A New High Accuracy Digital GPS Receiver,” International Union of Geodesy and Geophysics, XIX General Assembly, Vancouver, BC, Canada, Aug. 1987.

[9] Munson, T. N., E. S. Davis, L. E. Young, “In-Flight performance of the TOPEX / Poseidon Precision GPS Receiver,” Fall AGU Meeting Poster, 1992.

[10] Young, L. E., T. N. Munson, C. E. Dunn, E. S. Davis, “GPS Precision Orbit Determination: Measured Receiver Performance,” *Geophys. Res. Lett.*, submitted August 1993.

[11] Blewitt, G., “An automatic editing algorithm for GPS data”, *Geophys. Res. Lett., 17*, No. 3, 199–202, 1990

[12] Wu, S. C., R. J. Muellerschoen, W. I. Bertiger, T. P. Yunck, Y. E. Bar-Sever, and T. N. Munson, “Automated Precision Orbit Determination for TOPEX/POSEIDON with GPS,” paper AAS 93-576, AAS/AIAA Astrodynamics Specialist Conference, Victoria, British Columbia, Canada, August, 1993.

[13] Lerch, F., R. Nerem, J. Marshall, B. Putney, E. Pavlis, S. Klosko, S. Luthcke, G. Patel, N. Pavlis, R. Williamson, J. Chan, B. Tapley, C. Shum, J. Ries, R. Eanes, M. Watkins and B. Schutz, “Gravity Model Improvement for TOPEX/POSEIDON,” *EOS Trans. AGU, 74*, No. 16, April 1993, p. 96.

[14] Marshall, J.A., S.B. Luthcke, P.G. Antreasian, and G.W Rosborough, “Modeling Radiation Forces Acting on TOPEX/Poseidon for PrecisionOrbit Determination,” NASA Technical Memorandum 104564, June 1992.

[15] Kerr, D. A., “Technical Operating Report for Navstar Block II Satellite,” Volume IV: Solar Force Model, SSD81-0164-4, Rockwell International, 1982.

[16] Fliegel, H. F., Feess, W. A., Layton, W. C., and Rhodus, N. W., “The GPS Radiation Force Model,” *Proc. First International Symposium on Precise Positioning with GPS-1985,* (ed. C. Goad), Vol. I, 113–120, National Geodetic Information Center, NOAA, Rockville, MD.

[17] Bierman, G. J., *Factorization Methods for Discrete Sequential Estimation,* Academic Press, Orlando, FL, 1977.

[18] Schutz, B. E., B. E. Tapley, P. A. M. Abusali, H. J. Rim, “Dynamic Orbit Determination Using GPS Measurements from TOPEX/Poseidon,” *Geophys. Res. Lett.*, submitted August 1993.

[19] Gentleman, W., “Least suares computation by Givens Transformations without square roots,” *J. Inst. Math. Appl. 12,* 329–336, 1973.

[20] Fu, L.L., ed., TOPEX/Poseidon Verfication Workshop, A summary report, JPL D-10815 (Internal Document), May, 1993.

[21] AVISO, "AVISO User Handbook: Merged TOPEX/Poseidon", AVI-NT-02-101-CN, Edition 2, 1993.

[22] Wu, J.T., Wu, Sien C., Hajj, George A., and Bertiger, Willy I., “Effects of Antenna Orientation on GPS Carrier Phase,” vol. 18 no. 2, *Manuscripta Geodetica*, 1993.