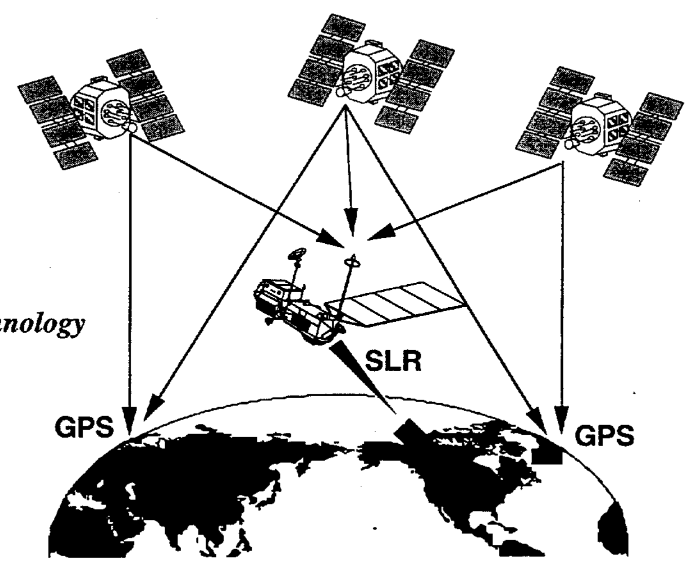
PAPER AAS 95-368

TOPEX/Poseidon Precision Orbit Determination: "Quick-Look" Operations With SLR and GPS Data

Laureano Cangahuala
Ronald Muellerschoen
Dah-Ning Yuan
Edward Christensen
Eric Graat
Joseph Guinn

Jet Propulsion Laboratory
California Institute of Technology
Pasadena California



AAS/AIAA Astrodynamics Specialist Conference

HALIFAX, NOVA SCOTIA, CANADA 14-17 AUGUST 1995

AAS Publications Office, P.O. Box 28130, San Diego, CA 92198

AAS 95-368

TOPEX/Poseidon Precision Orbit Determination: "Quick-Look" Operations With GPS and Laser Tracking Data

L. A. Cangahuala*, R. J. Muellerschoen§, D. N. Yuan§
E. J. Christensen†, E. J. Graat*, J. R. Guinn*

This paper presents a summary of TOPEX/Poseidon "quick-look" orbit determination using Global Positioning System (GPS) and satellite laser ranging (SLR) tracking data. The primary feature of this endeavor is that orbits are produced with small radial position errors (<5 cm RMS), on a short production schedule (≤ 4 days), with minimal resources.

The TOPEX/Poseidon spacecraft, launched on 10 August 1992, has gathered precise sea-level measurements for over two years. To take advantage of the quality of these measurements, the radial orbit component must be known to better than a decimeter. "Quick-look" orbits using two-way laser tracking data have been created for production of Interim Geophysical Data Records (IGDRs) since launch. This effort has been updated with new geodetic models and expanded to include GPS data. These changes resulted in more accurate orbits and added redundancy to the quick-look processing.

The orbit production with both SLR and GPS data has provided an opportunity to use updated station location, gravity field, and tide models. The impact of these updates upon orbit quality is reported. With the two data types, there are actually five data combination scenarios which can occur during operations: (i) GPS (w/ Anti-Spoofing) & SLR, (ii) GPS (w/o Anti-Spoofing) & SLR, (iii) GPS (w/Anti-Spoofing), (iv) GPS (w/o Anti-Spoofing), and (v) SLR only. Based on mission experience to date, the first scenario is most frequently encountered, and the last is the former processing mode. The filtering methodology is matched to the data combination available. Comparisons of these orbits are made to existing precision orbit ephemerides to demonstrate their relative accuracy as an orbit product.

---

* Members of the Technical Staff, Navigations Systems Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109.

§ Members of the Technical Staff, Tracking Systems and Applications Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, 91109.

† Deputy Project Scientist, TOPEX/Poseidon Project and Member of Section Staff, Tracking Systems and Applications Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, 91109.

INTRODUCTION

The TOPEX/Poseidon (T/P) spacecraft was launched into a 1334 km altitude orbit in August 1992, and is in the final months of its primary mission, with a three-year extended mission ahead of it. The mission has been jointly conducted by the United States National Aeronautics and Space Administration (NASA) and the French space agency, Centre National d'Etudes Spatiales (CNES). The T/P near-circular orbit defines a ground track with a ten-day repeat cycle; at the time this document was being prepared, 106 such cycles had been completed .

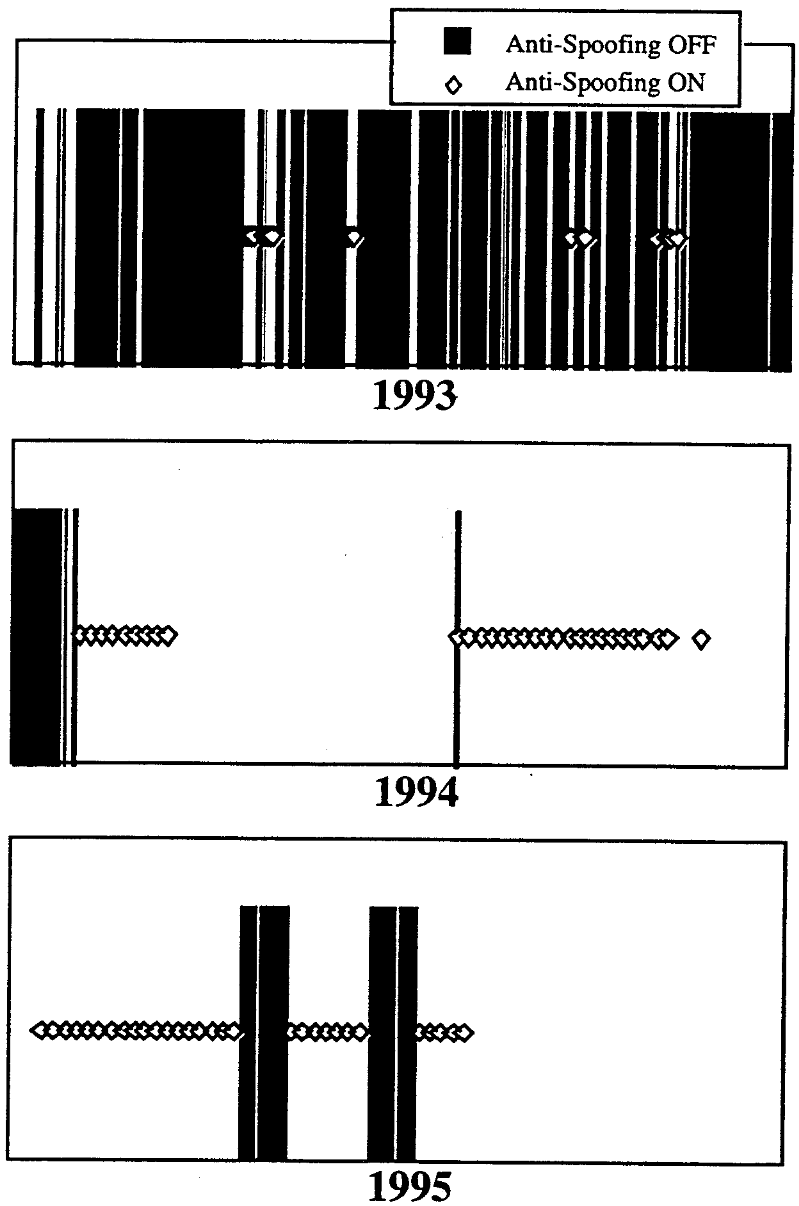
The principal goal of T/P is to measure sea level to such an accuracy that small-amplitude, basin-wide sea level changes caused by large-scale ocean circulation can be detected. To detect these changes, the T/P sensor system must be able to measure the sea level with decimeter accuracy. Thus, the radial component of the orbit must be known to at least the same accuracy. To achieve this end, the T/P spacecraft is configured with three independent precision tracking systems: (i) a Laser Retroreflector Array (LRA) (NASA), (ii) a Doppler Orbitography and Radio-Positioning Integrated by Satellite (DORIS) Dual-Doppler Tracking System Receiver (CNES), and (iii) a Global Positioning System Demonstration Receiver (GPSDR) (NASA), which is experimental. The LRA is used with a network of satellite laser ranging (SLR) stations to provide the NASA baseline tracking data for precision orbit determination. The DORIS tracking system provides the CNES baseline tracking data using microwave Doppler techniques for precision orbit determination. The DORIS system is composed of an onboard receiver and a network of 40 to 50 ground transmitting stations, providing all-weather global tracking of the satellite. The signals are transmitted at two frequencies to allow removal of the effects of ionospheric free electrons in the tracking data. The GPSDR, also operating at two frequencies, uses GPS differential ranging for precise, continuous tracking of the spacecraft with better than decimeter accuracy.

Precision orbit ephemerides (hereafter referred to as POEs), are created once per ten-day (127-orbit) cycle, thirty days after the tracking data has been collected (after-the-track), using the non-experimental SLR and DORIS data types. These orbits, created at the Goddard Space Flight Center (GSFC), are used for the construction of the mission Geophysical Data Records (GDRs). In April 1995, the set of geodetic models (gravity field, ocean tides, station locations, etc.) used for POE production was updated to account for the improvement in modeling that had taken place since launch (Reference 1).

Early after launch, it became evident that precision orbits could be generated quickly in support of Interim Geophysical Data Record (IGDR) production. SLR data could be used to construct (i) daily fits within 3-5 days after-the-track and (ii) verification orbits to support POE production. These orbits are called "Medium Precision Orbit Ephemerides," or MOEs. A small team, referred to as the Precision Orbit Determination and Verification Team (PVT) was incorporated into the T/P flight operations team. During the T/P mission the MOE production and POE verification has required only two people, with one analyst as the lead and the other as a backup. The daily computations have been performed on an HP 9000/720 series workstation. A description of this process and an orbit quality assessment is given in Reference 2.

The amount of SLR data available on a daily basis has decreased throughout the past year due to shrinking funding for the SLR network. This decrease in SLR data could lead to an erosion in orbit quality, especially over the holidays. Changes to the orbit determination strategy in operations has been avoided for the sake of consistency, which is desired by the science community using these orbits. However, the POE model changeover provided an opportunity to add a second data type to the MOE production, beyond simply updating the MOE models. GPS data is collected as quickly (if not quicker) than SLR data, which made it an excellent candidate for MOE production. Since launch, the reliability of the GPSDR software has increased considerably, and since early 1995 has operated nearly continuously. Figure 1 depicts the operational history of the GPSDR throughout the T/P mission.

Figure 1: T/P GPS Demonstration Receiver Tracking Status and GPS Constellation Anti-Spoofing Status (1993-Present)



The GPSDR can initialize itself and observe the GPS constellation in both Anti-Spoofing (AS) and non-Anti-Spoofing (non AS) modes. During non-AS tracking, the GPSDR uses P-code to obtain GPS pseudorange and carrier phase observables at L1 and L2 frequencies, providing ionosphere-free pseudorange and phase observables. While AS is on, the GPSDR can only track the L1 C/A signal from the GPS constellation and is thus unable to calibrate the observations for the ionospheric delay. As the constellation has recently been in AS mode more often than non-AS mode, it was necessary to develop a technique to circumvent the lack of information about the ionosphere.

This paper documents the successful implementation of the GPS/SLR "quick-look" orbit determination task, which has improved on the original SLR "quick-look" effort. The orbit determination models, data, and filter methodologies for the different data type combinations are described. Results of the initial proof-of-concept are demonstrated, along with an assessment of the GPS/SLR MOEs produced to date.

ORBIT DETERMINATION MODELS

The MOE modeling and parameter estimation scheme is similar to that used for POE orbit determination, and is summarized in Table 1. The most significant modeling difference is the treatment of the nonconservative forces. For POE production, the nonconservative force models account for the spacecraft's attitude history, geometry, and material properties. They are collectively known as the 'Macromodel,' and are tuned with tracking data from cycles 1-48. For MOE production, these forces are not modeled; it has been shown that an appropriate set of empirical acceleration estimates does effectively compensate for this lack of detailed modeling.

Table 1: Models and Estimated Parameters

	MOE	POE
Conservative Forces		
Gravity	JGM-3 (50x50)	JGM-3 (70x70)
Earth and Ocean Tides	TOPEX-Based	TOPEX-Based
Nonconservative Forces		
Solar Radiation	not modeled	Macromodel
Earth Radiation	not modeled	Macromodel
Atmospheric Drag	not modeled	Macromodel
Spacecraft Thermal Imbalance	not modeled	Macromodel
Measurement Corrections		
Attitude & CG Dependence	Applied	Applied
Wet and Dry Troposphere	Applied for GPS Data only	Applied
Relativity	Applied	Applied
T/P Estimated Parameters		
Epoch State		
Empirical Accelerations		
Along-track	Const. & 1/rev. (10 hr)	Const. (8 hr) & 1/rev. (24 hr)
Cross-track	1/rev. (10 hr)	1/rev. (24 hr)
Radial	None	None

The estimated stochastic acceleration parameters for the T/P spacecraft are in 10 hour batches: a constant downtrack acceleration and once-per-orbit downtrack and crosstrack accelerations (cosine and sine components). The time boundaries of these empirical accelerations are moved when necessary to coincide with spacecraft attitude events (including yaw flips, transitions to/from yaw steering, and maneuvers). This heuristic practice has consistently yielded more accurate orbits. The constant downtrack acceleration estimates provide an indication of the secular decay (or growth) of the semimajor axis. The resulting change in mean motion shifts the ground track away from its planned track. These estimates are currently supplied to the project Navigation team as part of their ground-track monitoring. The constant downtrack acceleration estimates include an atmospheric drag component which is subsequently removed.

DATA DESCRIPTION

The SLR Global tracking network is a consortium of many groups of stations, including (i) the Crustal Dynamics CDSLR network, (ii) university-led sites (Haleakala and Ft. Davis), (iii) Fundamental Foreign sites (Bar Giyyora, Grasse, Herstmonceux, Matera, Orroral Valley, Shanghai, Simosato, Wettzell), (iv) additional key foreign sits (Graz, Helwan, Metsahovi, and Zimmerwald), (v) the Chinese SLR Network, and (vi) miscellaneous cooperating foreign sites. The SLR quick-look data is collected every weekday morning from the Crustal Dynamics Information System (CDDIS) electronically via FTP. Typically, SLR data for a given pass is available to the PVT within 4 days after-the-track. There are variations from this timing due to weekends, holidays, and the turnaround time of the station itself.

The GPS ground data used in this effort comes from a global network of 16 stations. This data is a subset of that collected and reduced at the Jet Propulsion Laboratory as part of an effort with the International GPS Geodynamics Service (IGS). The GPSDR data is also processed on-lab by members of the flight team. The GPSDR and GPS ground data are both available in well under 48 hours after-the-track.

The SLR and GPS data weights are summarized in Table 1. The SLR data weights used for MOE production are a function of station of origin, and are based on recommendations from the University of Texas, Austin. These weights range from 1.0 cm to 200 cm. CDSLR stations have well-monitored quality control on their data collection; stations from other organizations are not as standardized. In fact, SLR passes from some foreign stations are processed only on a volunteer basis. The GPS data weights (based on a 300 sec processing rate) are based on the experiences of the authors, as some of them have previous experience with T/P GPS data through the GPS Demonstration Experiment. The GPSDR phase and pseudorange data are deweighted as part of the strategy when the GPS constellation is in Anti-Spoofing mode. The optimal relative weighting between SLR and GPS data has not yet been determined. However, GPS/SLR orbits created with these weights are such an improvement over any SLR-only product that it was considered prudent to proceed with GPS/SLR production, even without this optimization.

Table 2: SLR and GPS Data Weights

SLR	GPS (Ground)		GPS (T/P)	
Two-way (cm)	Carrier Phase (cm)	Pseudorange (cm)	Carrier Phase (cm)	Pseudorange (cm)
1.0 - 200	1.0 - 2.0	100	10, 80 (AS)	80, 240 (AS)

FILTER METHODOLOGY

The filtering was performed with the GPS Inferred Positioning System Orbit Analysis and Simulation Software (GIPSY-OASIS) set developed by the Tracking Systems and Applications Section at the Jet Propulsion Laboratory. The standard filter configuration used for MOE production is of the U-D factorized batch sequential filter. Nominally, MOEs based on GPS data are created from a 30 hour data fit; SLR-only solutions are created from a three-day data fit. Solutions from adjacent days would thus have an overlap ranging from 6 to 48 hours, depending on the data type combinations used. This overlap provides an opportunity to perform a quality check upon the latter solution. Under normal conditions, the overlap agrees in the radial component to well under ten centimeters RMS.

There are five data combination scenarios which can occur during MOE production: (i) GPS (AS on) & SLR, (ii) GPS (AS off) & SLR, (iii) GPS (AS on), (iv) GPS (AS off), and (v) SLR only. For solutions involving only SLR data, the filter strategy is essentially the same as that for the original SLR-only "quick-look" orbits, covered in Reference 2. For solutions involving GPS data, the basic GPS orbit determination strategy usually involves the simultaneous adjustment of: the GPS and T/P orbits, station and satellite clock parameters, selected station locations, zenith tropospheric delays, and solar pressure coefficients (scale factors and Y-Bias), and carrier phase biases. If the GPS constellation were to provide non-AS data, this would be the nominal strategy. In practice however, AS data is the norm, so it is more reliable to first solve for the GPS orbits and clocks, then determine the T/P orbit using the previously determined GPS orbits. With the GPS orbits fixed, solving for the T/P orbit (and GPS clocks to account for Selective Availability) with Anti-Spoofing data becomes more reliable. This two-part process is used regardless of the AS status; with a similar effort underway for the GPSMET mission (see Reference 4), there is the possibility of consolidating efforts by only generating one set of GPS orbits for both orbit determination efforts. As an additional note, to save processing time, no reduced dynamic iterations are performed in MOE production.

The data editing process does change with the AS status; for example, when AS is on, a higher elevation cutoff angle is used. The origin of this technique comes from work performed in the Tracking Systems and Applications Section at JPL (see Reference 3). The data editing process for AS data, as well as the two-step approach to orbit determination with AS data was refined and automated by Ronald Muellerschoen; Reference 4 gives a detailed description of this process, and how it has been successfully applied to the TOPEX/Poseidon and GPSMET missions.

Another approach to handling GPS data in Anti-Spoofing Mode, but not currently used by the PVT at present, is given in Reference 5. An approximation of the ionosphere above T/P was obtained by differencing the single frequency carrier phase and pseudorange measurements. This difference was then smoothed with cubic splines and applied to the observables as a rough ionosphere calibration.

ORBIT DETERMINATION EVALUATION

The MOEs are evaluated by their comparison to the independently determined and highly accurate POE orbits used for GDR production. In order to demonstrate the proof-of-concept of using GPS Anti-Spoofing data to the T/P project, a battery of solutions using different data type combinations was created over a complete 10 day cycle. Two methods are used to evaluate these solutions. First, their agreement with the GSFC POE is examined, with the radial and 3-dimensional RSS values of the comparison being the significant quantities. This comparison is valid since the original intent of the MOE is to provide the science community a working orbit for IGDR interpretation, as a prelude to the final GDR product which is based on the POE. Since the model structure of both the MOE and POE are similar, this comparison is not heavily corrupted by modeling differences. Second, the POE itself is only an approximation to the truth. Thus, it is necessary to find a quality measure which is orbit independent. The crossover variances of these orbits is such a measure, since high variances indicate corruption of altimeter data by geographically-correlated orbit error, all else being the same.

In addition to the proof-of-concept results, MOEs recently created for IGDR production are compared to the corresponding POE. At the time this document was being prepared, crossover results for these MOEs would still not be available for another month. However, radial and 3-D differences are reported for MOEs created with GPS AS and non-AS data against the POEs.

Proof-of-Concept Results

To demonstrate the validity of incorporating GPS Anti-Spoofing data into MOE production, orbits were created from 22 February 1995 to 04 March 1995 (T/P cycle 90). The GPS constellation was in Anti-Spoofing mode this cycle. Also, the T/P spacecraft passed from one attitude regime to another (fixed yaw to yaw steering); providing a typical level of spacecraft activity to be encountered during most cycles.

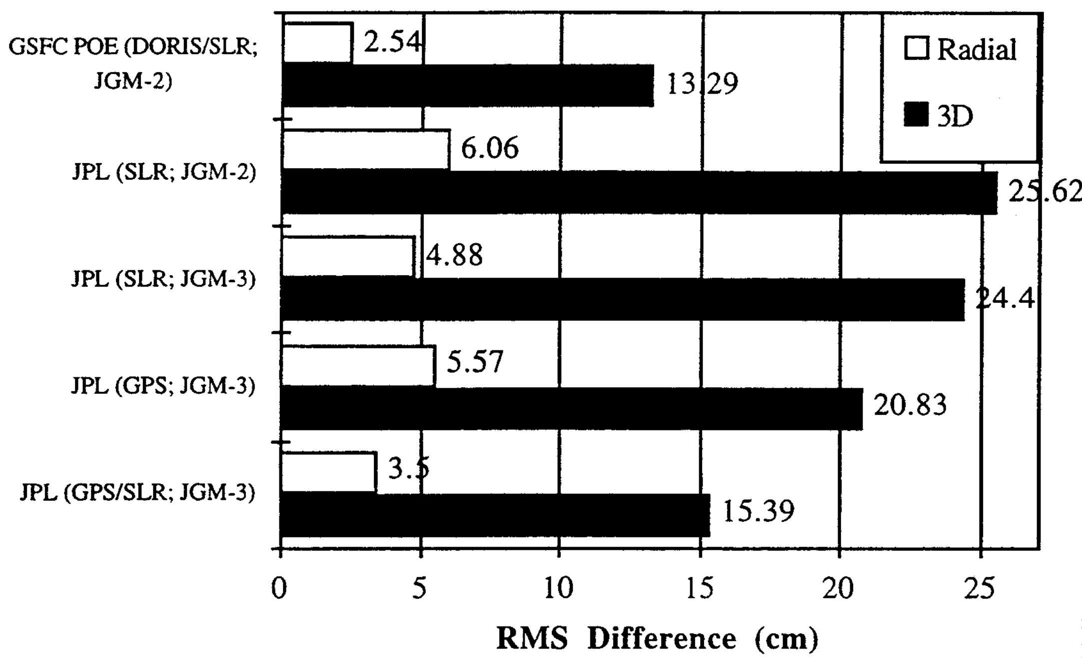
The set of solutions collected for this demonstration include the following: (i) the GSFC JGM-3 POE based on the latest models listed in Table 1[1], (ii) the GSFC JGM-2 POE, which was actually used for the original cycle 90 GDR, (iii) the JGM-2 SLR-only MOE, which was actually used for the cycle 90 IGDR, (iv) a JGM-3 SLR-only orbit, (v) a JGM-3 GPS-only (dynamic fit) orbit, and (vi) a JGM-3 GPS/SLR (dynamic fit) orbit. Orbits (iii)-(vi) were created at JPL by the PVT.

Orbits (ii)-(vi) are differenced against the GSFC DORIS/SLR JGM-3 POE (see Figure 2), which is considered the most accurate of the set. The comparison of the JGM-2 and JGM-3 POEs demonstrates the magnitude of the orbit solution change brought about by the geodetic model updates. Likewise, going from the JGM-2 to JGM-3 SLR-only solutions shows some improvement in the agreement, but not as much as the DORIS/SLR solutions. The GPS-only solution has a level of agreement similar to the SLR-only solution; bringing the two data types together results in an orbit that approaches the JGM-2 POE agreement with the JGM-3 POE.

---

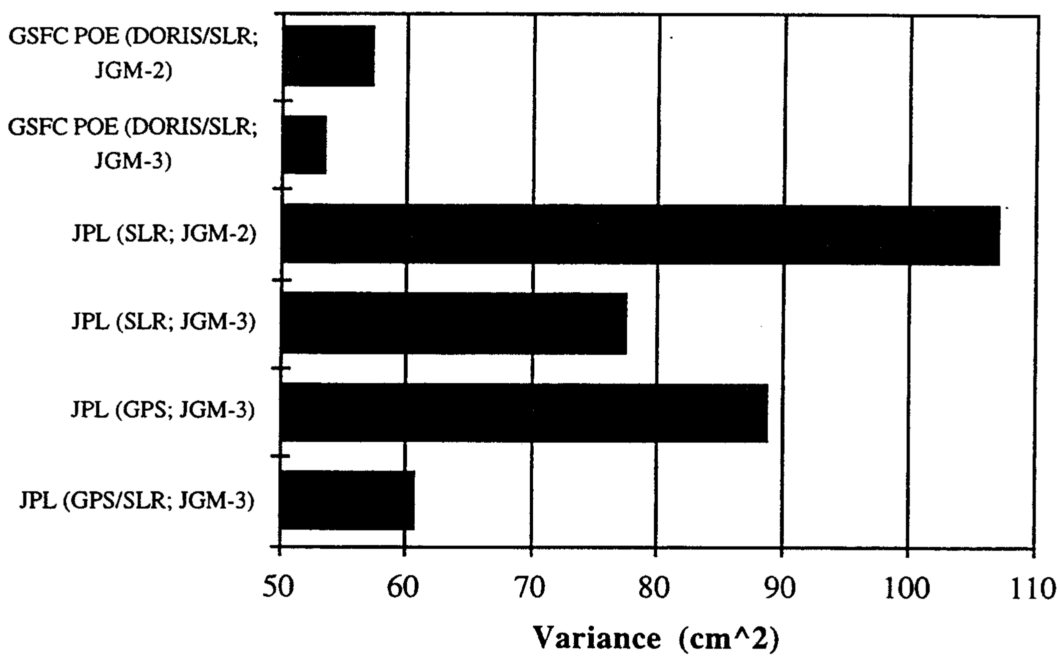
[1]In the update to the models used for MOE and POE production, the change of gravity field (from JGM-2 to JGM-3) yields the most dramatic reduction in geographically correlated orbit error. As a result, orbits based on the former model set are referred to as the "JGM-2" orbits, and those using the later models are referred to as "JGM-3" orbits.

Figure 2: Radial & 3D Agreement with Cycle 90 GSFC (JGM-3) POE (2/22/95 - 3/4/95)



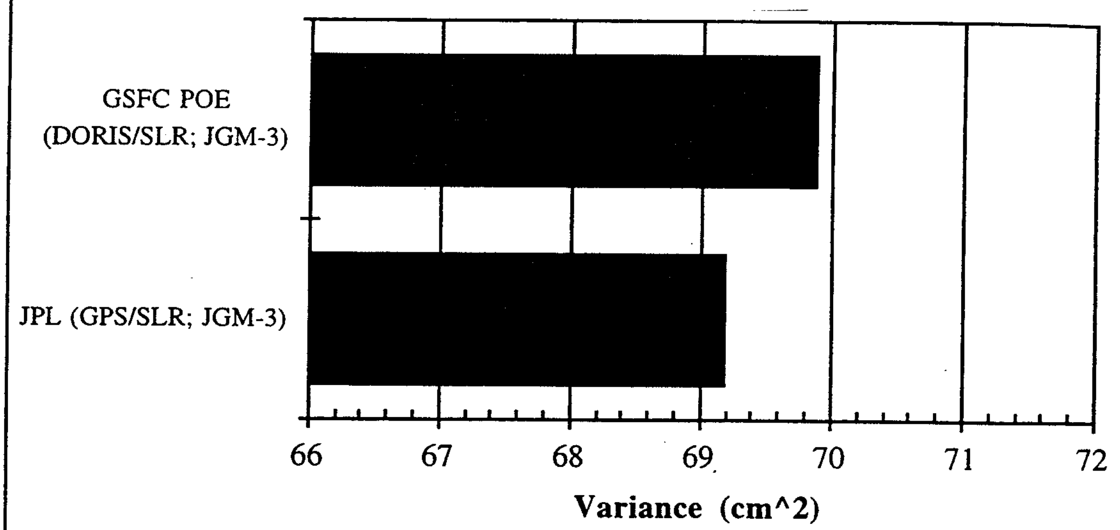
The altimeter crossover results (see Figure 3) tell a similar story. The model improvements result in lower crossover variances in both the DORIS/SLR and SLR-only fits. The combination of GPS and SLR data result in an orbit with a crossover variance approaching that of the JGM-2 POE.

Figure 3: T/P Altimeter Crossovers: Cycle 90 (22 February - 04 March 1995)



A parallel battery of solutions is not yet available for a cycle in which Anti-Spoofing was turned off. However, a GPS/SLR orbit was created for cycle 43 which has many of the characteristics of an MOE (JGM-3 models, dynamic fit only, GIPSY-OASIS software). The crossover variance from that orbit (see Figure 4) is slightly lower than that for the JGM-3 GSFC POE. The next opportunity to compare MOE and POE crossovers for an non-AS GPS constellation will be after the creation of the merged GDRs for 21 June - 01 July 1995 (T/P cycle 102).

Figure 4: T/P Altimeter Crossovers: Cycle 43 (13 - 23 November 1993)



Actual MOE Results

The new GPS/SLR MOE production mode began with the start of Cycle 100 on 01 June 1995. From late May to late June 1995, MOE production passed through three of the five possible data type combinations: SLR-only (with JGM-2 models), GPS(AS on)/SLR, and GPS(AS off)/SLR. These orbits, which span cycles 99-102, are compared to their corresponding POE. In Figure 5, the radial RMS agreement between MOEs and POEs is plotted for the daily solution. The trend amongst the three different solution types is as expected, with the GPS (non-AS)/SLR solution having the best agreement with its corresponding POE. The difference in the agreement between the MOEs with AS GPS data and those with non-AS GPS data can be considered a measure of the orbit degradation brought about by the ionosphere. Nevertheless, the GPS (AS)/SLR solutions are still an improvement over the SLR-only JGM-2 MOEs. Likewise, Figure 6 shows the same trend for three-dimensional comparisons of the orbits.

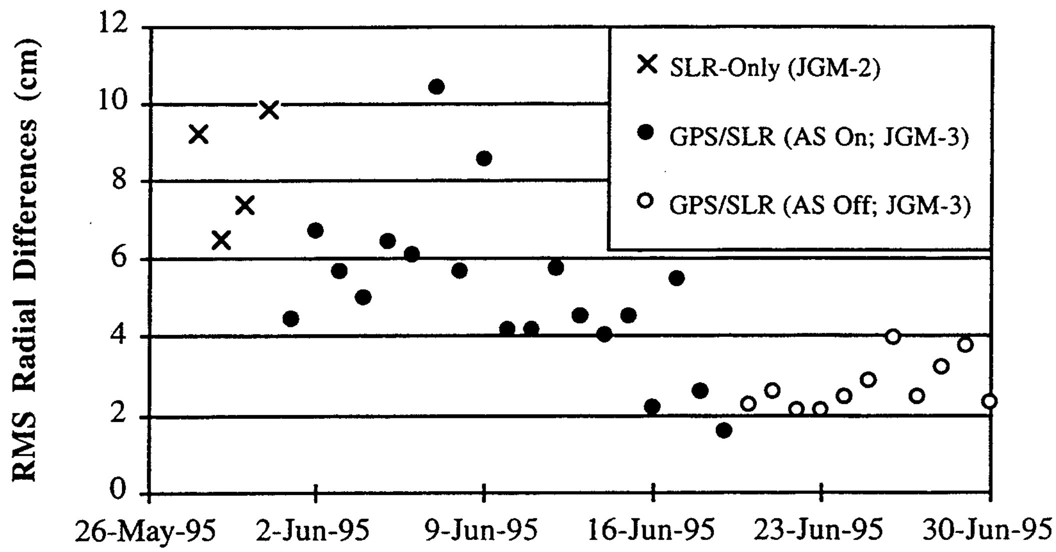


Figure 5: Radial Orbit Differences Between JPL MOEs and GSFC (JGM-3) POEs

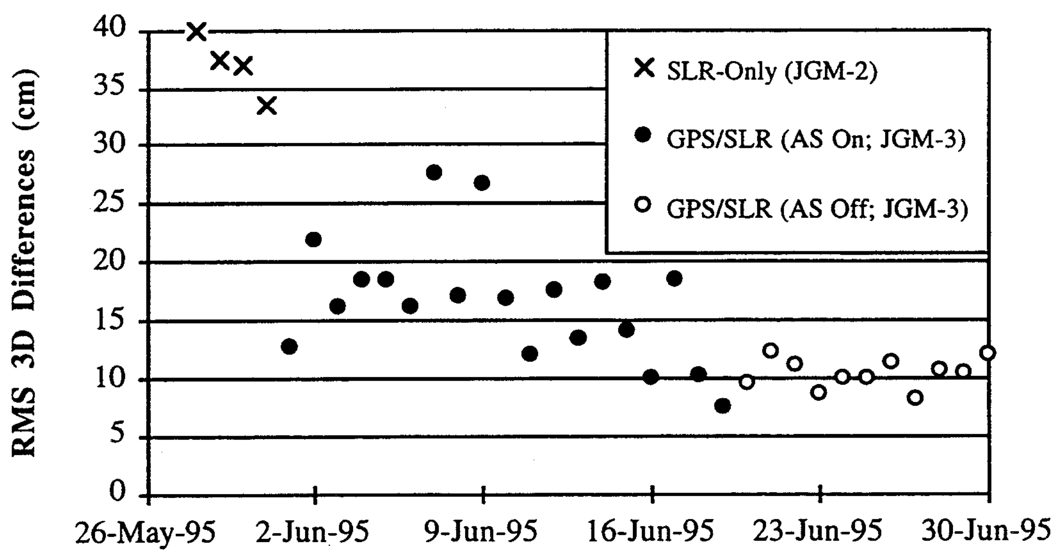


Figure 6: 3D Orbit Differences Between JPL MOEs and GSFC (JGM-3) POEs

SUMMARY

The PVT has not only met the mission requirement of sub-decimeter accuracy throughout the T/P prime mission, it has both improved the quality of its orbits and removed its vulnerability to a single data type with this upgrade, all with minimal resources and no interruption to mission operations. This paper documents the cooperative effort between the Tracking Systems and Applications Section and the Navigation and Flight Mechanics Section to provide precision orbits with minimal resources. Orbit comparisons and crossover statistics show that the accuracy of these "quick-look" orbits approaches that of the POEs supplied to the project during most of the prime mission, even under the degrading effects of Anti-Spoofing.

ACKNOWLEDGMENTS

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

REFERENCES

1. TOPEX/Poseidon POD Team, "Precision Orbit Reprocessing for the Improved MGDR," Memorandum, University of Texas at Austin, 28 March 1995.

2. Cangahuala, L. A., Christensen, E. J., Graat, E. J., Williams, B. G., Wolff, P. J., "TOPEX/Poseidon Precision Orbit Determination: 'Quick-Look' Operations and Orbit Verification," Paper AAS 95-228 presented at AAS/AIAA Spaceflight Mechanics Meeting, Albuquerque, NM, 13-16 February, 1995.

3. Blewitt, G. and Lindqwister, U., "GPS Parameter Estimation with Constrained Carrier Phase Biases," JPL Internal Memorandum 335.4-88-149, 1988.

4. Muellerschoen, R. J., Lichten, S., and Lindqwister, U., "Results of an Automated GPS Tracking System in Support of TOPEX/Poseidon and GPSMET," to be presented at ION Meeting, Palm Springs, CA, September 1995.

5. Guinn J. R., Jee, J. R., Munson, T. N., "TOPEX/Poseidon Orbit Determination Using Global Positioning Satellites in Anti-Spoofing Mode," Paper AAS 94-138 presented at AAS/AIAA Spaceflight Mechanics Meeting, Cocoa Beach, FL, 14-16 February 1994.