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L. A. Cangahuala, E. J. Christensen, E. J. Graat, B. G. Williams, P. J. Wolff

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

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TOPEX/Poseidon Precision Orbit Determination: "Quick-Look" Operations and Orbit Verification

L. A. Cangahuala*, E. J. Christensen†, E. J. Graat°, B. G. Williams•, P. J. Wolff*

This paper presents a summary of the TOPEX/Poseidon "quick-look" orbit determination and verification activities. 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. In order to aid some constituents of the science data user community, orbits are generated as quickly as possible, usually within four days. These orbits are also used for the production of Interim Geophysical Data Records (IGDRs). The primary time-limiting step in "quick-look" orbit production is the collection of the two-way laser tracking data from the world-wide tracking network. The orbits are also used for the verification of precision orbit ephemerides (POEs) used for the final production of geophysical data records (GDRs). In addition, estimates of empirically defined non-gravitational accelerations are supplied to the navigation team for their ground-track maintenance activities.

These orbits are called "Medium Precision Orbit Ephemerides" or MOEs. The strategy for the MOE is to fit three days of laser tracking data with the middle day being the only period used for IGDRs. Hence, each three day fit overlaps the preceding one by two days. This technique provides some immunity from "end effects" of the fit where accuracy is usually not as high as that for the mid-portion of the data arc. The overlap also provides a continuing quality check on orbit precision as new data is added each day. The orbit determination strategy includes estimating the spacecraft initial position and velocity along with daily values for along-track and cross-track empirical forces. A model summary and orbit estimation history are given.

INTRODUCTION

The TOPEX/Poseidon (T/P) satellite was launched on 10 August 1992, and is in the final year 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

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

° Sterling Software Corporation, Pasadena CA, 91109.

• Technical Group Supervisor, Navigation Systems Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 91109.

Administration (NASA) and the French Space agency, Centre National d'Etudes Spatiales (CNES). 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 achieve this goal, 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.

Two issues impact T/P's sampling of the actual sea level. First, the orbit altitude, orientation, and commensurability with the Earth's rotation dictates the temporal and spatial sampling pattern of the altimeter. A high-altitude orbit was preferred because reduced atmospheric drag and gravity perturbations acting on the satellite maximize the accuracy of the orbit determination. However, the orbit altitude was limited by the increased power needed by the altimeter to achieve the required signal-to-noise ratio. The compromise was in the range of 1200 to 1400 km. Within this range, the exact altitude that allowed the orbit to satisfy all other constraints (e.g. ground-track repeatability of ±1km) was 1336 km, with a 127 orbit ground track repeat cycle. Table 1 shows the baseline orbit characteristics.

Table 1: T/P BASELINE MEAN ORBIT CHARACTERISTICS

Parameter	Value
Semimajor Axis (km)	7714.4278
Eccentricity	0.000095
Inclination (deg)	66.039
Inertial Longitude of Ascending Node (deg)	116.5574
Argument of Perigee (deg)	90.0
Reference Equatorial Altitude (km)	1336
Nodal Period (hh:mm:ss.ss)	01:52:25.72
Ground Track Repeat Cycle (days)	9.9156
Inertial Nodal Rate (deg/day)	-2.0791
Longitude of Equator Crossing, Pass 1 (deg)	99.9242
Acute Angle of Equator Crossing (deg)	39.5

The second issue is the ability to determine the radial component of the orbit, as obtained through the process of orbit determination. T/P has made it possible to obtain precision orbits through different approaches to filtering strategy and varying combinations of tracking data. For example, 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 both non experimental data types, SLR and DORIS data. These orbits, created at the Goddard Space Flight Center (GSFC), are used for the construction of the mission Geophysical Data Records (GDRs). Early after launch, it became evident that precision orbits could be generated quickly in support of Interim Geophysical Data Record (IGDR) production (Reference 1). 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.

A small team, referred to as the Precision Orbit Determination Verification Team (PVT) was incorporated into the T/P flight operations team. At any time during the mission the MOE production has required only two people, with one analyst as the lead and the other as a backup. The time demand upon the analyst is small; the seven MOEs for the week can comfortably be created and validated during a regular forty-hour work week. In addition, the simplicity of the MOE process has made it possible to train undergraduate engineering students in MOE production during their summer tour at the lab. The daily computations are performed on an HP 9000/700 series workstation.

This paper documents the successful implementation of the "quick-look" orbit determination task, which has achieved sub-decimeter level accuracies using laser tracking data for over two years. The orbit determination models and filter strategy are described, along with statistics assessing the SLR data collection. The MOE performance is described, along with the POE verification efforts.

ORBIT DETERMINATION MODELS

SLR tracking data is not a direct measurement of the orbital state and is generally not continuous in time. As a result, dynamical equations were required to produce a continuous precise orbit for the mission. To achieve the expected 13-cm (global RMS) radial orbit accuracy for the mission, models with sub-decimeter accuracy were incorporated into the solution. Since MOE orbits were not needed for predictive purposes, however, it was possible to eliminate dependence on certain models through the proper selection of an empirical acceleration model. The elimination of these models reduces the processing time by a factor of three. The significant orbit determination models used for MOE production are categorized in Table 2.

Table 2: MOE MODEL ORGANIZATION

Category	Description
Observables	• Phase Center Offset • Spacecraft Attitude
Spacecraft Dynamics	• Finite Burn (Note: Atmospheric Drag, Solar Radiation Pressure, Albedo, & Infrared Radiation are <u>not</u> explicitly modeled.)
Geodetic Dynamics	• Central Body Perturbations • Third-Body Perturbations • Solid-Earth Tide Deformations • Ocean Tide Perturbations • General Relativity Perturbations • Earth Rotation and Orientation
Filter	• Daily Estimates of Constant and Once-per-orbit accelerations

Observable Models

Phase Center Offset. The phase center offset (in a spacecraft-fixed frame) is interpolated from a table provided by the Spacecraft Analysis Team (SPAT). This table is updated after every Orbit Maintenance Maneuver (OMM), and is accurate to the sub-centimeter level. This accuracy is partially due to the small magnitude of the seven maneuvers that have taken place during the mission.

Spacecraft Attitude. The spacecraft altimeter is always pointed along the local nadir. When the angle between the sunline and orbit plane is greater than ~15 degrees, the spacecraft steers about the nadir (this mode is referred to as "yaw steering"). When the angle drops under this magnitude, the spacecraft yaw angle is fixed. During this attitude mode (known as "fixed yaw"), the spacecraft performs an 180 degree "yaw flip." These attitude regimes and events are modeled to obtain the correct orientation of the phase center offset, based upon inputs provided by the SPAT.

Spacecraft Dynamic Models

Finite Burn. For the production of MOEs on days where an OMM took place, the burn was modeled with the nominal burn parameters supplied by the SPAT and NAV team. OMMs are on the order of 3-5 mm/s, and no burn parameters are estimated. The accuracy criterion was met for MOEs which spanned an OMM event.

Atmospheric Drag, Solar Radiation Pressure, Albedo, & Infrared Radiation. Collectively, these models were known as the TOPEX "Macromodel." Originally, the Macromodel was included in the initial SLR-only orbits (Reference 2). Since MOEs were not needed for predictive purposes, the Macromodel was removed, reducing the MOE production time. The removal of the Macromodel reduced the total runtime of a typical two-iteration solution from 145 minutes to 51 minutes. The resulting non-modeled accelerations were absorbed by the empirical non-gravitational acceleration estimates.

Geodetic Dynamic Models

Table 3 summarizes the geodetic models used. These models are used to correct (i) the dynamic forces acting on the spacecraft and (ii) the nominal coordinates of the tracking stations. The greatest contributions to the orbit error budget from these models comes from the geopotential model (2.2 cm) and the solid and ocean tides (2.0 cm) (Reference 3). The timing and polar motion inputs are obtained weekly from the University of Texas.

Table 3: GEODETIC MODEL SUMMARY

Model	Description
Central Body Perturbations:	JGM-2 geopotential model
Third-Body Perturbations:	Point mass Sun, Moon, and planets
Third-Body Ephemerides:	DE-200 [*Standish*, 1982]
Solid-Earth Tide Deformations	
Frequency Dependent:	k_2 using Wahr formulation [*Wahr*, 1981]
Frequency Independent:	Love number (k_2) = 0.3, lag angle (δ) = 0
Permanent Tide Correction:	Applied to $\bar{C}_{20}$ ($\Delta\bar{C}_{20} = -1.391(10^{-8})$ per unit k_2)
Ocean Tide Perturbations:	Merit ocean tide model [*Melbourne et al.*, 1983, *Eanes et al.*, 1982]
Timing and Polar Motion	UT1-UTC Correction; X-, Y-Pole Coordinates
General Relativity Perturbations:	One-body relativistic perturbations [*Moyer*, 1971]

Filter Model

The filtering was performed with the MIRAGE (Multiple Interferometric Ranging Analysis using GPS Ensemble) software set developed by the Navigation Systems Section at the Jet Propulsion Laboratory for NASA's Deep Space Network (DSN). The standard filter configuration used for MOE production is of the single batch weighted least squares, square-root information type. Nominally, the MOEs are created daily from a three-day data fit. Solutions from adjacent days would thus have a 48-hour overlap. 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.

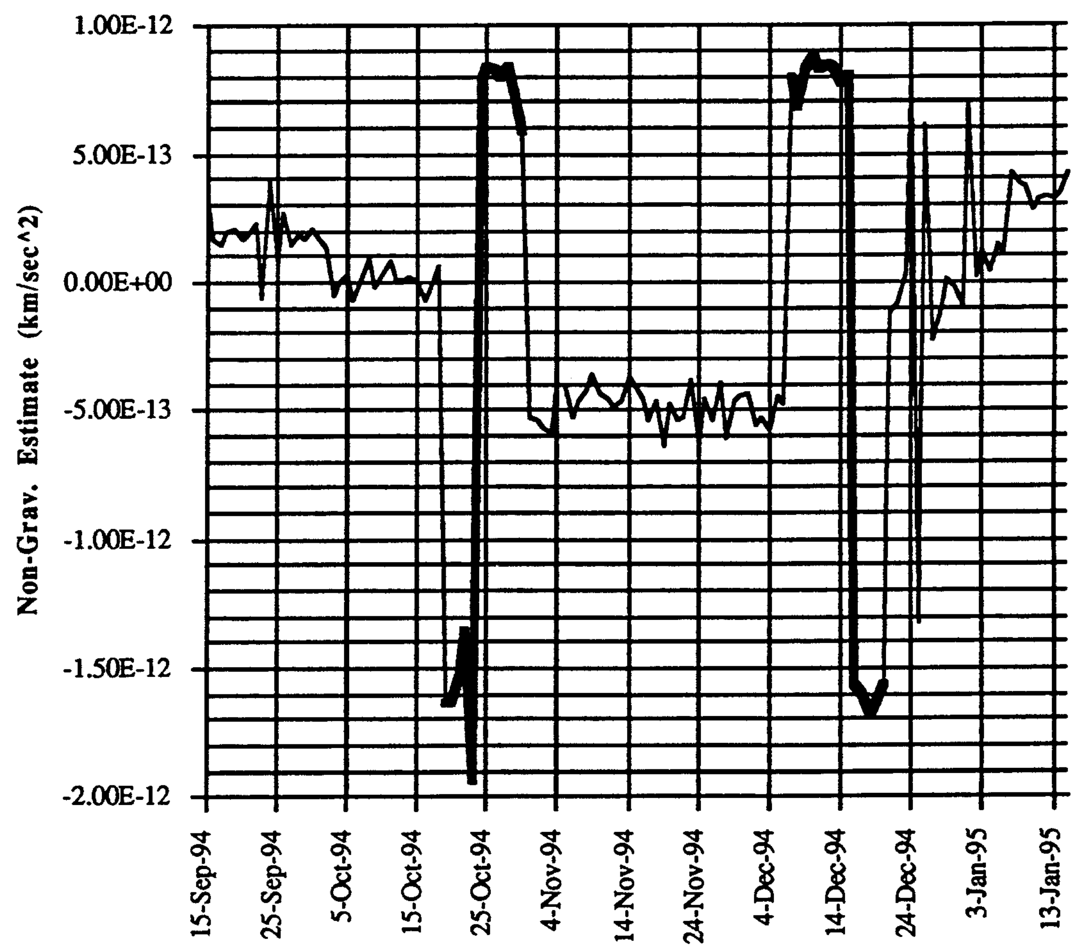
Table 4: ESTIMATION PARAMETER MODELS

Estimated Parameters	*A priori* Uncertainty (1σ)	*A posteriori* Uncertainty (1σ)
Spacecraft State at Epoch - Position	1000.0 m	0.01 to 0.03 m
Spacecraft State at Epoch - Velocity	0.01 m/s	$1(10)^{-5}$ to $3(10)^{-5}$ m/s
Empirical Accelerations		
Constant Downtrack	None	$1(10)^{-12}$ to $3(10)^{-12}$ m/s^2
Once-Per-Orbit Downtrack	None	$(10)^{-14}$ - $(10)^{-13}$ m/s^2
Once-Per-Orbit Crosstrack	None	$(10)^{-13}$ - $(10)^{-12}$ m/s^2

The estimated parameters include the spacecraft state and a daily set of five empirical non-gravitational accelerations: a constant downtrack acceleration and once-per-orbit downtrack and crosstrack accelerations (cosine and sine components). The time boundaries of the empirical accelerations are moved to coincide with spacecraft attitude events (including yaw flips, transitions to/from yaw steering, and maneuvers). This practice has consistently yielded more accurate orbits.

The constant downtrack acceleration estimates provide an indication of the secular growth (or decay) 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. These estimates include an atmospheric drag component which is subsequently removed. Figure 1 shows the daily estimates; the heavy plot lines show estimates during fixed yaw periods, and the large jumps in estimate values coincide with yaw flip events. The remaining estimates took place during yaw steering regimes.

Figure 1: Daily Constant Downtrack Non-Gravitational Accel. Estimates (Based on Sampling Taken September 1994 - January 1995)



SLR DATA COLLECTION

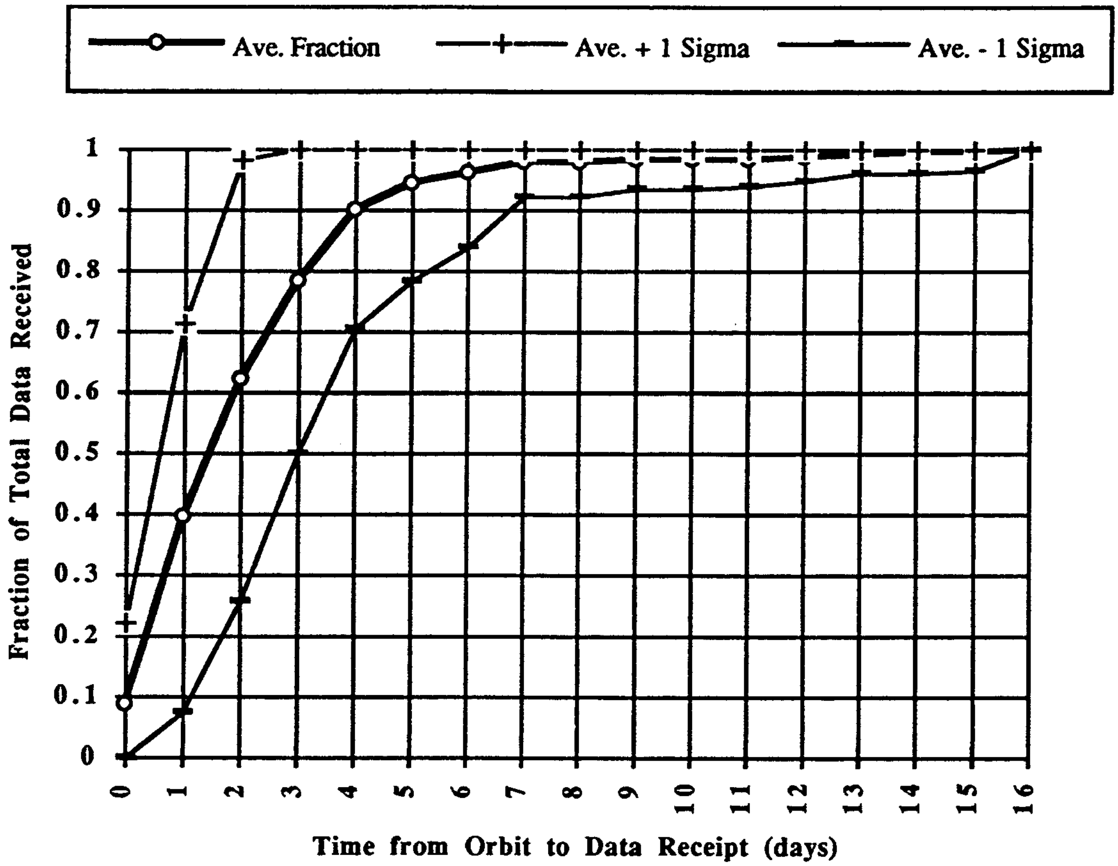
The SLR Global tracking network is a consortium of many groups of stations (Reference 9). The groups are (i) the Crustal Dynamics CDSLR network, (ii) university-led sites (Haleakala and Ft. Davis), (iii) Fundamental Foreign Sites (Bar Giyyora, Grasse, Herstmonceux, Matera, Orroral Valley, Shanghai, Simosato, Wettzell), (iv) additional key foreign sites (Graz, Helwan, Metsahovi, and Zimmerwald), (v) the Chinese SLR Network, and (vi) miscellaneous cooperating foreign sites. Table 5 gives an overall breakdown of the stations by coordinating institution, and shows the percentage of data passes obtained from each set of stations.

Table 5: SLR STATION GROUPS & CONTRIBUTION TO THE DATA SET (Based on Sampling Taken September - December 1994)

Organization	# of Passes	Ave. # of Passes per Day	% of Total Passes
CDSLR	550	5.19	26.1
University	294	2.77	13.9
Foreign (Fund.)	680	6.42	21.1
Addl. Key Foreign	164	1.55	7.7
Chinese	47	0.44	2.2
Foreign (Misc.)	388	3.66	18.4
Total	2123	20.03	100.0

The SLR quick look data is collected every weekday morning from the Crustal Dynamics Data 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. Figure 2 shows the fraction of total data available as a function of time.

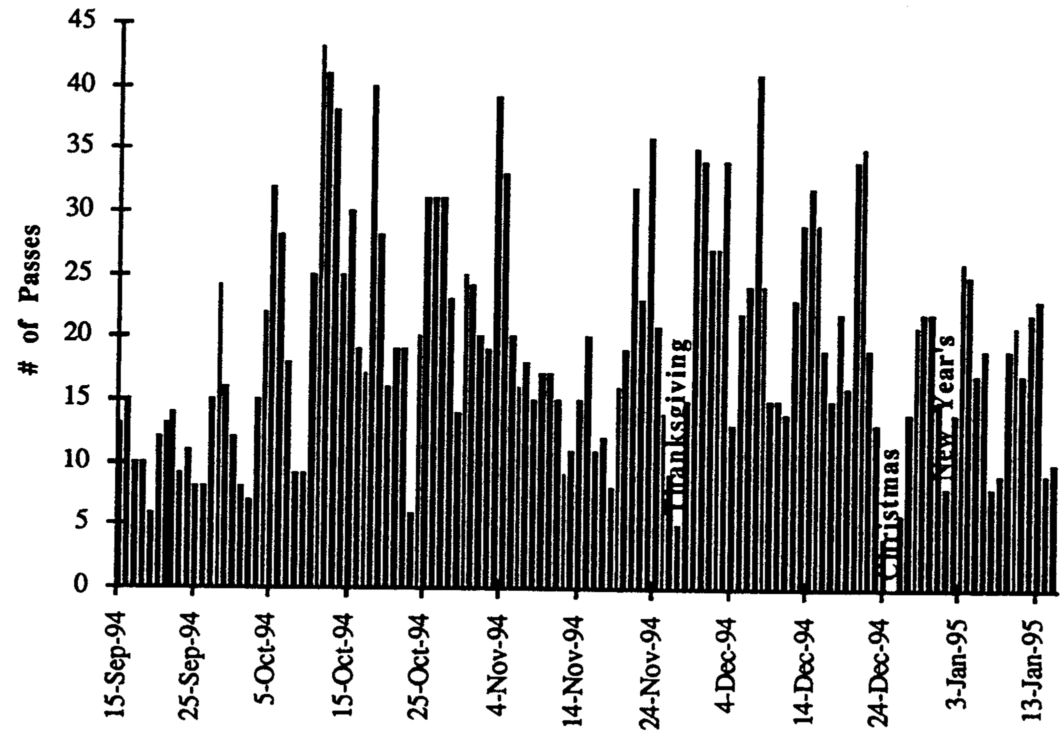
Figure 2: Fraction of Total SLR Data Received After-the-Track (Based on Sampling Taken September - December 1994)



The total number of passes received each day is also volatile, with the holidays (e.g. Christmas) providing the minimum tracking collection. In addition, since most stations are located in the Northern Hemisphere, they are susceptible to data outages during winter storms. This effect can be seen in Figure 3.

The 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 100 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.

Figure 3: Total Number of SLR Data Passes Received (Based on Sampling Taken September 1994 - January 1995)



ORBIT DETERMINATION EVALUATION

Two methods are used to evaluate MOE orbits. First, the agreement between MOEs and POEs is examined, with the radial component of the comparison being the significant quantity. This comparison is valid since the original intent of the MOE product 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, since the POE itself is only an approximation to the truth, 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 orbit error, all else being the same.

MOE - POE comparisons, Verification orbit - POE comparisons, and crossover variances are shown (where available) for MOE production from September 1994 to January 1995. The results for this period are characteristic for the entire mission.

MOE - POE Comparisons

Figure 4 shows the agreement in the radial component between the 24-hour period of validity for an MOE and the same period in the corresponding POE. The open diamonds denote MOEs generated with three-day data arcs. The average daily RMS agreement is 6.5

cm overall. On certain days, denoted by 'x' plot symbols, the low amount of data available forced the analyst to resort to a longer (4-7 day) data arcs to create MOEs. The number of passes of SLR data received for each day (from Figure 3) is superimposed upon this plot to show the correlation between low data volume and the need for longer-arc solutions. In these cases, the average daily radial agreement was 9.9 cm; only when the number of passes per day dropped to about five did the RMS difference climb significantly above a decimeter. Any constant offset between the two orbits is at the sub-centimeter level.

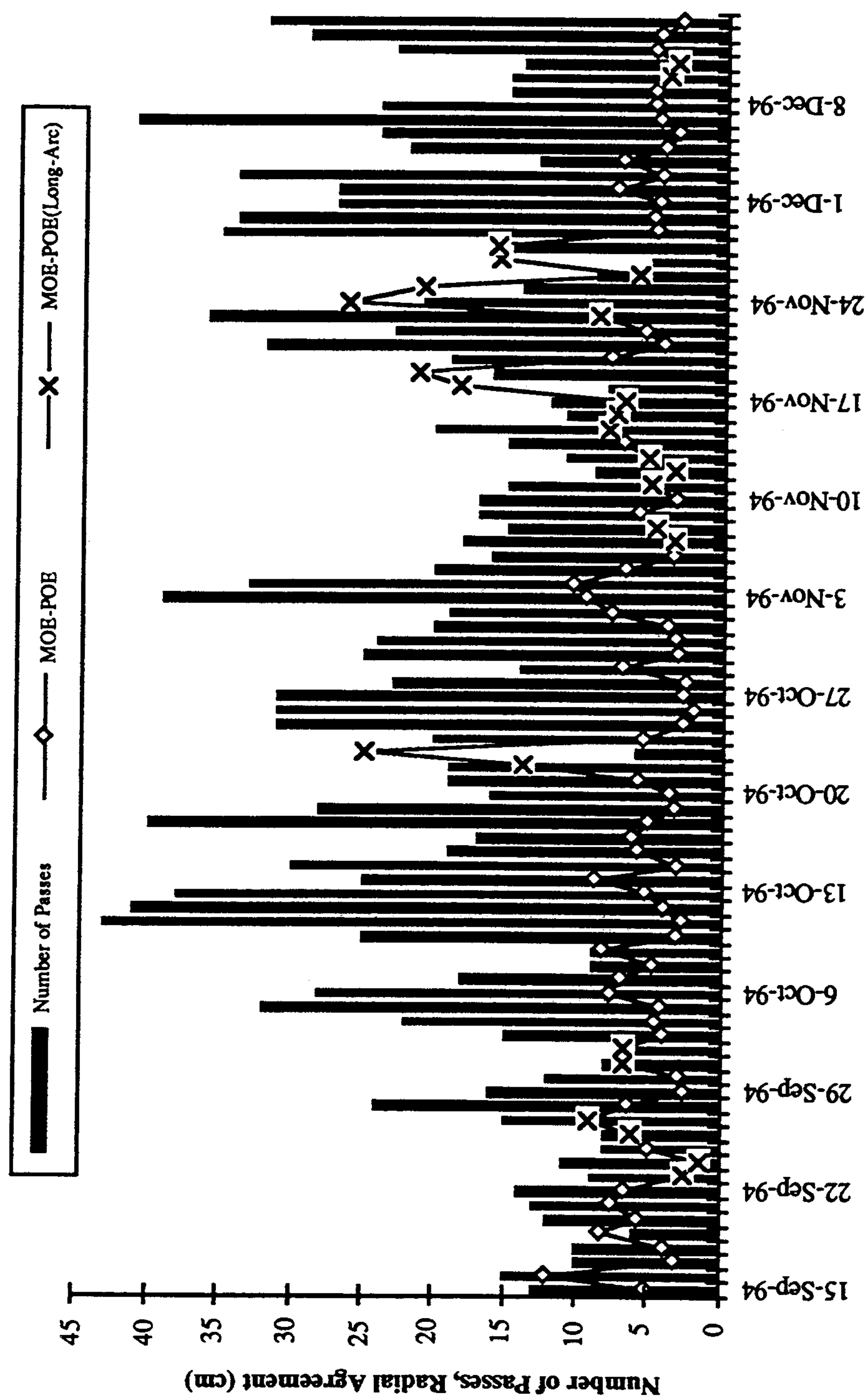
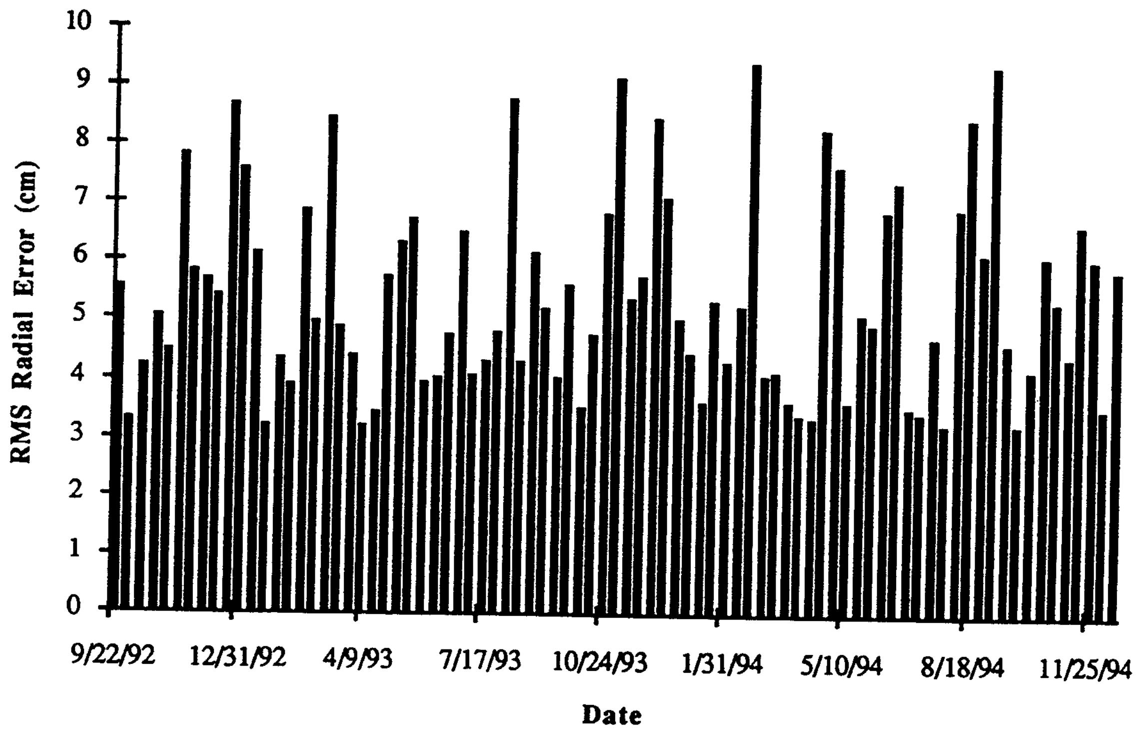


Figure 4: RMS Radial Differences - MOEs vs. Corresponding POE Arc
(Based on Sampling Taken September - December 1994)

POE Verification with Long-Arc Solutions

The limit of the practice of using longer-arc solutions for MOE production is the creation of orbits for POE verification. These orbits span approximately ten days, and are created close to the scheduled POE delivery date so as to have the maximum amount of SLR data possible. Figure 5 shows the radial agreement between the two sets of orbits; the average RMS radial difference over the cycles to date is 5.4 cm. Again, the offset between the orbits is at the sub-centimeter level.

Figure 5: RMS Radial Differences - POEs vs. Verification Orbits

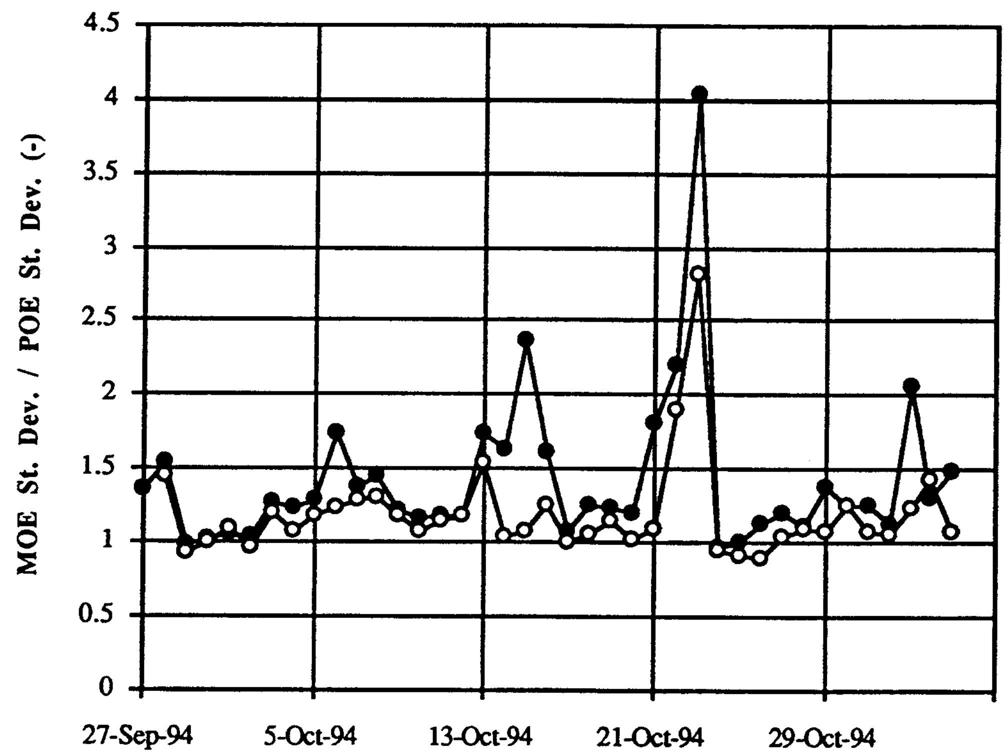


Crossover Variances

MOEs fulfill the mission requirement by keeping within sub-decimeter radial agreement of the POE. But the more fundamental characteristic is the ability of the MOE to approximate the truth, relative to the POE. To make this assessment the spacecraft radial position is compared at points where the ground track crosses itself. The variance of these values is a measure of orbit error in an absolute sense. In Figure 6, the solid points show the ratio of MOE crossover standard deviation to POE crossover standard deviation. The average daily ratio for MOEs is 1.4. Deviations from this level usually occurred on days with extremely low data (refer to Figure 4).

As part of a routine software validation, a second set of orbits were generated concurrently with the daily MOEs. These orbits had the same data set and estimated parameters as the MOEs, but the MERIT tide model was replaced with the TEG2B tide model supplied by the University of Texas Center for Space Research (CSR). These orbits had a lower average crossover variance than their daily MOE counterparts; their daily ratio to the POE variance is 1.2. These orbits also appear to be less susceptible to data outages than MOEs.

Figure 6: RMS Radial Differences - POEs vs. Verification Orbits



SUMMARY

The PVT has successfully met the mission requirement of sub-decimeter accuracy MOEs for over two and one-half years with minimal resources. The average daily RMS radial agreement between MOEs and POEs has been 6.5 cm to date. The average cyclical RMS radial agreement between the PVT verification orbits and POEs has been 5.4 cm. The average crossover variance of MOEs is within a factor of two for those of corresponding POEs.

The time-limiting factor for the creation of MOEs is the collection of sufficient SLR data. MOEs spanning days with low data totals are generated by building longer arcs. This practice provides a suitable orbit. Only when SLR data collection falls below ~5 passes per day does the orbit quality significantly deteriorate. Updates of the tide model improves the orbit quality, even for solutions with low amounts of data.

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While the PVT takes pride in being a small efficient team, the authors would be remiss if they did not acknowledge the contributions made by others over the years. Dah-Ning Yuan of the JPL Tracking Systems and Applications Section originally developed the MOE operational procedure and Unix scripts for the workstations, and Joseph Guinn of the JPL Navigation Systems Section acted as the original PVT lead. Rick Sunseri and Jim Collier of the JPL Navigation Systems Section contributed heavily towards the development of the MIRAGE software. Andrew Marshall and the POD center at GSFC have provided much information about their POE production. Alan Murdoch of Bendix/Allied Signal and the CDDIS center at GSFC have provided not only the SLR data, but have also provided supplementary information about the daily status of SLR data collection. Finally, John Ries and Richard Eanes of the University of Texas, Austin have provided timing and polar motion information and recommendations for laser station data weights throughout the entire mission.

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