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DETERMINING PRECISE ORBITS FOR TOPEX/POSEIDON WITHIN ONE DAY OF REAL TIME: RESULTS AND IMPLICATIONS

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Radar altimeter missions require precise estimates of the satellite radial orbit position in order to support measurement of surface heights. Traditional applications of altimeter data have not placed serious demands on the timeliness of this precise orbit information. Many of these applications involve retrospective scientific analysis of phenomena such as ocean current patterns, permanent geoid features, and slow changes in the thickness of the polar ice sheets. For these studies, latencies of days to weeks in receiving the precise altimeter data sets provide little impediment to successfully completing the research. Owing to the continuing successes of the Topex/Poseidon (T/P) and ERS missions, however, we are presently witness to the beginnings of a new operational era in satellite altimetry. The most demanding of the operational applications, e.g., short-term climate forecasting, require that accurate orbits be made available in near-real time. Precise orbit determination techniques based on data from on-board global positioning system (GPS) receivers have contributed significantly to meeting these requirements and show great promise for keeping pace with the demands of future missions. In this paper, we describe recent advances in near-real-time orbit determination for the T/P mission. New results suggest that GPS-based orbits computed within one day of recording the last element of tracking data have radial accuracies of about 3 cm in a root-mean-square (RMS) sense. These orbits are used by a variety of specialized users in the oceanographic community in order to support climate forecasting and real-time monitoring of the global ocean.

INTRODUCTION

Satellites carrying radar altimeters rely on precise orbit determination (POD) in order to make accurate observations of sea-surface height and surface (e.g., ice, land) elevations. Many advances in POD for low-Earth orbiters have in fact been driven by the requirements set forth by past and extant altimeter missions, e.g., Seasat (1978), Geosat (1985-1990), ERS–1/2 (1991–present) and Topex/Poseidon (1992-present). Particularly demanding from an accuracy standpoint are oceanographic applications of satellite altimeter data. Changes in sea level that bear significantly on climate change may in some cases amount to only a few centimeters over thousands of kilometers. Any error in the radial component of the satellite orbit will map fully into height estimates derived from the altimeter ranges. Many oceanographic applications thus require knowledge of the radial orbit position at the few-cm level.

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The joint U.S./France Topex/Poseidon (T/P) satellite is the first altimeter mission specifically designed to measure the subtle variations in large-scale sea level that accompany changes in the climate [1, 2]. Significant efforts have been devoted to the POD component of the mission, and the orbit accuracies achieved have far surpassed pre-launch expectations [3]. The cornerstones of this POD system are three advanced tracking systems: 1) a Doppler Orbitography and Radiopositioning Integrated by Satellite (Doris) receiver from the French space agency (CNES); 2) retroreflectors to serve as targets for ground-based satellite laser ranging (SLR) systems; and 3) an experimental GPS demonstration receiver (GPSDR) from the Jet Propulsion Laboratory (JPL) and Motorola.

We focus herein on POD using GPSDR data, and specifically on recent advances that have enabled the computation of highly-accurate T/P orbits within one day of real time. The availability of these orbits has helped to usher in a new era in operational oceanography from space. Real-time applications of T/P data have emerged in many disciplines. Especially noteworthy was the use of T/P data to improve the forecasting and monitoring of the 1997–1998 El Niño event [4]. Capitalizing on these unforeseen successes, the T/P follow-on mission, Jason-1, will feature operational oceanography as a significant mission objective. The rapid availability of precise orbits will be central to the success of Jason-1, scheduled for launch in May, 2000.

TOPEX/POSEIDON GPS EXPERIMENT

The GPSDR experiment on Topex/Poseidon is described by *Melbourne et al.* [5]. The Motorola Monarch receiver is designed to track dual-frequency GPS transmissions (L1/L2) from up to six satellites when the GPS anti-spoofing (AS) function is turned off. There were significant periods early in the T/P mission (1992–1993) when AS was not activated. Many of the prominent results from the GPSDR experiment were derived from data collected during these periods [6, 7]. (The L1/L2 data are needed to compensate for ionospheric delay and thus achieve the highest possible measurement accuracies.) Among the successes was the achievement of radial orbit accuracies of 2 cm in a root-mean-square (RMS) sense [8]. These results were based on the use of the reduced-dynamic tracking technique, wherein local geometric position corrections are used to reduce orbit errors caused by the mismodeling of satellite forces [6, 7]. The resulting orbits were used to characterize the effects of tidal and gravitational modeling errors on estimates of sea-surface topography [9,10], and figured prominently in the accurate calibration of the altimeter system using *in situ* data from the Platform Harvest [11].

Beginning in January, 1994, the GPS AS function was activated on a routine basis. The GPSDR, owing to its older design, reverted to single frequency (L1) tracking. This implied that unmodeled ionosphere delays emerged as the single largest hindrance to achieving high accuracies in determining the orbit with GPS. Despite the high altitude (1336 km) of T/P—placing the satellite above 90% of the ionosphere—the delays can still amount to tens of centimeters at the GPS L1 frequency (1575.42 MHz). *Muellerschoen et al.* [12] studied several POD methods for contending with this difficulty, and concluded that orbits with 4–5 cm radial RMS accuracy could still be achieved by using an ionosphere model to compensate the delays, and by fixing the GPS orbits and clocks to precise estimates determined *a priori*. In parallel, the development of a system to automatically produce the T/P orbits in near-real time was undertaken [13, 14]. The system went operational in 1995, and is still evolving. Currently, it produces T/P orbits that have estimated radial accuracies of 3 cm (RMS) within one day of recording the last element of tracking data.

TOPEX RAPID PRECISE ORBIT DETERMINATION SYSTEM (RPOD)

Muellerschoen et al. [15] describe the elements of an early version of a rapid (near-real time) system for determining the T/P orbits with GPS. In brief, the system keys off the daily arrival of global data from terrestrial GPS stations participating in the International GPS Service (IGS)* and from other sites of opportunity. The daily data sets from ground stations begin to arrive at the JPL IGS analysis center (AC) at midnight UTC. The arrival of sufficient ground data triggers automated processing to determine GPS spacecraft orbits and clocks. Data from the IGS network are also used to monitor the global total electron content (TEC), information used in the current T/P POD system to compensate for the ionospheric delays in the GPSDR data. A more detailed description of the various components of the system follows. To place the timing of the automated procedures in better context, we note that all the processing is currently hosted on HP9000/780 work stations.

GPS Spacecraft: Quick-look Precise Orbit and Clock Information

When a minimum of 21 stations with adequate global coverage are represented in the JPL AC archive, the Gipsy/Oasis (GOA) II software [16] is automatically triggered to compute precise values for the GPS spacecraft orbits and clocks for the previous day. With over 200 globally distributed stations participating in IGS, the threshold for initiating the processing is generally reached between 0400 and 0700 UTC. The GOA II software is structured as a square-root information filter (SRIF) which processes undifferenced ionosphere-free GPS pseudorange and carrier phase collected concurrently from all receivers. The orbits of the GPS spacecraft are solved for, along with the clock offsets of all participants, the unknown bias of the GPS carrier phase measurements, the positions of the ground stations, and the wet tropospheric delay at zenith for each ground receiver.† By about 1600 UTC, the previous-day orbits of the GPS spacecraft are determined with estimated accuracies of 20 cm (3D) in the International Terrestrial Reference Frame (ITRF96), while the accompanying GPS clock solutions are determined to better than 1 nsec.‡

Global Ionosphere Maps: Total Electron Content in Near-Real Time

An independent automated procedure at JPL applies data from the IGS network to compute rapid estimates of global TEC. Because the ionosphere is a dispersive medium, dual-frequency data from GPS ground stations provide a direct measure of TEC along the line of sight (LOS) to each GPS spacecraft. By adopting some simplifying physical assumptions about the ionospheric layer, the LOS data from GPS stations distributed worldwide can be simultaneously fit to generate a global ionosphere map (GIM) [17]. Comparisons with global columnar TEC measured by the dual-frequency Topex radar altimeter show that the data-driven GIM models are superior to

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* http://igscb.jpl.nasa.gov

† One participating (atomic) ground clock is fixed, and the clock offsets from all other participants (GPS spacecraft + ground stations) are adjusted every 5-min time step as uncorrelated (white-noise) processes. The zenith wet troposphere at each station is adjusted as a random-walk process with a variance accumulation of 9 mm^2 every hr. The positions of 5 (fiducial) stations are fixed to their International Terrestrial Reference Frame (ITRF96) values.

‡ Seven IGS ACs, in addition to JPL, compute rapid orbit and/or clock solutions for the GPS spacecraft. The products for the previous day are posted by 2200 UTC, after which IGS performs a weighted combination of the independent solutions. The agreement between the JPL and IGS combined products are 5 cm and 0.1–0.2 ns for orbits and clocks [27]. It is difficult to assess the true accuracies, but they may be several factors worse than the level of agreement between JPL and IGS.

climatological models in terms of their ability to specify the ionosphere [17]. Near-real-time GIMs with 15-minute resolution are generated at JPL on a daily basis. Results for the previous day are usually available by about 1800 UTC.

GPSDR Data from Topex/Poseidon

The telemetered T/P data, including all output from the GPSDR, are received at JPL from the Tracking and Data Relay Satellite System (TDRSS) via White Sands, NM, and Goddard Space Flight Center. The telemetered data are sent in 8-hr batches, and arrive 3–5 hours after the last telemetry element recorded on the onboard tape. Thus GPSDR data for the previous day are generally available to us by 0500 UTC, well before the completion of the processes for determining the GPS spacecraft orbits and clocks, and the global TEC.

Topex/Poseidon Orbit Determination

The RPOD system initiates the procedure for computing the T/P orbit as soon as the GPS spacecraft information (orbit + clock) and GIMs for the previous day are available, usually by about 1800 UTC. In this section, we describe the main elements of the T/P solution strategy and discuss the overall flow of the processing. Additional detail on the current model standards and estimation strategies can be found in Table 1.

The first step in the T/P RPOD procedure is to smooth and fit the onboard navigation solution (accurate to 75 m) from the GPSDR. The resulting integrated orbit spans 27 hours* and serves as the nominal T/P trajectory for initializing the partial derivatives and measurement model parameters. The GPSDR observations of carrier phase and pseudorange are then conditioned and compressed to 5-minute intervals coinciding with the time tags of the GPS spacecraft clock solutions.

In the GOA-II measurement module, the precise GPS spacecraft orbit and clock information are then used to adjust the GPSDR observations of carrier phase and pseudorange. In addition, the GIM estimates of TEC are used to derive corrections for the LOS ionospheric path delays. In order to use the GIM information for this application, however, some assumptions must be made about the vertical profile of the ionosphere. The GIMs are generated by assuming the ionosphere is concentrated in a spherical shell at an altitude of 450 km, and as such, provide TEC estimates in the zenith direction only. To obtain the LOS delays from the T/P to individual GPS spacecraft, we assume a profile shape from the climatological model of *Bent et al.* [18]. By using the profile in combination with the GIM zenith estimate for the location and time in question, the delay from T/P to an arbitrary GPS spacecraft can be obtained by numerically integrating along the LOS.

The GPSDR carrier phase and pseudorange data are subsequently fit using the GOA-II SRIF sequence. A dynamic solution, wherein all force-model parameters are treated as constant throughout the 27-hr data arc, is iterated to convergence. Included in the extended state vector are empirical acceleration terms meant to accommodate residual unmodeled surface forces (Table 1). In a final iteration, we treat perturbations to these acceleration terms as exponentially correlated noise processes with a time constant (τ) of 6 hr [19]. This "colored noise" treatment of unmodeled

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* The data are processed in 27-hour arcs beginning at 2100 UTC on the prior day. For example, the daily orbit solution for Jan. 20 will actually begin at 2100 UTC on Jan 19. This implies that consecutive solutions will overlap by 3 hrs, providing a means for automatically checking the orbit consistency from one day to the next.

satellite forces is a variation of the reduced-dynamic orbit determination technique described by *Yunck et al.* [6]. Along the continuum of POD strategies from classical dynamic to purely geometric, however, the current strategy is much closer to dynamic. The process noise uncertainties are small (Table 1), preventing large excursions from the converged dynamic solution. More important, the parameter space was designed so that the reduced-dynamic step would target only those orbit errors manifesting themselves as slow modulations in the one cycle-per-revolution frequency (1 cpr). The traditional T/P reduced-dynamic approach [6] is not advisable for the T/P RPOD solutions, because high-frequency variations in the single-frequency GPSDR data arising from rapid fluctuations in the ionosphere could lead to spurious reduced-dynamic acceleration estimates.

TABLE 1. ESTIMATION STRATEGY FOR T/P RPOD ANALYSIS

Data Type	σ (Dynamic passes)	σ (Reduced-dynamic pass)
GPSDR Carrier Phase (5-min)	20 cm	5 cm
GPSDR Pseudorange (5-min)	80 cm	50 cm

Model	Current T/P RPOD Standard
T/P Solar Radiation Pressure	"Box-wing" Model [28]
T/P Area	"Box-wing" Model [28]
T/P Mass	Variable (2406 kg in Jan-1999)
Ionosphere Above T/P	GIM [17] with Bent [18] profile
Earth orientation/rotation	International Earth Rotation Service (IERS) Bulletin B
GPS spacecraft ephemerides	JPL quick-look estimates (see text) in ITRF96
GPS spacecraft clocks	JPL quick-look estimates (see text)
GPS spacecraft interfrequency biases	from GIM analysis [19]
Luni-solar Perturbations	JPL DE-200 ephemerides
Earth Gravity Field	Joint Gravity Model(JGM)-3 [29]
Ocean and Earth Tides	Ctr. for Space Res. 3.0 (R. Eanes) + TEG2B

Estimated Parameters	Parameterization	A priori σ
T/P epoch state		
3-D epoch position (X, Y, Z)	Bias per arc	1 km
3-D epoch velocity (X, Y, Z)	Bias per arc	10 m/s
T/P empirical accel. (dynamic passes):		
Down track	Bias per arc	1 mm/s^2
1 cpr cross track (cos, sin)	Bias per arc	1 mm/s^2
1 cpr down track (cos, sin)	Bias per arc	1 mm/s^2
T/P empirical forces (reduced pass):		
Down track	Colored noise with $\tau = 6$ hr	0.5 nm/s^2
1 cpr cross track (cos, sin)	Colored noise with $\tau = 6$ hr	1 nm/s^2
1 cpr down track (cos, sin)	Colored noise with $\tau = 6$ hr	1 nm/s^2
Ionosphere scale	Bias per arc	100 %
Carrier phase biases	Bias over continuous pass	3×10^5 km
GPSDR clock offset	White-noise process (reset every 5-min obs.)	1 sec

The T/P RPOD estimation process consumes less than 30 minutes of wall clock time, and thus is usually complete by 1830 UTC. The expediency of the RPOD process can be attributed primarily to the absence of data from any receivers other than the GPSDR. There are no ground data involved, and the terrestrial reference frame is realized entirely through the fixed, precise estimates of the GPS ephemerides and clock offsets. The concept is similar to the technique of precise point positioning (PPP) [20], wherein data from a single GPS ground receiver are used to determine the site's geocentric position at the 1–2 cm level using a days worth of data. Like the PPP technique, the T/P RPOD process relies on fixing the GPS satellite parameters to precise values determined *a priori* in a global solution. In the T/P case, however, the receiver is roving in Earth orbit and satellite dynamical information is needed overcome the systematic measurement errors (e.g., residual ionosphere errors in the GPSDR data) to which kinematic applications can be especially sensitive.

Topex/Poseidon Orbit Validation and Delivery

Tracking data residuals and orbit overlaps (3 hr) for adjoining 27-hr solutions (current solution vs previous day's solutions) are examined by the automated RPOD process before the orbit products are delivered for science data processing. Automatic warning messages to prompt operator intervention are issued via e-mail if predetermined thresholds are exceeded. Table 2 provides a summary of the validation statistics for the first nine days of January, 1999. The postfit tracking data residuals provide a useful first-order check on the quality of the orbit fit, and are valuable for identifying potential problems in the measurement models. The statistics of the 3-hr overlaps are better indicators of the orbit error, but are only relative measures. Equally important, we have determined that the overlap statistics in the RPOD system tend to overestimate the true orbit error. This can be attributed to sampling of the solution at extremes of the orbit arc, where the errors are largest owing to the amplification of initial condition errors. Despite these limitations, we have found the orbit overlaps statistics to be reliable indicators of problems in the orbit solutions.

TABLE 2. SAMPLE VALIDATION STATISTICS FOR T/P RAPID ORBITS

Day	No. Phase Obs	Postfit Phase RMS (cm)	No. Range Obs	Postfit Range RMS (cm)	RMS Radial Overlap (cm)
01-Jan-1999	1830	8.53	1830	52.5	7.70
02-Jan-1999	1792	8.29	1792	53.3	8.58
03-Jan-1999	1690	7.86	1689	53.8	6.36
04-Jan-1999	1757	8.28	1755	59.4	6.44
05-Jan-1999	1799	8.47	1798	59.9	7.30
06-Jan-1999	1755	7.82	1755	55.0	3.99
07-Jan-1999	1654	8.44	1653	56.2	4.86
08-Jan-1999	1702	8.37	1702	58.3	6.99
09-Jan-1999	1577	8.24	1577	57.7	4.02

Owing to the near-real-time nature of the processing, no further means of providing on-the-fly orbit validation are presently available. We do perform *ex post facto* comparisons of RPOD solutions with externally-produced solutions as they are made available. We also examine the repeatability of sea height measurements when the fully validated altimeter data are released. Results from these tests are described in the next section.

After the validation of the orbit solutions, two orbit product files are generated. One file contains orbit information spanning only the 27 hours corresponding to the data fit. This "definitive" orbit file is based on the final reduced-dynamic filter pass through the tracking data. A second orbit product file spans 75 hours and is based in part on a 48-hr prediction of the orbit computed in the last dynamic iteration. The forward prediction implies that real-time estimates of the T/P radial orbit position are available, albeit at reduced accuracies (10–50 cm) that depend on the latency from the last tracking data element [15]. The orbit predicts are needed to reduce latency for certain operational oceanographic applications where very rapid turnaround is required.

The product files are subsequently transferred via ftp to a science data processing computer at JPL. This computer hosts software to combine the orbit information with T/P sensor and environmental data to create an interim geophysical data record (IGDR). The IGDR is automatically sent to the U.S. Navy Altimeter Data Fusion Center (ADFC) at Stennis Space Center, MS, where corrections for the effects of atmospheric pressure loading are applied. The IGDR products are then released to users representing various interests in the operational oceanographic community. A special IGDR based on the definitive orbit is transferred to the NOAA National Oceanographic Data Center to support short-term climate forecasting [4]. We discuss further the various applications of these data in a subsequent section.

ACCURACY ASSESSMENT OF TOPEX/POSEIDON RAPID ORBITS

The accuracy of the archived RPOD solutions is assessed on an ongoing basis using various comparison data as they become available. These assessments provide more incisive, and largely independent, measures of the orbit accuracy. The results are used to continuously tune and improve the RPOD strategy.

Radial Orbit Differences

Based on SLR and Doris tracking data, the NASA precise orbit ephemeris (POE) is the T/P orbit solution placed on the definitive (fully validated) Topex GDR [3]. The POE undergoes a battery of validation tests, and is released with a latency of about one month. Estimates place the RMS radial accuracy at about 2 cm [21, 22]. Figure 1 depicts the differences of T/P RPOD solutions with respect to the NASA POE for a 40-day span beginning on October 3, 1998.* The RMS radial difference for the 40-day span is 2.5 cm, and the largest excursions are –10 cm and 11 cm.† Although the two POD systems (POE vs RPOD) share common force-model standards, they are based on different tracking systems (SLR+Doris vs. GPS). The differences thus provide a very useful measure of relative orbit accuracy.

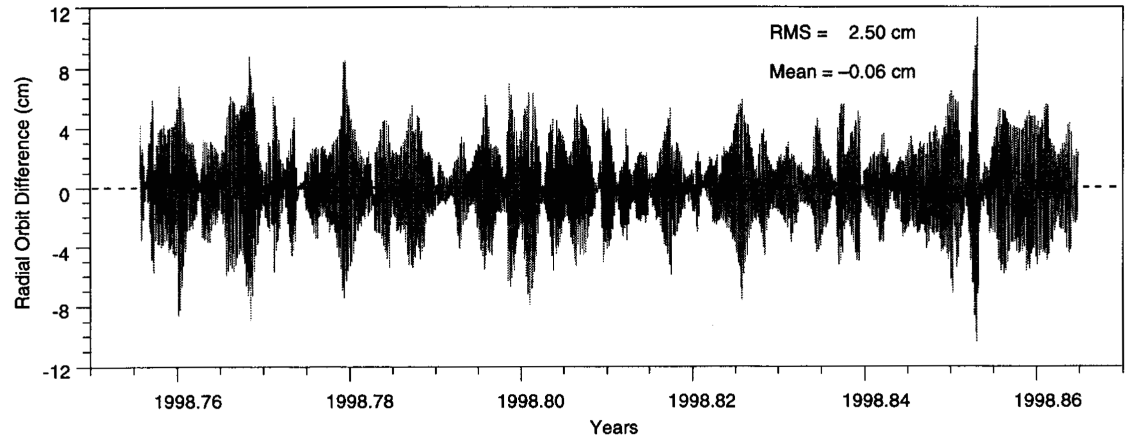

Figure 1. Time series of the radial orbit differences between the NASA POE and the RPOD solutions. The data span October 3, 1998, to November 12, 1998. The POE is the definitive NASA science orbit for T/P and is based on laser and Doris data only. The RPOD solution is based on GPS data processed within one day of real time.

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* The official RPOD solutions during this time frame were not based on the latest solution strategy (Table 1), so the results are from a test-bed process used to develop new strategies. The test-bed process keys off the archived quick-look GPS products; therefore the results are representative of what can be achieved on a next-day basis.

† The extrema both occur on November 6, 1998, a day during which the GPSDR suffered an outage.

Altimeter Crossover Residuals

Altimeter crossover data provide another powerful means of assessing the radial accuracy of the RPOD solutions. A crossover residual is simply the difference of the sea-surface height measurements from an ascending and descending pass of the satellite at the location where the ground tracks intersect. Because the crossing passes may occur days apart, corrections for known surface variations (e.g., ocean tides, pressure loading) must be applied. The effects of real ocean current variations, as well as errors in the orbit height and other components of the altimeter measurement, will guarantee that the sea-height measurement will never repeat perfectly at a crossover location. If the effects of true sea-level variations can be adequately reduced, the closeness of the measurements provides an estimate of the combined errors of the radial orbit, and altimeter range system.

In our analysis, we restrict the sample to include only those crossovers formed within a single repeat cycle (10 days) of the T/P orbit. This minimizes sea-height changes from real variations in the ocean currents. Moreover, we consider only quiescent regions over the ocean, where short-term current variability and atmospheric pressure variations are known to be small. Finally, we eliminate all data collected over shallow waters (on account of large tide-model errors) and during extreme (low and high) wind and wave conditions. Further information on the formation of these "super-edited" crossover residuals is given by *Bertiger et al.* [7]. Figure 2 shows the distribution of super-edited crossovers for the same 40-day period represented in the orbit comparison plot (Figure 1).

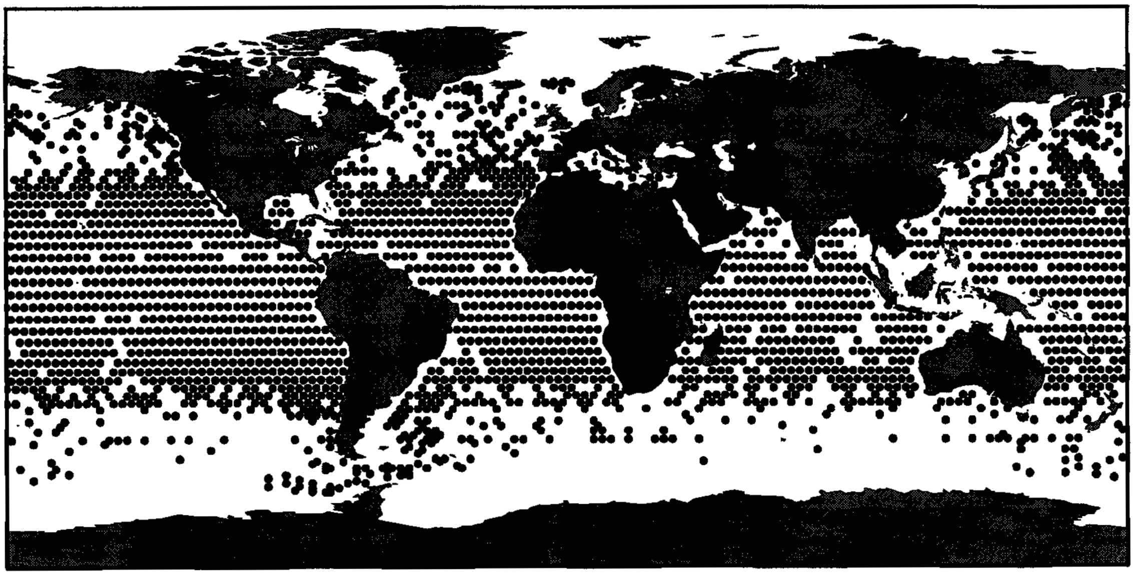

Figure 2: Distribution of "super-edited" altimeter crossover (sea-surface height) residuals used in evaluating T/P radial orbit accuracy from October 3 to November 12, 1998. Nearly 5000 crossover observations spanning the global oceans are represented. The maximum time lag between the crossing passes of any given observation is 10 days. The paucity of data at extreme latitudes is due to the more extreme wind/wave and storm conditions.

Table 3 gives the statistics of the altimeter crossover residuals for the four individual 10-day T/P repeat cycles comprising the 40-day span. In the first case, the NASA POE was used to form the sea-surface heights. With the identical crossover sample, the RPOD solutions were then applied to compute the height residuals. While the crossover RMS figures are higher for the RPOD, the differences are small. The amount of radial orbit error signal required to explain the discrepancies in the crossover RMS values is consistent with the radial orbit differences depicted in Figure 1. Not suprisingly, this suggests that the differences observed in Figure 1 are explained principally by errors in the RPOD solutions. If we assume that: a) the POE is indeed accurate to 2 cm in an RMS radial sense, and b) all the energy observed in the differences are due to errors in the RPOD solutions, however, we can estimate that the RMS radial errors in the RPOD solutions are no larger than about 3 cm.

TABLE 3: STATISTICS OF ALTIMETER CROSSOVER RESIDUALS (POE VS RPOD)

Repeat cycle	Start Date	Stop Data	Number Obs.	Crossover RMS (cm)		Addl. Radial Error (cm)[*]
				POE	RPOD	
223	03-Oct-1998	13-Oct-1998	1146	5.21	7.20	3.51
224	13-Oct-1998	23-Oct-1998	1334	5.85	6.63	2.21
225	23-Oct-1998	02-Nov-1998	1148	4.71	5.21	1.58
226	02-Nov-1998	22-Nov-1998	1156	5.25	6.03	2.10
			AVERAGE:	5.26	6.27	2.35

The Harvest Experiment

The crossover residuals provide a valuable orbit test, in large part because the sea-height data are entirely independent of the means used to compute the orbit. However, the crossover residual is a relative measure; thus, orbit errors common to both the ascending and descending tracks (i.e., geographically correlated errors) are not observable. A more direct measure of the orbit error is provided by the data collected at dedicated *in situ* calibration sites for the T/P mission. The NASA prime calibration site for T/P is located on an oil platform (Harvest) off the coast of central California near Vandenburg Air Force Base [11]. Every 10 days as T/P traces out its repeating orbit, the satellite passes directly over the platform. Instruments on the platform, notably a precise GPS receiver and redundant tide gauges, support the measurement of the local sea level relative to the geocenter. Direct comparisons of sea level derived independently from the satellite and platform data at overflight times are used to estimate the absolute bias in the satellite measurement system. At this writing, the satellite has overflown the platform over 230 times since its launch in 1992, yielding a 6-yr absolute calibration record for the T/P measurement system.

Shown in Figure 3 are recent estimates of the Topex altimeter measurement system bias[†] based on both the definitive science orbit (POE) and the actual (next-day) RPOD solutions. The standard deviation and mean of the biases determined with the next-day orbit are 4.5 cm and 0.0 cm respectively. It must be remembered that the determination of the absolute Topex bias is a central objective of the Harvest experiment. The scale of the ordinate is absolute, and thus obtaining a null result for the sample mean suggests that there is no discernible bias in the Topex altimeter measurement system and radial orbit estimate at this location.

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[*] This is the amount of radial orbit error required to explain the difference in the crossover RMS, assuming that orbit signals are decorrelated with the underlying sea-surface height signals. It is derived as follows: 1) take the root-difference-square of the crossover RMS figures; 2) divide by two (to account for contributions of ascending and descending passes); and 3) take the square root.

[†] Topex and Poseidon are actually separate altimeter systems. Because they share a single antenna, they are never turned on simultaneously. The NASA altimeter (Topex) is on about 90% of the time, because the CNES solid-state altimeter is considered experimental.

The remarkable consistency of the independently determined sea level readings testifies to the unprecedented accuracy of the T/P system. The estimates of 2 cm and 3 cm for the RMS radial accuracies of the NASA POE and RPOD solutions respectively are further corroborated by the results of the Harvest experiment.

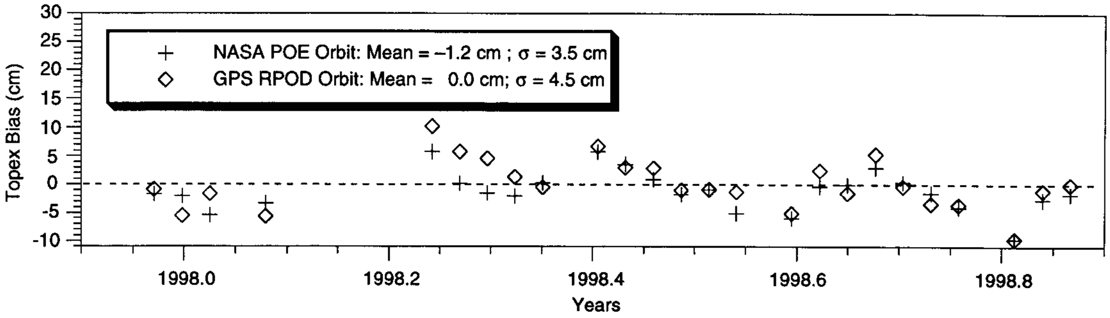

Figure 3. Estimates of the Topex altimeter measurement system bias from recent overflights of the Harvest Platform calibration site. Reflected in the time series are the systematic and random error contributions from the radial orbit, as well as the altimeter and in situ measurement systems.

APPLICATIONS

The near-real-time orbits for T/P support a growing number of diverse operational oceanographic applications. One of our partners on this project, the U.S. Navy Oceanographic Office (NAVO), uses the predicted orbit in combination with rapid altimetry to monitor the global oceans in real time.[*] After conditioning the sea-surface height data, the information is passed to the Fleet Numerical Oceanographic Center where it is assimilated into a layered ocean model. Another prominent user of the near-real-time orbit information is the Colorado Center for Astrodynamics Research (CCAR) in Boulder, CO.[†] Using blended data from T/P and ERS, they generate near-real-time maps of the anomalies in the sea-surface height at wavelengths up to a few hundred km. The anomaly maps reflect rapidly changing surface currents at the ocean "mesoscale", and are used in a surprising numbers of diverse interests. Biologists recently relied on the maps to aid in finding sperm whales in the Gulf of Mexico. Oil companies use them in the same region to monitor the progression of strong surface current variations that disrupt operations of offshore platforms.

From the combined standpoint of orbit accuracy and timeliness, the most demanding application is arguably the use of the rapid T/P IGDR to assist in short-term climate forecasting. The NOAA National Oceanographic Data Center (NODC) generates estimates of global large-scale sea-level variations with 2-day latency.[‡] These data are passed to the National Center for Environmental Prediction (NCEP) where they are assimilated into a climate forecast model updated on a weekly basis. The inclusion of the Topex data, as enabled by the availability of the Rapid precise orbits, has been shown to increase the forecast skill of the NCEP model [4]. This figured positively in the early NCEP prediction of the damaging 1997–98 El Niño event. As the climate pattern has reversed to a La Niña condition, the large changes in the Pacific sea-level patterns continue to be monitored in near-real time using the data from T/P.[§]

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[*] http://www7300.nrlssc.navy.mil/altimetry

[†] http://www-ccar.colorado.edu/~leben/research.html

[‡] http://ibis.grdl.noaa.gov/SAT/near_rt/topex_2day.html

[§] http://topex-www.jpl.nasa.gov/elnino/elnino.html

FUTURE PROSPECTS

The success of the Topex/Poseidon rapid orbit project has helped to accelerate plans for establishing operational altimeter programs. The follow-on mission, Jason–1, will feature a prominent operational component. Scheduled for launch in May, 2000, Jason–1 will carry an advanced codeless GPS TurboRogue space receiver (TRSR), capable of tracking up to 16 GPS spacecraft simultaneously on two frequencies, independent of AS status. The goal for radial orbit accuracy, as elaborated by the Jason Science Working Team, is 1 cm in an RMS sense [23]. While this will be challenging to achieve, we anticipate that the GPS-based orbit solutions for Jason will be significantly improved over their T/P counterparts. This can be attributed primarily to the TRSR enhancements which will enable ionosphere-free tracking of all GPS spacecraft in view.

By the time Jason-1 launches, we also anticipate the potential for significant improvements in turnaround time. Almost 40 stations from the global GPS ground network are presently transferring data on an hourly rather than daily basis [24]. This could enable the restructuring of the daily processing to provide more frequent updates to orbit products. In the long run, these developments may lead to global GPS augmentation system, wherein GPS clock and orbit-error corrections are disseminated in real time to specially equipped users of terrestrial and orbiting GPS receivers. A similar wide-area augmentation system is already in operation over the continental U. S. [25]. Extending this system for worldwide applications could enable sub-decimeter orbit determination with kinematic GPS in real time [26].

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