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Dynamic orbit determination using GPS measurements from TOPEX/POSEIDON

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Abstract. The GPS data acquired by the TOPEX/POSEIDON (T/P) Demonstration Receiver (DR) have been used in a dynamic orbit determination, which was based on the description of the gravitational and nongravitational forces in the equations of motion. The GPS carrier phase data were processed in a double difference mode to remove clock errors, including the effects of Selective Availability. Simultaneous estimation of the T/P orbit and GPS orbits was performed using five 10-day cycles in the interval between December (1992) and April (1993). The resulting T/P orbits have been compared with the orbits determined from Satellite Laser Ranging, the French one-way Doppler tracking system, DORIS, and with the JPL reduced dynamic orbits obtained from the GPS/DR data. Using similar dynamic orbit determination strategies and force models with the GPS/DR to those used with SLR/DORIS, the radial component of the T/P orbit (based on JGM-2) was found to agree to better than 30 mm (rms) and 35 mm with the JPL reduced dynamic orbit. An experimental gravity tuning was accomplished using four cycles of GPS/DR data. The resulting GPS/DR-orbits, determined by the dynamic technique with the experimental gravity field, are in better agreement with the JPL reduced dynamic orbits in both the radial component (21-25 mm) and altimeter crossover residuals than the JGM-2 orbits.

Introduction

The prelaunch mission goals for oceanographic applications of TOPEX/POSEIDON included determination of the radial component of the orbit to an accuracy of 13 cm or better [Stewart et al., 1986]. This requirement led to the inclusion of several precision tracking systems: a laser reflector ring to echo laser pulses from precision Satellite Laser Ranging (SLR) systems, a French DORIS receiver (Doppler Orbitography and Radiopositioning Integrated by Satellite), and a Global Positioning System (GPS) Demonstration Receiver (GPS/DR).

The GPS/DR is described by Melbourne et al. [1994] and Zieger et al. [1994]. As described in these reports, the receiver uses the P-code to obtain GPS pseudo-range and carrier phase on the L1 and L2 frequencies, tracking up to six satellites simultaneously. The carrier phase measurements have a precision of a few mm and the pseudo-range measurements have precision of several tens of centimeters.

The ground-based SLR data [Degnan, 1985] are used for both precision orbit determination and calibration of the radar altimeter. In general, the SLR systems pulse at 1 Hz with a single-shot range precision at the cm-level for third and higher generation systems. Compressed data (normal points) are commonly produced with a precision of 5-10 mm over a 15 second averaging interval for the better stations. Approximately 25 SLR stations track T/P [Tapley et al., 1994].

The DORIS system [Nouel et al., 1988] was provided by CNES (Centre National d'Etudes Spatiale). The system used a network of approximately 50 ground-based beacons that transmit at two frequencies (401 and 2036 MHz). The T/P DORIS receiver effectively measures the range-rate (Doppler shift) between the ground beacon and T/P to a precision of about 0.5 mm/sec.

The primary purpose of this paper is to summarize initial results obtained at The University of Texas/Center for Space Research (UT/CSR) with the GPS/DR. These results have been obtained using an estimation technique based on the solution of the equations of satellite motion and referred to as "dynamic orbit determination". The orbit of T/P has been determined using the same estimation technique with SLR and DORIS and the various results have been compared as one measure to assess the quality and accuracy of the GPS/DR. In addition, the GPS/DR data have been used in a preliminary gravity model and the results have been compared with "reduced dynamic" results obtained by JPL [Yunck et al., 1994].

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GPS/DR Processing

For the orbit determination analyses described in this paper, the GPS/DR L1 and L2 carrier phase data were used in a linear combination to remove first-order ionosphere effects. Double Differenced (DD) ionosphere-free carrier phase measurements were formed between a pair of GPS satellites, the GPS/DR and a ground-based GPS receiver to remove common error sources. Consequently, each DD measurement contained data from the GPS/DR; however, some experiments were investigated in which DD measurements between two ground-based receivers and two GPS satellites were included also. The DD precision was estimated to be about 8-9 mm.

The pseudo-range data were used only to determine the GPS/DR clock correction in a preprocessing mode. Once initialized, the GPS/DR clock drifted at a rate of about 4 millisec/day until the next reset. Clock offsets exceeding 100 millisec from GPS time were reached during some of the T/P cycles used in the analysis, as determined from the pseudo-range data. Although clock errors in the carrier phase measurements, including the Department of Defense dithering of the GPS clocks (Selective Availability or SA), are mostly removed in the double difference process (for example, Hoffman-Wellenhof et al., 1993), the complete removal requires additional processing.

To enhance the removal of common error sources in the DD measurements, an interpolation polynomial of degree two was fit to five 1-sec GPS/DR L1 and L2 carrier phase points near the time used to record GPS data at the ground stations. Evaluation of this polynomial at the ground station time provided a T/P "phase measurement" which, when differenced with the ground stations to form the DD measurement, removed most of the SA/clock-induced error, as discussed by Rocken and Meertens [1991].

Fourteen well-distributed ground-based GPS receivers were used in the processing. The stations were: Fairbanks (Alaska), Goldstone* (California), Hartebeesthoek* (S. Africa), Kokee Park (Hawaii), Kourou (French Guiana), Madrid* (Spain), McMurdo (Antarctica), Santiago* (Chile), Pamatai (Tahiti), St. Johns (Newfoundland), Tidbinbilla* (Australia), Tromso (Norway), Usuda (Japan), and Yaragadee (Australia). The sites denoted with * were fixed to a priori coordinate values and the coordinates of all other sites were simultaneously estimated with other parameters in the orbit determination process. All ground sites were P-code Rogue receivers that recorded GPS pseudo-range and carrier phase for L1 and L2 at a 30-sec interval. GPS data above the T/P local horizon were used in forming the DD; however, only data above 15° elevation at the ground site were used.

Antenna phase center variations determined in pre-launch testing were applied to both the T/P antenna and the ground receiver antennas [Zieger et al., 1994]. In addition, polarity corrections to the phase were applied [Wu et al., 1993].

The explicit double differences were processed in MSODP1 (Multi-Satellite Orbit Determination Program) using a batch least-squares procedure, augmented with a square-root-free Givens solution algorithm [Gentleman, 1973]. The MSODP1 software has been developed at UT/CSR [Rim, 1992], but it has heritage rooted in UTOPIA, the single satellite orbit determination program used at UT/CSR for analysis of SLR, DORIS and altimeter data. A description of the dynamic orbit procedure used in these computer programs is given by Christensen et al., [1994]. In MSODP1, simultaneous estimation of epoch positions and velocities of all GPS satellites, T/P and other parameters was performed. UTOPIA was used in a similar manner for the SLR/DORIS results described in this paper.

The model standards are given by Tapley et al. [1994] and McCarthy [1992]. The JGM-2 gravitational force model (Nerem et al., 1994) used for T/P and GPS differed only in the degree and order of field truncation (T/P: 70; GPS: 12). The GPS nongravitational model included the Rock4 radiation pressure and y-axis force [Fliegel et al., 1992]. The GPS station coordinates are given in the IERS Terrestrial Reference Frame (ITRF), identified as SSC(IERS)93C02 [Boucher and Altamimi, 1993]. The SLR-derived series for Earth polar motion and UT1 were used in the analysis of the GPS/DR and the SLR/DORIS data. The SLR analysis used SSC(CSR)93L02 coordinates [Eanes and Watkins, 1993]. The origins of the two reference frames are coincident, the relative orientations differ by 1 milliarcsecond and no scale factor exists (Table T-2, 1992 IERS Annual Report).

One day arcs were used with GPS/DR data. For each daily arc, the positions and velocities of T/P and all GPS satellites were simultaneously estimated at the initial arc time. A Rock4 scale parameter and a y-bias were estimated in the daily arc for each GPS satellite. For T/P, empirical force parameters were estimated, namely a constant along-track force and once per orbital revolution amplitude and phase coefficients in the along-track and cross-track directions. In addition to the position/velocity components, a typical one-day arc required estimation of about 850 carrier phase biases, 150 2.5-hour zenith delay parameters for all ground stations (assumed constant over each 2.5-hour interval for each station) and coordinates for nine GPS stations. For comparison, the T/P orbit determination from SLR/DORIS data was performed using a single 9.9-day arc for the estimation of the T/P position and velocity, but the empirical force parameters were assumed to be a different constant over successive one-day subintervals. Thus, although a single T/P position and velocity was estimated with SLR/DORIS data, 10 sets of empirical force parameters were estimated over the 9.9-day arc. Comparable 9.9-day arcs were not used with the GPS/DR because of GPS nongravitational force modeling difficulties over a multi-day interval, but these difficulties were minimized with independent one-day arcs spanning the 9.9 day cycle.

Table 1. TOPEX/POSEIDON Orbit Comparisons in Cycles 10, 15, 17, 19, 20

	Ephemeris Difference rms (mm)		
Cycle	Radial	A-T	C-T
10	30	103	108
15	18	70	84
17	21	88	81
19	25	112	89
20	20	91	67

Differenced orbits: SLR/DORIS-determined orbits and GPS/DR-determined orbits. The GPS/DR orbit was obtained using the 14 ground-station network and double differences formed between T/P and a ground-station only. 86,000 ephemeris points were used in the statistics. A-T is "along-track" component and C-T is "cross-track" component.

GPS/DR Results

Data from the GPS/DR were analyzed for the following T/P cycles: Cycle 10 (Days 356-366, 1992), Cycle 15 (Days 39-49, 1993), Cycle 17 (Days 59-69, 1993), Cycle 19 (Days 79-89, 1993) and Cycle 20 (Days 89-99, 1993). No orbital maneuvers of T/P occurred during the respective 10-day periods. The T/P spacecraft is controlled in yaw, normally with a sinusoidal control law. On Day 364 and on Day 67, the yaw control ramped from sinusoidal yaw to fixed yaw; however, no GPS tracking data were edited during these periods since the change in yaw was modeled in MSODP1. The T/P was not occulted by the Earth during Cycle 15, but experienced occultation during the first few days of Cycle 20 and all of the remaining cycles. During all of Cycle 19 and most of Cycle 20, the GPS satellites were not occulted by the Earth.

The comparisons of orbit results obtained using the GPS/DR and SLR/DORIS are given in Table 1. The orbits (ephemerides) determined from each technique describe the T/P spacecraft center of mass position in their respective terrestrial reference frame (x,y,z). The comparisons have been made by transforming the (x,y,z)-ephemeris differences into radial, along-track (A-T) and cross-track (C-T) components. The radial rms ephemeris differences shown in Table 1 range from 18 mm in Cycle 15 to 30 mm in Cycle 10, whereas the comparison expressed in the A-T and C-T directions range from 67 mm to 112 mm. Although the rms difference in the radial component was 30 mm or less, the radial mean difference in each cycle was less than 2 mm. The results exhibit no significant effect that can be attributed to unmodeled effects from either T/P or GPS occultation. The leading explanation for the Cycle 10 ephemeris difference level is sparse SLR and DORIS data during this cycle.

Although the compared orbits in Table 1 were derived using similar "dynamic orbit determination" procedures and models, the 30 mm or less agreement in the radial components is indicative of the compatibility level between the GPS/DR and the SLR/DORIS. Since some aspects of the estimation strategy (e.g., arc lengths) and the error sources (e.g., GPS orbits) are dissimilar, the level of agreement can also be interpreted as an indication of the ephemeris accuracy. The A-T and C-T ephemeris differences, which are higher than the radial component, are influenced by a complex combination of force models, arc length and data distribution.

Table 2 shows the results of experiments obtained using a six station subset of the GPS network. The six-stations were the five fixed sites plus Usuda. The purpose of this experiment was to evaluate the quality of the GPS/DR-determined orbit for a six-station versus a 14 station network. The six-station results exhibit less agreement with the SLR/DORIS results, although the radial effect is only a few millimeters, but the A-T and C-T results change by tens of millimeters. While the six-station network has processing advantages, single station outages and coordinate errors will be more detrimental than in the 14-station (or larger) network.

As noted above, explicit double differences were formed between T/P and each ground station. While this strategy enabled continuous observation of T/P over each one-day arc, it did not provide continuous data on each GPS satellite. In fact, the strategy allows tracking of each GPS satellite for approximately 25-30% of the orbit. This strategy was evaluated with the inclusion of all possible independent double differences formed between ground stations as well as between the ground stations and T/P. The experiment was conducted in Cycle 15 and produced agreement with the SLR/DORIS results in the radial, A-T and C-T directions, respectively: 18 mm, 70 mm and 81 mm. These results are nearly identical with the Table 1 results, thereby suggesting that little information is added with double differences formed between stations. However, some preprocessing complexity is introduced with these additional double differences to avoid inclusion of dependent measurements. For the Cycle 15 experiment, all double differences were independent.

The GPS/DR determined orbits were compared with the JPL "reduced dynamic" orbits, in which a filter strategy was selected to balance the dynamic model with the powerful kinematic, or geometric, strength of the GPS data [Yunck et al., 1994]. This approach places less reliance on the detailed modeling of the T/P forces. The comparison results, shown in Table 3, show radial ephemeris differences ranging from 31 mm to 35 mm. While this level of agreement is indicative of the accuracy, especially if the reduced dependency on force model errors is taken into consideration, additional tests are required to assess the orbit accuracy.

The GPS/DR data from four cycles were used in an experiment to assess the contribution of the data to gravity model improvement. The JGM-1 gravity coefficients and their associated covariance were combined with data from SLR, DORIS and the GPS/DR from T/P to obtain an experimental gravity field. This experimental field differs from JGM-2 primarily with the inclusion of GPS data and the specific arcs of SLR and DORIS data. Using the JPL reduced dynamic solution [Yunck et al., 1994] for comparison, the ephemeris results are given in Table 4. Note that the tuned gravity field results have moved toward the reduced dynamic solution, which should be less dependent on the dynamic model errors of T/P, consistent with the expectations of Christensen et al. [1994]. Cycle 20 GPS/DR data were not included in the gravity adjustment, therefore comparisons with this cycle used "withheld" data. This result demonstrates the GPS potential for gravity improvement using a host satellite. These data and other data are being incorporated in a new gravity model that will be designated JGM-3 (B. Tapley, personal communication, 1994).

As an additional evaluation of the resulting orbits, crossover residuals from the T/P altimeters were computed. The crossovers were computed using two different times, but at the spatial location defined by the intersection of two ground tracks. Crossover residuals were formed from the differenced altimeter measurement and the computed "measurement", based on the ephemerides, as noted in Table 5. Common error sources cancel in the altimeter crossover measurement, thus the crossover residuals reflect orbit error and ocean surface variability. The crossover statistics given in Table 5 for the different cycles show millimeter changes in rms between the various ephemerides since unmodeled ocean surface variability and uncertainty in ocean tide models are the dominant source of signal observed in these crossover misclosures. Nevertheless, it is of interest that the experimental gravity field obtained with T/P GPS/DR data has produced a dynamic solution that is closer to the JPL reduced dynamic solution than the ephemerides computed using JGM-2. Furthermore, the experimental gravity field also produces altimeter crossover residuals with a lower rms of fit than JGM-2.

Table 2. Six-Station GPS Network Solution Compared with SLR/DORIS

Cycle	Ephemeris Difference rms (mm) Radial	A-T	C-T
10	32	147	177
15	19	96	101
17	26	154	140

Table 3. Comparisons with JPL Reduced Dynamic Orbits

Cycle	Ephemeris Difference rms (mm) Radial	A-T	C-T
10	31	104	82
15	35	101	72
17	31	98	71
19	31	99	61
20	33	106	56

Table 4. Preliminary Results from GPS-Tuned Gravity

Cycle	RMS Differences(mm)with JPL Reduced Dynamic Orbits Radial	Along-Track	Cross-Track
10	24	90	62
15	21	74	64
17	22	75	67
19	22	75	60
20	25	90	52

Cycle 20 was not included in the preliminary gravity field.

Table 5. TOPEX/POSEIDON Altimeter Crossovers

	Altimeter Crossover rms (mm)			
Cycle	SLR/DORIS	GPS/DR	GPS*	Red. Dyn.
10	102	100	93	94
15	97	100	94	92
17	99	97	95	93
19	94	91	91	90
20	107	105	103	102

GPS* used the experimental gravity field.
Red. Dyn. is JPL reduced dynamic orbit.
Cycle 20 used POSEIDON altimeter data.

Conclusions

The preceding results, computed using five 10-day cycles, show that the GPS/DR data processed in a dynamic mode produce results that agree with SLR/DORIS dynamic orbits to better than 30 mm radial rms in most cases. Even though nearly identical models have been used for the representation of forces acting on T/P in the analysis of the different tracking data types, this level of agreement demonstrates that the GPS/DR can provide results with similar accuracy to those obtained with SLR and DORIS. The agreement between the various tracking techniques is a necessary condition for establishing accuracy, but further analysis is required. The accomplishment of the level of agreement is particularly significant in the context of the application of different software, potentially different models and parameters, the different locations of the tracking reference points on T/P, the differences in reference frames, T/P eclipsing and non-eclipsing cases and somewhat different error sources associated with each technique. Furthermore, the experimental gravity results obtained using the GPS/DR produce T/P orbits that agree more closely with the JPL reduced dynamic orbits than with SLR/DORIS orbits determined with JGM-2. Furthermore, the experimental gravity field produces altimeter crossovers that are systematically more consistent with those computed using the JPL reduced dynamic orbits. Because of the reduced dependency on the force model in the JPL reduced dynamic strategy, these results suggest that the T/P radial orbit accuracy is better than 30 mm (rms) in the cycles studied.

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