TOPEX/POSEIDON PRECISE ORBIT DETERMINATION USING GPS DOUBLE DIFFERENCE PHASE OBSERVABLES

S. Casotto,* J. M. Dow** and T. Martin-Mur**

** LOGICA Space and Communications at ESA/ESOC, Robert-Bosch-Strasse 5, D-64293 Darmstadt, Germany*
*** ESA/European Space Operations Centre, Robert-Bosch-Strasse 5, D-64293 Darmstadt, Germany*

ABSTRACT

Data from the experimental onboard GPS receiver were used to accurately compute the orbit of TOPEX/Poseidon. This represents a unique opportunity to intercompare with two other classical tracking techniques (SLR and DORIS). A review of the methodology used is given together with current results.

INTRODUCTION

TOPEX/Poseidon (T/P) is a joint US/French altimetric mission launched in August 1992. The orbit determination requirements for this mission were set almost a decade ago with the then very demanding constraint of a 13 cm error budget for the radial position. In order to satisfy this challenge an unprecendented effort was made to improve the gravity model of the Earth, culminating in the recent JGM2 model. To further guarantee the best possible results in precise orbit determination (POD), several tracking systems were placed onboard: laser ranging retroreflectors (SLR), doppler (DORIS), and an experimental GPS package. This effectively has made the T/P spacecraft (S/C) a veritable POD laboratory which allows the intercomparison of the three tracking techniques. In the following we analyse the capabilities of GPS.

GPS DATA PREPROCESSING

The T/P onboard experimental GPS receiver raw data from cycle 21 (10-18 April 1993) were processed in 48-hr batches to generate an ionosphere-free, double difference (DD) data stream, including ground-based GPS data from a core set of 13 receivers plus additional sites for a total between 17 and 20 ground receivers. In order to avoid SV attitude modeling problems, only non-eclipsing SVs were considered. Data from SV-19 and SV-20 were also neglected due respectively to carrier phase problems and manoeuvreing during cycle 21. A total of 15 GPS SVs was thus considered. All independent DD's were generated at a frequency of one every 2 minutes for those involving T/P and one every 4 minutes otherwise. In the generation algorithm priority was given to the formation of DD's involving the orbiting receiver and to the completion of passes in which this was involved. This strategy resulted in a continuous T/P DD stream typically constituting about 24% of the observation data set for a given arc. Each arc begins at 12:00 UTC, the 48-hr length being set on the basis of our previous experience with IGS data processing /1/. The typical number of DD observations generated during any such arc is about 18000. The last arc in the cycle has only the first 36 hrs of T/P data. Cycle slip detection was based on smoothing the triple time differences of the 4/3 and 5/4, almost-ionosphere-free combinations (generated at 30 s intervals) against a priori ephemerides of both SVs and T/P. The same method was applied for the computation of an approximate integer ambiguity correction. Corrections were also applied to the data to account for the attitude motion of the transmitting SVs, for which the nominal GPS SV attitude law was adopted, and the receiver on T/P, where the yaw steering law developed by Fairchild was used /2/. The latter is briefly described in the following section. No corrections were applied to eliminate azimuth dependent effects of the receiver antenna orientation on the phase (phase wind-up) /3/. A Kalman filter was used to estimate receiver clock biases and drifts. No appreciable drift was detected on the T/P clock. For ground receivers, clock resets were signaled and initial estimates produced for bias and drift to be input to the BAHN orbit processor. Receiver clock parameter estimation was performed by constraining the drift variations over 30 s of each of a selected number of hydrogen maser stations (Tidbinbilla, Kokee, Goldstone, Fairbanks, Algonquin, Onsala, Madrid) using a standard deviation of 0.2 ps/s ($\sigma = 0.2 \times 10^{-12}$, slightly higher than the measurement noise level). This

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takes care of short term clock variations. The long term time scale behaviour was instead driven by the SV clocks, whose biases were constrained to be equal to the values in the navigation message (using a $\sigma = 100$ ns, which is about three times the standard deviation due to Selective Availability).

ATTITUDE MOTION AND THE SKIN FORCES MODEL

For highly accurate results in the POD process, the complicated spacecraft geometry and intricate attitude motion of T/P must be carefully modeled. This information is necessary to apply the center of mass (CoM) correction to the data and to compute the variable area tables for use in the radiation pressure and atmospheric drag force models. T/P is an Earth-pointing satellite which follows the yaw motion about the nadir direction according to the law /2/ represented in Fig. 1. The range of variation of the solar aspect angle β' is divided into six regions with different yaw attitude regimes. The yaw angle Ψ is a function of β' and the orbit angle α, i.e. the angular separation of the S/C from the orbital 6 a.m. position. Most of the complication in implementing the yaw algorithms stems from the complexity of the transition regimes which are reproduced in the blown-up boxes in Fig. 1. Yaw mode transitions start after the appropriate β' boundary has been crossed, but only when the orbit angle enters the pre-defined interval specified by the black arrows in accordance with the left-to-right time evolution direction. A second degree of freedom is allocated to the motion of the solar array about the Y_v axis in such a way as to point as closely as possible to the sun. The full attitude motion algorithm was implemented in the preprocessing S/W in order to apply the CoM correction using the body-fixed vector describing the CoM position with respect to the GPS receiver center of phase with components (-1.9455, 0.0395, 4.5836) metres /4/. The same algorithm, amended by the 57° positive solar array pitch bias /5/, was also used in the FREFLW code, developed at ESOC /6/, to generate variable equivalent area tables for each yaw regime according to the reflectivity and temperature parameters of the several simple bodies used to model the S/C. For both radiation pressure and air drag models only the acceleration component along the S/C-sun direction and the S/C velocity, respectively, were later used in orbit determination.

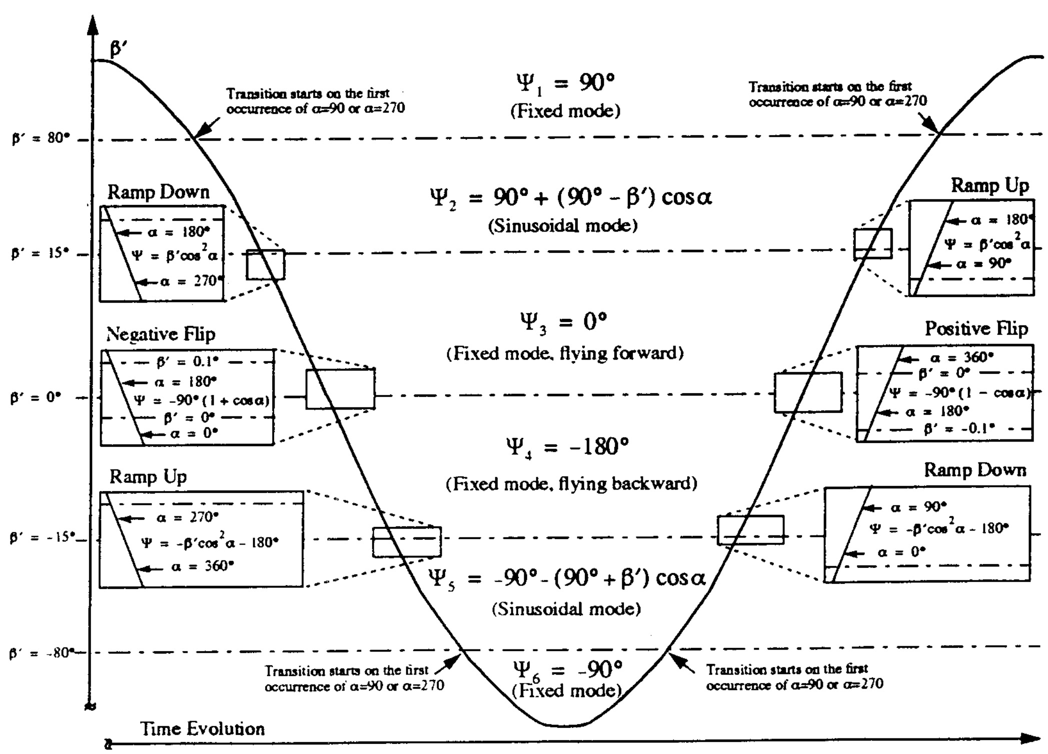

Figure 1. TOPEX/Poseidon yaw steering law

FORCE MODEL AND SOLUTION DESIGN

The ESOC S/W system BAHN adopts a *fully dynamic approach* to orbit determination and geodetic parameter estimation. It is routinely used for IGS data processing and has been recently upgraded to handle an orbiting GPS receiver. The integration reference system in BAHN is the J2000.0 inertial frame and measurements are referred to it by the 1976 precession and the 1984 IAU nutation theories. In this particular study Celestial Pole corrections to the nutation angles were not applied. GPS ground receiver coordinates are in the ITRF92 system as used by ESOC in the framework of its IGS activities /7/. The force model adopted for the analysis included the JGM2 (70×70) Earth gravity field, lunisolar perturbations, Wahr's solid Earth and Schwiderski's extended ocean tides. Direct solar radiation pressure and air drag perturbations were computed according to the variable area approach described above. No stochastic force models were used. The solution parameter set included

- T/P and SVs' positions and velocities at epoch
- Selected GPS ground receiver coordinates (Kourou, Maspalomas, Matera, McMurdo,Taiwan)
- SRP scaling coefficients (ROCK 4 /8/)
- Y-biases (SV's) (ROCK 4)
- 12-hr T/P drag coefficient
- 1 cycle-per-revolution empirical force (transverse and normal, T/P and SV's)
- Daily ERP's (x_p, y_p, $UT1$ rate)
- Tropospheric parameters (2 per station every 4 hrs)
- DD pass ambiguities (GPS)
- Selected GPS receiver clock parameters

Essentially no observations were rejected and the total DD post-fit residual rms for each 48-hr arc is 9-10 mm. The post-fit residual rms for TOPEX/Poseidon only is 16-17 mm. The solar radiation pressure coefficient scale value oscillates around 0.5. This is to be considered as an anomalous value with respect to the expected unity. The 5 12-hr linear drag coefficient scale parameters present an M-shaped variation during each 48-hr arc. The end values are near 2, while the second and the fourth reach 3.5-4 and the middle one is around 3. This behaviour can be interpreted as an indication that other non-drag-generated acceleration effects are being absorbed. These could also be related to the degree 2 order 1 gravity harmonics. The values of the sine and cosine amplitudes of the 1 c.p.r. empirical accelerations in the transverse and normal directions are of the order of 10^{-12} m/s^2 to 10^{-13} m/s^2.

ORBIT COMPARISONS

In order to assess the performance of the different tracking data types for T/P POD, orbits generated by each method were compared for cycle 21. The orbits were the ESOC GPS dynamical (GPS_Dyn), laser (SLR) and DORIS /9/; the Delft University of Technology (DUT) GPS reduced dynamic (GPS_RD), GPS dynamical, laser and DORIS /10/; and the JPL GPS reduced dynamic. All ESOC orbits are in the J2000.0 frame, all others in the True of Date frame. The results of the comparisons in the RTN components are shown in Table 1, where the average rms's over the 9 daily arcs are exhibited for ESOC orbit pairs and for ESOC vs DUT and JPL orbits before and after the application of Helmert transformations (HT). It can be seen that before HTs are applied the radial rms between most orbit pairs is close to 2 cm, with the exception of pairs involving GPS_RD orbits, when the rms is about 3 cm. The transverse and normal rms in most cases is between 10 and 15 cm with peaks to 19 cm for the normal. A notable exception is the comparisons with JPL orbits where rms's reach between 16 and 27 cm. It must be mentioned that most of these relatively high rms's exhibit large mean components (and low standard deviations).
Since such discrepancies are likely to be due to reference frame inconsistencies, Helmert transformations were applied to each 24-hr arc. The results show dramatic improvements, especially in the case of the JPL orbits, which are now in line with the D/GPS_RD orbits. The most likely explanation in this case is that JPL orbits were computed while accounting for Celestial Pole corrections to the nutation angles, while ESOC and DUT orbits were not. In general the radial consistency is reduced to levels of 1-2 cm. The striking 1 cm rms occurs between ESOC GPS_Dyn and the ESOC and DUT DORIS orbits. The transverse rms with respect to E/GPS_Dyn orbits is now between 5 cm and 7 cm. E/SLR orbits show an rms around 9-10 cm and E/DORIS orbits are at the 6-8 cm level. The normal component is likewise reduced to 2-3 cm, but not with respect to D/DORIS, where we find 5 cm.

			ESOC		DUT				JPL
			SLR	DORIS	GPS/RD	GPS/Dyn	SLR	DORIS	GPS/RD
ESOC	GPS/ Dyn	R	3.1/1.9	1.7/1.1	3.2/2.9	2.1/1.5	2.7/1.7	1.8/1.2	3.2/2.8
		T	16.1/9.4	13.5/5.8	10.6/8.1	8.7/5.3	12.3/6.7	10.7/5.4	16.4/8.2
		N	7.5/2.1	12.3/3.0	10.8/4.1	10.3/2.7	3.1/2.5	9.7/4.9	24.8/4.5
	SLR	R		2.4/1.4	4.1/3.2	3.4/2.2	2.6/1.8	3.0/1.8	4.1/3.1
		T		10.2/8.8	16.8/12.1	15.2/10.2	12.1/9.4	11.5/9.5	23.9/12.5
		N		10.5/2.0	14.8/3.7	14.9/2.1	7.7/2.4	8.5/5.3	27.6/4.1
	DO-RIS	R			3.2/2.8	2.2/1.6	2.1/1.6	1.6/1.1	3.1/2.8
		T			14.7/10.4	12.9/7.8	9.0/6.2	7.2/5.9	22.1/10.8
		N			17.9/4.4	19.2/3.1	13.2/3.4	12.6/5.8	26.3/4.8

Table 1: Averages of 24-hr comparison statistics for cycle 21 orbits as computed by ESOC, DUT and JPL. Shown are rms values (cm) *before/after* daily Helmert transformations

Comparisons involving GPS_RD orbits are consistently higher than the rest. Radial rms's are at the level of 3 cm, while the transverse rms varies between 8 cm and 12 cm, the lowest values being reached in comparisons with ESOC GPS_Dyn orbits. The best overall agreement is between E/GPS_Dyn and D/GPS_Dyn: 1.5 cm radially, 5.3 cm along-track and 2.7 cm cross-track. It can be added that these values are quite constant over the 9 arcs. The best agreement between ESOC orbits happens for GPS_Dyn vs DORIS. It is interesting to look for systematic features in the Helmert transformation parameters for the various sets of orbits. Unfortunately no such systematics have been noticed and it is believed that this is due to the unconnectedness in terms of Earth Rotation Parameters between the various subarcs, since no continuity of ERP's was enforced during GPS data processing.

CONCLUSIONS

The comparison of T/P ephemerides computed by ESOC, DUT and JPL during cycle 21 show a remarkable agreement: the rms in the radial direction varies between the 1 cm of the ESOC GPS_Dyn, ESOC DORIS and DUT DORIS orbits and the 3 cm of all comparisons with the JPL GPS_RD orbit (excluding the case DUT GPS_RD vs JPL GPS_RD, which is at the 1 cm level). The along-track comparisons show an rms range from the 5.3 cm of the ESOC GPS_Dyn vs the DUT GPS_Dyn orbits and the 12.5 cm of the ESOC SLR vs the JPL GPS_RD orbits. Finally, the cross-track rms ranges from the 2 cm of the ESOC SLR vs the ESOC DORIS orbits and the 5.7 cm of the ESOC DORIS vs DUT DORIS orbits.

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