

TOPEX/Poseidon Orbit Determination Using Global Positioning Satellites in Anti-Spoofing Mode

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Results of orbit determination for the TOPEX/Poseidon (T/P) mission using Global Positioning Satellites (GPS) during Anti-Spoofing (A-S) activities are presented in this paper. During A-S tracking the T/P GPS flight receiver is unable to collect dual frequency measurements from the GPS constellation and thus unable to calibrate the observations for ionospheric delay. An approximation of the ionosphere above T/P can be obtained by differencing the available single frequency carrier phase and pseudorange measurements. With this technique, sub-decimeter radial orbit comparisons are obtained with solutions determined from LASER and DORIS tracking.

INTRODUCTION

The TOPEX/Poseidon (T/P) satellite carries a high precision Global Positioning Satellite (GPS) receiver. During its first year of operation, all of the available flight receiver measurements were processed. Outages during this experimental phase were primarily related to Anti-Spoofing (A-S) operation of the GPS constellation. Updates to the flight receiver software and ground processing procedures were implemented to produce near continuous operation during A-S.

Elements of T/P GPS orbit determination include the GPS satellite constellation, GPS flight receiver on-board T/P, six globally distributed GPS ground receivers, the GPS Data Handling Facility (GDHF) and the GPS Data Processing Facility (GDPF). The GDPF collects the GPS flight measurements from the T/P flight operations team while the

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ground station data are obtained through the GDHF. Carrier phase and P-code pseudorange measurements from 24 GPS satellites to the seven GPS receivers are then processed simultaneously with the GDFP software MIRAGE to produce orbit solutions of T/P and the GPS satellites.

With no A-S, orbit solutions based solely on the GPSDR observations and a global network of six ground receivers compare at the three to four centimeter (radial, RMS) level with orbit solutions derived independent of the GPS data [1-3]. During A-S, the orbit solutions show comparisons of five to six centimeters (radial, RMS).

OBSERVATIONS DURING ANTI-SPOOFING

During A-S tracking the T/P GPS flight receiver tracks only the L_1 carrier and CA-code pseudorange [4]. Thus, the ionosphere calibration based on the linear combination of the L_1 and L_2 carrier signals is unavailable [5]. For the GPSDR, a rough ionosphere calibration is computed by **differencing** and smoothing the single frequency carrier phase and **pseudorange**. The GPS receivers used at the ground sites have an advanced hardware design that allows for the reproduction of the full wavelength L_2 carrier phase [6-7], thus; the ionospheric calibration procedures for ground stations are unchanged.

Flight Receiver - An approximation of the ionosphere above T/P can be obtained by **differencing** the available carrier phase and pseudorange measurements. This difference is smoothed to remove the **multipath** associated with the pseudorange measurements. The remaining signal consists primarily of ionosphere. The following mathematical description shows the procedure:

$$1) \text{ Form } A = L_1 - P_1 = \rho + I + B_L - (\rho - I + M + B_P) = 2I - M + B_L - B_P$$

where: L_1 = CA-code carrier phase
 P_1 = CA-code pseudorange
 ρ = True Range
 I = Ionosphere
 M = Multipath
 B_L = CA-code carrier phase bias
 B_P = CA-code pseudorange bias

$$2) \text{ Smooth } A \text{ with cubic splines to remove multipath; } S(A) \approx 2I + B_L - B_P$$

3) Apply remaining ionosphere calibration to L_1 and P_1

$$L_{1C} = L_1 - S(\Delta) / 2$$

$$P_{1c} = (L_1 + P_1) / 2 \text{ and carrier added smoothing}$$

Figures 1-4 give examples from the observation processing. T/P flight receiver pseudorange measurements, from one of the GPS satellites (PRN 31), are shown for 10 passes in Figure 1. Performing the standard linear combination of dual-frequency carrier phase measurements yields the true ionospheric calibration shown in Figure 2. In Figure 3 the single-frequency ionospheric results are presented and the difference between the truth calibration (Figure 2) and the smoothed **single-frequency** calibrations are plotted in Figure 4. For these sample passes, the single-frequency ionospheric calibration captures about 80 to 85 percent of the actual value,

Ground Receivers - For the ground GPS receivers, the ionosphere calibration is obtained with the usual dual-frequency calculations. Full wavelength L_2 is produced using cross-channel correlation in the receiver hardware. During A-S the only difference is that the pseudoranges are CA-code and thus have slightly higher noise characteristics, For the orbit determination processing the effective antenna phase center locations and the observation weights are the only adjustments required.

BASELINE SOLUTION SCENARIO

During normal tracking (no A-S) the L_1 and L_2 carrier signals are modulated with the P-code. In addition, the L_1 carrier is also modulated with the CA-code. For A-S tracking the P-code is replaced by the Y-code (encrypted security code) which makes it impossible for **unclassified** users to track the L_2 carrier. The L_1 carrier is always available since it is modulated with the CA-code. During A-S, some GPS satellites continue to transmit the **normal** CA-code and P-code signals. The Block I satellites do not have A-S capabilities and on occasion some of the BLOCK 11 satellites have not activated A-S.

Carrier phase and P-code pseudorange data are available on the flight receiver at rates of one per second and one per 10 seconds respectively. **Pre-processing** of the observations consists of detecting and correcting cycle slips, **determining** and applying **TOPEX/Poseidon** clock offsets, and decimating to the desired processing rate and calibrating for ionosphere. Since the noise level is different for CA-code and P-code measurements the data weights are chosen to balance this effect in the orbit determination process. Table 1. shows the data rates and weights used for operational orbit determination.

RESULTS

Six 30 hour arcs and one 10 hour arc were processed. Orbit comparisons with solutions

from LASER and **DORIS** tracking show RMS radial agreement at the sub-decimeter level. Figure 5. shows the GPS carrier phase residual errors between the actual observations and the computed values from the converged solutions. The total and GPSDR only results **are** provided, Orbit comparisons with the official T/P precision orbit ephemeris solutions are provided in Figures 6 and 7.

CONCLUSIONS

Mitigation of the effects of anti-spoofing on the T/P GPS flight receiver observations is achieved by means of a data conditioning technique used prior to orbit adjustment. For the ground receivers a hardware solution exists that effectively eliminates special processing of those data. With these techniques and the initial results of this paper, continuous, subdecimeter RMS radial T/P orbits can be obtained using only GPS observations.

Table 1- Data Rates and Processing Weights

<u>Data Type</u>	<u>Processing Rate</u>	<u>Weight</u>
T/P P-code Carrier Phase	5 min. (decimated)	2 cm
T/P CA-code Carrier Phase	5 min. (decimated)	15 cm
T/P P-code Pseudo Range	5 min. (decimated)	2 meters
T/P CA-code Pseudo Range	5 min. (decimated)	500 meters
Ground P-code Carrier Phase	5 min. (decimated)	1 cm
Ground CA-code Carrier Phase	5 min. (decimated)	3 cm
Ground P-code Pseudo Range	5 min. (decimated)	1 meters
Ground CA-code Pseudo Range	5 min. (decimated)	50 meters

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REFERENCES

- [1] Bertiger, W., and others, "Early Results from the TOPEX/POSEIDON GPS Precise Orbit Determination Demonstration," **AAS-93-154**, presented at the Third Annual **AAS/AIAA Spaceflight Mechanics Meeting**, Pasadena, CA., 22-24 Feb., 1993.
- [2] Guinn, J. and P. Wolff, "TOPEX/POSEIDON Operational Orbit Determination Results Using Global Positioning Satellites," **AAS-93-573**, presented at the **AAS/AIAA Astrodynamics Specialist Conference**, **Victoria, B.C., Canada**, 16-19 Aug., 1993.
- [3] Wu, S.C. and others, "Automated Precision Orbit Determination for TOPEX/POSEIDON with GPS," **AAS-93-576**, presented at the **AAS/AIAA Astrodynamics Specialist Conference**, **Victoria, B.C., Canada**, 16-19 Aug., 1993.
- [4] B. Hofmann-Wellenhof and others, *GPSTheory and Practice*, Springer-Verlag, 2nd ed. 1993.
- [5] L. Carson and others, "Design and Predicted Performance of the GPS Demonstration Receiver for the NASA TOPEX Satellite," *IEEE Transactions on Communications*, vol. CH-2675, pp.422-454, July 1988,
- [6] Srinivasan, J., T. Meehan, and L. Young, "Code and Codeless Ionospheric Measurements with NASA's Rogue GPS Receiver," *Proceedings of Third International Meeting of Navigation Satellite Division*, September, 1989.
- [7] Meehan, T. and others, "The TurboRogue GPS Receiver," presented at the Sixth International Geodetic Symposium on Satellite Positioning, Columbus, OH., 18 March 1992,
- [8] Wu, S.C., and others, "Minimizing Selective Availability Error on TOPEX GPS Measurements," **AIAA-90-2942**, **AIAA/AAS Astrodynamics Conference**, Portland, OR., August, 1990

Figure 1- Flight Receiver Pseudorange from GPS31 (10 Passes)

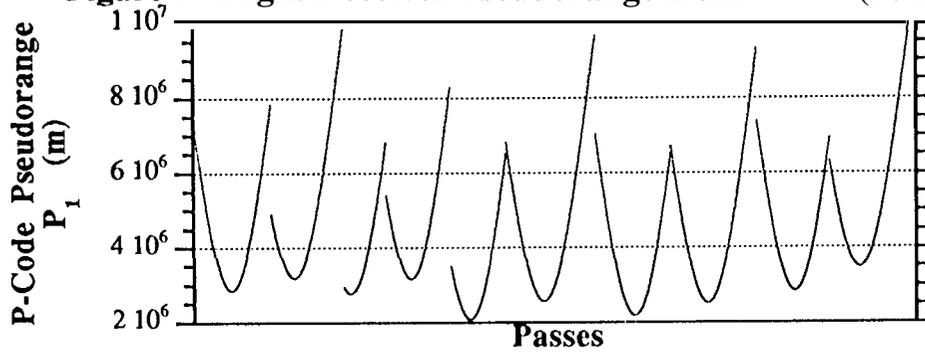


Figure 2- Dual-Frequency Ionospheric Calibration

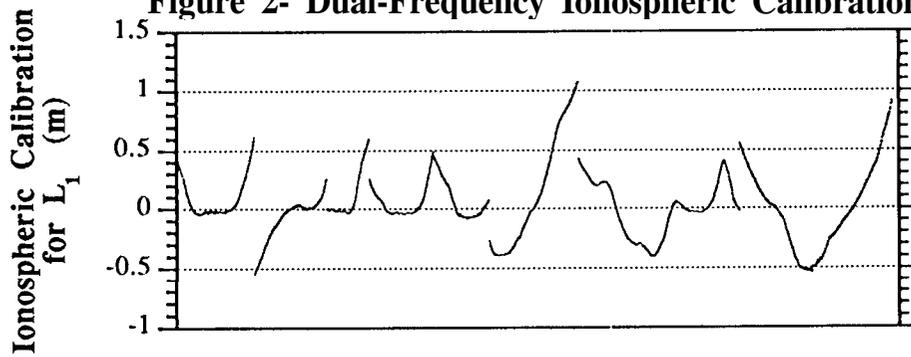


Figure 3 - Single-Frequency Ionospheric Calibration

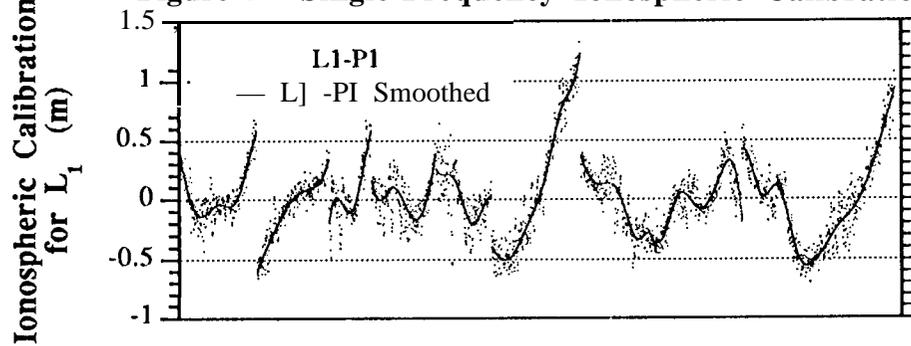
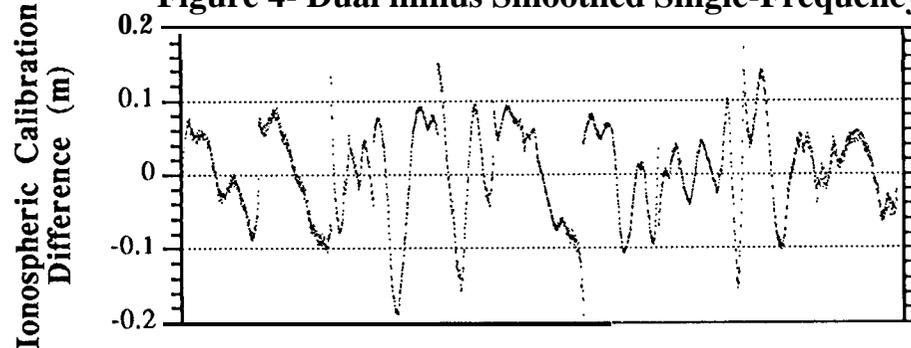


Figure 4- Dual minus Smoothed Single-Frequency



RMS of Carrier Phase Residuals (cm)

**Figure 5 - GPS Observation Residuals
(TOPEX and 6 Ground Stations)**

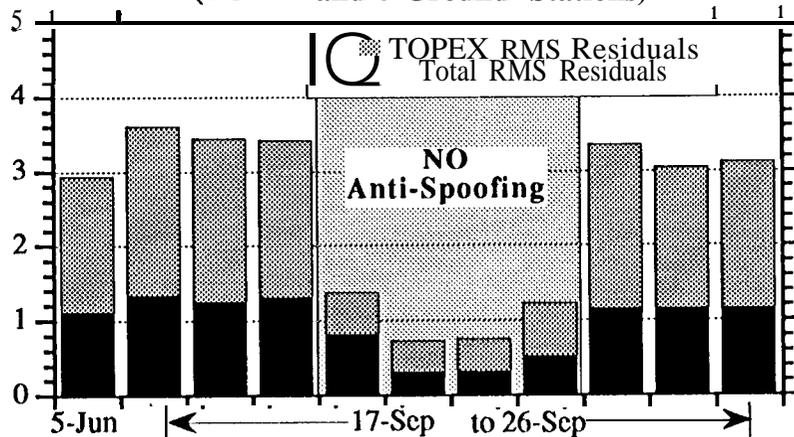


Figure 6- Radial Orbit Comparisons with NASA POE

RMS Radial Differences (cm)

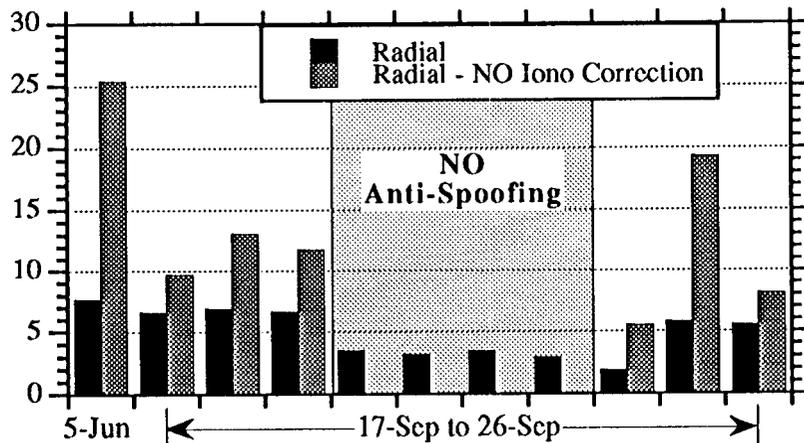


Figure 7 - 3D Orbit Differences with NASA POE

RMS 3D Differences (cm)

