THE GPS FLIGHT EXPERIMENT ON TOPEX/POSEIDON

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Abstract. After a decade of preparation, the GPS precise orbit determination (POD) experiment on TOPEX/Poseidon is now yielding definite results. A wide range of orbit consistency and accuracy tests indicate that GPS is routinely providing satellite altitude with an RMS accuracy of about 3 cm. Here we review the rationale for the GPS experiment, basic GPS concepts, POD techniques, and key experimental results, and discuss the possible cost and performance benefits that may flow to future missions.

Introduction

TOPEX/Poseidon, a joint NASA/CNES mission to study ocean circulation by measurement of sea surface topography, was launched on 10 August 1992. During the following 3-5 years, the mission will map regional and global ocean currents and their time variation by observing their surface signatures with two precise (2-3 cm) microwave altimeters, one provided by NASA and one by CNES. In the 1970s and 80s, the Geosat and Seasat missions returned valuable information about mesoscale oceanic features and variability. Because of its unprecedented altimeter and orbit accuracy, TOPEX/Poseidon is the first mission that can meaningfully recover global ocean circulation.

The principal limitation of past missions to study ocean circulation has been the error in determining the geocentric radial position of the altimeter, which was provided by precise orbit determination (POD) with tracking data from ground-based Doppler or laser ranging systems (SLR). The best Seasat orbits, for example, had a radial accuracy of about 40 cm RMS. Although that can suffice for regional and ocean variability studies, for global circulation a radial accuracy of 10 cm or better is needed. To reach 10 cm, the TOPEX/Poseidon Project raised its planned orbit altitude from 800 to 1336 km, reducing drag and gravity perturbations, and selected two operational precise tracking instruments—a laser reflector array and a Doppler receiver to track the signals from the French network of radio beacons known as DORIS (ref.)**, It also supported extensive development in the ground segments of those systems, and of spacecraft dynamic models. Finally (and our

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subject here) the Project chose to carry a Global Positioning System (GPS) flight receiver as a tracking experiment.

The GPS experiment on TOPEX/Poseidon was conceived in the early 1980s by a group at JPL seeking alternatives to conventional Doppler and ranging. The motivation was simple: With the high precision of altimetry, ocean science would benefit from centimeter level orbit accuracies. But traditional POD techniques, which depend on precise models of satellite forces to recover the orbit, were expected at that time to be limited to approximately 13 cm by force model errors, even after an extensive refinement effort, JPL turned to geometrical techniques, which are less sensitive to dynamical limitations, and soon realized that the enveloping coverage given by GPS offered an almost ideal solution. By the mid-1980s, a strategy known as reduced dynamic tracking emerged that sought to combine the best elements of dynamical and geometrical positioning to minimize overall error (WU at al 1991).

The goals of the GPS experiment are to assess the accuracy of GPS-based POD on TOPEX/Poseidon, evaluate the cost and maturity of the technologies, and to demonstrate the operational readiness of the experimental system. In this issue we present, in addition to this overview, three papers (Yunck et al; Young et al; Schutz et al) that discuss different aspects of the GPS experiment, including early POD results and flight receiver performance. Here we review the basic GPS system concepts, summarize recent results, and consider their implications for future missions.

GPS Tracking System Elements

The GPS tracking system consists of four segments: the GPS constellation, the flight receiver, a global network of GPS ground receivers, and a central monitor, control and processing facility (Fig. 1). The POD strategy requires continuous tracking of the visible GPS satellites by ground and flight receivers. Data from all receivers are brought together and processed in a grand solution in which the TOPEX/Poseidon orbit, all GPS orbits, receiver and transmitter clock offsets, and other parameters are estimated, Simultaneous sampling at all receivers (which may be achieved by later interpolation) eliminates common errors, such as clock dithering from GPS selective availability. In the end, TOPEX/Poseidon position and velocity are determined in a reference frame established by key sites in the global network, known to about 2 cm in the International Terrestrial Reference Frame.

The Global Positioning System. Each of the 24 GPS satellites (Fig.2) broadcasts the L1 and L2 navigation signals to the Earth's surface, or in the space below about 3000 km altitude. Typically 5 to 9 GPS satellites are visible within a hemispherical field of view.

For precise applications dual-band carrier phase measurements are the primary GPS data type. The information content in the measurement is range change (integrated doppler) over the satellite pass. Typical l-see phase precision with the best commercial receivers is 0.2 mm.

The GPS Flight System. Figure 3 shows the locations of key subsystems and instruments on TOPEX/Poseidon. The GPS antenna sits atop a 4.3-m mast, which is needed to avoid reflected signals from the TDRS high-gain antenna and other surfaces. The Monarch™ GPS flight receiver is located inside. It tracks up to 6 GPS satellites concurrently and measures the phase of both carriers at 1 sec intervals and P-code phase at 10 sec intervals. Young et al (this issue) discuss receiver and antenna performance.

The Global Tracking Network. Figure 4 shows the primary ground sites used in the experiment. These will be part of the new IAG-sponsored International GPS Service due to begin in 1994 to provide scientific users GPS data products of high accuracy, For TOPEX/Poseidon fewer than a dozen sites are needed to obtain full accuracy because the satellite's orbital motion provides ample flight/ground covisibility of the GPS satellites, For GPS ground programs (which now achieve a weekly geocentric station location precision of about 1 cm), 20-40 sites are generally required (Blewitt et al 1993),

The GPS Operations Center. All transactions involving GPS data and POD products flow through the operations center, which automatically retrieves data from all GPS sources-about 8 Mbyte/day from the flight receiver & 1 Mbyte/day from each ground site. The center monitors and controls the ground and flight receivers and initiates actions to repair system faults. The ground receivers can store their data for, in most cases, up to 12 days to protect against communication outages. In the first 6 months of experimental operation we acquired 99% of the possible data from the flight receiver when GPS antispoofing (P-code encryption) was turned off, and approximately 95% from the ground receivers. Precise orbits from GPS are now produced with 30-hour data arcs on 24-hour centers, providing 6-hr overlaps for orbit comparisons. Precise orbits and statistical quality measures are available to analysts about 3 hrs after all data for 1 day are received. External release of the orbits occurs about 1 week after the end of each 10-day orbit repeat cycle.

POD Strategies

The extraordinary coverage from GPS can be seen in Figure 2. Continuity of high accuracy tracking data in three dimensions and wide GPS covisibility by the flight and ground receivers provide a geometric data strength unrivaled by any other system. SLR, for example, provides highly accurate scalar measurements (slant range) during short intervals (10- 15 rein), but large coverage gaps along the orbit remain. This observational weakness must be overcome with precise models of all forces acting on the spacecraft. DORIS with its 40-50 station ground network provides more coverage using an inherently weaker range rate scalar measurement; it also requires accurate models. GPS, by contrast, provides a continuous 3D position change vector as long as the receiver operates, giving the analyst new options for reducing POD errors arising from deficiencies in the spacecraft dynamic models and in the measurement system.

Full Dynamic POD. In a dynamic approach the orbital motion of the spacecraft is strongly constrained by dynamic models. Deficiencies in those models, if unaccounted for, can result in magnified POD errors in components of the state vector that are weakly observed, Judicious least squares adjustment of empirical (e.g., once-per-revolution) global force parameters to relax the grip of the model errors is still considered fully dynamic. More localized relaxation with sparse (e.g., SLR) tracking data may greatly increase POD error because of the limited tracking coverage and observability.

Reduced Dynamic POD. With GPS one can approach a purely geometric solution, and lessen the influence of force model errors, by adding to the dynamic model a stochastic acceleration vector that is re-estimated (subject to constraints) at each time step. This purely local adjustment must rely on geometry and measurement accuracy rather than dynamics. Reduced dynamic POD attempts to optimize the result by choosing the constraints (variance and correlation time of the stochastic vector) to balance dynamic error against geometric limitations—to draw the best from both the models and the measurements (Fig. 5). Dynamic model errors still appear but at a diminished level that depends on the constraints. Observe, however, that if the aim is to improve the gravity field, the stochastic vector estimate must be inhibited so the dynamic model is strongly determined. Ultimately, the best GPS-based orbit solutions will come from a dual approach (Yunck et al 1993; Schutz et al 1993) that strives to improve the dynamic models and the measurement system.

For TOPEX/Poseidon a purely geometric solution (i.e., lifting all constraint from the stochastic force estimate) is inadvisable. The Monarch can track only six satellites at once, and the current onboard satellite selection algorithm (which can be modified) holds the effective field of view to less than a hemisphere, limiting geometric strength. Experiments show that TOPEX/Poseidon radial accuracy falls to 12-15 cm when the solution is nearly geometric. Covariance studies indicate, however, that an all-in-view receiver with a full sky field of view could provide geometric POD accuracies of about 2 cm (WU et al, 1991).

Summary of the Analysis

Two groups have been analyzing the TOPEX/Poseidon GPS data, one at JPL and one at the Center for Space Research of the University of Texas at Austin (CSR). In addition, the Goddard Space Flight Center (GSFC) and CSR generate precise' orbits from laser and DORIS data. CSR and GSFC have focused on a fully dynamic POD strategy, steadily refining the force models, while JPL has pursued reduced dynamic estimation. The result has been an almost stunning convergence of the two approaches.

The analysis groups have evolved a battery of quantitative measures of performance. These include internal data quality and orbit consistency tests (post-fit residuals, formal errors, orbit overlap agreements); direct comparisons of GPS solutions between groups and with laser/DORIS solutions; and objective external tests, such as altimeter crossover residuals. Each approach has limitations, but each provides a necessary condition toward assessment of accuracy.

An early result illustrates the advantages of GPS data in the reduced dynamic approach. As a starting point for reduced dynamic estimates JPL initially used a simple dynamic solution with no empirical once-per-rev force adjustment. The dynamic solution therefore contained a pronounced once-per-rev error, which the reduced dynamic solution was then faced with correcting. Figure 6 shows the discrepancy between the two orbit estimates. Although the reduced dynamic procedure had no prior knowledge of the nature of the dynamic error, it removed an almost perfectly smooth once-per-rev signature, with an imperceptible level of noise, When a once-per-rev empirical force was then adjusted in the dynamic solution, this signature virtually disappeared.

GSFC and CSR have derived a succession of improved force models from the TOPEX/Poseidon data. These include a tuned "box-and-wing" spacecraft macromodel for drag and radiation effects, and several gravity model updates. It is telling that, without exception, when a refined dynamic model has been introduced, recomputed dynamic orbits have moved closer to reduced dynamic orbits. Early GSFC and CSR SLR/DORIS orbit solutions employing the prelaunch gravity (JGM - 1) and macro-models differed in altitude from the reduced dynamic GPS solutions by 6-7 cm RMS. GSFC's tuned macro-model brought this down to about 5 cm. A new GSFC gravity model (JGM-2), tuned with laser and DORIS data, reduced this to about 3.5 cm. A later gravity model, tuned by CSR with 30 days of GPS data, has brought the RMS altitude agreement between laser/DORIS dynamic solutions and GPS reduced dynamic solutions to about 2.5 cm. Moreover, the GPS-tuned gravity model has markedly reduced systematic geographic orbit differences that were prominent even with JGM-2.

While the dynamic and reduced dynamic agreement is close, we note that so long as significant dynamic model errors (drag, gravity, thermal, solar) remain, a well tuned reduced dynamic solution should in theory do better. TOPEX altimeter crossover residuals (Christensen et al, 1993; Yunck et al, 1993), which are dominated by ocean variability, are slightly but consistently lower using the reduced dynamic solutions. The reduced dynamic technique has itself been refined over time, as illustrated by the agreement on overlaps of consecutive 30-hr solutions. Early solutions agreed in altitude to about 5 cm RMS on the overlaps. Tuning of the stochastic force constraints, refinement of ths GPS satellite orbit solutions, and other strategy tweaks have brought this to about 1 cm, with some full 10-day cycles (9 overlaps) averaging 6-7 mm.

Discussion and Conclusions

While the current estimated altitude accuracy of 3 cm RMS surpasses our expectations, a number of improvements can yet be made. These include updating the tidal models and the GPS satellite maneuver and phase center models, adding site- and elevation-dependent data weighting, extending the GPS satellite solution arcs, and adding empirical force adjustments to the GPS orbit solutions.

One clear message from these results is that both the dynamic and reduced dynamic techniques are surpassingly accurate on TOPEX/Poseidon because of its high altitude and extensive modeling. But future missions at lower altitudes will face a tougher challenge. Below 700 km, atmospheric drag and gravity errors explode and dynamic orbit solutions become correspondingly less accurate. TOPSAT, for example, proposing to fly at 560 km yet requiring 7 cm RMS altitude accuracy, cannot consider a full dynamic approach. Reduced dynamic tracking can, in principle, sustain few-centimeter accuracy down to the lowest altitudes. Figure 7 shows the projected POD accuracies for ground-based and GPS tracking as a function of altitude, assuming a 12-channel GPS receiver and full sky field of view. (At 800 km a full field of view will see 13-17 GPS satellites continuously.) In addition to TOPSAT missions such as TOPEX Follow-on, GAMES for geopotential fields studies, GP-B and STEP for relativity, and EOS all could benefit both scientifically and operationally from GPS.

The GPS experiment has demonstrated that the production of operational precise orbits from the GPS POD system will be significantly cheaper than any of the tracking alternatives - fewer ground stations and people are required. Extensive automation in data handling, and synergies with related NASA Earth Science and Space Communications programs (e.g., deployment of a global receiver network; high volume data analysis), have kept the recurring costs of GPS tracking and the marginal cost to support an additional mission exceptionally low.

While the GPS advantage for missions like TOPSAT is evident, full implications go deeper. GPS enables a new class of low-cost and low-orbit altimetry missions. Centimeter tracking at lower altitudes allows the use of low-power, solid-state, dual-band, altimeters. For a given precision, the required altimeter radiated power varies as the fourth power of altitude. Lower power enables smaller solar arrays on smaller satellites that are launched by smaller launch vehicles. Altimetry missions like TOPEX follow-on, and EOS ALT can be significantly cheaper because of GPS.

With NASA and its international partners now planning a series of ocean altimetry missions into the next century, the lessons of the TOPEX/Poseidon GPS experiment could not be more timely. This experiment sets a standard in both POD accuracy and operational efficiency that planners of future missions will do well to heed.

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References

Christensen et al, submitted to JGR, 1993.

Blewitt, G.,M.B. Heflin, K.J. Hurst, D.C. Jefferson, F.H. Webb, and J.F. Zumberge, Absolute far-field displacements from the 28 June 1992 Landers earthquake sequence, *Nature, 361,340-342, 1993*

Schutz et al, GRL, this issue,

Wu, S. C., T.P. Yunck, and C.L. Thornton, Reduced-Dynamic technique for precise orbit determination of low Earth satellites, *J. Guid., Ctrl, and Dyn.*, 14, No. 1, ,24-30, 1991.
Young et al, GRL, this issue.

Yunck et al, GRL, this issue.

Fu, L.-L., E. J. Christensen, and M. Lefebvre , 1991: TOPEX/Poseidon: The Ocean Topography Experiment, Eos, Trans. Amer. Geophys. Union, Vol. 72, No. 35, pp. 369-373.

Nouel, F., J. Bardina, C. Jayles, Y. Labrune, and B. Truong, DORIS: A precise satellite positioning doppler system, Astrodynamics 1987,65, Adv. Astron. Sci., J. K. Solder et al. (eds), 311-320, 1988.

FIGURES:

1 GPS CONSTELLATION PLUS TOPEX
2. TRACKING SYSTEM ELEMENTS.
3. TOPEX/Poseidon S/C WITH MAST
4. GPS GLOBAL TRACKING NETWORK FOR TOPEX
5. DYN VS RED DYN TRADE OFF ?
6. Reduced dyn result plot.
7. POD ACC VS ALTITUDE

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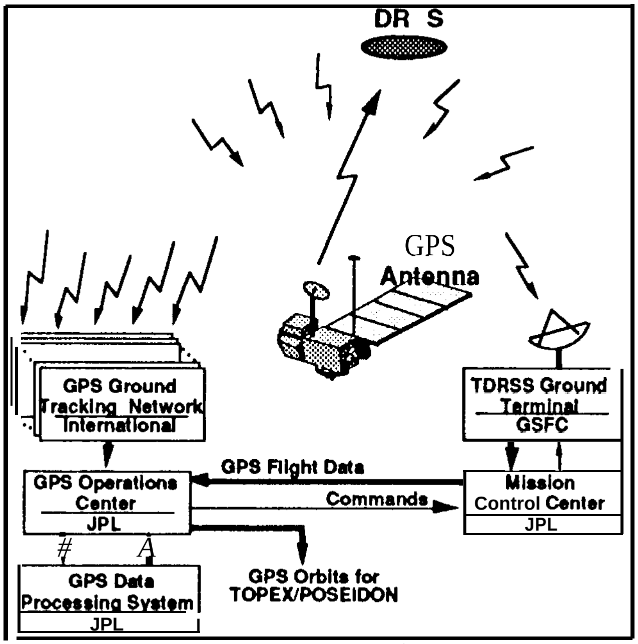

Figure 1. GPS tracking system for 10PEX POD.

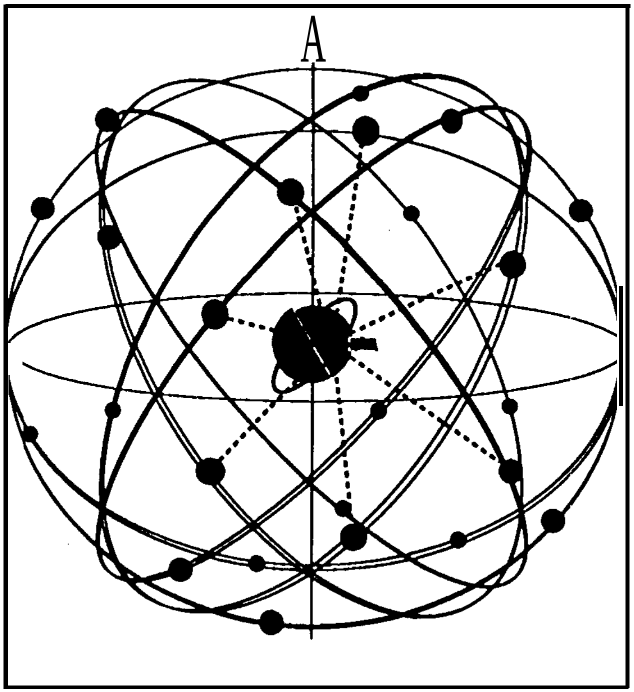

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Figure 3. TOPEX Spacecraft

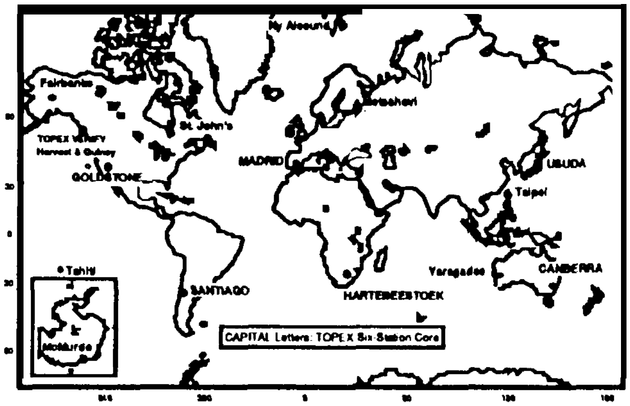

Figure 4. GPS global tracking network for TOPEX. Stations are part of the larger IGS network for Geodynamics programs

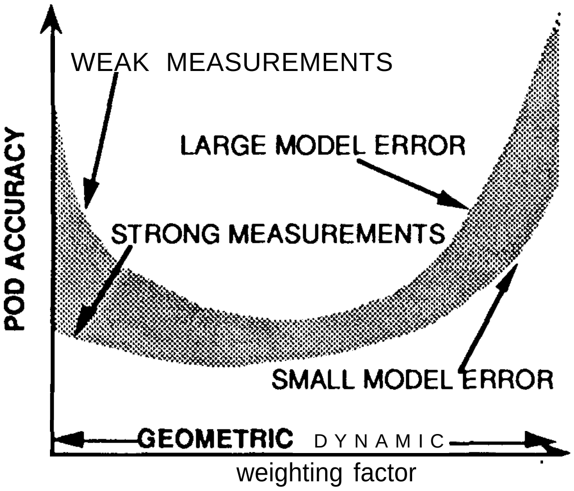

Figure 5. POD accuracy band versus weighting strategy. Optimum depends on model and measurement strengths.

Figure 6. radial results with red dyn vs dyn

Figure 7. Estimated POD accuracy versus orbit altitude.