GPS Precision Orbit Determination: Measured Receiver Performance

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Abstract The TOPEX/Poseidon satellite was launched on 10 August 1992. Its mission is to map the time-varying topography of the world's oceans. The GPS Demonstration Receiver (GPSDR) is carried as a flight experiment to demonstrate the use of GPS for Precision Orbif Determination (POD). 1 he Motorola-developed GPSDR is the first dual-frequency GPS receiver to be applied to POD.

An international tracking network with six to sixteen GPS receivers is used to provide continuous mutual visibility of GPS satellites with TOPEX/Poseidon. The ground network consists of Rogue and TurboRogue receivers developed at JPL to satisfy NASA's requirements for high-performance dual-frequency ground receivers. Choke-ring antennas and special on-receiver processing are used to reduce multipath at the ground sites.

T his paper describes the pre-mission testing used to determine the performance of receivers and antennas, and gives results of in-flight data collection. Some operational problems which resulted in loss of flight data are described, GPS tracking is currently providing sub-decimeter determination of the vertical component of the TOPEX/Poseidon orbit.

Introduction

Achieving accurate GPS-based orbits for an earth satellite requires precise radiometric observable. For TOPEX/Poseidon, accuracy has been achieved through careful design and calibration of the equipment involved. In certain cases it has been possible to validate pre-flight calibrations and analytical estimates of performance with post-launch data. 1 he equipment involved in the GPS POD system includes: the flight receiver, the flight antenna and the 4.3-meter boom that supports it, the 6 to 16 receivers in the ground network and their antennas. All of the receivers in the ground network are Rogue or TurboRogue receivers, each using the same antenna type, T he accurate observable and lack of cycle slips from those receivers facilitate automated processing of the large amounts of data obtained each day.

While the flight receiver and ground antennas do not meet all of the accuracy targets established at the outset of the design effort for TOPE. X/Poseidon, results to date do demonstrate the utility of GPS for high-accuracy orbit determination. The GPS system is providing data for determining orbits with sub-decimeter accuracy.

Summary of Required Performance

The most important goal of the GPS POD experiment is to determine TOPEX/Poseidon altitude with sub-decimeter accuracy. This system-level goal places requirements on the GPS receivers and antennas used on the spacecraft and in the ground network. To provide few-cm positions, the most important requirement is to measure carrier phase with 1-cm or better accuracy. Pseudoranges with cm (decimeter) accuracy were specified for the ground (flight) receivers. Accurate pseudorange allows automated data processing techniques to be used on the large volumes of data that must be handled. The availability of high-quality pseudorange also enables accurate real-time navigation, and provides another data type for validation and enhancement of the carrier phase solutions for the satellite orbit. Requirements for accuracy and precision are given below in tables 1 and 2.

Ground Receiver Performance Verification; Techniques and Results

A variety of techniques were used to validate the design and performance of the Rogue and Turbo Rogue receivers. These included analysis, and realistic computer tests of signal-processing algorithms using simulated signals buried in noise. Bench tests followed to confirm the analysis and simulations, and to validate the performance of analog components. The following bench tests were done:

1. Signals with accelerations up to 8 g were tracked.
2. Output SNR was measured over a range of known input SNR's.
3. Amplitude and phase of the baseband filters were measured vs baseband frequency offsets.
4. Delay, phase and phase-rate errors were measured vs SNR.
5. Noise correlation was measured between lags, and between Reaf and Imaginary channels.
6. Pseudorange errors were measured as a function of Doppler and feedback error.
7. Downconverler phase drift between the L1 and L2 channels was measured.
8. Pseudorange and phase observable were compared in code vs codeless modes, by tracking the same GPS satellite simultaneously in each mode on separate channels
9. Pseudorange performance was determined through comparison with the much more precise carrier phase measurements.

In addition to bench testing, both single antenna (zero baseline) and short baseline tests were done to verify intrinsic receiver precision. Repeatability of 0.1 mm in each component was demonstrated for five measurements of a 20 m baseline. The target and measured ground receiver precision and accuracies are given in Table 1.

Flight Receiver Performance Verification; Techniques and Results

Because of the demonstrated accuracy and precision of Rogue receivers, they were used to quantify flight receiver performance using zero baseline tests. Figure 1 shows the zero baseline configuration used for these measurements.

The required and measured flight receiver precision and accuracies are **given in Table 2**.

Systematic P2 pseudorange errors exceed specifications due to truncations and other arithmetic errors in the signal processing hardware. Figure 2 shows flight data that illustrate systematic variations of the P2 pseudorange with received Signal-to-Noise Ratio (SNR). These data match the results of pre-launch zero baseline testing. The effects of similar errors in PI have already been corrected by modifications to receiver software. Formal errors for pseudorange observable have been appropriately adjusted in the POD solutions.

Design 1 rade-offs for Flight and Ground Antennas

T he flight and ground antennas were designed to satisfy quite different criteria. The flight antenna must allow satellites to be tracked to low elevation angles, so the maximum number of satellites would be available, with good geometric separation among those tracked. The specification was for a gain of at least -2 dBiC (dB relative to isotropic for circular polarization) at the L1 frequency, and at least -7 dBiC at the L2 frequency, for elevation angles above 10°, A drooping crossed-dipole was used, mounted on a 30 cm choke-ring backplane to electrically decouple the antenna from structures below the antenna. In order to reduce multipath, and blockage from the 1.5-meter TDRSS antenna, the GPS antenna was mounted on a boom 4.3 m above the spacecraft body, so that reflected GPS signals would be directed to the backside of the antenna, where gain is minimal.

The ground receivers will acquire and track with lower signal levels. Therefore, we optimized the antenna/backplane design for low multipath with a sharp gain cutoff and careful retention of right circular polarization at low elevations [Young, Meehan and Spitzmesser, 1988]. In order to further reduce the effects of multipath at ground sites, software was developed for the Rogue and TurboRogue receivers which uses the measured cross-correlation shape to reduce pseudorange multipath [Meehan and Young, 1992]. The RMS of P-code multipath was targeted for less than 5 cm with 30-minute smoothing, and less than 30 cm with 5-minute smoothing.

The location of the phase center of the flight and ground antennas needed to be calibrated with an accuracy of 0.5 cm.

Antenna Phase Center Measurement Technique

In addition to having the required gain characteristics, an antenna must have known phase response to be useful for precision GPS measurements. An ideal GPS antenna would behave as if its location were a single point, the phase center. Signals arriving at such an ideal antenna would exhibit carrier phases proportional to the geometric distance between the signal source and the phase center. In reality, the GPS antennas have dimensions comparable to the wavelengths they are intended to receive and so behave quite differently than a point. The manifestation of this behavior is a phase shift imparted to incoming signals, which varies as a function of the direction to the source. In order to calibrate phase biases which are systematic with GPS satellite elevation, and thus map into orbit solutions, these phase variations must be measured,

Phase calibration measurements were made at JPL in April and May of 1992 [Dunn and Young, 4/92 & 9/92]. A unique antenna range instrumentation system was used which allowed accurate quantification of the effects of multipath on the phase center measurements, The carrier phases of a 10-MHz PN-code modulated on L1 and L2 RCP carriers were measured by a modified GPS receiver, after being received by the antenna under test. The data points thus obtained were used to obtain the centers of the best-fit spheres for the L1 and L2 response of each of the antennas under test. Only data above 15° elevation was used in the fit. Finally, a regularized table of residuals from each of these spheres was reported every 5° in azimuth and elevation [ibid.],

Flight Antenna Phase Center

The L1 and L2 phase residuals measured for the flight antenna are displayed in Figure 3. The variation between 15° elevation and 90° is 3.3 cm at L1 and 1.8 cm at L2. The azimuth angle is measured from the spacecraft X axis and increases in the counter-clockwise direction when the antenna is viewed from above (looking in the direction of the +Z axis). Zenith angles are measured from the normal of the GPS boom-antenna interface. The L1 phase calibration has a worst-case systematic error of .40 cm and a random error of 0.29 cm. For L 2, systematic and random errors were 0.56 cm and 0.23 cm.

These phase residuals are the differences in measured phase from those that would be obtained by an ideal point-like antenna located at a physical point, the phase center, on the spacecraft. The location of this point for L1 is (2.1 087 m, -0.4589 m, -4.6125 m) in spacecraft coordinates. For L2, the phase center falls at (2.1081 m, -0.4591 m, -4.6642 m). If the phase residual calibration is not used, however, the intrinsic phase variation of the antenna introduces a 2 to 3 cm RMS systematic error which is primarily a function of the elevation angle to the GPS satellite.

Ground Antenna Phase Center

A representative ground antenna was also measured. Due to space limitations, the phase response of the ground antenna is not presented here, The total variation between 15° and 90° was 1 cm at L1 and L2 frequencies. The phase center of the ground antenna was found to be 1.66 cm above the face of the choke rings at L1 and 4.33 cm at L2, on the symmetry axis of the antenna. The error in each phase center measurement was 4 mm.

Multipath From F-light and Ground Antennas

Figure 4 shows PI multipath during a track in which, near the center of the interval displayed, the GPS signal is reflected from a satellite surface, leading to meter-level multipath. Notice the characteristic temporal coherence between amplitude and delay variations during the period of strong multipath. The RMS multipath during typical tracks is 10 cm with 100 second smoothing.

F'-code multipath at the ground sites had RMS values of 12 cm for 5-minute smoothing, and 8 cm for 30-minute smoothing. This meets the target of 30 cm for 5-minute smoothing, but does not meet the target of 5-cm for 30 minute smoothing.

Flight Receiver Data Acquisition Performance

The flight receiver requires an initial upload from the ground to load ephemerides and to set the receiver clock. Once initialized, it is designed to operate autonomously, using TOPEX/Poseidon position solutions and GPS ephemerides to generate estimates of Doppler to aid GPS acquisition. The receiver calculates GPS view periods, and a set of 6 is chosen based on length of track , mutual visibility with ground stations, and geometric strength. If 6 GPS satellites are not available, the receiver assigns multiple channels to track the same satellite. On a typical day, each channel was locked to a satellite for 980/. of the time, with about 2% spent in acquisition.

The demonstration phase of the GPS POD experiment began on 2 November 1992. In 146 days when P-code data have been available since then, only 21.1 hours of data have been lost.

During the start-up phase, which lasted from 10 August 1992 until 2 November 1992, problems were identified in ground control and in the data from the GPS satellites. On 5 occasions during startup, P-code data were lost for at least parts of 22 days.

Lack of an autonomous receiver initialization scheme caused delays in the initial and one of the subsequent receiver start-ups when incorrect GPS and TOPEX/Poseidon almanacs were uploaded. Verification tests have been added for almanac uploads to prevent future occurrences of this problem,

Two types of bad data were received from the GPS constellation. Both erroneous ranging codes and GPS ephemeris errors caused the loss of parts of 7 days of data, totaling 127 hours. While the flight receiver was designed to check the parity of incoming GPS data bits, the experienced severity of GPS-signal errors was not anticipated. A test of pseudoranges and ephemerides has been added which differences observed and model ranges. If this difference exceeds a limit, the data from that satellite is rejected for the on-board position solution, Data from all satellites tracked, however, are transmitted to the ground for post processing. Additional tests of observable, and of both GPS and TOPEX/Poseidon ephemerides, will be implemented if necessary.

In one case, the flight receiver failed to start for unknown reasons, resulting in the loss of 23 hours of data, An additional 16 hours have been used for flight receiver maintenance.

Modifications made to the flight software during the start-up period account for the reliable operation of the receiver during the demonstration phase. Since 2 November 1992, data were lost during only two occasions, when pseudorange or ephemeris data were in error but within the test limits of the cm-receiver tests.

Close watch is maintained on the flight receiver as well as on the status of GPS satellites. The receiver data is monitored in real time approximately 6 times a day and each full day's data is analyzed the following morning. When excessive receiver restarts were required due to a GPS satellite. PRN 11, that satellite was removed from the list of available spacecraft to track. An additional monitor of the GPS constellation is provided by a ground receiver in continuous operation at JPL.

On-board Navigation Solution

The on-board position solution is used to provide Doppler predicts for GPS satellite acquisition, and to provide the time tag correction for observable data. This time tag correction is required to be within 0.5 μseconds, which is typically met. The time tag is used in the precise orbit determination to align observations which are double difference with ground-receiver observable. Ground processing also uses the on-board position solution to provide a-priori TOPEX/Poseidon positions to initialize the precision orbit solution. During times when valid data are received from 4 or more satellites, the real-time position solution agrees with the post-fit precise orbit to about 100 m rms.

Conclusion

Both flight and ground GPS receivers have produced high quality data with good reliability. These data provide a successful demonstration of the ability of GPS to provide precision orbits, as required for altimetric missions like TOPEX/Poseidon, and for future gravity field mapping missions. Readily accomplished plans exist for improving both the accuracy and reliability of GPS satellite tracking, using the valuable experience provided in this first flight demonstration.

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I-ABLE 1. Ground Receiver Errors (cm)

	Target	Measured
Systematic (L 1 & L2)	0.1	< 0.1
Random (1 see) (LI & L2)	0.1	< 0.1
Systematic (PI & P2)	2.0	1.0
Random (10 see) (P1& P2)	6.3	3.2

TABLE 2. Flight Receiver E rrors (cm)

	Required	Measured
Systematic (L 1 & 1.2)	0.5	< 0.5
Random (1 see) (L1 & L2)	1.0	0.2
Systematic (PI)	10.0	10.0
Systematic (P2)	10.0	30.0
Random (10 see) (P1 & P2)	19.0	16.0

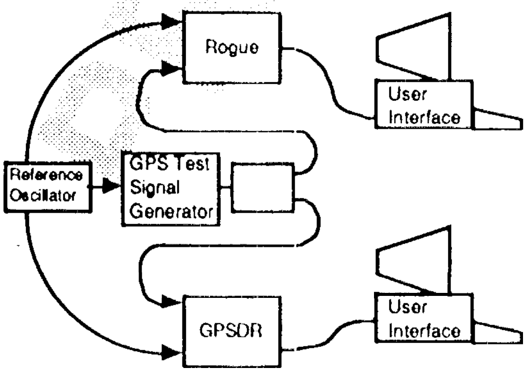

Fig. 1. In a zero baseline test, the same signal is input to the receiver under test and to a reference receiver. The signal can come from a GPS simulator or an antenna. Both receivers use the same frequency reference.

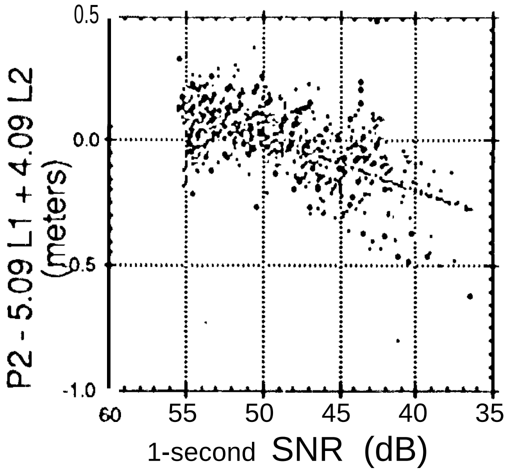

Fig. 2. P2 systematic error is plotted as a function of SNR. The P2 error is formed from the linear combination which removes the effects of geometry, clocks, and ionosphere, leaving primarily multipath, along with system noise and systematic errors. The effects of multipath and system noise are reduced by averaging over 100 seconds.

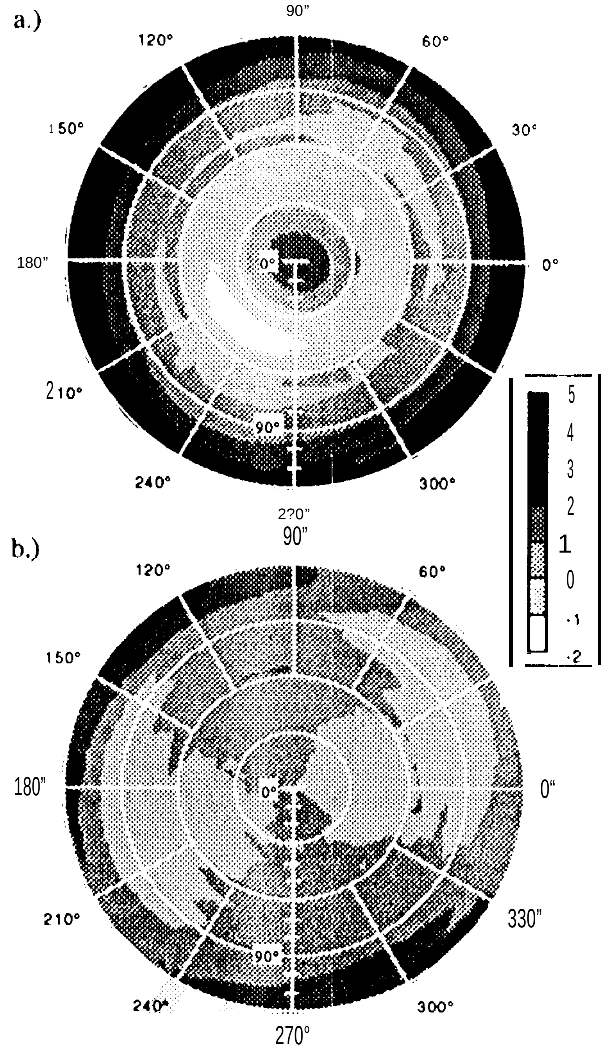

Fig 3a: L1 Phase response of the TOPEX/Poseidon flight GPS antenna. Contour values are in cm. Positive residual phase corresponds to added effective path length. b: 1 he same for L2.

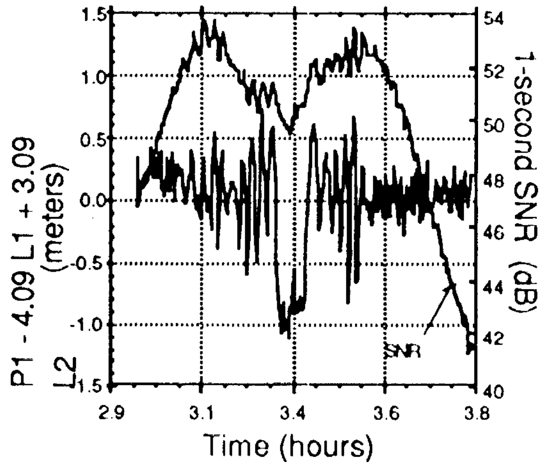

Fig. 4. PI multipath and SNR taken from flight data are shown vs time, The multipath observable is the linear combination of pseudorange and carrier phase observable which removes the effects of geometry, clocks, and ionosphere, leaving primarily multipath, along with system noise and systematic errors. Ten second data points are plotted.