TOPEX/POSEIDON Operational Orbit Determination Results Using Global Positioning Satellites

J. Guinn, J. Jee, P. Wolff, F. Lagattuta, T. Drain, and V. Sierra
Navigation Systems Section

Results of operational orbit determination, performed as part of the TOPEX/POSEIDON (T/P) Global Positioning System (GPS) demonstration experiment, are presented in this article. Elements of this experiment include the GPS satellite constellation, the GPS demonstration receiver on board T/P, six ground GPS receivers, the GPS Data Handling Facility, and the GPS Data Processing Facility (GDPF). Carrier phase and P-code pseudorange measurements from up to 24 GPS satellites to the 7 GPS receivers are processed simultaneously with the GDPF software MIRAGE to produce orbit solutions of T/P and the GPS satellites. Daily solutions yield subdecimeter radial accuracies compared to other GPS, LASER, and DORIS precision orbit solutions.

I. Introduction

The Global Positioning System (GPS) Data Processing Facility (GDPF) was developed to demonstrate operational orbit determination and navigation support for TOPEX/POSEIDON. Orbit solutions are based on data collected by the GPS demonstration receiver (GPSDR) on board TOPEX/POSEIDON and six ground receivers. In addition, the GDPF is intended to evolve into a NASA resource for future low Earth-orbiting missions under the NASA Office of Space Communications.

An updated software set, based on the JPL institutional Orbit Determination Program (ODP), was created and named "MIRAGE." It stands for Multiple Interferometric Ranging Analysis using GPS Ensemble. MIRAGE maintains the complete interplanetary capability of the ODP software with the additional multisatellite and precision modelling features required for subdecimeter orbit determination. The GDPF scope of work includes preprocessing observations, performing orbit determination, producing predicted GPS and TOPEX/POSEIDON satellite almanacs for mission operations, and archiving raw and processed data. Figure 1 shows the interfaces of the GDPF.

II. Observation Preprocessing

Daily TOPEX/POSEIDON flight receiver raw data are collected from the TOPEX/POSEIDON ground system within 24 hours of the last observation. The raw data consist of carrier phase every second and P-Code pseudorange every 10 sec. In addition, the GPSDR onboard navigation solution (i.e., clock, position, and velocity) are provided every 10 sec. Descriptions of these observables can be found in many publications [1,2].

Automated reformatting and outlier and cycle slip editing are performed first. Next, the data are decimated to 5-min intervals, and a time-tag correction, based on a linear fit to the navigation clock solution, is applied. Finally, linear combinations of the pseudorange (P_1 and P_2) and carrier phase (L_1 and L_2) dual-frequency measurements are computed to produce ionosphere calibrations. These are applied to the raw P_1 and L_1 observations to produce the orbit determination observables P_C and L_C.

The ground GPS receiver observations are available from the GPS Data Handling Facility about 36 hr after the last data are collected. Both the carrier phase and pseudorange data are provided in receiver-independent exchange (RINEX) [3] format at 30-sec samples. The same editing and calibration steps are performed as described above for the GPSDR. Besides the six core ground sites, data from nine backup sites are also collected and processed. The primary and backup ground receiver locations are shown in Fig. 2.

For MIRAGE orbit determination processing, a merged file of edited GPSDR and ground receiver data is created in standard MIRAGE format. Two additional text files, in RINEX format, are produced for export. One is the raw GPSDR data while the other is the edited, calibrated, and compressed GPSDR measurements. All files are archived along with data collection and preprocessing statistics.

III. Orbit Determination Strategy

Thirty-hour data sets are constructed from the preprocessed observations to produce a 24-hr orbit solution. The additional data are fit to allow for internal consistency checks of the daily overlaps. Global GPS constellation coverage is realized by selecting a minimum of six ground station GPS receiver sites. Additional sites are selected to fill gaps during primary site outages.

Orbit determination using MIRAGE consists of three major steps. Iteration through each step is done until convergence of the state solutions and observation residuals is achieved. The three steps are

(1) Trajectory propagation.

(2) Observation processing.

(3) Filtering and smoothing.

A. Trajectory Propagation

To achieve subdecimeter accuracies, several dynamic force models are required. Tables 1 and 2 summarize the force models used in the numerical integration of the TOPEX/POSEIDON and GPS satellite trajectories. Reference frame, force, and measurement model parameters are based on TOPEX/POSEIDON and International Earth Rotation Service (IERS) standards [4].

B. Observation Processing

Both carrier phase and P-Code pseudorange data are processed. Table 3 lists the measurement models used for producing observation residuals. Again, these models are based largely on IERS standards.

C. Filtering and Smoothing

The filter and smoother generate corrections to the parameters affecting the trajectory propagation and the observation processing. MIRAGE employs a numerically stable square-root information filter that can compute smoothed estimates of time-varying stochastic parameters. Our orbit determination strategy employs a fiducial concept where three ground receivers, assumed to have well-known coordinates, are held fixed while the filter estimates the positions of three nonfiducial ground stations [5]. In addition, the states of the GPS satellites and TOPEX/POSEIDON are estimated along with the GPS satellite solar-pressure model parameters. The filtering strategy consists of a two-stage process—dynamic tracking followed by reduced dynamic tracking. In dynamic tracking, the accuracy of the orbit is limited by the precision of the dynamic models applied during trajectory propagation. In reduced dynamic tracking, the high-quality geometric information provided by the GPS measurement system is used to obtain a high-precision TOPEX/POSEIDON trajectory. Essentially, reduced dynamic tracking exploits the extreme precision of carrier phase tracking by using it to smooth the geometric solutions obtained from the less-precise pseudorange measurements. Although the success of the reduced dynamic technique is contingent on high-precision modeling of the GPS observations, the accuracies of the resultant trajectories are not degraded by deficiencies in the a priori dynamical models.

1. Data Weighting. The measurement precisions expected from the GPSDR and ground receiver observations were determined from ground tests before launch. Data weights consistent with these analyses and applied during filtering are shown in Table 4.

2. Stochastic Clock Estimation. To eliminate synchronization errors due to unstable oscillators, clock biases at the receivers and GPS transmitters are estimated at each measurement time. In the filter, one ground clock is chosen as a reference and a stochastic clock bias is estimated at each of the other receivers and GPS transmitters. A white noise stochastic process is employed with a batch length coinciding with the measurement intervals and the estimated smoothed clock biases are fed back to the observation processing module. As with standard double differencing techniques, the stochastic clock estimation strategy eliminates common clock errors. However, the stochastic method avoids both the difficulties of selecting a set of nonredundant double-difference combinations and the data noise correlations inherent in differenced measurements.

3. Stochastic Phase Bias Estimation. The continuously tracked GPS carrier phase precisely measures the relative range change between a GPS transmitter and its receiver. However, the carrier phase is ambiguous, which requires the estimation of a constant phase bias for each continuous pass between a transmitter and a receiver. In the filter, each phase bias is estimated as a white noise stochastic parameter that remains constant over a pass. At tracking discontinuities, the filter applies a white noise stochastic update for the bias parameter corresponding to an individual transmitter–receiver pair. The smoother generates a time profile of phase bias corrections that are applied during subsequent observation processing. This stochastic phase bias estimation strategy is efficient in terms of computation time and memory requirements, but does not attempt to resolve the integer nature of the phase biases.

4. Stochastic Estimation of Tropospheric Fluctuations. The model for troposphere delay is decomposed into a wet and a dry component.

$$\rho = \rho_{Z_d} R_d(\theta) + \rho_{Z_w} R_w(\theta)$$

where ρ_Z is the zenith delay and R is a mapping function that maps the zenith delay to the line of site at elevation θ. The fluctuations in the wet zenith delay are modeled as a stochastic random walk. The wet zenith delay is estimated at 5-min intervals (coincident with the measurement interval) using an a priori sigma of 5 cm and an effective batch-to-batch sigma of 3 mm for the noise driving the random walk process. As with the phase and clock biases, the smoothed time profiles of the stochastic fluctuations are fed back into the observation processing module on subsequent iterations of the orbit determination program.

5. Reduced Dynamic Tracking. The MIRAGE filter executes the reduced dynamic tracking strategy by modeling the three-dimensional accelerations on TOPEX/POSEIDON as exponentially time-correlated stochastic processes. The relative weighting of the dynamics and geometry may be adjusted by varying the time constant and the magnitude of the process noise uncertainty. A large time constant corresponds to a dynamic strategy while a short time constant emphasizes the geometry. In the orbit determination for TOPEX/POSEIDON, the three accelerations were updated at 5-min intervals; the time constant was 15 min with a corresponding batch-to-batch sigma of 7×10^{-9} m/sec^2 for the radial acceleration and 14×10^{-9} m/sec^2 for the spacecraft X and Y accelerations. This choice of filter parameters allowed deficiencies in the nongravitational force models to be compensated for by the stochastic accelerations; however, enough dynamical information is retained so that temporary degradation of the viewing geometry would not seriously reduce the accuracy of the output trajectory [6,7,8]. A summary of estimated parameters is given in Table 5.

IV. Orbit Determination Accuracy

Before launch, the MIRAGE software was intercompared with the GEODYN and UTOPIA software sets from the Goddard Space Flight Center (GSFC) and the University of Texas Center for Space Research (UTCSR), respectively. The intercomparison validated all dynamic trajectory models for TOPEX/POSEIDON and verified the laser range measurement models. For all cases, including the combined models case, the maximum radial differences were approximately 1 cm or less for a 10-day orbit. An additional intercomparison with the UTCSR GPS software MSODP to validate trajectory models for the GPS satellites was performed. All but the occulting solar radiation pressure produced subcentimeter, 10-day orbit comparisons. The solar radiation pressure intercomparison tests have been postponed due to the expected release of improved models.

After launch, the operational orbit determination accuracies have steadily improved as the procedures and techniques have been fine-tuned. Accuracy comparisons are broken into three distinct processing phases. The dates and groundtrack repeat cycles for each are presented in Table 6.

Data prior to cycle five were not considered for this analysis due to difficulties in the early days of the GPSDR plus the occurrence of several anti-spoofing days. Phase 1 processing was performed before most internal and external consistency checks (see below) were used; thus, it is not representative of the achievable accuracies. Phase 2 processing used 24-hr arcs with the dynamic technique augmented with empirical once- and twice-per-revolution parameters. Phase 3 consisted of 30-hr arcs with the additional reduced dynamic tracking strategy.

Statistics collected for the GPS carrier phase residuals (observations minus computed values) are presented in Fig. 3. These residuals are from phases 2 and 3 only. A marked reduction in the residuals is seen when the reduced dynamic technique is employed. Most of the gaps are due to GPS constellation anti-spoofing activity when no GPSDR data were available. Only 15 days of outage are associated with GPSDR software problems.

TOPEX/POSEIDON orbit comparisons have displayed subdecimeter agreements in the radial component with 1-day GPS precision orbit determination (POD) solutions and orbits derived from satellite LASER range (SLR) and Doppler orbitography and radiopositioning integrated by satellite (DORIS) data. Figures 4 and 5 show the three-dimensional and radial rms orbit differences during phases 2 and 3. The MIRAGE dynamic solutions are compared with dynamic solutions determined from laser data. These laser solutions are based on 10-day fits from GSFC's GEODYN program. In Fig. 5, the MIRAGE reduced dynamic solutions are compared. They are compared with another reduced dynamic solution from the GPS GIPSY-OASIS software that is part of the GPS Demonstration Experiment POD segment.

V. Processing Automation and Error Checking

One goal of the GDPF was to automate as much of the processing as possible. Beginning with the data collection through the delivery of final products, each aspect of the processing was examined and automated by means of standard Unix scripts and X-window interfaces to the scripts. Dashed lines in Fig. 1 denote automatic procedures that do not require human intervention. User inputs changing from day to day, such as the date, duration, and transmitting and receiving participants, are controlled via a graphical X-window interface that eliminates user input errors and ensures operational consistency. Error mail messages are generated to alert operators of malfunctions in the automated noninteractive scripts.

VI. Off-Nominal TOPEX/POSEIDON Attitude Modelling

Robust processing of off-nominal TOPEX/POSEIDON satellite attitude events is available in two ways. First, the actual attitude event change times (e.g., fixed to sinusoidal yaw steering event) are designed as user inputs. Secondly, the trajectory processing can use the attitude quaternions from telemetry. So far, all attitude events, except orbit maintenance maneuvers, have been accurately modelled with the user input overrides. The actual telemetry was required only for the maneuver.

VII. SLR and DORIS Data Types

In addition to the GPS P-code pseudorange and carrier phase observables, the MIRAGE software can process SLR and DORIS data. SLR and DORIS data types were incorporated to support TOPEX/POSEIDON verification activities. The SLR orbits are included in the Interim Geophysical Data Records (IGDR) science product [9]. Orbit file formats are identical for all data types (i.e., PFILE format); therefore, no interface changes are required for IGDR processing with MIRAGE GPS orbits. A utility has also been developed as part of the MIRAGE software to convert any MIRAGE orbit file into the precision orbit ephemeris (POE) format.

VIII. TOPEX/POSEIDON Mission Operations Support

A routine GDPF task is to produce GPSDR almanac predictions for initial acquisition operations. Almanac data are produced twice weekly as a contingency for rapid GPSDR failure recovery. The data are delivered to the Spacecraft Performance Analysis Team for reformatting and subsequent uplink to the GPSDR by the Flight Control Team.

IX. GPS Anti-Spoofing Results

During GPS constellation anti-spoofing activities, only Clear-Acquisition (CA) code pseudorange and L_1 carrier phase data are available from the GPSDR. However, an internal receiver calibration provides for an ionosphere correction to the ground receiver data. Preliminary tests have produced subdecimeter radial differences for limited sets of data by producing an approximate ionosphere calibration. This calibration is derived by subtracting the carrier phase measurements from the CA-code pseudorange measurements and smoothing the resulting signal to remove the multipath signal. This yields an ionosphere correction that can then be applied to both the CA-code pseudorange and carrier phase data.

X. GDPF Resources

Required GDPF resources in terms of personnel, computer time, and actual time to produce a 1-day (30-hr) solution are given in Table 7. Members of the operational orbit determination team work on a five-day-per-week schedule. Weekend backlogs are eliminated during this schedule. The totals given in Table 7 are for one team member per workstation. Continuous operation of the GDPF required a total of three members. The breakdown of tasks for the GDPF team is shown in Table 8. With the automation developed thus far, a single person could easily handle nominal production. The remainder of the team consists of backups, a lead, and sustaining hardware maintenance personnel.

XI. Conclusions

Operational orbit determination has been demonstrated for TOPEX/POSEIDON using the GPS constellation (20 to 24 satellites), the TOPEX/POSEIDON demonstration receiver, 6 ground receivers, the GPS Data Handling Facility, and the GPS Data Processing Facility. Comparisons between the MIRAGE orbit solutions and other precision orbit solutions based on LASER, DORIS, and GPS yield subdecimeter radial results. Both the GPS dynamic and reduced dynamic results from MIRAGE appear to exceed the original performance requirements (approximate 1-m radial position) and give results comparable to other geodetic quality software.

Acknowledgments

The authors would like to recognize the technical contributions of Bobby G. Williams to the overall design and development of the MIRAGE software. Also appreciated were other members of the software development team: Jim Collier, Vic Legerton, Rick Sunseri, and Mike Wang.

References

[1] L. Carson, L. Hailey, G. Geier, R. Davis, G. Huth, and T. Munson, "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.

[2] B. Hofmann-Wellenhof, H. Lichtenegger, and J. Collins, *GPS Theory and Practice*, 2nd ed., New York: Springer-Verlag, 1993.

[3] W. Gurtner and G. Mader, "RINEX: The Receiver Independent Exchange Format Version 2," *CSTG GPS Bulletin*, National Geodetic Survey, vol. 3, no. 3, September–October 1990.

[4] D. D. McCarthy, *IERS Standards*, IERS Technical Note 13, Paris: Observatoire de Paris, July 1992.

[5] B. G. Williams, K. C. McColl, and J. R. Guinn, "Navigation Accuracies for GPS Demonstration on TOPEX/POSEIDON," paper AIAA-90-2940, presented at the AIAA/AAS Astrodynamics Conference, Portland, Oregon, August 20–22, 1990.

[6] W. Bertiger, S. Wu, T. Yunck, R. Muellerschoen, P. Willis, Y. Bar-Sever, A. Davis, B. Haines, T. Munson, S. Lichten, and R. Sunseri, "Early Results From the TOPEX/POSEIDON GPS Precise Orbit Determination Demonstration," paper AAS-93-154, presented at the Third Annual AAS/AIAA Spaceflight Mechanics Meeting, Pasadena, California, February 22–24, 1993.

[7] B. G. Williams, "Precise Orbit Determination for NASA's Earth Observing System Using GPS," in *AAS Advances in the Astronautical Sciences*, vol. 65, San Diego, California: Univelt, Inc., pp. 83–100, 1988.

[8] S. C. Wu, T. P. Yunck, and C. L. Thornton, "Reduced-Dynamic Technique for Precise Orbit Determination of Low Earth Satellites," in *AAS Advances in the Astronautical Sciences*, vol. 65, San Diego, California: Univelt, Inc., pp. 101–113, 1988.

[9] B. G. Williams, E. J. Christensen, P. N. Yuan, K. C. McColl, and R. F. Sunseri, "Short Arc Orbit Determination for Altimeter Calibration and Validation on TOPEX/POSEIDON," in *AAS Advances in the Astronautical Sciences*, vol. 82, San Diego, California: Univelt, Inc., pp. 877–888, 1993.

Table 1. Force models for TOPEX/POSEIDON.

Model	Description
N-body	All planets, Sun, and Moon
Earth geopotential	50 x 50 truncated Joint Gravity Model-2 (JGM-2)
Indirect Earth–Moon Oblateness	2 x 2 lunar model
Solid Earth tides	IERS
Ocean tides	JGM-2
Rotational deformation	IERS
Relativity	Point mass Earth + Lense–Thirring
Solar radiation pressure	Conical shadow model
Atmospheric drag	Drag/temperature air density model
Albedo and infrared Earth radiation	2nd degree zonal model
Empirical accelerations	Once/rev and twice/rev models

Table 2. Dynamic force models for GPS satellites.

Model	Description
N-body	All planets, Sun, and Moon
Earth geopotential	12 x 12 truncated JGM-2
Indirect Earth–Moon oblateness	2 x 2 lunar model
Solid Earth tides	IERS
Ocean tides	JGM-2
Rotational deformation	IERS
Relativity	Point mass Earth + Lense–Thirring
Solar radiation pressure	Rock4 and Rock42 models

Table 3. Measurement models.

Model	Description
Solid Earth tides	0th-, 1st-, and 2nd-order corrections
Rotational deformation (pole tide)	IERS
Ocean loading	IERS
Polar motion	Daily values from University of Texas
Plate motion	Linear velocities
Earth center-of-mass offset	Currently zero

Table 4. GPS observation weights.

Data type	GPSDR	Ground station
Carrier phase, cm	2	1
Pseudorange, m	2	1

Table 5. Estimated parameters.

Parameter(s)	Number of parameters
TOPEX state	6
GPS states (24 satellites average)	144
Station locations (3 ground stations)	9
GPS solar pressure scale factors and Y-bias	72
Empirical dynamic parameters	9
Stochastics: (30-hr arcs with 5-min updates)	
Troposphere (six ground stations)	6
TOPEX and ground clocks (one master clock fixed)	30
Carrier phase biases	~160
TOPEX body-fixed accelerations (X, Y, Z)	3
Total	~439

Table 6. Dates for groundtrack repeat cycles.

Phase	Dates	Cycles
1	November 3, 1992–December 21, 1992	5–9
2	December 22, 1992–May 2, 1993	10–23
3	May 3, 1993–October 28, 1993	24–40

Table 7. GDPF processing performance.

Processing phase	CPU time, hr	Actual time, hr
Data preprocessing[a]		
Collection	0.1	0.1
TOPEX/POSEIDON editing	1.3	1.4
Ground station editing	0.4	0.5
Editing	0.1	0.1
Reformatting	0.1	0.1
Total	2.0	2.2
Orbit estimation (per iteration)		
Initialization	0.1	0.2
Trajectory propagation	0.3	0.3
Observation residual computation	0.5	0.5
Parameter estimation	0.1	0.1
Stochastic parameter smoothing	0.1	0.1
Three-iteration total	3.3	3.6
Archive	0.1	0.2
Total	5.4	6.0

[a] Automated processing performed prior to start of work day.

Table 8. GDPF personnel requirements.

Task	Personnel
Lead[a]	1
Data conditioning	1
Orbit conditioning	1
Hardware maintenance	0.5

[a] Lead will also assist and back up data-conditioning and orbit determination functions.

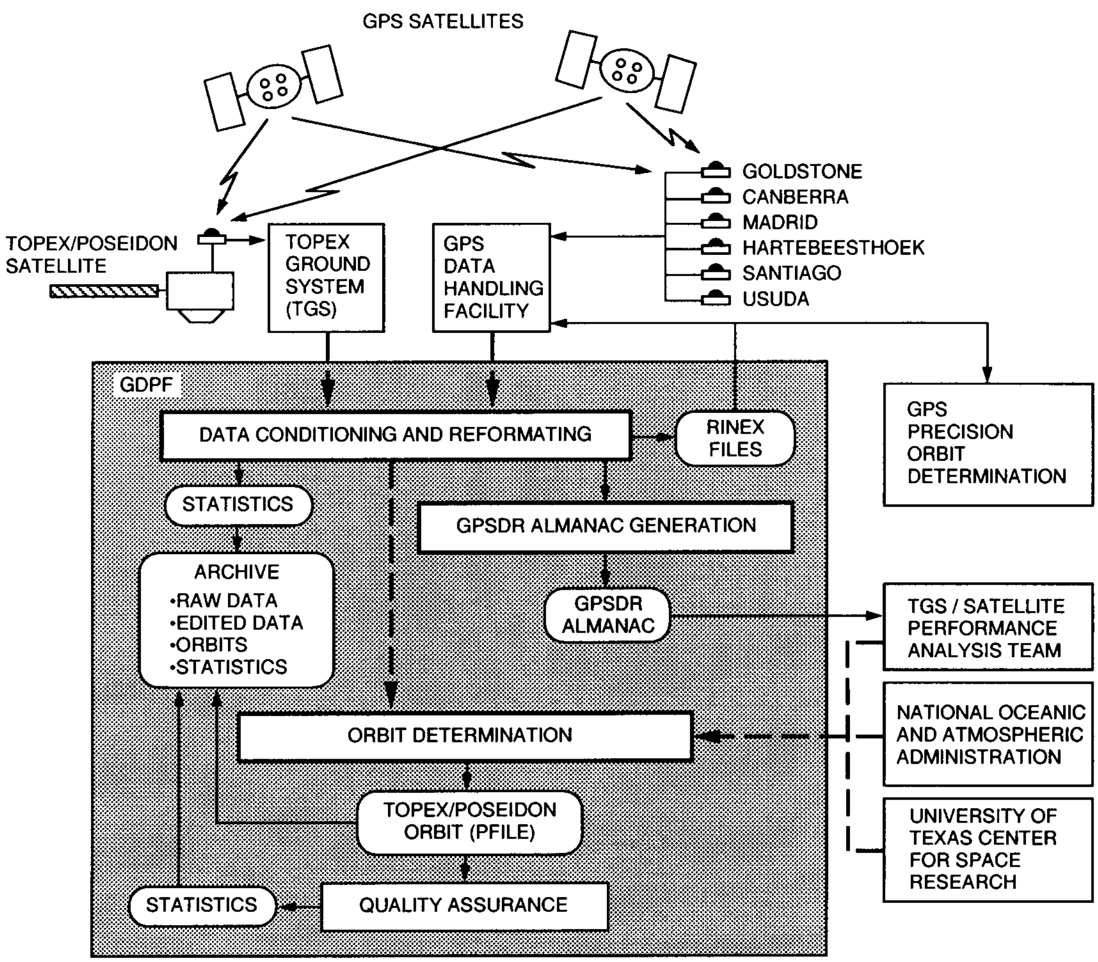

Fig. 1. GPS Data Processing Facility interfaces.

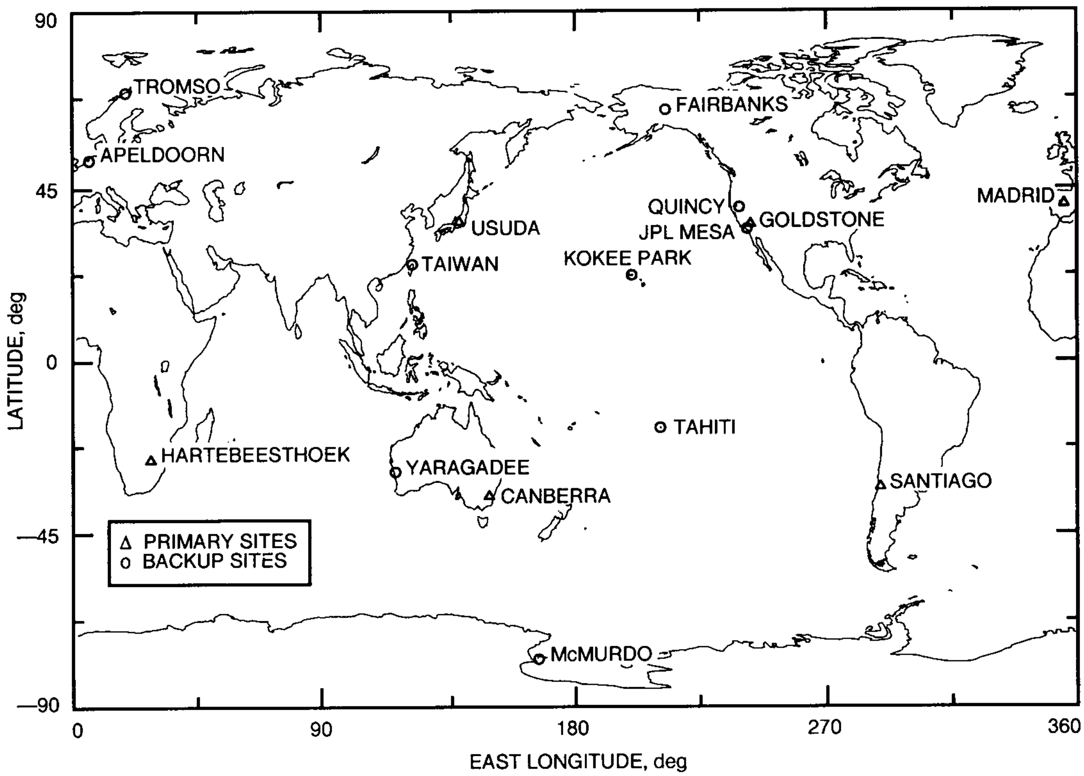

Fig. 2. TOPEX/POSEIDON GPS Ground Receiver Network.

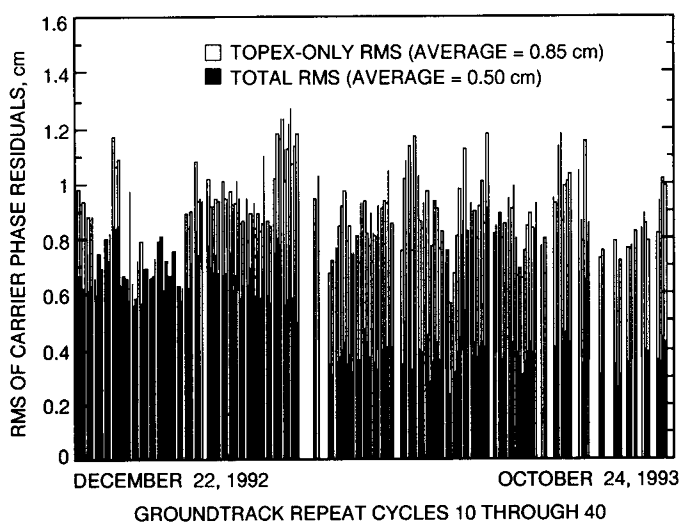

Fig. 3. MIRAGE observation residuals from TOPEX/POSEIDON flight receiver and six ground receivers.

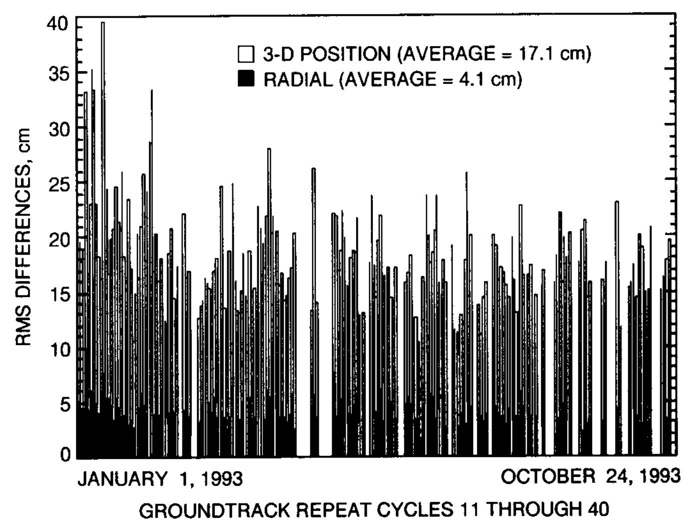

Fig. 4. MIRAGE GPS dynamic orbit solutions compared with laser and DORIS solutions.

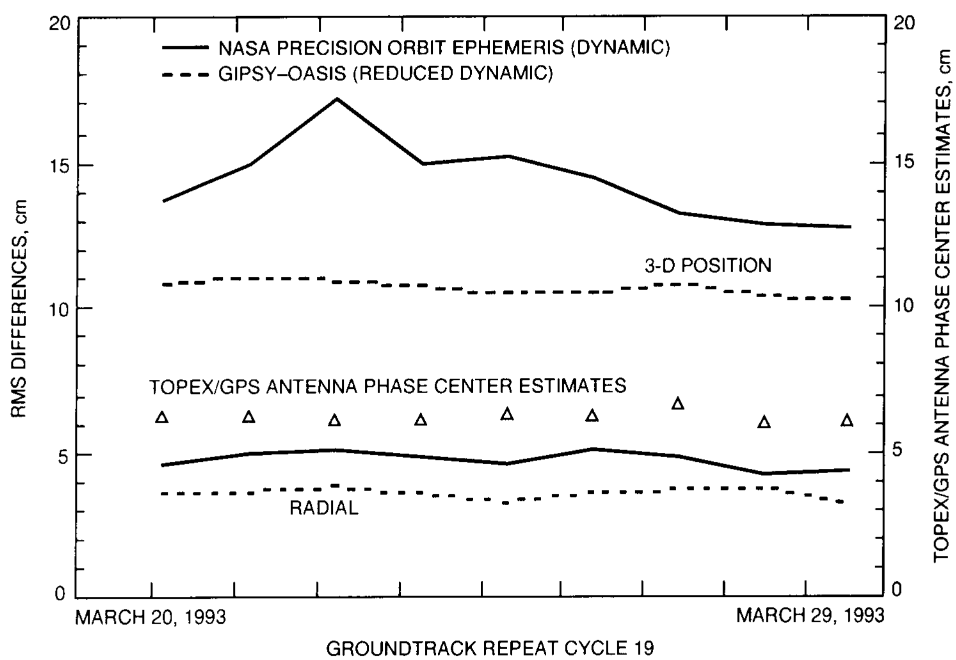

Fig. 5. MIRAGE GPS reduced dynamic orbit comparisons.