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Use of Global Positioning System Measurements to Determine Geocentric Coordinates and Variations in Earth Orientation

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Geocentric tracking station coordinates and short-period Earth-orientation variations can be measured with Global Positioning System (GPS) measurements. Unless calibrated, geocentric coordinate errors and changes in Earth orientation can lead to significant deep-space tracking errors. Ground-based GPS estimates of daily and subdaily changes in Earth orientation presently show centimeter-level precision. Comparison between GPS-estimated Earth-rotation variations, which are the differences between Universal Time 1 and Universal Coordinated Time (UT1–UTC), and those calculated from ocean tide models suggests that observed subdaily variations in Earth rotation are dominated by oceanic tidal effects. Preliminary GPS estimates for the geocenter location (from a 3-week experiment) agree with independent satellite laser-ranging estimates to better than 10 cm. Covariance analysis predicts that temporal resolution of GPS estimates for Earth orientation and geocenter improves significantly when data collected from low Earth-orbiting satellites as well as from ground sites are combined. The low Earth GPS tracking data enhance the accuracy and resolution for measuring high-frequency global geodynamical signals over time scales of less than 1 day.

I. Introduction

Measurement of Earth orientation determines the Earth's rotation rate and the position of the pole (rotation axis) with respect to inertial space. Monitoring changes in global geodynamical parameters (GGP)—Earth-orientation parameters and the location of the geocenter, or Earth's center of mass, relative to a defined terrestrial-reference frame—is necessary to correctly model deep-space tracking data used for navigation and trajectory determination. At the present time, the Deep Space Network (DSN) has no direct means of measuring geocentric station coordinates. While DSN baselines (*relative* coordinates) have been measured to better than 10 cm using very long baseline interferometry (VLBI), these coordinates can share much larger common geocentric coordinate bias errors. Global Positioning System (GPS) data, on the other hand, are very sensitive to the geocentric components which cannot be provided by VLBI. For Earth orientation, present-day calibrations for deep-space

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tracking are provided from a combination of DSN VLBI quasar-observing sessions and non-DSN VLBI data which are provided on a "best-efforts" basis. Unfortunately, the DSN VLBI measurements require the use of large DSN antennas, which are unavailable for deep-space tracking or telemetry during these sessions. The incorporation of GPS data for deep-space Earth-orientation calibrations is motivated by a need to reduce the burden on DSN antennas for making Earth platform calibrations, thus freeing up blocks of antenna time for spacecraft tracking.

Recent GPS experiments have demonstrated baseline determination across continental plates to the centimeter level [1,2] and regional baseline determination to within a few millimeters' precision [3]. Analyses have indicated that GPS measurements can additionally provide subnanosecond global clock synchronization [4,5], subcentimeter-level media calibrations [6], and subdecimeter orbits of low Earth satellites [7]. In the past, two strategies were devised to determine the offset between the reference-frame origin and the geocenter using GPS observations [8]. Initial Casa Uno (1988) GPS solutions, with data from just seven satellites, agreed with satellite laser ranging (SLR) measurements to within 20–90 cm per geocenter component [9]. The first GPS International Earth Rotation Service (IERS) and Geodynamics (GIG '91) experiment (January–February 1991) provided a somewhat superior and more global data set. Preliminary GIG '91 GPS solutions for the geocenter agree with SLR to within 10–15 cm [15]. The improved accuracy was mainly due to the more uniformly distributed ground network equipped with better receivers and the greater number of GPS satellites in the constellation. As discussed in this article, the authors expect that GPS estimates for the geocenter will continue to improve to the few-centimeter level.

As the accuracy of GGP estimates improves, the capability to model their variation with time is enhanced. Particularly for Earth-orientation parameters, it is desirable to monitor subdaily variations with relatively short satellite-tracking data arcs in order to minimize systematic orbit-modeling errors. Past studies have shown that the addition of data from a low Earth satellite observing GPS to data collected from ground receivers improves geometrical strength for determining GPS orbits, clock-synchronization parameters, and ground baselines [4,10]. This article also investigates the expected enhancement in performance of GGP determination by the introduction of low Earth satellites. Because the orbital period of a low Earth satellite (typically 90–120 min) is much shorter than the GPS orbital period (12 hr) and the Earth-rotation period (24 hr), a GPS flight receiver on the low Earth satellite can track more GPS satellites than a ground receiver does in a shorter period of time. Precise GPS orbits can be obtained in shorter time and this, in turn, helps improve time resolution for estimation of Earth-orientation parameters. The flight GPS data also provide stronger correlation between GPS orbits. This in effect reduces the error in determining nonrotational coordinate parameters (such as the geocenter). For example, the U.S./French Ocean Topography Experiment (TOPEX/POSEIDON) satellite [11] launched on August 10, 1992, is the first low Earth satellite to carry on board a high-precision dual-frequency multichannel GPS receiver. A full (or nearly full) constellation of 21 GPS satellites is expected during the 3-year mission of TOPEX/POSEIDON. The orbital period of TOPEX/POSEIDON is far shorter (112 min) than that of GPS satellites (12 hr). These data should enhance sensitivity to subdaily Earth-rotation variations and could eventually improve tidal models by resolving subtle centimeter-level signatures in the Earth-orientation time series. The anticipated performance of GPS ground data with or without the GPS data from TOPEX/POSEIDON for determination of the GGP, which were modeled as random-walk parameters, has been studied. Future low Earth satellites, such as the Earth Observing System (EOS) platforms, Gravity Probe-B, and Aristoteles, will also carry onboard GPS flight receivers. It is very likely that there will be opportunities to include GPS data from more than one low Earth satellite for the determination of the GGP. To investigate the improved performance due to such a scenario, a covariance analysis using GPS data from two low Earth satellites in orthogonal orbital planes is also presented in this article.

II. GGP Variations

During the GIG '91 experiment, a global network of over 100 stations collected GPS measurements for a period of 3 weeks (January 22–February 13, 1991). Data from 21 Rogue GPS receivers were processed (Fig. 1) [12] using the Jet Propulsion Laboratory's GPS Inferred Positioning System (GIPSY) software. Fifteen GPS satellites were operational during this experiment. In this analysis, the coordinates of Goldstone (California), Kokee (Hawaii), and Kootwijk (The Netherlands) were fixed to align the coordinate system with the SV5 reference frame [13], which is based on a combination of SLR and VLBI observations. The origin and scale of the SV5 reference system is defined by the Center for Space Research (CSR)-8902-SLR [14], and its orientation is consistent with the 1989 International Terrestrial Reference Frame (ITRF '89). The estimated parameters include GPS orbits, nonfiducial ground-station position vectors, GGP (Earth orientation and geocenter location), random-walk zenith tropospheric delays for each station, and white-noise receiver/transmitter clocks

(Table 1). A priori random-walk constraints for the zenith tropospheric delay variation were 1.2 cm/$\sqrt{\text{hr}}$. The GPS solutions for the difference between Universal Time 1 and Universal Coordinated Time (UT1–UTC) and polar motion variations are relative to the *IERS Bulletin-B (B37 and B38)* nominal time series, which contains a smoothed time series from VLBI and SLR measurements separated by several days.

GPS pseudorange and the carrier-phase measurements over a period of time can be combined to solve for the satellite positions and velocities at an epoch. The geocenter is the origin of a satellite-based dynamical system. Any time-dependent origin shift can be estimated from the satellite tracking data as a common coordinate offset of all the ground station locations that realigns the dynamical origin and the origin of the coordinate system. Geocenter offsets with respect to the SV5 reference frame were estimated along with other parameters. The 3-week GIG '91 data were processed with 1-day and 2-day arcs, which gave very similar results. The mean of the daily GPS geocenter solutions differs from the SV5 value by $\Delta X = -8.3$ cm, $\Delta Y = 13.4$ cm, and $\Delta Z = -7.7$ cm [15]. The GPS single-day arc (daily) geocenter estimates had rms repeatabilities of 5 cm in X and Y and 30 cm in Z, with corresponding formal errors of 5 cm and 20 cm, respectively. The weaker result for the daily Z component estimates is due to several factors, such as the uneven distribution of ground sites with fewer sites in the southern hemisphere and polar regions and the incomplete GPS constellation which was available in 1991. During the International GPS Geodynamics Service 1992 campaign, 18 available GPS satellites were observed from 30 globally distributed Rogue receiver sites [16]. The geocenter estimates differ from the 1991 International Terrestrial Reference Frame (ITRF '91) by $\Delta X = 0.0 \pm 1.4$ cm, $\Delta Y = 1.5 \pm 1.3$ cm, and $\Delta Z = -8.2 \pm 3.0$ cm. The Z component still suffers from the lesser number of participating sites in the southern hemisphere. The improvement in results indicates better quality of data and more even distribution of global network sites.

Variability in Earth rotation is measured by estimation of UT1–UTC (typically in milliseconds). Changes in Earth rotation cause changes in UT1, while UTC is a fixed point of reference based on energy levels in the cesium atom. Well-modeled satellite dynamics are essential to detect time variations of UT1–UTC with satellite tracking data. For the GIG '91 experiment, independent GPS orbits were estimated every 24 hr, with new unconstrained GPS orbit parameters introduced at midnight every day. At noon every day (the midpoint of the GPS orbit solution arc), the UT1–UTC parameters were reset with a white process noise update in the filter. This offset between white noise resets for UT1–UTC and GPS orbital states is important to minimize the natural coupling between the orbital nodes and UT1. The results are presented and discussed in Lichten et al. [17]: The UT1–UTC daily estimates agree to about 0.04 msec rms with international radio interferometric surveying (IRIS)-intensive VLBI daily solutions (2-hr VLBI experiments using only two stations) and with the JPL Kalman Earth Orientation Filter daily solutions incorporating IRIS multibaseline VLBI data, the U.S. Naval Observatory's VLBI network (NAVNET) data, SLR polar motion, and NASA DSN VLBI data. The GPS daily estimate formal errors are between 0.01 and 0.02 msec ($\approx$1 cm), and the agreement between the GPS and VLBI estimates is consistent with the combined formal errors from the GPS and VLBI results. The GPS UT1 estimates also agree with the operational SLR estimates for UT1[2] with an rms difference of approximately 0.04 msec. Similarly accurate (1–2 cm) daily polar motion estimates have been reported with the same data set by Herring et al. [18] and by Lindqwister et al. [19].

Stochastic estimates of subhourly UT1–UTC and polar motion (UTPM) variations were also made using a factorized Kalman filter. The UT1–UTC variations were estimated with a random-walk model constrained at 2 msec/$\sqrt{\text{hr}}$. The polar motion variations (also random walk) were constrained at 0.6 cm $\sqrt{\text{hr}}$ ($\approx$3 cm over a day), but the initial overall a priori constraint was several meters, a fairly loose constraint. Note that these estimated variations correspond to corrections to the *IERS Bulletin B* Earth orientation time series. The UTPM solutions were obtained every 6 min with the GPS data. The UT1–UTC formal errors range from a few hundredths of a msec to nearly 0.1 msec near the end of the 24-hr period. Polar motion estimates show formal errors below 2 cm with the 24-hr solution. The formal errors do not reflect systematic effects caused by possible errors in fiducial station coordinates and some types of GPS orbit mismodeling. Blewitt et al. [20] demonstrate GPS–VLBI baseline agreement at the 1- to 2-cm level and a consistency with ITRF at the cm level. Even an error of 5 cm in each of the fiducial station coordinates would lead to less than a 0.01-msec error over 1 day in UT1–UTC changes. Figures 2 and 3 show a sample of smoothed estimates of UTPM fluctuations with 6-min time resolution. Figure 2 compares the UT1–UTC variation with the predictions from ocean tide models developed by Brosche et al. [21] and Herring and Dong [22] at every 6-min interval. Herring and Dong [22] used the approach of empirically fitting the major tidal

[2] Provided by R. Eanes, University of Texas, Austin, Texas, February 1992.

components to subdaily VLBI observations. The variations in UT1–UTC are clearly well correlated with models for UT1 variations from diurnal and semidiurnal oceanic tides [17]. The stochastic estimation of polar motion components (X_p, Y_p) fluctuations with 6-min time resolution are shown in Fig. 3. The observed time variations are being studied for further understanding. The influence of the atmosphere on rapid polar motion variations has been studied by Gross and Lindqwister [23], which shows that the atmosphere can play a major role in polar motion excitation to cause diurnal variations.

These preliminary GIG '91 results show that GPS tracking has the potential for high time-resolution estimation of GGP. It would be desirable, however, to further improve the strength of the ground GPS data to monitor changes in Earth orientation, especially UT1–UTC. In the following section, the use of additional data from low-Earth orbiters is discussed. While centimeter-accurate results have already been achieved for subdaily UT1–UTC variations and for daily polar motion variations, the data from GIG '91 did not have sufficient strength to achieve this level of accuracy on a *daily* basis for the geocenter. The International GPS Geodynamic Service (IGS) '92 campaign results, however, show a 5-cm-level offset between the GPS mean geocenter estimate and the ITRF '91 value [16]. There also remain some questions to be answered regarding the stability of the GPS daily time series for UT1 over periods of more than 1 week. The recent results reported by Freedman et al. [24] on subdaily Earth-rotation determination show highly encouraging results. In the next section, future expected performance of the GPS tracking system for GGP estimation with a full global ground network and a complete (24-satellite) GPS constellation augmented with GPS tracking data from one or more low Earth orbiters is examined.

III. Covariance Analysis

A covariance study was performed to evaluate anticipated speed and accuracy improvement in GGP estimation when the GPS data collected by a precise GPS flight receiver on board a low Earth satellite are combined with those from a global ground network. The TOPEX/POSEIDON satellite will provide such opportunities. A global network of 10 evenly distributed stations (Fig. 4) was used for the study. As in previous covariance studies [8], the fiducial baselines between NASA DSN sites at Goldstone, California; Madrid, Spain; and Canberra, Australia, were fixed as reference baselines in the estimation process. The data noise was assumed to be 20 cm in pseudorange and 0.4 cm in carrier phase at 5-min intervals (Table 2). Post-fit residuals from GIG '91 with Rogue GPS receivers were typically 20–30 cm for pseudorange and 0.3 cm for carrier phase at 6-min intervals (corrected for the ionosphere). Thus, the assumptions in this covariance analysis for data noise are consistent with present-day receiver performance. A full constellation of 24 GPS satellites distributed in 6 orbital planes was assumed for this study [25]. A full or nearly full GPS constellation is expected to be operational by mid-1993. The abundance of the GPS measurements allows rapid simultaneous estimation of the geocenter offset, polar motion, and changes in UT1–UTC, along with GPS orbits, ground stations, and other parameters. To allow for temporal variations, the tropospheric delays were modeled as random-walk parameters with the same constraints as are currently used when processing the real data.

The performance of low Earth satellites in enhancing the GGP estimation can be described in terms of three different cases. Case one includes only GPS measurement data from the 10 ground stations (Fig. 4). Case two includes GPS data from one low Earth orbiter and data from the ground sites. Case three analyzes the situation when GPS data from two low Earth orbiters are combined with the ground data. Both low Earth satellites were considered to be similar to TOPEX/POSEIDON, but in two orthogonal orbital planes with respect to each other with their ascending nodes separated by 180 deg. The temporal variations of polar motion and UT1–UTC were represented in this analysis by random-walk parameters [26]. The geocenter offset can still be treated as constant since it is unlikely to change significantly over short data spans (a few hours). Since GPS observations are sensitive to the rate of change of UT1–UTC rather than its absolute (inertially determined) offset, a perfect a priori value was assumed prior to the observation; the temporal UT1 variation was then estimated using the GPS tracking data. This assumption implies that VLBI is available to calibrate at least one UT1–UTC value in the GPS time series. Error in such a priori VLBI estimates of UT1–UTC would result in a common GPS node shift without affecting UT1–UTC *variation* determination. The random-walk constraint (1 sec) for polar motion was 2 $\text{cm}/\sqrt{\text{day}}$, and for UT1–UTC variations the constraint was 10 $\text{msec}/\sqrt{\text{day}}$ (Table 2).

In this covariance study, the effect of mismodeled dynamics on the TOPEX/POSEIDON spacecraft was reduced by adjusting its orbital elements along with a constrained three-dimensional fictitious force treated as process noise [7]. Adjustment of the fictitious force reduces the effects of mismodeled dynamics in the low Earth orbiter. The errors calculated also include systematic error due to mismodeled unadjusted parameters. These include 6 cm in each component of the fiducial baselines;

TOPEX/POSEIDON dynamic errors, which were quantified as 20 percent of the nominal values of solar radiation pressure, atmospheric drag, and albedo; and a gravity error, which was assumed to be 25 percent of the difference between two existing models, Goddard Earth Model (GEM)10 and GEML2 [27,28]. This gravity error is comparable to the error covariance of GEMT2 gravity [29].

IV. Comparison of GGP Estimation Errors

The future anticipated error in GGP as indicated by covariance analyses both with and without GPS measurements from TOPEX/POSEIDON is presented here. The expected errors from all three cases discussed in the previous section were calculated by using data spans of 2, 4, and 8 hr at 5-min intervals. The findings of the covariance analyses are strictly based upon the scenario as specified in Table 2. Although the assumptions made here are kept as close as possible to the real data processing, as in the case of GIG '91, there are still several differences. One of the differences in the covariance study was the scenario of fewer, more evenly distributed tracking sites to represent a routine operation rather than a dedicated experiment. A major difference is also due to the partial (2/3) GPS constellation operating during GIG '91 and somewhat incomplete tracking data from the southern hemisphere. For example, during GIG '91 one of the southern hemisphere sites which would have provided critical common view of GPS satellites was operating for less than 12 hr per day, which significantly degraded the accuracy of the Z component of the geocenter estimates. Because of these differences in the assumptions, a one-to-one comparison with the GIG '91 experiment results will not be meaningful. The main objective here is to demonstrate the extent of anticipated improvement in the determination of GGP variations when the GPS data from the low Earth satellites are introduced in the future, with the full GPS constellation.

Figure 5 presents only the X component of polar motion and geocenter offset; similar behavior was observed in other components as well. The comparison of the GGP estimates between case one, where no low Earth satellite was available, and case two, where data from one low Earth satellite were included, shows that TOPEX/POSEIDON helps to improve the accuracy and convergence speed by a factor of two, especially in the first 2–4 hr. The single dominating error source in the GGP variations estimates for a short data span, as shown in Fig. 5, is the GPS data noise. The introduction of the second low Earth satellite serves the similar purposes of improving the geometry and providing more measurements to combat this dominating effect of the data noise. As a result, further improvement can be expected both in accuracy and speed of convergence by another factor of two (compared to the case of one low Earth satellite) when GPS data from two low Earth satellites are included.

Some improvement in time resolution of GPS solutions could be achieved by simply adding more ground sites, as opposed to incorporating data from a low Earth orbiter. However, the two approaches are not equivalent. After a certain minimal global coverage is reached—for example, with 12 ground sites evenly distributed—additional sites tend to improve the formal estimation error proportionally with the square root of the additional number of measurements. Hence, a very large number of additional ground sites are needed to lead to a significant improvement, particularly in temporal resolution. The data processing also significantly increases in complexity when many ground sites are included. A more fundamental limitation of a ground-based-only approach, however, is the 12-hr period of the GPS satellites. Even with many more ground sites, ground-based carrier-phase data require several hours to determine a solution for the phase biases, due to the relatively slow GPS satellite velocities. The low Earth orbiter, however, provides rapid change in viewing geometries, completing its orbit approximately once every 90 min. This richness in geometrical coverage, rather than simply the additional measurements, provides the significant improvement in time resolution of the GPS data. Finally, the incorporation of Earth orbiters with periods much shorter than the 12-hr GPS orbital period may enable researchers to better separate semidiurnal geodetic signals and tidal effects from GPS orbit error, which may also resonate at 12-hr periods. Thus, there are certainly important advantages to adding low Earth GPS tracking data which cannot be achieved simply by adding additional ground sites. This has not been fully quantified in the analysis, but there are plans to study it in the future with GPS data from the TOPEX/POSEIDON satellite.

It appears that the speed and accuracy in the determination of the GGP can be enhanced by including the GPS data from one or more low earth satellites like TOPEX/POSEIDON. Consequently one should eventually be able to substantially better resolve centimeter- and subcentimeter-level signatures in the Earth-orientation time series over a few hours, which may be expected to appear due to tidal mismodeling or atmospheric effects.

V. Conclusions

Preliminary estimates of Earth-orientation variations and location of the geocenter using global GPS data have been obtained. The average geocenter offset estimate from the 3-week-long GPS experiment agrees with the SLR determined value to better than 10 cm. The estimated UTPM variations show few-centimeter-level agreement with VLBI time series. A comparison with expected variations from diurnal and semidiurnal ocean tidal models suggests that the observed subdaily variations in UTPM with GPS are dominated by tidal effects. With the 1991 data, the GPS daily Earth-orientation estimates are accurate to the 1- to 2-cm level, and filtered solutions at 6-min intervals for stochastic UT1–UTC and polar motion are precise to the level of 2–4 cm. The preliminary results appear to be somewhat limited by the placement of the ground receivers and the fact that in 1991 only two-thirds of the GPS constellation was operational. However, the geocenter offset results from the IGS '92 campaign [16] have already shown 5-cm-level agreement with ITRF '91, and improved results have been reported for subdaily determination of the Earth's rotation [24]. Further improvement is expected, particularly for short-arc (daily or subdaily) geocenter estimation, as the full GPS constellation and evenly distributed ground network becomes available in the future.

The covariance studies indicate that temporal variations in global geodynamical parameters can be monitored with high precision using high-quality GPS pseudorange and carrier-phase data from a global ground network and a low Earth satellite. The expected errors in polar motion variations and the geocenter offset may be lowered to a few centimeters, and in UT1–UTC variations to a few hundredths of 1 msec, with only 4 hr of GPS data. The temporal resolution is expected to be a factor of two better with ground and low Earth GPS data as compared to ground-based tracking only. Including two low Earth orbiters placed in orthogonal orbital planes further improves the accuracy and time resolution (by an additional factor of two). The incorporation of low Earth orbiters with periods (90–120 min) much shorter than the 12-hr GPS orbital period may enable a better separation of diurnal and semidiurnal geodetic signals and tidal effects from GPS orbit error, which may also resonate at 12-hr periods. These important advantages of adding GPS data from low Earth satellites cannot be achieved simply by including more ground sites. Demonstration of the accuracy and resolution enhancements for subdaily (and even subhourly) Earth-orientation parameters predicted by these covariance analyses is planned when the GPS data from TOPEX/POSEIDON become available in the near future. Ultimately, such data may provide valuable information about tidal and other geophysical models which complement data from other techniques, such as VLBI and laser tracking.

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Table 1. Estimation strategy applied to the GIG '91 data processing.[a]

Parameters	Treatment	A priori σ
GPS orbits	Adjusted	Unconstrained
G_y (Y bias)	Adjusted	2×10^{-12} km/sec^2
G_x and G_z	Adjusted	100 percent (scale factor)
GPS carrier biases	Adjusted (real-valued)	Unconstrained
3 fiducial site locations	Fixed at a priori coordinates	—
18 nonfiducial site locations	Adjusted	Unconstrained
Tropospheric delay (1 per site)	Adjusted (as random walk)	50 cm + 1.2 cm/$\sqrt{\text{hr}}$ (6 cm over 1 day)
Clock biases (stations/transmitters)	Adjusted (as white noise)	Unconstrained
Geocenter offset	Adjusted	Unconstrained
UT1–UTC variations	Adjusted	2 msec/$\sqrt{\text{hr}}$ (10 msec over 1 day)
(X_p, Y_p) pole position	Adjusted	0.6 cm/$\sqrt{\text{hr}}$ (3 cm over 1 day)
Gravity	Fixed at [GEM-T2 (12 x 12)] value	—
Earth's GM	Fixed at IERS value	—

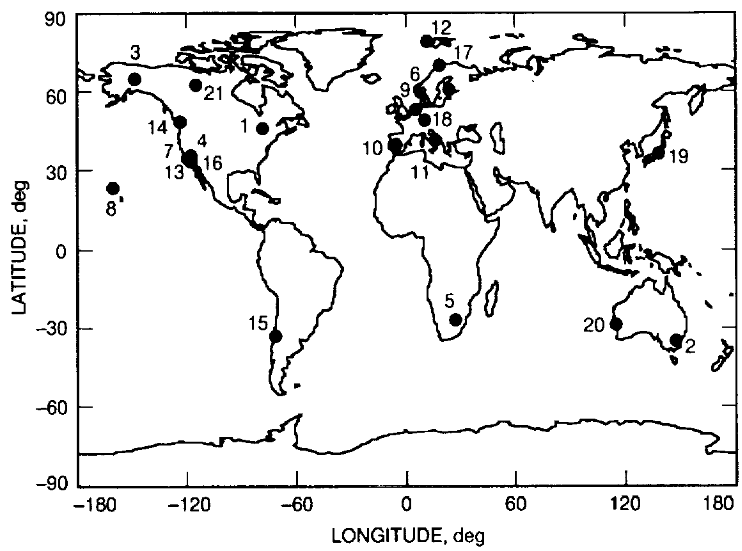
[a] Note that the nominal models for G_x, G_y, and G_z were believed to be accurate to about 10 percent. Therefore, the a priori constraints used are fairly loose.

Data span	= 24 hr
Data interval	= 6 min
Data noise	= 100-cm pseudorange
	= 1-cm carrier phase
GPS constellation	= 15 satellites

Table 2. Basic estimation models applied to the covariance analysis.[a]

Parameters	Treatment	A priori σ
GPS orbits	Adjusted	Unconstrained
G_y (Y bias)	Adjusted	2×10^{-12} km/sec^2
G_x and G_z	Adjusted	100 percent (scale factor)
GPS carrier biases	Adjusted	Unconstrained
TOPEX/POSEIDON orbits	Adjusted	Unconstrained
Fictitious force on TOPEX/POSEIDON	Adjusted (as process noise)	0.5 μm/sec^2 bias; 0.35 μm/sec^2 batch-to-batch
Gravity on TOPEX/POSEIDON	Considered	25 percent (GEM10–GEML2)
Solar pressure on TOPEX/POSEIDON	Considered	20 percent of nominal model
Albedo TOPEX/POSEIDON	Considered	20 percent of nominal model
Atmospheric Drag TOPEX/POSEIDON	Considered	20 percent of nominal model
3 fiducial site locations	Considered	6 cm each component
7 nonfiducial site locations	Adjusted	20 cm each component
Tropospheric delay (1 per site)	Adjusted (as random walk)	40 cm + 12 cm over 1 day
Clock biases (stations/transmitters)	Adjusted (as white process noise)	Unconstrained
Geocenter offset	Adjusted	20 m each component
UT1–UTC variations	Adjusted	10 msec over 1 day
(X_p, Y_p) pole position	Adjusted	2 cm over 1 day
Earth's GM	Adjusted	2 parts in 10^8

[a] Tracking network = 10 sites (cf. Fig. 4)
Data span = 2–8 hr
Data noise = 20-cm pseudorange
= 0.4-cm carrier phase
Data interval = 5 min
GPS constellation = 24 satellites
Cutoff elevation = 10 deg (ground receivers)
= 0 deg (TOPEX/POSEIDON receiver)
Number of GPS observed = Up to 8 at a time (ground receivers)
= Up to 6 at a time (TOPEX/POSEIDON receiver)



1. ALGONQUIN, CANADA
2. CANBERRA, AUSTRALIA
3. FAIRBANKS, ALASKA
4. GOLDSTONE, CALIFORNIA
5. HARTEBEESTHOEK, SOUTH AFRICA
6. HONEFOSS, NORWAY
7. JPL, PASADENA, CALIFORNIA
8. KOKEE, HAWAII
9. KOOTWIJK, THE NETHERLANDS
10. MADRID, SPAIN
11. MATERA, ITALY
12. NY ÅLESUND, NORWAY
13. PINYON, CALIFORNIA
14. VICTORIA, CANADA
15. SANTIAGO, CHILE
16. LA JOLLA, CALIFORNIA
17. TROMSO, NORWAY
18. WETTZEL, GERMANY
19. USUDA, JAPAN
20. YARRAGADEE, AUSTRALIA
21. YELLOWKNIFE, CANADA

Fig. 1. The 21 GPS Rogue receiver sites of the GIG '91 network.

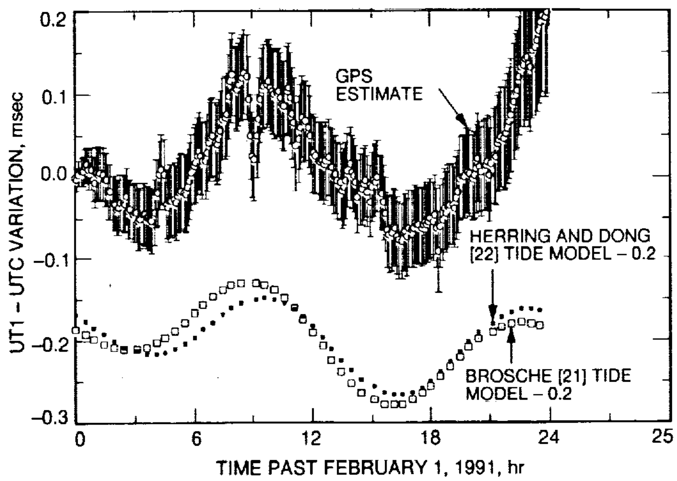


Fig. 2. Variations in UT1–UTC estimated from GPS relative to the *IERS Bulletin B* nominal series. One-sigma GPS formal errors are also plotted. Comparison with oceanic tidal model predictions from Herring and Dong [22] and from Brosche et al. [21] (plotted with an offset of 0.2 msec for clarity in the figure) shows clearly the effect of tides detected in the GPS 6-min estimates.

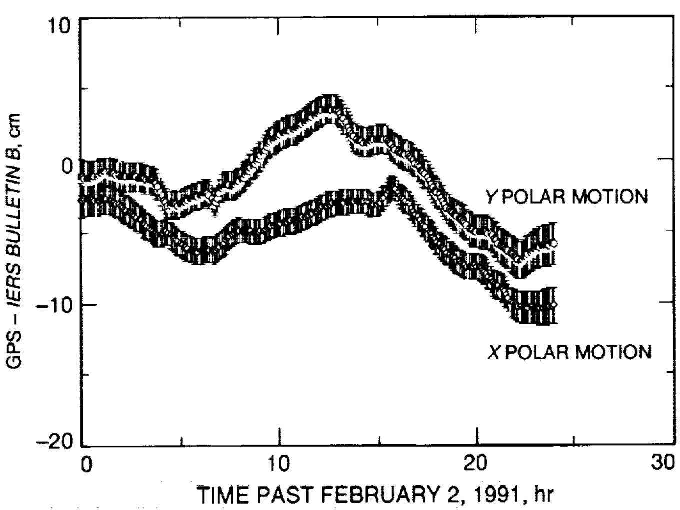


Fig. 3. GPS stochastic estimation of polar-motion fluctuations with 6-min time resolution. GPS formal one-sigma errors are also plotted.

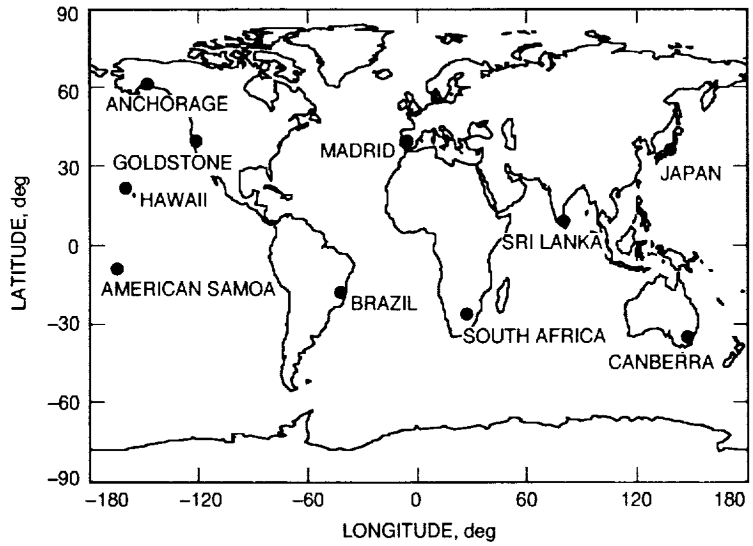


Fig. 4. Global GPS tracking network for covariance analysis. All the sites are assumed to be occupied by GPS Rogue-type receivers tracking GPS satellites simultaneously with high-precision dual-frequency multichannel flight receivers on board one or two low Earth satellites.

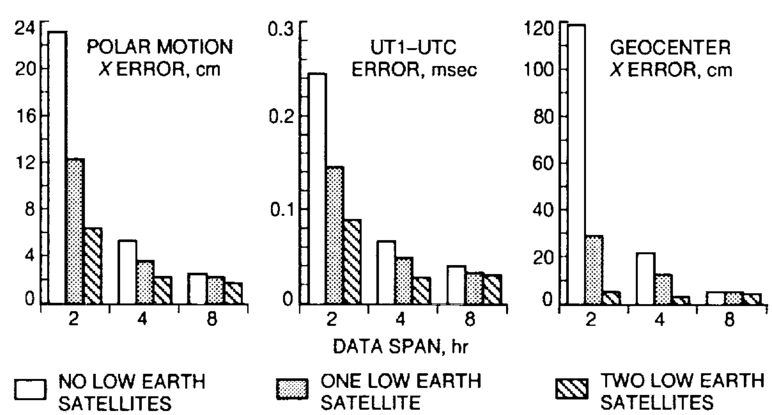


Fig. 5. Anticipated errors in GGP using global network with precision GPS data. The *X* components of polar motion and geocenter offset are presented here; the other components vary similarly.