GEOPHYSICAL RESEARCH LETTERS, VOL. 19, NO. 9, PAGES 845-848, MAY 4, 1992

DAILY ESTIMATES OF THE EARTH'S POLE POSITION WITH THE GLOBAL POSITIONING SYSTEM

Ulf J. Lindqwister, Adam P. Freedman, and Geoffrey Blewitt

Jet Propulsion Laboratory, California Institute of Technology

Abstract. Daily estimates of the Earth's pole position have been obtained with measurements from a worldwide network of Global Positioning System (GPS) receivers, obtained during the three week GIG'91 experiment in January-February, 1991. For this short-term study, the GPS based polar motion series agrees with the other space based geodetic techniques (Very Long Baseline Interferometry and Satellite Laser Ranging) to ~0.4 mas rms, after the removal of mean biases of order 1-3 mas. The small error in day-to-day variability is not sensitive to the fiducial strategy used, nor are fiducial sites even necessary for monitoring high frequency pole position variability. The small biases indicate that the applied reference frames of the three geodetic techniques are nearly aligned, that the GPS fiducial errors are small, and that systematic errors in GPS are also small (of order 5 ppb). A well determined reference frame is necessary for monitoring the long-term stability of polar motion and for separating it from other long-term signals such as tectonic motion and internal systematic errors.

Introduction

The variations in direction of the Earth's rotation vector with respect to a terrestrial reference frame have been measured for over a century with optical astrometry [Munk and MacDonald, 1975]. More recently high precision polar motion estimation has been the province of two space geodetic techniques: Very Long Baseline Interferometry (VLBI) and Satellite Laser Ranging (SLR). Reported accuracies from these techniques are typically at the level of 0.3-0.7 mas, and these techniques generate either 24-hour estimates every few days (VLBI) or three-day averaged estimates every three days (SLR) [IERS, 1990; 1991]. A Global Positioning System (GPS) experiment (GIG'91) performed in early 1991, under the auspices of the International Earth Rotation Service (IERS), using GPS receivers distributed worldwide, provided an opportunity to test GPS as a complementary technique for measuring Earth orientation [Freedman, 1990]. The goals of this letter are to determine the internal precision and accuracy of the GPS measurements of polar motion, such that reliable conclusions may be drawn concerning any signals obtained with the GPS technique.

Analysis

The GIG'91 experiment was carried out between January 22 and February 13, 1991 by numerous international agencies and utilized over 120 GPS receivers of several different manufacturers and antenna types. A subset of 21 Rogue GPS receivers was chosen to minimize the effects of antenna phase center offsets and systematic errors internal to receivers [Thomas, 1988]. The Rogue receivers were globally distributed as indicated in Figure 1, where only the set of fixed (fiducial) stations have been labelled explicitly. For a complete list of station names and coordinates, see Heflin, et al. [1992].

Paper number 92GL00576
0094-8534/92/92GL-00576$03.00

The GPS data were reduced with the GIPSY orbit determination and baseline estimation software using two basic strategies: (1) a standard parameter estimation strategy with three "fiducial" stations constrained to a priori coordinates [Lichten and Border, 1987], and (2) a variation of the above strategy with no fixed sites, i.e., the free network strategy [Heflin, et al., 1992]. The standard strategy for the daily solutions may be summarized as follows: station locations, satellite epoch states, and carrier phase bias parameters were estimated as constants. Station and satellite clocks were estimated as white process noise. A 2.2 meter zenith tropospheric delay was removed and the residual delay was estimated using a random-walk stochastic model. When fiducial constraints were imposed, the station locations were constrained to coordinates from the SV5 reference frame [Murray, et al., 1991]. The SV5 reference frame in principle has the same origin and orientation as the International Terrestrial Reference Frame (ITRF) used by IERS. In addition, the offset of the Earth's center of mass from the origin of the SV5 frame (the geocenter offset) was assumed to be zero.

The location of the rotation axis with respect to a crust-fixed axis (e.g., the IERS reference pole [McCarthy, 1989]) can be described by two coordinates, polar motion x (PMX) and y (PMY), where the x-axis lies along the Greenwich meridian, orthogonal to the reference pole z-axis, and the y-axis is 90 degrees to the west, as indicated in Figure 1. The two pole parameters were estimated daily as constant adjustments to nominal values obtained from the IERS [Bulletins B37 and B38, 1991]. The daily Bulletin-B values

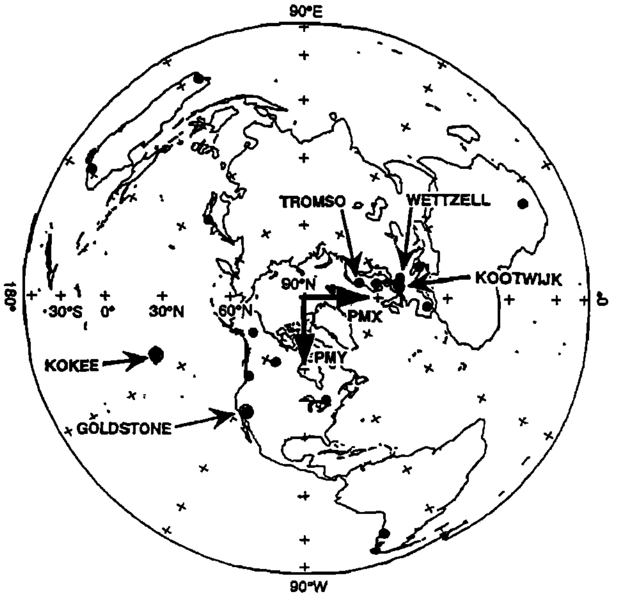

Fig. 1. Shown are 18 of the 21 Rogue sites, distributed worldwide during the GIG'91 experiment (3 additional Rogues in Southern California were also included in the analysis). The fiducial sites at Goldstone (CA), Wettzell (Germany), Tromso (Norway), Kootwijk (Holland), and Kokee (HI) have been labelled explicitly.

were interpolated and smoothed from solutions evaluated at five-day intervals.

All parameters were simultaneously estimated in a factorized Kalman filter. The satellite states were re-estimated every day to minimize systematic force model errors. Most parameters were essentially unconstrained, with a priori formal errors orders of magnitude larger than the final computed errors. Meaningful constraints were only used for the fiducial stations, whose coordinates were constrained to 0.1 mm. Solutions from distinct, consecutive 24 hour data spans were computed, hence pole positions were obtained daily as estimated offsets from the Bulletin-B values.

Results

Fiducial Network Studies

Station locations were estimated as constants over the entire three week interval, defining a rigid polyhedron for which daily variations of the pole position could be estimated. Solutions were obtained from 22 separate 24-hour periods between January 22 - February 13 (solutions for January 31 were not available). Shown in Figure 2 and listed in Table 1 are the daily GPS pole position estimates for PMX and PMY versus time as corrections to the nominal Bulletin-B values. The open symbols indicate solutions employing three fiducial sites: Goldstone (CA), Tromso (Norway) and Wettzell (Germany). The GPS polar motion series exhibits both an apparent bias and systematic variability with respect to the IERS solution. The mean bias of (GPS–Bulletin B) is -0.5 mas in PMX and 2.5 mas in PMY. In addition to the biases, PMX and PMY show a variability over 3 weeks of ~5 mas and ~2 mas, respectively, with respect to the smoothed reference series.

In the free network case, the fiducial constraints were removed. The filled triangles in Figure 2 show the pole positions for the no fiducial case, where a mean bias has been added so that the two GPS solutions are aligned. The reference frame is indeterminate for the free network solution and the pole biases are arbitrary. The rms agreement between the two cases was ~0.08 mas for each pole component. It is clear from geometrical arguments and borne out by the above results that polar motion variability in time is invariant under small rigid rotations of the reference frame and that any such coordinate transformation would only add constant biases to the pole parameters.

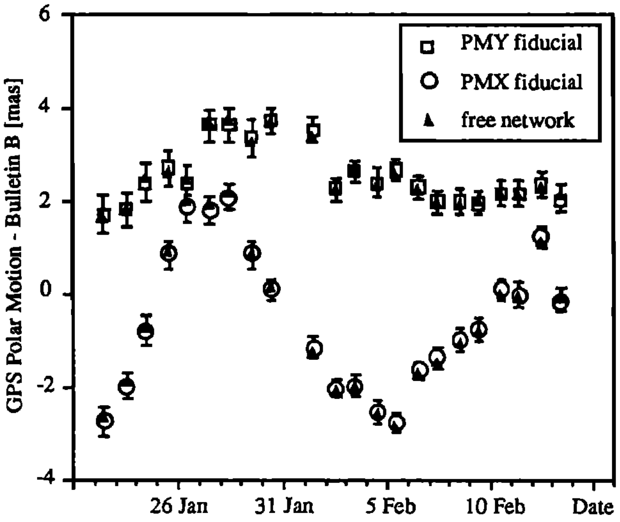

Fig. 2. A comparison of polar motion estimates for the fiducial versus the free network cases. The open circles and rectangles represent the day-to-day x-pole and y-pole position estimates for the fiducial case. The filled triangles represent the free network case after the addition of a bias to align the two GPS solutions.

Table 1. GPS pole position estimates using 3 fixed stations (SV5). Listed are estimated corrections to the Bulletin B values for PMX and PMY. In parenthesis are the full estimates including Bulletin B values.

Date	PMX [mas]	PMY [mas]
01-22-91	-2.7 ± 0.3 (-53.3)	1.7 ± 0.4 (89.1)
01-23-91	-1.9 ± 0.3 (-55.7)	1.8 ± 0.3 (90.2)
01-24-91	-0.8 ± 0.3 (-57.7)	2.4 ± 0.4 (91.9)
01-25-91	0.8 ± 0.3 (-59.3)	2.7 ± 0.4 (93.5)
01-26-91	1.8 ± 0.3 (-61.6)	2.4 ± 0.4 (94.6)
01-27-91	1.8 ± 0.3 (-65.1)	3.6 ± 0.3 (97.3)
01-28-91	2.1 ± 0.3 (-68.3)	3.6 ± 0.3 (98.8)
01-29-91	0.8 ± 0.3 (-73.1)	3.4 ± 0.4 (100.1)
01-30-91	0.1 ± 0.2 (-77.6)	3.7 ± 0.3 (102.0)
02-01-91	-1.1 ± 0.2 (-86.6)	3.5 ± 0.3 (104.9)
02-02-91	-2.0 ± 0.2 (-91.2)	2.2 ± 0.3 (105.1)
02-03-91	-1.9 ± 0.2 (-94.6)	2.6 ± 0.3 (106.8)
02-04-91	-2.5 ± 0.2 (-98.7)	2.4 ± 0.3 (107.9)
02-05-91	-2.7 ± 0.2 (-102.5)	2.7 ± 0.3 (109.7)
02-06-91	-1.6 ± 0.2 (-104.9)	2.3 ± 0.3 (110.9)
02-07-91	-1.4 ± 0.2 (-108.1)	2.0 ± 0.3 (112.2)
02-08-91	-1.0 ± 0.2 (-111.0)	2.0 ± 0.3 (114.0)
02-09-91	-0.7 ± 0.2 (-114.1)	1.9 ± 0.3 (115.8)
02-10-91	0.1 ± 0.2 (-116.4)	2.2 ± 0.3 (118.0)
02-11-91	0.0 ± 0.3 (-119.6)	2.2 ± 0.3 (120.2)
02-12-91	1.2 ± 0.3 (-121.4)	2.3 ± 0.3 (122.6)
02-13-91	-0.1 ± 0.3 (-125.7)	2.0 ± 0.3 (124.7)

Note: all epochs are at noon UTC and the Bulletin-B nominal values were obtained from B37 and B38, 1991.

To specify fiducial coordinates for a GPS station it is necessary to know (1) the coordinates of a nearby VLBI or SLR station in a known reference frame, (2) the ground tie between the two station monuments, and (3) the site vector between the GPS monument and the GPS antenna phase center. For the GIG'91 experiment only 7 stations have at the time of this analysis been collocated with VLBI and SLR. Any errors in the above three collocation measurements would limit how well these stations are tied into the SV5 reference frame. To study this question, polar motion series were obtained with two different sets of three-station fiducial networks. Shown in Table 2 are mean biases obtained

Table 2. Mean biases between polar motion series obtained from various geodetic techniques for two fiducial strategies. Shown in brackets are offsets for PMX and PMY respectively in units of mas.

	Fiducial A	Fiducial B
(GPS - IERS)	[-0.5, 2.5]	[0.6, 4.7]
(SLR - GPS)	[0.4, -0.9]	[-0.7, -3.1]
(VLBI - GPS)	[2.7, 1.0]	[1.6, -1.2]

Fiducial Network A: Goldstone, Tromso, Wettzell.
Fiducial Network B: Goldstone, Kootwijk, Kokee.

between GPS and IERS determined polar motion series for fiducials at either Goldstone, Tromso, and Wettzell (Case A) or Goldstone, Kootwijk (Holland), and Kokee (HI) (Case B). The A network appears to produce on average smaller biases compared to B, suggesting that the GPS monuments at Tromso and Wettzell are more accurately tied to the SV5 frame than those at Kootwijk or Kokee.

Sensitivity Analysis

A number of sensitivity studies [Bierman, 1977] were performed to determine the biases in pole position estimates due to possible systematic errors in fiducial station coordinates and in geocenter offset. Fiducial errors were assumed to be 3 cm in each of the three station coordinates for Goldstone, Kootwijk and Kokee, and 10 cm for each of the geocenter components. The root-sum-square (rss) polar motion biases due to errors in the fiducial components at each site are represented by cross-hatched columns in Figure 3, while geocenter-induced biases are shown by the solid black column. Systematic fiducial and geocenter errors (of order 3 cm and 10 cm) induce biases of order 1 mas and 2 mas in PMX and PMY, respectively, for fiducial network B. The observed polar motion biases relative to IERS for case A are 1-2 mas and for case B 1-5 mas, with PMY roughly twice as large as PMX, as predicted from the sensitivity analysis. Part of the bias may be accounted for by offsets between the SV5 and IERS (Bulletin-B) reference frames, which are known to be misaligned at the mas level. Independent GPS analyses have shown that fiducial offsets are largest at Goldstone (3-4 cm) and smaller at the other fixed sites (1-2 cm) and that the geocenter offset for SV5 is a few cm. Note that the pole position biases induced by the sensitivity errors scale linearly with the input value, such that a few cm geocenter offset would reduce the induced pole position biases shown in Figure 3 by a factor of 2 or more. The observed biases are hence likely to be dominated by fiducial errors, i.e., site tie errors and SV5-IERS reference frame misalignment.

GPS versus VLBI and SLR Estimates of Pole Position

Solutions from nine VLBI experiments have been obtained spanning January 23 to February 12 [Herring, et al., 1991].

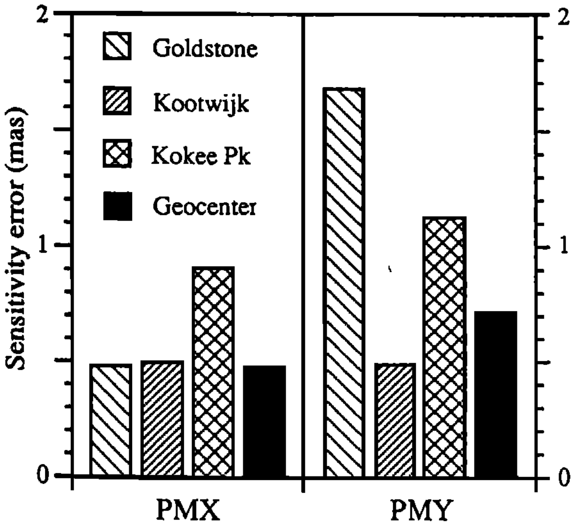

Fig. 3. Effect of systematic errors on polar motion estimates. The cross-hatched bars show the induced pole position biases based on a 3-cm error in each fiducial station coordinate, while the solid black bar shows the total bias due to 10-cm offsets in each geocenter component.

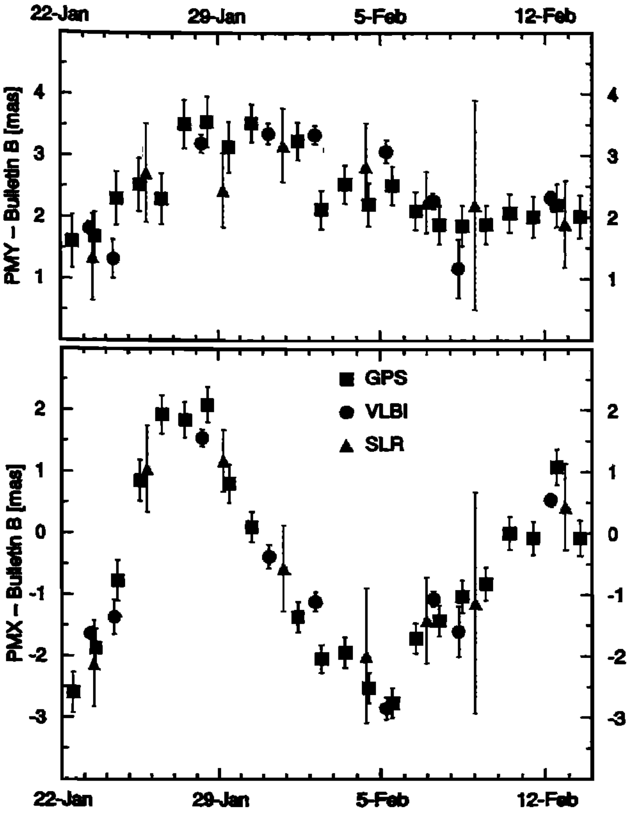

Fig. 4. Estimates of pole position with GPS, VLBI, and SLR. Bulletin B values have been subtracted from all the estimates, and mean differences with GPS have been removed from the VLBI and SLR data. The polar motion series from these space geodetic techniques agree within their formal errors (~0.5 mas).

Each solution was obtained from 24 hours of measurements on one of several VLBI networks utilizing typically 4-5 stations. To remove unevenness in network geometries, the station coordinates were fixed at values determined from ~1300 experiments. A concise description of the analysis is given by Herring, et al., [1991]. The VLBI solution epochs occurred at varying times for each daily solution, whereas the GPS epochs occurred at 12:00 noon, UTC, each day (obtained from a 24 hour solution running from midnight to the following midnight). In order to compute the rms differences at the same epoch, the GPS pole position estimates were linearly interpolated to the times of the VLBI measurements (which introduces some small error). The GPS and VLBI estimates are shown in Figure 4, where a mean bias has been removed for each pole parameter from the VLBI solutions with respect to GPS to show the close correlation between the two polar motion series. The resulting rms agreements between GPS and VLBI, after removing the mean biases, were 0.4 mas for PMX and 0.5 mas for PMY. The formal errors for the GPS pole position estimates ranged from 0.2-0.4 mas, while the VLBI formal errors ranged from 0.1-0.4 mas. Hence the GPS and VLBI solutions were consistent with each other to within their respective error bars (similar to the result obtained by Herring, et al., 1991). The biases between GPS (using fiducial network A) and VLBI were 2.7 mas in PMX and 1.0 mas for PMY, where the mean of the (VLBI–GPS) differences have been computed for nine points. For completeness, the biases between VLBI and network B are also shown in Table 2.

SLR data were obtained from the CSR 91 L 02 series produced by the Center for Space Research, University of Texas at Austin [IERS, 1990; 1991]. Each data point represents the mean of approximately three days worth of SLR measurements. The SLR estimates are shown in Figure 4 together with the GPS and VLBI results, where mean biases have been removed from the SLR solutions with respect to GPS to show the close correlation between all three polar motion series. The rms agreements between GPS and SLR, after removing the biases, were 0.3 mas for PMX and 0.4 mas for PMY. The mean biases for the (SLR–GPS) differences were 0.4 mas for PMX and -0.9 mas for PMY using network A (see Table 2). The reported errors for the SLR data average ~0.8 mas, hence the computed polar motion series from all three space geodetic techniques are consistent with each other (after removing constant biases).

Discussion and Conclusions

The above results show that the GPS technique can, at least in the short-term, determine pole position variations independent from, and at a level comparable to, estimates obtained from either VLBI or SLR. Also important are the absolute pole position estimates. The small pole biases imply an upper limit on the errors in the GPS fiducial coordinates (and geocenter errors). According to the sensitivity analysis, a 1-2 mas bias would be the result of at most a station error of 3 cm per component, which would suggest that the fiducial coordinates for network A are known to ~3 cm. In addition, the small pole biases obtained when comparing geodetic techniques imply that the internal systematic errors in GPS must be small, placing an upper limit of such errors at the level of ~1 mas (~5 ppb). These errors include satellite orbit errors, atmospheric delay mismodeling, and antenna multipath errors. The fact that the mean pole offset between each technique is small indicates that each reference frame must be closely aligned. This is not surprising, since the GPS frame is defined through station coordinates in the SV5 frame and the SV5 reference is a composite of recent SLR and VLBI solutions (CSR8902 and GLB659 respectively) aligned with ITRF. Absolute pole position estimates in a well defined reference frame are also useful for studying the long term variations in polar motion. For example, if the pole biases due to reference frame errors are assumed to remain constant when an identical fiducial strategy is employed, a drift in the polar motion bias from experiment to experiment would then imply either true polar motion drift or unmodeled tectonic motion at the observing sites, rather than systematic errors in GPS data processing.

From the above discussion and comparison with other techniques, daily variations in polar motion larger than ~0.5 mas observed with GPS as compared with the Bulletin-B values must be significant. For this 3 week study, variations of 2-5 mas were observed over ~7 days. Gross and Lindqwister [1992] have interpreted these polar motion variations in terms of atmospheric wind and pressure fluctuations by using available atmospheric angular momentum χ-functions.

Acknowledgments. The authors wish to thank Tom Herring for providing the VLBI solutions and Richard Eanes for the SLR data. Discussions with R. Gross, A. Steppe, S. Lichten, and T. Yunck were much appreciated. The work described in this letter was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

References

Bierman, G. J., *Factorization Methods for Discrete Sequential Estimation*, V128, Mathematics in Science and Engineering Series, Academic Press, 1977.

Blewitt, G., An Automatic Editing Algorithm for GPS data *GRL.*, 17, pp. 199-202, March 1990.

Freedman, A. P., S. M. Lichten, W. G. Melbourne, and S. Pogorelc, A GPS Campaign to Assess High Frequency Earth Rotation Variability, (Abstract) *EOS, Trans., AGU*, 43, p. 1272, 1990.

Gross, R. S., and U. J. Lindqwister, Atmospheric Excitation of Polar Motion During the GIG'91 Measurement Campaign, *GRL*, this issue, 1992.

Heflin, M., W. Bertiger, G. Blewitt, A. Freedman, K. Hurst, S. Lichten, U. Lindqwister, Y. Vigue, F. Webb, T. Yunck, and J. Zumberge, Global Geodesy Using GPS Without Fiducial Sites, *GRL*, 19, p. 131-134, 1992.

Herring, T. A., D. Dong, and R. W. King, Sub-Milliarcsecond Determination of Pole Position Using Global Positioning System Data, *GRL*, 18, 1893-6, 1991.

IERS, *IERS Technical Note 5*, Central Bureau of IERS, Observatoire de Paris, June, 1990.

IERS, *IERS Annual Report for 1990*, Central Bureau of IERS, Observatoire de Paris, July, 1991.

Lichten, S. M., and J. S. Border, Strategies for High Precision Global Positioning System Orbit Determination, *J. Geophys. Res.*, 92, pp. 12751-12762, 1987.

McCarthy, D. D., *IERS Standards*, IERS Technical Note 3, Central Bureau of IERS, Observatoire de Paris, 1989.

Munk, M. H., and G. J. MacDonald, *The Rotation of the Earth*, Cambridge University Press, 1975.

Murray, M. H., R. W. King, and P. J. Morgan, SV5: A Terrestrial Reference Frame for Monitoring Crustal Deformation With the Global Positioning System, (Abstract) *EOS Trans, AGU*, 71, p. 1274, 1990.

Thomas, J. B., Functional Description of Signal Processing in the Rogue GPS Receiver, *JPL Pub. 88-15*, Jet Propulsion Laboratory, Pasadena, June, 1988.

U. Lindqwister, A. Freedman, and G. Blewitt, MS: 238-624, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109.

(Received October 22, 1991;
revised January 9, 1992;
accepted March 5, 1992.)