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EVALUATION OF GPS ESTIMATES OF RELATIVE POSITIONS FROM CENTRAL CALIFORNIA, 1986-1988

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Abstract. I report estimates of long-term precision and accuracy of interstation vectors using the Global Positioning System (GPS). Precision is estimated from three experiments conducted in central California over a period of 1.2 years. Horizontal precision is 3 to 8 mm for baseline vectors between 100 and 450 km in length, and the vertical precision ranges from 11 to 33 mm. Accuracy is assessed by comparing VLBI estimates with results from 6 GPS experiments conducted at Mojave and Palos Verdes over a period of 2.2 years. Rates for all vector components agree with VLBI within one standard deviation.

Introduction

Between mid-1986 and 1988, seven satellites of the Global Positioning System (GPS) were operational. The constellation is scheduled for completion in 1992 and will consist of 21 satellites. These satellites are currently being used by geologists and geophysicists in an effort to measure crustal deformation in many tectonically active regions, including Alaska, California, and South America [e.g. Beutler et al., 1987; Prescott et al., 1989; Kornreich-Wolf et al., 1990]. GPS satellites are being used because one can easily and inexpensively measure three-dimensional vectors between sites that are not mutually visible. GPS determined crustal deformation rates have only been reported by the USGS Crustal Strain Group [Davis et al., 1989; Svarc and Prescott, 1989]. The focus of their work was long-term precision and accuracy of interstation vectors on scales of 100 m to 50 km, and over one longer baseline of 223 km length. Although reports of short-term horizontal precision better than 10 mm for baselines between 50 and 500 km in length is encouraging [Dong and Bock, 1989; Blewitt, 1989], they have not been confirmed in long-term studies, which are required before GPS will be able to reliably measure long-term deformation signals. Only long-term precision and accuracy studies will be able to isolate systematic errors, such as error sources which are seasonal in nature.

GPS cannot be used as a scientific tool, in particular to measure crustal deformation rates, until the inherent precision and accuracy of the technique is understood. A precision estimate will allow geophysicists to determine how many years of measurements are required to elucidate tectonic features. Accuracy assessments will make it possible to mix GPS estimates with data from other techniques, such as electronic distance measurements and VLBI. To address these issues, I present analysis of two data sets. For precision, data collected during three experiments spanning 1.2 years are used. To assess accuracy, estimates for a baseline vector with longer and more frequent temporal sampling are compared with VLBI estimates.

Precision

The precision of GPS derived interstation vectors depends on the geometry of the GPS satellites in the sky, the ability to model errors which affect the observables, and the precision of the instruments used to track the satellites. In particular, the precision of horizontal components of interstation vectors are approximately an order of magnitude more precise than the vertical components. This is because as the satellites traverse the sky, the horizontal sampling is far superior to the vertical sampling. For horizontal components, the analysis of several days of GPS data has found that north-south components are determined more precisely than east-west components [e.g. Blewitt, 1989]. The general explanation of this phenomenon is that the satellite sky tracks over California (Blewitt's research area) in this period were preferentially aligned in the north-south direction. The precision of GPS interstation vectors is described by the following relationship:

$$\frac{\delta r}{r} \sim \frac{\delta b}{b} \qquad (1)$$

where δr is the orbit error, r is the altitude of GPS satellites (approx. 20,000 km), δb is the vector error, and b is the vector length. Depending on one's ability to model the satellite motion, and therefore reduce δr, one expects that precision may depend on the vector length. The addition of more GPS satellites will remove the north-south precision bias, but will not dramatically improve vertical precision, which is sensitive to atmospheric propagation errors.

The data were collected in three experiments in December 1986, September 1987, and March 1988 [Larson, 1990]. The GPS satellites were tracked with TI-4100's, dual-frequency high precision receivers [Henson et al., 1985]. Both pseudorange and carrier phase data were recorded at 30 sec intervals for approximately 7.5 hrs during each experiment.

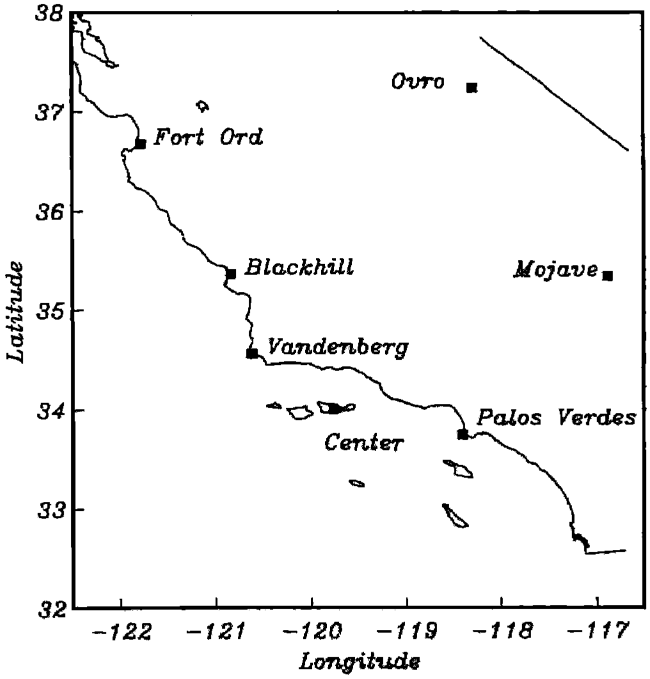

Fig. 1. GPS measurement sites in California.

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The crustal deformation network was located in southern and central California (Figure 1). Additionally, three North American sites were used as part of the fiducial network (see Table 1). During the period 1986-1988, the GPS constellation was visible over California for only 8 hours. The September 1987 experiment was conducted during daylight, and the December 1986/March 1988 data were collected primarily at night. The fiducial coordinates were determined from a Goddard Space Flight Center VLBI global site velocity model [Ma, personal communication], which was mapped to the time of the GPS experiment and corrected for the geocenter offset [Murray and King, 1988], and local surveys between GPS and VLBI monuments [NASA, 1988]. Since the choice of fiducial network can strongly affect the precision and accuracy of interstation vectors [Larson, 1990], I used identical fiducial networks in the three experiments. This choice limits the analysis to the days in which all fiducial sites were available, 3 days per experiment.

The data were analyzed with the GIPSY software developed at the Jet Propulsion Laboratory [Lichten and Border, 1987]. The estimation procedure is described in detail in Table 2. The positions of the fiducial sites were held fixed, and the positions of the satellites and non-fiducial sites were estimated. Additionally, satellite and receiver clocks, the wet zenith troposphere delay, and carrier phase ambiguity terms were simultaneously estimated. Ambiguity resolution was attempted using the method described by Blewitt [1989].

TABLE 1. Experiment Sites

Station[1]	Long (deg)	Lat (deg)	Ht (m)	Observations
Blackhill	-120.83	35.36	201	9
Center	-119.75	33.99	394	9
Churchill	-94.09	58.76	31	9
Fort Ord	-121.77	36.67	39	9
Haystack	-71.49	42.62	125	9
Mojave	-116.89	35.33	904	5
OVRO	-118.29	37.23	1195	7
Palos Verdes	-118.40	33.74	73	6
Platteville	-104.73	40.18	1530	9
Vandenberg	-120.62	34.56	24	8

1. Fiducial stations are shown in italics.

TABLE 2. Parameter Estimation

Parameter	Standard deviation
Satellite position	100 km
Satellite velocity	1 km/sec
White noise clock	1 sec
Non-fiducial station position	2 km
Phase ambiguity	10^{-6} sec
Zenith wet troposphere delay	300 mm
Data Weights:	
Pseudorange	2250 mm
Carrier phase	10 mm

Time series of GPS estimates of north, east, and vertical components for 10 baselines ranging from 91 to 464 km in length are shown in Figure 2. In assessing horizontal precision in a tectonically active region, I have taken into account possible relative motion between sites, and therefore compute the weighted RMS about the best-fitting line. For vertical precision, the weighted RMS about the mean is calculated; thus vertical tectonic motion is ignored. Using the baselines shown in Figure 2, Table 3 lists precision, as defined above, and the values are plotted in Figure 3. The east scatter ranges from 2.7 to 6.3 mm, and the north scatter ranges from 2.9 to 7.8 mm. Both horizontal and vertical component precisions show little dependence on baseline length. The means of the scatter statistics in Table 3 are 5.0, 4.6, and 20.4 mm for the north, east, and vertical components, respectively. These long-term precision results are in good agreement with estimates from the work of Davis et al. [1989] for baselines under 50 km in length, with RMS scatter of 2-4 mm, 7-8 mm,

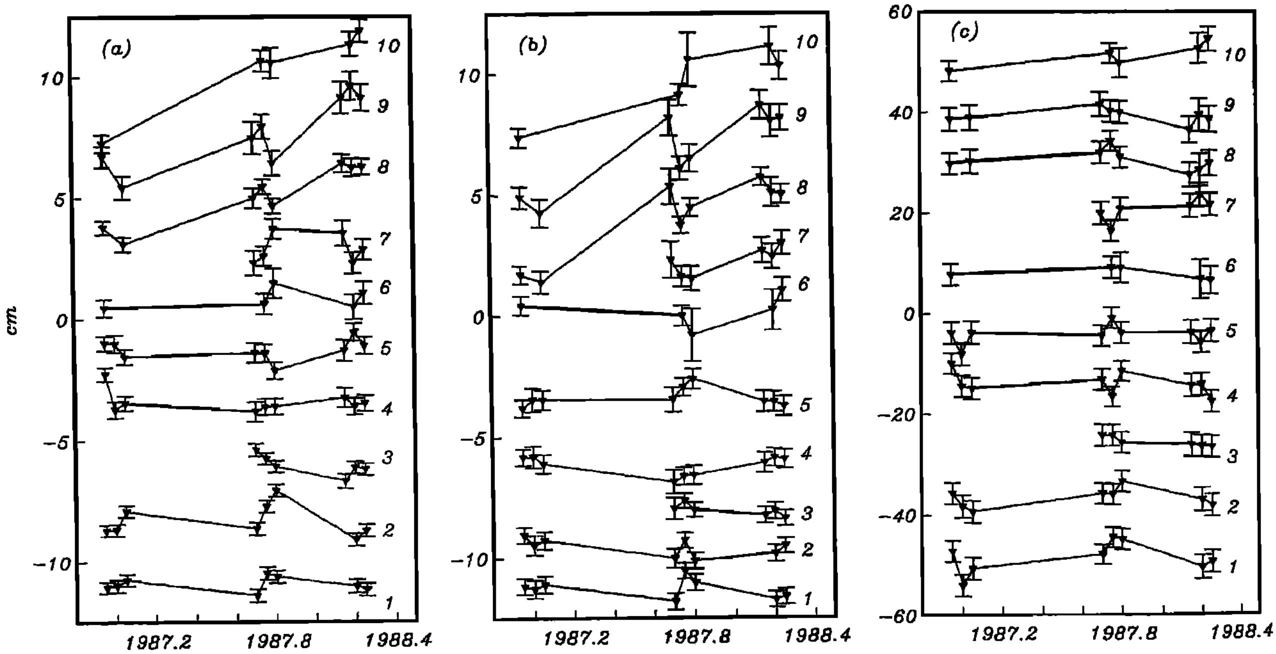

Fig. 2. Evolution of relative coordinates for the north (a), east (b), and vertical (c) components of the interstation vectors listed in Table 3. Individual interstation vectors are offset for display purposes. Error bars are one standard deviation.

TABLE 3. Precision

Interstation vector	Length km	East mm	North mm	Vertical mm	Obs.
1. Blackhill-Vandenberg	91	4.3	2.9	32.5	8
2. Center-Vandenberg	101	3.9	6.7	19.0	8
3. Center-PVerdes	127	2.7	4.2	11.0	6
4. Fort Ord-Blackhill	168	3.8	5.3	27.5	9
5. Blackhill-Center	181	3.9	4.4	14.2	9
6. Mojave-OVRO	245	5.2	3.8	12.1	5
7. PVerdes-Blackhill	285	6.3	6.1	24.5	6
8. OVRO-Blackhill	308	5.0	3.5	21.9	8
9. Center-OVRO	382	6.3	7.8	14.9	8
10.Mojave-Fort Ord	464	4.6	4.9	25.2	5

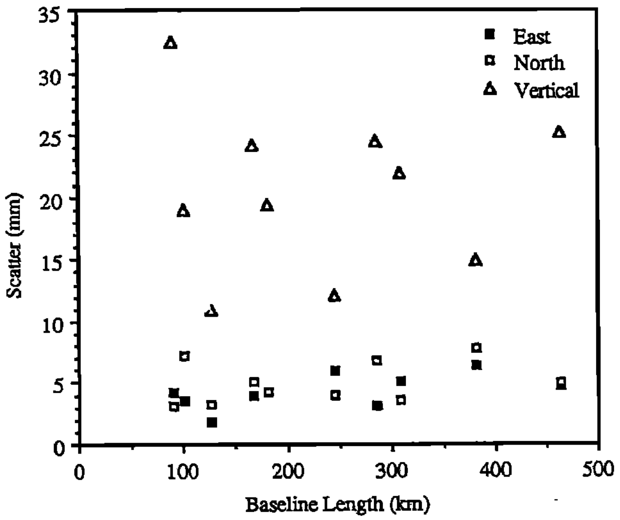

Fig. 3. Baseline precision, as a function of baseline length. The horizontal precision is computed by the weighted RMS about the best-fitting line. Vertical precision is determined by the weighted RMS about the mean.

and 12-21 mm, for the north, east, and vertical components, respectively. The agreement indicates that GPS orbits have been effectively modeled, and that GPS is as precise at 500 km as 50 km.

Accuracy

High-precision is not necessarily indicative of accuracy, which requires comparison with an independent technique. Therefore, I also present results of a long-term comparison between VLBI and GPS interstation vectors. Most estimates of GPS accuracy at baseline lengths over 50 kilometers have restricted comment to single epoch agreement with VLBI or SLR (Satellite Laser Ranging) [Dong and Bock, 1989; Blewitt, 1989; Bock et al., 1986]. An exception is work by Davis et al. [1989], that reports sub-centimeter agreement between VLBI and GPS estimates of length between Palos Verdes and Vandenberg (223 km).

The baseline between Mojave and Palos Verdes is 224 km long. Data from 6 experiments conducted between June 1986 and September 1988 were analyzed with the GIPSY software, with the same estimation procedure as described in Table 2. The difference in the quality of these data, compared with the data presented in the previous section, is that a variety of fiducial network configurations were used. It has been shown that some fiducial configurations can produce errors as large as 8 parts in 10^8 of baseline length, which would produce noise levels of 18 millimeters on a baseline of this length [Larson, 1990]. Since these were data were collected more frequently, seasonal effects also might degrade precision and accuracy. Statistics for this interstation vector are listed in Table 4.

Figure 4 displays the north, east, and vertical vector components for GPS experiments conducted between 1986 and 1988. The line drawn through the figure is the VLBI component estimate, which was calculated using the global velocity model that was used to determine the fiducial coordinates. The VLBI estimate is based on 5 independent estimates over 4.1 yrs. Although the horizontal vector components disagree by as much as 15 mm, the linear trends are similar. The GPS rates are -21 ± 3 mm/yr and 28 ± 4 mm/yr, for the north and east components, respectively. This agrees within one standard deviation of the VLBI estimates of -19 ± 4 mm/yr and 20 ± 4 mm/yr. The relative motion of Palos Verdes differs significantly from that predicted by global plate motion models [DeMets et al., 1987]. These GPS results can be interpreted either as compression in the Los Angeles Basin [Davis, personal communication], or that Palos Verdes is a geologically unstable site for crustal deformation studies. In the vertical component, GPS and VLBI rates indicate that vertical motion is insignificant.

Conclusions

I have examined GPS data collected in North America in order to assess the precision and accuracy of these measurements on baseline vectors between 90 and 400 kilometers in length. Long-term precision is sub-centimeter, and GPS determined vector rates agree within one standard deviation with estimates from over 4 years of VLBI data. Given these precision and accuracy results, and annual surveys, crustal deformation rates can be measured with GPS with a standard deviation of 2 mm/yr in 4 years. These data can then be used in conjunction with geologic data and geophysical models to further our understanding of the distribution of motion across plate boundaries.

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TABLE 4. Accuracy: Mojave to Palos Verdes.

	GPS	VLBI
Measurement History		
Number of Observations	18	5
Years of Observations	2.2	4.1
Local Surveys Required	3	-
Comparison of Vector Rates (mm/yr)[1]		
East	28±4	20±4
North	-21±3	-19±4
Vertical	5±11	0±4
Absolute difference between GPS and VLBI vectors (mm)		
East	15	
North	12	
Vertical	80	
Length	17	

1. Uncertainties are one (unscaled) standard deviation.

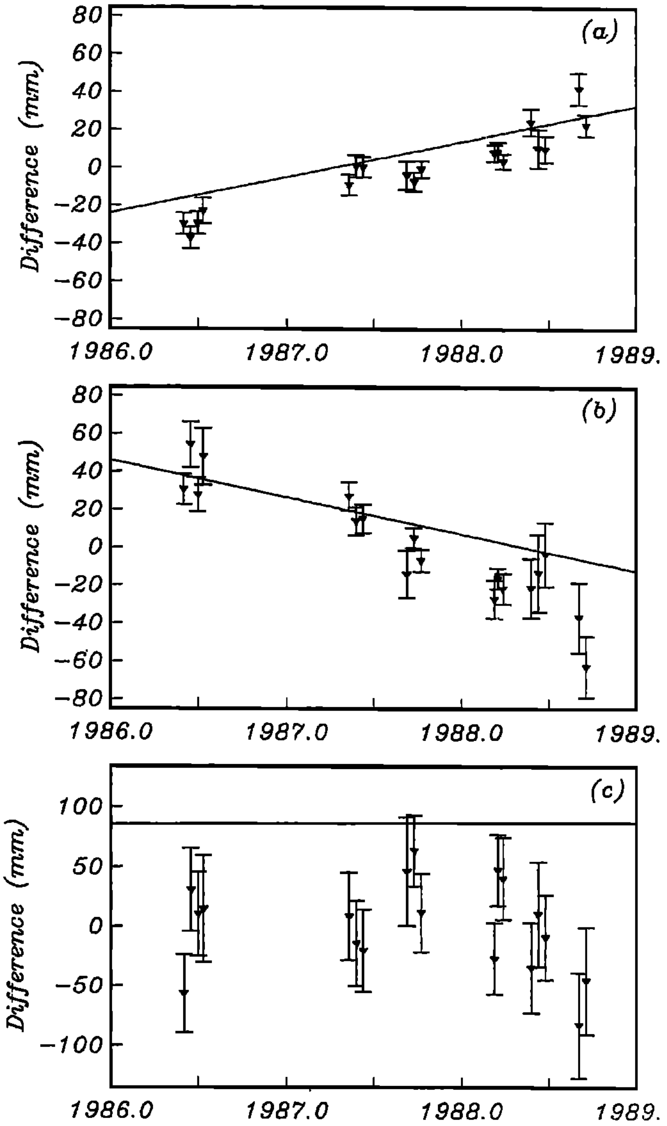

Fig. 4. Evolution of relative coordinates for the north (a), east (b), and vertical (c) components of the Palos Verdes to Mojave vector. The line drawn is derived from the global VLBI solution which was used to define the fiducial coordinates. The differences from the GPS means are shown.

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