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GPS Measurements of Regional Deformation in Southern California

Some Constraints on Performance

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Geodetic measurements are an important tool for understanding plate boundary zone deformation. They provide data on fault motion rates and indirectly provide constraints on crustal rheology, earthquake processes, and evolution of geologic structures. In southern California the pattern of strain resulting from interaction of the Pacific and North American plates is very complex, and a robust geodetic experiment requires dense spatial sampling. In addition, the signals of interest may have strain rates smaller than 10^{-7}/yr. Taken together, these conditions imply the need for geodetic techniques that are both economical, enabling large numbers of measurements, and highly accurate. Conventional terrestrial surveying techniques can satisfy the requirements for sampling density and accuracy for some applications, but are limited to line-of-sight, or distances less than about 50 km [e.g., *Snay et al.*, 1983; *Savage et al.*, 1986]. The precision σ of these techniques may be described by

$$\sigma = (a^2 + b^2L^2)^{1/2} \qquad (1)$$

where L is baseline length (station separation) and a and b are constants representing, respectively, length-independent and length-dependent sources of error [*Savage and Prescott*, 1973]. For high-precision Geodolite surveys, $a = 3$ mm, and $b = 2 \times 10^{-7}$ [*Savage et al.*, 1987]. Very Long Baseline Interferometry (VLBI), performed by the National Aeronautics and Space Administration's Crustal Dynamics Project, has proven to be a highly precise geodetic technique, applicable over longer distances where line of sight techniques cannot be used. For VLBI, a is less than 1 cm, while b is less than 1×10^{-8}; intercontinental baselines have been measured using large, fixed radio telescopes with centimeter-level precision, that is, $b \approx$ several parts in 10^9 [*Clark et al.*, 1987]. Although smaller, mobile VLBI systems have been deployed successfully in southern California [*Davidson and Trask*, 1985; *Kroger et al.*, 1987], their size, complexity, and cost still prohibit comprehensive mapping of the complex strain field associated with Pacific-North American plate interaction.

Geodetic measurements with the Global Positioning System (GPS) have the potential to deliver high precision at relatively low cost and thus can complement or perhaps replace existing geodetic techniques. However, rigorous assessment of GPS precision and accuracy over a range of baseline lengths and conditions is required before this potential can be fully realized. For measurement of longer (>50 km) baselines, the value of b in equation (1) ideally would be much less than 2×10^{-7} (the exact amount depending on the length of interest) to ensure sufficient accuracy in the resulting strain rate estimates within a reasonable (several year) time span.

In June 1986 a number of investigators pooled their resources to conduct the first major survey of southern California with GPS equipment. The experiment involved occupation of many fixed and mobile VLBI sites, as well as additional sites not previously accessible for space geodetic measurements. The large number of VLBI sites occupied in the experiment means that direct GPS-VLBI comparisons can be made on numerous baselines of varying length and orientation, providing an unprecedented opportunity to assess the performance of GPS through comparison to another technique. We present results from this experiment, as well as some limited results from later experiments, assessing GPS performance by analysis of day-to-day and longer-term repeatability, and comparison to VLBI. *Davis et al.* [1989] review GPS performance on shorter (<50 km) baselines, appropriate, for example, for studies of the earthquake process and crustal rheology. In this paper, we emphasize GPS performance on longer (50–500 km or longer) baselines, a length range useful for measurement of regional deformation and fault block velocities. We then assess the implications of this level of performance for meeting longer-term scientific objectives. Our major conclusion is that GPS techniques can yield results comparable to those achieved with mobile VLBI techniques in California, assuming that appropriate network design and analysis techniques are used; GPS can thus provide important constraints on regional deformation in California with 5 years or less of measurements.

Scientific Objectives and Accuracy Requirements

Relative motion between the Pacific and North American plates in southern California is accommodated at the surface and in the brittle, upper crust by a series of faults that interact in a complex way (Figure 1). A useful model for understanding some of this complexity, and for initial planning of geodetic experiments, is one where faults divide the upper (10–15 km) crust into blocks that behave elastically over short time scales. Deeper layers may deform in a more viscous manner. Transient motions near the bounding faults may occur due to buildup and release of elastic strain energy associated with the earthquake cycle, while the "interiors" of the upper crustal blocks, that is, locations more than several elastic layer thicknesses (roughly 50 km) away from the fault boundary, move more or less steadily with respect to each other. High-precision geodetic measurements are useful in characterizing and understanding both types of motion, depending on spatial coverage, precision and accuracy, and the time span of the experiments. However, because of the greater distances involved, accurate determination of the "far field" steady velocity of fault blocks may be more difficult with GPS, because of the length dependence of several error sources.

The far-field motion observed by geodetic measurements between sites on different fault blocks may be very similar to the geologic rate, the long-term average rate of motion determined by measurement of displacement of a geologic unit of known age.

Whether determined geologically or geodetically, knowledge of these rates, when coupled with knowledge of the total plate rate from

Cover. Plumb bob and its shadow over cover plate for geodetic marker 7263 at the ARIES 9 meter "Mesa" site, located at the Jet Propulsion Laboratory, California Institute of Technology, Pasadena. Site has been used since 1975 for geodetic measurements to monitor crustal motion in southern California, initially by very long baseline interferometry (VLBI), and, since 1986, by the Global Positioning System (GPS). Plumb line helps position GPS antenna over center of mark (small circle at apex of cones). Two circles to left are impact points generated during early deployments of the first mobile VLBI system built at JPL, MV-1. Inscription indicates specific experiment and date; "JPL 6A" is marker number. The points helped locate phase center of large (9 m) antenna with respect to center mark, and was later replaced by a laser device. The accuracy of GPS measurements is assessed through comparisons to VLBI data in "GPS Measurements of Regional Deformation in Southern California: Some Constraints on Performance," by T. Dixon et al., this issue. Photograph by T. K. Meehan, JPL.

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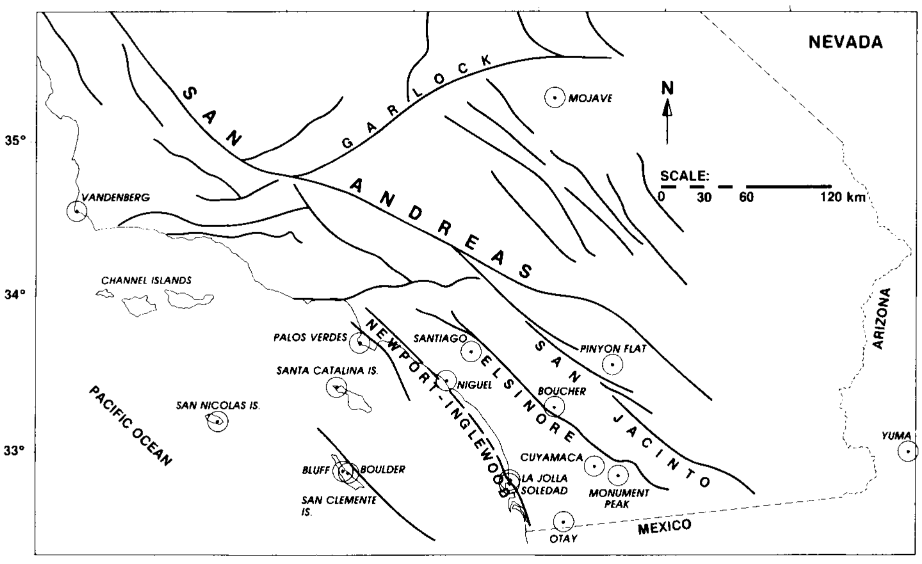

Fig. 1. Map of Southern California, showing major faults and sites discussed in the text.

global models [*Demets et al.*, 1990] can lead to development of internally consistent kinematic block models [*Bird and Rosenstock*, 1984; *Weldon and Humphreys*, 1986]. Transient elastic effects close to faults are neglected in such models. An important aspect of the June 1986 experiment is that for the first time, space geodetic techniques were extended offshore to the southern California borderland, a key area in any kinematic model of the region.

Bird and Rosenstock [1984] suggest the precision of their block rate estimates from geologic data is 3 mm/yr. GPS evaluation of such models would require a similar level of precision. *Jordan and Minster* [1988] review various types of secular plate motion and suggest that space geodetic measurements in the western U.S. could generate geologically useful constraints if fault motion rates were determined to better than 5 mm/yr. It is apparent that the accuracy of GPS geodetic measurements must be rigorously assessed before this approach to block model evaluation can be fully exploited. The subsequent discussion will provide some insight into this topic.

GPS Background

GPS satellites transmit signals on two carrier frequencies (about 1.23 and 1.58 GHz) modulated with lower-frequency codes, including the P-code at 10.23 MHz, containing timing information used for clock synchronization and meter-level positioning. Certain GPS receivers are capable of extracting both group delay information (from the P-code) and phase delay information (from the carrier itself) with meter and subcentimeter precision, respectively. It is possible to do high-precision geodesy with only carrier phase measurements, although there are advantages to incorporating the less precise P-code (often termed pseudorange) data [*Tralli and Dixon*, 1988; *Dong and Bock*, 1989; *Blewitt*, 1989]. Using known dispersion relations, carrier phase measurements at the two frequencies enable accurate calibration of the time-varying component of ionospheric delay [*Spilker*, 1978]. Simultaneous phase measurements from at least two satellites with at least two ground receivers allow removal of errors associated with satellite and receiver hardware (mainly clock and instrument delay errors) by common mode cancellation (often termed "double differencing"), enabling precise tracking of the differential range change to the satellites [*Remondi*, 1985]. The absolute receiver-satellite range in the phase approach is ambiguous by an integer number of carrier wavelengths. Nevertheless, vector baselines between receivers can be estimated to a precision of a few centimeters or better using the observed time evolution of the differenced satellite ranges, together with models of the forces acting on the satellites, knowledge of the Earth's orientation in inertial space during the experiment, and models for Earth tides and atmospheric delay. Baseline precision degrades with increasing baseline length, the exact amount depending strongly on the quality of the GPS orbit model and the geometric strength of the data. We will suggest that for baselines 500 km or longer (adequate for determination of far-field block velocities), subcentimeter precision in horizontal components is possible, depending on experiment design and analytical techniques. Some aspects of experiment design will be briefly discussed.

Experiment Description and Data Analysis

Table 1 summarizes site and equipment information for the June 1986 experiment, which is representative of the scope of several subsequent experiments. A total of 21 sites were occupied between June 17 and 20, 1986, with up to 16 sites occupied simultaneously. Ten sites were occupied for 3 or 4 days, while most of the remaining sites were occupied for 2 days each, either June 17–18 or June 19–20. Data were collected for about 7–8 hours per day at each site. The network had baseline lengths from 18 km to more than 1000 km. Ten sites were occupied previously by VLBI techniques. GPS observations at three of these "fiducial" sites (Haystack, Mass., Richmond, Fla., and Fort Davis, Tex.) were used to constrain the ephemerides of the GPS satellites and define a reference frame. GPS baseline estimates between the remaining seven VLBI sites give an important comparison data set with which to assess GPS performance. Of these seven sites, four were mobile VLBI sites, and three (Vandenberg, Mojave and Hat Creek) were fixed VLBI sites. One advantage of the mobile VLBI sites for such comparisons is that the GPS antenna can be located directly over the same mark as that used for the VLBI measurements, eliminating uncertainties associated with site ties connecting phase centers of the large fixed antennas and the ground marks used for GPS experiments. TI-4100 GPS receivers were used at all sites discussed in this report, providing dual frequency carrier phase and pseudorange data types. Water vapor radiometer (WVR) data for calibration of wet tropospheric effects were available from some sites, including the humid Richmond, Fla., site.

Data for this report were analyzed at the Jet Propulsion Laboratory, Pasadena, Calif., using the GIPSY (GPS Inferred Positioning System) software, described by *Blewitt* [1989] and *Lichten* [1990]. GIPSY enables simultaneous estimation of satellite state vectors (three spatial coordinates and three velocity components), three spatial coordinates for each ground station (except the three fiducial stations), station and satellite clocks (modeled as white noise), and a troposphere parameter for each ground station. The wet tropospheric path delay can be calibrated with water vapor radiometers, with surface meteorological measurements and an atmospheric model, or estimated entirely from the GPS data without prior calibration [*Tralli et al.*, 1988; *Dixon et al.*, 1990]. For this study, water vapor radiometer data were used where available, with estimation of a constant residual delay. At other sites, surface meteorological data combined with a model were used, with estimation of a stochastic residual delay. Fixed parameters in the analysis included the three fiducial station positions, the dry tropospheric path delay (based on surface pressure measurements at each station), a reference clock at Fort Davis, and parameters necessary to define the Earth's orientation in space at the time of satellite observation (pole position, and UT1-UTC for a common time standard, both derived from VLBI). Station positions were loosely constrained with a priori uncertainties of 2 km. A priori uncertainties for other estimated parameters, data weights for carrier phase and pseudorange observables, and additional analytical details are given by *Lichten and Border* [1987] and *Blewitt* [1989].

The initial phase measurement upon acquisition of the carrier signal is biased by an unknown number of cycles, that is, only the fractional part of the initial phase measurement is meaningful. If a receiver can subsequently maintain lock on the signal and keep count of the number of cycles accumulated since signal acquisition, the range change between the receiver and satellite can be determined, and the initial range (the cycle ambiguity) can be estimated along with parameters such as satellite state, clocks, and the geodetic parameters of interest. However, this results in roughly a factor of three degradation in baseline accuracy relative to the case where

TABLE 1. Sites and Equipment Used in the June 1986 GPS Experiment

Site	Receiver	WVR
	Fiducial Sites	
Ft. Davis, Tex.	TI-4100	—
Richmond, Fla.	TI-4100	R-05
Haystack, Mass.	TI-4100	R-08
	Other Sites (California, unless noted)	
Mojave	TI-4100	R-07
Hatcreek§	TI-4100	—
Boucher-2**	TI-4100	—
Cuyumaca**	TI-4100	—
La Jolla**	TI-4100	—
Monument Peak	TI-4100	—
Niguel*	TI-4100	—
Otay*	TI-4100	—
Palos Verdes	TI-4100	J-01
Pinyon Flat*	TI-4100	—
San Clemente Is.:		
Boulder*	TI-4100	—
Bluff**	TI-4100	—
San Nicolas Is.	TI-4100	SCAM
Santa Catalina Is.	TI-4100	—
Santiago**	TI-4100	—
Soledad*	TI-4100	—
Vandenberg***	TI-4100	R-04
Yuma, Ariz.	TI-4100	—

All sites observed June 17-20, 1986, except:
*June 17-18
**June 19-20
***June 18-20
§Only June 20 data are used

the cycle ambiguity is known, a critical difference in terms of accurate fault block velocity determination. Techniques have been developed to resolve this ambiguity, and generally rely on the fact that given enough data, the range ambiguity can be estimated to better than half a carrier wavelength (cycle), after which it is fixed to the nearest integer value. Unfortunately, ionospheric activity and other error sources can corrupt GPS signals such that phase errors become significant relative to one half wavelength. One approach is to first resolve the ambiguities on shorter (less than about 100 km) baselines where these errors tend to be correlated at the two stations [*Abbot and Counselman*, 1987; *Dong and Bock*, 1989]. The method used here additionally exploits the fact that the ionospheric group delay of the P-code modulation is the same magnitude, though opposite sign, as the phase delay, provided the correct number of cycles is associated with the phase measurement [*Blewitt*, 1989].

Results

Repeatability

Assuming that each day of observation is treated independently, the day-to-day repeatability of baseline components for an experiment spanning several days gives some indication of GPS precision. We used only single-day orbital arcs to reduce possible statistical correlations between successive days. The extent to which day-to-day repeatability is a valid measure of performance is addressed in the next two sections. Figure 2 shows north, east and vertical repeatabilities (1-σ deviations from the weighted mean) for all stations occupied for 3 or 4 days in June 1986, plotted as a function of baseline length. This criterion resulted in 21 baselines up to 620 km long among the seven nonfiducial sites in California and Arizona. Repeatability in the north component is nearly independent of length and is always less than 1 cm, with a mean value for all baselines of 3.8 mm. East repeatability is more dependent on baseline length, but is less than 1 cm for most baselines, with a mean of 8.0 mm. Vertical repeatability is uncorrelated with baseline length, and is worse than the horizontal components, between 1.1 and 4.7 cm, with a mean of 2.9 cm. The difference between horizontal (east and north) and vertical repeatability is similar to results obtained with VLBI and reflects the geometric limitation that the sky can only be observed in one hemisphere, coupled with sensitivity of the vertical component estimate to the accuracy of the troposphere calibration [*Herring*, 1986].

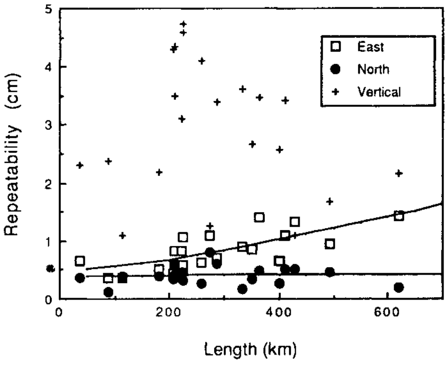

Fig. 2. Baseline repeatability (rms scatter about the weighted mean) for all GPS sites in southern California occupied 3 or 4 days in June 1986, for north, east, and vertical components. Best fit curves (unweighted data) of the form described by equation (1) are shown for the horizontal (east and north) components.

Equation (1) provides a useful standard for comparing the repeatability of horizontal components of GPS-determined baselines with other geodetic techniques. A best fit curve of the form described by equation (1) through the north component repeatabilities gives a = 4 mm and b = $<1 \times 10^{-9}$, while the corresponding values for the east components are a = 5 mm and b = 2.2×10^{-8} (Figure 2). The greater dependence of east component repeatability on baseline length reflects orbital geometry, as the satellites have dominantly north-south ground tracks. Ambiguity resolution improved the repeatability of the horizontal component estimates by factors of 2-3, but did not significantly affect vertical repeatability [*Blewitt*, 1989].

How well does repeatability over a few days predict the long-term performance of GPS? Is day to day repeatability a valid measure of precision, and if so, what is the relation between precision and accuracy? Comparison of the results presented in this section to measurements obtained by an independent technique, and repeated measurements over a longer interval, give important clues to these questions, and are addressed below.

Comparison to VLBI

The accuracy of any long baseline measurement is difficult to determine rigorously since completely independent techniques of known accuracy are not available for comparison. However, if two independent techniques provide similar results, we can be more confident in each. VLBI measurements using large radio astronomy antennas are now widely accepted as a highly precise geodetic technique, repeatable at the centimeter level or better for both intra- and inter-continental baselines [*Clark et al.*, 1987]. Mobile VLBI measurements, using smaller, portable antennas, have been performed extensively in southern California and have produced results nearly as precise, roughly a centimeter or better plus 1 part in 10^8 of baseline length or better [*Davidson and Trask*, 1985; *Clark et al.*, 1987; *Kroger et al.*, 1987; *Ma et al.*, 1989]. VLBI thus provides an important data set for assessment of GPS performance over a large range of length scales and to some extent is a measure of GPS accuracy. However, it should be noted that VLBI and GPS techniques are not completely independent, sharing, for example, a similar level of sensitivity to tropospheric effects. Also, GPS relies on Earth orientation parameters provided by VLBI, as well as VLBI location data for the fiducial sites, so that VLBI defines the reference coordinate system for GPS. Nevertheless, we believe that VLBI-GPS comparisons allow the best available standard for GPS accuracy assessment for baselines longer than about 50 km, and in the following discussion we will use the term accuracy to describe the results of GPS-VLBI comparisons, recognizing the limitations mentioned above.

In many cases, the history of VLBI measurements is long enough to define tectonic motion between two sites. Figure 3 shows a

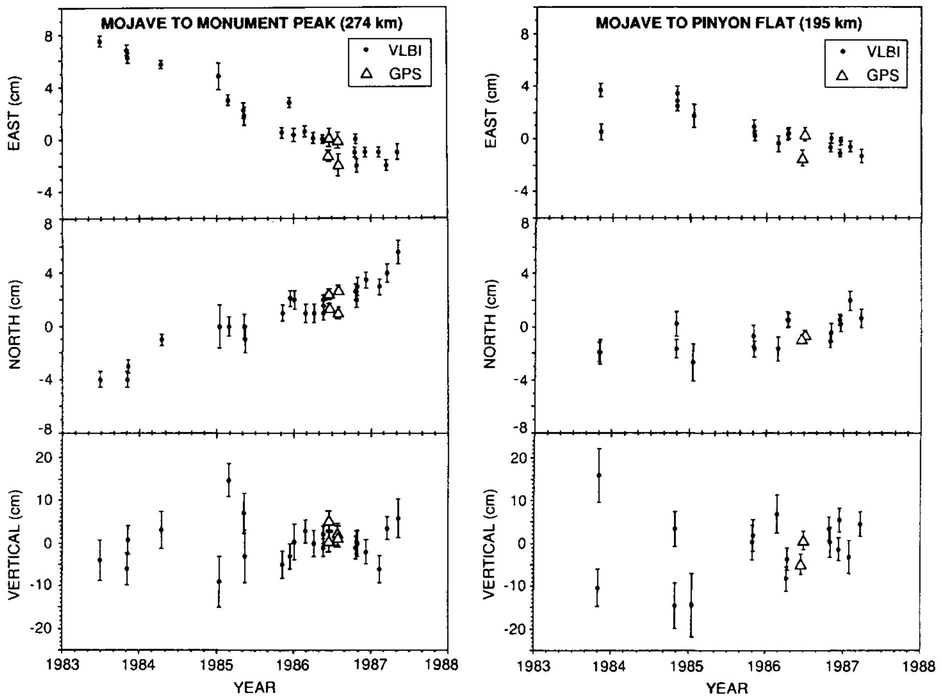

Fig. 3. Comparison of GPS and VLBI estimates on two representative baselines. Four independent GPS baseline estimates for Mojave to Monument Peak (left side) acquired June 17–20, 1986, and two independent GPS baseline estimates for Mojave to Pinyon Flat (right side) acquired June 17–18, 1986, are shown in open triangles, displaced slightly in time for clarity. VLBI data for the period 1983-1987 are shown in solid circles (M. Abel, National Geodetic Survey, written communication, 1987). Error bars for both GPS and VLBI are 1-σ formal (data noise) errors only and do not indicate systematic errors. Estimates are shown relative to an arbitrary initial value.

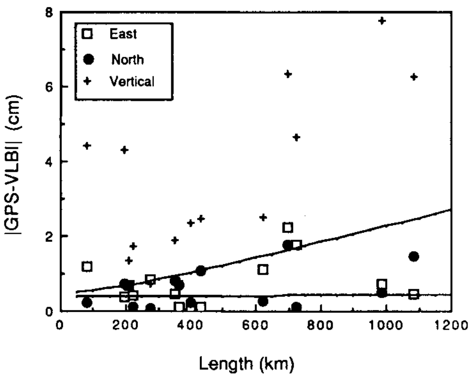

Fig. 4. GPS baseline data collected June 17–20, 1986, plotted as differences from VLBI solutions at Hat Creek, Vandenberg, Mojave, Pinyon Flat, Monument Peak and Yuma, from GLB223 GSFC global solution (J. W. Ryan, C. Ma and E. Himwich, written communication, 1988) mapped to GPS experiment epoch. For comparison, curves describing repeatability for horizontal (north and east) components are also shown, from Figure 2. Note similarity of repeatability curves (a measure of precision) and GPS-VLBI differences (a measure of accuracy) for horizontal components.

comparison of the available 4 days of GPS data from the June 1986 experiment for the Mojave to Monument Peak baseline (224 km) with the recent history of individual VLBI observations (1983–1987). The scatter (1σ) of the four daily GPS estimates in both north and east components is about 1 cm, not significantly different from the scatter of the VLBI data itself about the best fit straight line. The scatter of the GPS vertical component estimates is actually lower than the corresponding VLBI scatter. For sites occupied with GPS less than 3 days, baseline repeatability is less useful as an indicator of performance (for the 2-day occupations) or is undefined (for single-day occupations), but comparisons to VLBI again allow an assessment of performance. Figure 3 also shows VLBI estimates for the Mojave to Pinyon Flat baseline (195 km) for the period 1984-1987, and the two available GPS estimates from the June 1986 experiment. The GPS results agree with the VLBI results at the centimeter level. The scatter in the east component of the GPS estimates is comparable to VLBI, while the scatter in the north and vertical components of the GPS estimates is actually better than VLBI. There are no outliers in the entire sample of baseline estimates, and we conclude that the network and data analysis strategy were very robust, even when sites were occupied for only 1 or 2 days.

Figure 4 shows the difference between mean VLBI and GPS solutions plotted as a function of baseline length for all available GPS data (including the 1- and 2-day occupations) at sites where VLBI locations are well determined. This criterion resulted in 14 baselines among six VLBI sites with lengths between about 80 and 1100 km. Palos Verdes was not used because the VLBI data set at this site is sparse. Note that this is a different set of GPS baselines relative to those used in Figure 2 because VLBI data are only available for some sites, while other sites were only occupied for one day, precluding calculation of repeatability. For comparison with the horizontal component repeatability data, we have also plotted the best fit curves (equation (1)) from Figure 2.

The root mean square (rms) difference between the GPS and VLBI estimates for all the baselines is 8.0 mm (north), 9.7 mm (east) and 4.0 cm (vertical). The worst vertical results occur for baselines where data are available for only 1 day, suggesting the importance of averaging several days of observations. Considering only baselines 620 km or shorter (for comparison with repeatability data shown in Figure 2), these values are 4.9 mm (north), 5.5 mm (east) and 2.3 cm (vertical). Recall that mean repeatabilities over 3–4 days were 3.8 mm (north), 8.0 mm (east) and 2.9 cm (vertical). This similarity between the GPS repeatability data and the GPS-VLBI comparison data is an important result. It suggests that the accuracy of GPS baseline estimates (defined by VLBI comparison) does not differ significantly from the precision of these estimates (defined by day to day repeatability when at least 3 days of data are available) for the conditions of the June 1986 experiment. We will argue below that similar performance can be obtained routinely over longer periods, providing certain key conditions are met.

These results are consistent with other published results on GPS performance. *Dong and Bock* [1989] discuss repeatability for GPS baseline estimates up to 500 km in length from an experiment in January 1987, and note the importance of carrier phase cycle ambiguity resolution. They suggest that repeatability and accuracy are comparable, based on VLBI data for a single baseline between OVRO and Mojave. The significance of the work reported here is that the assessment of GPS accuracy is based on a larger number of baselines (14) of varying lengths (up to 1100 km) and orientations. *Davis et al.* [1989] report GPS precision of 1–18 mm in horizontal components for numerous baselines below 50 km in length and a single longer (223 km) baseline, for experiments spanning several years. Comparison of these data to Geodolite and VLBI data also suggests roughly comparable precision and accuracy.

Longer-Term Comparisons

An important question is whether the closely comparable results from GPS and VLBI shown in Figures 3 and 4 are indicative of the long-term repeatability and accuracy of GPS. Were the conditions of the June 1986 experiment special in some way such that similar results will be difficult to achieve again? Numerous repeated experiments on all or most of the VLBI sites used in 1986 would be necessary to answer this question definitively, and these have not yet been conducted. However, the results of several subsequent experiments employing some of these sites convince us that it is possible to achieve similar results on a routine basis, assuming minimum experiment standards (discussed below) are met. Results from one representative baseline are discussed below, but a complete discussion is beyond the scope of this report, and is the subject of ongoing research (see, for example, *Agnew et al.* [1988], *Dong and Bock* [1989]).

Most of the results shown in Figure 4 were obtained using mobile VLBI sites, and thus do not suffer from possible errors in local surveys tying the GPS marks and the theoretical phase centers of larger, fixed VLBI antennas. This can hamper interpretation of VLBI-GPS comparisons from a single experiment involving fixed VLBI sites but should not be problematic when data from several experiments are available because rates, unlike positions, are insensitive to such constant offsets. Figure 5 shows the results of seven experiments for the Mojave-Vandenberg baseline conducted between 1986 and 1988. Although both sites are fixed VLBI sites and hence may suffer from the problem noted above, a sufficient number of GPS experiments have been conducted here to enable rate comparisons. The GPS results (Figure 5) are again closely comparable with VLBI, except for a near-constant offset, which we assume is related to the site tie problem noted above. Although identical data analysis techniques were used for the seven experiments, the actual GPS networks differed, and in fact no two experiments had identical fiducial networks. Also, a total of three different ground monuments were used at Mojave, possibly exacerbating the site tie problem. Despite these complications, the slopes of best fit straight lines through the GPS and VLBI data sets, indicating the rate of motion between the two sites, as well as the scatter about the lines, are very similar. The similarity in slopes is encouraging, considering the fact that the GPS data span a much shorter time interval compared to the VLBI data. As noted by *Davis et al.* [1989], the rms scatter of individual measurements spanning several years about the best fit straight line through the data is a good measure of precision. The rms deviations of the GPS points from their best fit line are 6.3 mm (north), 10.0 mm (east) and 34 mm (vertical), similar to the VLBI deviations, which are 7.8 mm (transverse), 7.1 mm (length), and 37.5 mm (vertical) [*Ma et al.*, 1989]. The transverse and length VLBI component deviations correspond approximately (within about 1 mm) to the north and east GPS component deviations, respectively, for this baseline. The scatter of the GPS components about the best fit lines over 2 years is very similar to the day to day scatter over 3-4 days observed in our 1986 experiment for baselines of this length (Figure 2). The greater uncertainty in the east component GPS estimates from some experiments probably reflects weak fiducial control, which presumably can be improved in the future. A full discussion of these data is presented in the work of *Larson* [1990].

Discussion and Conclusions

The network covered in June 1986 was ideal for testing GPS accuracy because a relatively large number of VLBI sites (10) were occupied, providing numerous comparison baselines of varying lengths and orientations. Inspection of Figures 2-5 suggests that GPS data is comparable to VLBI data in its ability to accurately define fault motion rates over lengths up to at least 600 km. Excellent agreement between the horizontal components of VLBI and GPS baseline estimates at mobile VLBI sites is found even if only 2 days of GPS data are available. Although offsets are sometimes observed between GPS and VLBI estimates when fixed station VLBI sites are used, these offsets can be explained by site tie uncertainties and do not bias fault motion rate estimates. It should be noted that for the GPS experiments described here, a "day" of GPS data is actually limited to 7–8 hours of satellite visibility, reflecting the partial deployment of the GPS constellation, while a VLBI observation typically spans about 24 hours. As additional satellites are launched, as new receivers capable of tracking more than four satellites become available, and as the use of new, low multipath antennas becomes common, it is likely that the quality of GPS baseline estimates will become even better.

During the course of our analyses, several factors in GPS experiment design were identified that may help to ensure similar or better GPS performance in future surveys. Foremost among these is network design. A network with similar or greater station density relative to the June 1986 experiment, and with equivalent or better quality of fiducial control, that is, number and geometry of fiducial sites, as well as data quality at these sites, is important, particularly for longer (>50 km) baselines designed to monitor block velocities. A mix of baseline lengths is necessary for carrier phase cycle ambiguity resolution over all baselines [*Dong and Bock*, 1989; *Blewitt*, 1989], while adequate fiducial control will ensure accurate satellite ephemerides. Atmospheric calibration, while apparently not a critical factor in the results presented here, may be more important in some future experiments. Zenith wet tropospheric path delays were generally low (<10 cm) and atmospheric conditions were benign in the June 1986 experiment, suggesting that azimuthal asymmetries in the wet and dry components of the troposphere were probably low. In such cases, the precision and accuracy of GPS results are relatively insensitive to atmospheric calibration [*Tralli et al.*, 1988]. More severe weather conditions could degrade GPS results or necessitate use of WVR's for wet tropospheric calibration. Identical receiver-antenna combinations minimize the possibility of nonstandard data sets but may be difficult to achieve in the future as different receiver systems become more widespread. Different antennas may be particularly troublesome, as their phase center behavior can vary significantly [*Kleusberg*, 1986]. If different antennas are used, it will be important to calibrate these phase center effects.

The trends shown in Figures 3 and 5 reflect part of the relative motion between the Pacific and North American plates over the time span of the experiments. The VLBI data in this region and its geological significance have been discussed by *Lyzenga and Golombek* [1986], *Kroger et al.* [1987], *Clarke et al.* [1987] and *Ward* [1988] and will not be elaborated here. Assuming a similar level of performance in future GPS experiments, it is clear that GPS can monitor tectonic motion in southern California with accuracy comparable to mobile VLBI systems, suggesting that GPS can densify and complement existing VLBI measurements in the western U.S. GPS campaigns subsequent to the June 1986 experiment have already extended coverage to the Channel Islands and Central California [*Dong and Bock*, 1989], and contributed to more detailed surveys of parts of the San Andreas fault [*Davis et al.*, 1989; *Feigl et al.*, 1990]. It was previously suggested that improvements to block tectonic models in southern California required determination of rates to an accuracy of 3–5 mm/yr. Consideration of the major fault blocks shown in Figure 1 suggests that this requires a geodetic network with station separations in the range 50–300 km. Assuming 1-cm horizontal accuracy can be achieved with such a network for a particular GPS experiment (as suggested by Figure 4), rate estimates with this level of accuracy could be achieved in less than 5 years, assuming yearly experiments.

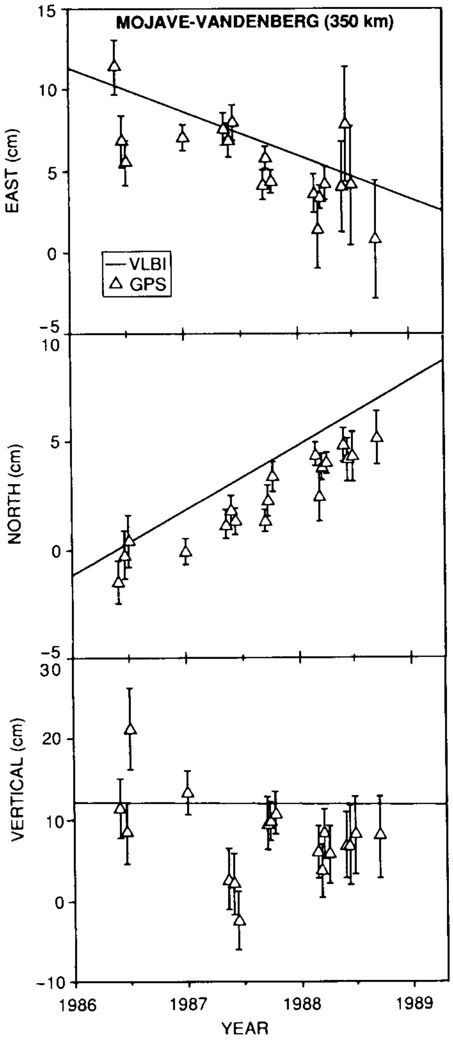

Fig. 5. Similar to Figure 3, for the Mojave-Vandenburg baseline, except individual VLBI data points are omitted for clarity; solid line is VLBI global solution GLB223. Results from seven GPS experiments (1986-1988) are shown, from *Larson* [1990]. Estimates are shown relative to an arbitrary initial value. Note similarity in slopes derived from GPS and VLBI position estimates; scatter about the best fit lines through each data set is also similar (see text).

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Planning for Chemical Air-Sea Exchange Research

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The International Global Atmospheric Chemistry (IGAC) Programme has been created in response to growing international concern about rapid atmospheric chemical changes and their impact on mankind. This program, while emphasizing atmospheric composition and chemistry, recognizes that the Earth's atmosphere, oceans, land, and biota form an interacting system that collectively determine the global environment and its susceptibility to change. The IGAC Programme is intended to be a vital contributor to the broader interdisciplinary program of the International Geosphere Biosphere Programme (IGBP), providing the important atmospheric chemistry component and recognizing its linkages with the biosphere and human activities. The IGAC Programme is building on existing national programs by providing the international cooperation whereby essential scientific endeavors can be accomplished, even though they involve large demands for man power, technology, geographic coverage, or monetary resources beyond the capability of a single nation.

One of the six initial IGAC foci is the natural variability and anthropogenic perturbations of the marine atmosphere. Since the oceans cover about 70% of the planet and act as both a source and sink of many important atmospheric constituents, it is an essential area in which to study source, sink, and transformation processes in detail. IGAC therefore proposed a project to study Marine Aerosol and Gas Exchange, Atmospheric Chemistry and Climate (MAGE).

The goals of MAGE are to understand the

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