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Preliminary Determination of Pacfic-North America Relative Motion in the Southern Gulf of Calfornia Using the Global Positioning System

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PRELIMINARY DETERMINATION OF PACIFIC-NORTH AMERICA RELATIVE MOTION IN THE SOUTHERN GULF OF CALIFORNIA USING THE GLOBAL POSITIONING SYSTEM

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Abstract. Global Positioning System (GPS) data from experiments conducted in 1985 and 1989 in the southern Gulf of California, Mexico, allow a determination of relative motion between the Pacific and North American plates. The data indicate motion of Cabo San Lucas on the Pacific plate relative to North America at a rate of 47±7 mm/yr and azimuth of 57±6° west of north (1σ errors), equivalent within uncertainties to the NUVEL-1 global plate motion model.

Introduction

The rotation vector describing relative motion between the Pacific and North American plates is an important constraint for kinematic models of plate boundary zone deformation. The vector rate averaged over several million years is constrained by magnetic anomalies in the southern Gulf of California. Recent interpretations give rates between 47 mm/yr and 65 mm/yr [DeMets et al., 1990; Ness et al., 1991]. The vector orientation is constrained mainly by the azimuths of the Tamayo fracture zone (in oceanic crust) and fracture zones to the north (in transitional oceanic-continental crust) but differences up to 5° exist in estimates by various workers [Macdonald, 1979; Goff et al., 1987; DeMets et al., 1990; Humphreys and Weldon, 1991; Argus and Gordon, 1990]. The orientation is not well constrained by the San Andreas fault or northern Gulf transforms because of the influence of weaker, structurally complex continental crust. On shorter time scales, earthquake slip vectors provide azimuth data, but show considerable variation. Global plate models such as NUVEL-1 [DeMets et al., 1990] use magnetic anomalies, fracture zone trends and earthquake slip vectors from all plate boundaries, and are less affected by local tectonic complexity. Global models still average over several million years, and may be biased if a specific plate boundary is evolving rapidly.

Geodetic measurement of plate motion is complicated in continental parts of the plate boundary by distributed deformation, e.g., Basin and Range extension, making it difficult to perform measurements from stable plate interiors. However, the plate boundary is narrow in the southern Gulf of California (Figure 1). Measurements here should record most of the relative motion between the Pacific and North American plates. Satellite laser ranging (SLR) measurements between Mazatlan and Cabo San Lucas (Figure 1) were begun in 1984, but to date have not yielded precise rate estimates. Ground-based laser measurements in the central Gulf suggest a rate of 80±30 mm/yr [Ortlieb et al., 1989], anomalously high in relation to other data and models. We report here an estimate of Pacific-North America relative motion based on Global Positioning System (GPS) measurements in the southern Gulf of California made in November 1985 and May 1989.

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Data Analysis

Results from the first experiment are given in Tralli and Dixon [1988], Tralli et al. [1988], Lichten and Bertiger [1989] and Dixon et al. [1991a]. The 1989 experiment had two observing sessions, May 1-5 and May 8-13. Satellite tracking data were provided by 8-channel ROGUE receivers operated at Haystack, Massachusetts; Richmond, Florida; and Hat Creek; California, as well as a TI-4100 receiver operated at Fort Davis, Texas. Very long baseline interferometry (VLBI) data from these sites provide precise a priori locations. The 1985 experiment used TI-4100 receivers for satellite tracking at the same general sites, although in some cases at different local marks. TI-4100 receivers were operated at the 'mobile' sites in the southern Gulf for both the 1985 and 1989 experiments, and at several additional VLBI sites in southern California in 1989. The first observing session for the 1989 experiment, the focus of this paper, included three stations common to the 1985 experiment around the southern and central Gulf (Figure 1). Our data analysis strategy is given in Lichten and Border [1987], Tralli et al. [1988], Blewitt [1989], Tralli and Lichten [1990] and Dixon et al. [1991a,b].

An important difference between the 1985 and 1989 experiments is our treatment of carrier phase cycle ambiguities. Increased awareness of the importance of short baselines in the network to ensure resolution of these ambiguities ('bias-fixing') coupled with receiver availability in 1989, allowed us to implement a denser network, facilitating ambiguity resolution. For single day orbital arcs, this leads to factors of 2-3 improvement in both repeatability and accuracy of horizontal baseline component estimates [Dong and Bock, 1989; Blewitt, 1989]. Unfortunately, the sparse 1985 network (shortest baseline ~ 350 km) has so far precluded resolution of cycle ambiguities for that experiment. To partly compensate, we computed multi-day orbital arcs for the 1985 data. This technique improves the precision and accuracy of baseline vector estimates, especially for non-bias-fixed data [Lichten and Bertiger, 1989]. The 1989 results are bias-fixed, and employed only single day arcs.

Uncertainties

Since only two experiments have been conducted, we cannot define scatter about a best-fitting straight line through the position vs. time data, an otherwise good measure of uncertainty in a geodetic rate determination assuming steady motion between sites [Davis et al., 1989]. Formal error, based on propagation of data noise through the estimation process, is one available measure of uncertainty. Care is taken to ensure that assigned data noise (1 cm for carrier phase) is consistent with post-fit residuals, such that χ^2 per degree of freedom ≈ 1, but formal error still underestimates true error since it does not represent all random errors, nor most systematic errors.

The root-mean-square (rms) scatter of daily solutions about the weighted mean (the 'short term', or day-to-day repeatability), is another measure of uncertainty. Dixon et al.

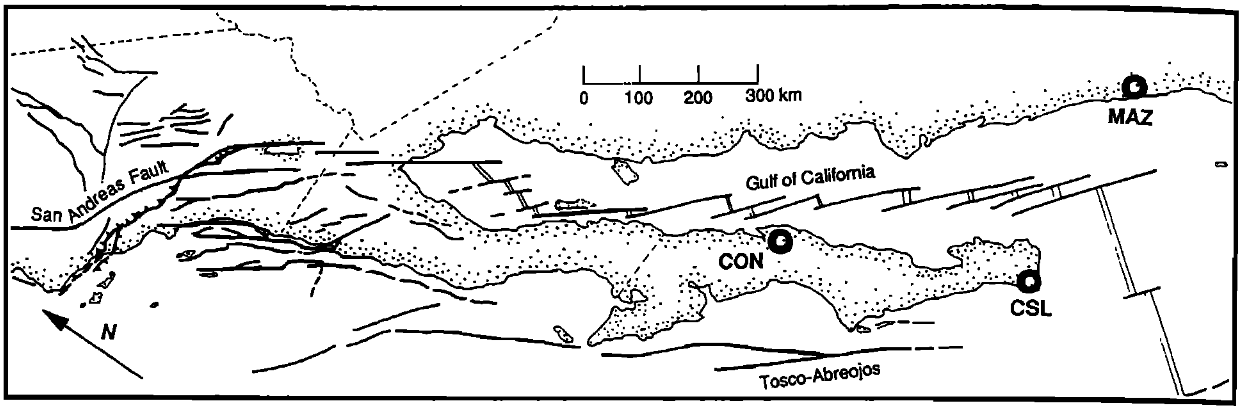

Fig. 1. Tectonic setting and GPS sites around the Gulf of California: Cabo San Lucas (CSL), Mazatlan (MAZ) and Bahia de Concepcion (CON).

[1990] argued that day-to-day repeatability for observations spanning several days is a reasonable indicator of longer term uncertainty if fiducial networks are robust, carrier phase cycle ambiguities are resolved, tropospheric conditions and/or calibrations are similar, and identical receiver/antenna combinations are used for all experiments. These conditions minimize the magnitude of systematic errors. The argument is based on limited data in southern California where VLBI results are available for comparison; its validity in other areas can only be evaluated properly with a larger data base than now exists. The above conditions are met for the Gulf experiments, with the exception that cycle ambiguities in the 1985 data are unresolved. The possibility therefore exists that errors are larger in 1985 relative to 1989 data, and these errors might not be reflected in short-term repeatability.

Input parameters that are fixed rather than estimated in the data analysis contribute systematic error that is not represented in either formal error or short term repeatability. We estimated the magnitude of this systematic error by performing sensitivity ('consider') analyses for both experiments. By assigning plausible uncertainties to critical input parameters (Table 1), we can determine the sensitivity of baseline vector estimates to input parameter errors. We omitted parameters such as the geocenter and UT1-UTC from this analysis if previous results indicated negligible sensitivity [Lichten and Border, 1987; Lichten and Bertiger, 1989]. Fiducial station location turns out to be the largest systematic error source in

TABLE 1: Analytical Conditions for GEOMEX Data

Parameter	A Priori Sigma or Uncertainty	
Estimated Parameters:		
Satellite coordinates at epoch	20 km	
Satellite velocities at epoch	1 km/sec	
Station, satellite clocks[1]	1 sec	
Mobile station coordinates	2 km	
Carrier phase bias	10^6 km	
Zenith wet troposphere or calibration residual	Stochastic model	
Considered Parameters:	1985	1989
Zenith dry troposphere	5 mm	5 mm
Fiducial coordinates	3,3,3 cm	3,3,10 cm
Polar Motion (x,y)	3, 3 cm	3, 3 cm
Solar radiation pressure[2]	Estimated	Considered
X, Z (Reflectance)	25%	5%
Y (Acceleration, km/sec^2)	$1*10^{-12}$	$1*10^{-13}$

1. One clock (Ft. Davis) is fixed to define an absolute time reference; remaining clocks modeled as white noise.
2. Parameter treatment differs for single and multi-day arcs.

the Gulf baseline estimates. The uncertainty in the baseline vector, hereafter termed total error, is given by the root-sum-square (rss) of the formal error, reflecting most random error, and the systematic error computed in the sensitivity analyses. While the effect of random error is reduced by averaging several days of data, the effect of most systematic error cannot be so reduced, as it varies slowly or not at all over the observation period. Ideally, systematic fiducial error would be a constant bias for both experiments (e.g., given identical fiducial sites, observation scenarios, etc.) and would not affect rate estimates. Unfortunately, there are numerous subtle differences between fiducial data from the two experiments. We therefore assign the full systematic error from the sensitivity analyses to the 1985 and 1989 results.

Fiducial station location errors were estimated by comparing GPS results from 1985 and 1989 with known VLBI values (Table 2). Offsets were typically less than 3 cm in all components, with a single larger vertical value in 1989. We used 3 cm in all components as an upper limit for the 1985 fiducial error, and 3 and 10 cm for horizontal and vertical errors respectively, for 1989 data. The resulting total error is of course larger than the formal error, and usually larger than day-to-day repeatability (Table 3). It is a more conservative, and we believe more appropriate, weighting factor for error estimation.

Velocities (Table 4) are defined by the slopes of lines through the weighted means of each position component plotted as a function of time. The error assigned to each position component is the total error (Table 3), and the velocity error is defined by the corresponding slope uncertainty (York, 1969). This assumes that the 1985 and 1989 results are independent. Since a series of GPS experiments are not completely independent, an estimation procedure accounting for possibly correlated errors between experiments may be preferable. Given other uncertainties and the limited available data, our approach is adequate for this preliminary report.

TABLE 2: Difference (mm) between VLBI and GPS Results for 1985 and 1989 GEOMEX Experiments

Baseline	East	North	Vertical
1985, non-bias fixed, multi-day arc:			
Hat Creek*-Ft. Davis (1933 km)	-20	-27	+18
Hat Creek-Ft. Davis*	-13	-16	-10
Richmond*-Haystack (2046 km)	-13	-19	-24
Richmond-Haystack*	-37	-29	+8
1989, bias fixed, single day arc:			
Hat Creek-Monument Pk. (986 km)	+10	-3	+99

*Estimated station

TABLE 3: Position Error Estimates (mm)

	East			North			Vertical		
Mazatlan-Cabo San Lucas (352 km)									
1985	6.3	7.7	14.5	1.9	5.1	4.1	8.7	20.4	10.6
1989	2.1	4.8	19.5	1.2	1.5	9.5	14.9	26.4	36.5
Mazatlan-Concepcion (651 km)									
1985	6.9	19.5	14.9	2.2	1.3	10.7	10.7	37.1	20.7
1989	2.4	12.9	22.4	1.7	6.4	26.3	17.6	19.1	37.7
Cabo San Lucas-Concepcion (455 km)									
1985	6.7	17.3	19.0	2.2	3.6	9.4	10.2	32.7	23.9
1989	2.1	8.7	22.9	1.8	7.2	22.6	18.6	40.4	59.9

Formal error listed first, repeatability listed second, total error (rss of formal and 'consider' error [text]) listed third.

The precision and accuracy of a GPS baseline estimate is a function of baseline length. Mazatlan-Cabo San Lucas (~350 km) is considerably shorter than Mazatlan-Concepcion (~650 km), and thus provides a better estimate of Pacific-North America motion. We avoid defining the weighted average of these two velocity determinations because of possible tectonic differences between our two 'Pacific plate' sites (see below).

Results and Discussion

Table 4 summarizes the GPS-based velocity data and errors. There was no change in the vertical component between 1985 and 1989 for any of the three Gulf baselines within errors. Also, there was no change in the horizontal components between 1985 and 1989 for the Cabo San Lucas-Concepcion baseline (both sites presumably on the Pacific plate). Both Cabo San Lucas and Concepcion show the expected northwest motion with respect to Mazatlan, with rates and azimuths of, respectively, 47±7 and 44±8 mm/yr, and 57°±6° and 53°±10° west of north (all quoted uncertainties are 1σ, and unless indicated are based on total error; Tables 3 and 4). Figure 2 plots our estimate of the Pacific-North America relative motion vector for a location at Cabo San Lucas (Mazatlan fixed), and the corresponding NUVEL-1 global plate motion vector, 'best-fitting' vector (based only on Pacific-North America data), and the 'closure-fitting' vector (based on all data except Pacific-North America data) [DeMets et al., 1990]. Differences between these latter two vectors give some indication of the influence of local tectonic complexities on the global determination. The GPS-based Pacific-North America relative motion vector is equivalent, within one sigma total error, to the NUVEL-1 model (Figure 2; Table 5). Perhaps the most important result of our study is the general agreement of the estimates over such a large range of time scales.

The GPS-based vector has a slightly lower rate and more westerly (i.e., counter-clockwise) azimuth relative to the NUVEL-1 vector (Figure 2; Tables 4 and 5). The trend of the GPS vector is very similar to some estimates of local fracture zone trends [Humphreys and Weldon, 1991] although it is not consistent with others [e.g., DeMets et al., 1990]. The difference between the GPS and NUVEL-1 vectors is statistically significant only if smaller, formal errors are used to weight the position determinations. Further experiments will be required to evaluate the significance of the difference, and the extent to which fiducial effects introduce small systematic biases in the GPS estimates. If confirmed by additional data, the GPS-NUVEL-1 difference has interesting tectonic implications. Assuming Mazatlan is part of stable North America, we see two plausible interpretations. First, the GPS-based vector may be a better measure of modern plate motion than the global model, which averages over several million years, perhaps implying evolution of the plate boundary over this time period. This interpretation would reduce the San Andreas 'discrepancy vector', the difference between predicted and observed motions on the San Andreas fault in central California [Minster and Jordan, 1987; DeMets et al., 1990], in particular reducing predicted fault-normal compression. The second possibility, and one we prefer, requires little or no evolution in the plate boundary over the last several million years. The NUVEL-1 global model correctly predicts modern plate motion across this boundary, and the GPS determination, although south of deformation associated with the San Andreas system and Basin and Range extension, is still not immune from confounding local tectonic complexity. Four lines of evidence support this latter hypothesis. First, seismicity near the base of the continental shelf west of southern Baja and disrupted young sediments suggest activity on the northwest-trending Tosco-Abreojos fault zone [Spencer and Normark, 1979; Normark et al., 1987] (Figure 1). Second, a recent determination of Pacific-North America relative motion with VLBI data shows insignificant differences with the NUVEL-1 global model [Argus and Gordon, 1990]

TABLE 4: Velocities and Velocity Errors (mm/yr)

	MAZ-CSL*	MAZ-CON*	CSL-CON*
East	-39.9±7.0	-34.9±7.8	3.9±8.6
North	25.5±3.1	26.5±8.3	0.1±7.1
Vertical	-1±16	-11±15	10±20

*MAZ=Mazatlan; CSL=Cabo San Lucas; CON=Concepcion. Second station moves at listed rate with respect to first station. Errors (1σ) based on total error (Table 3).

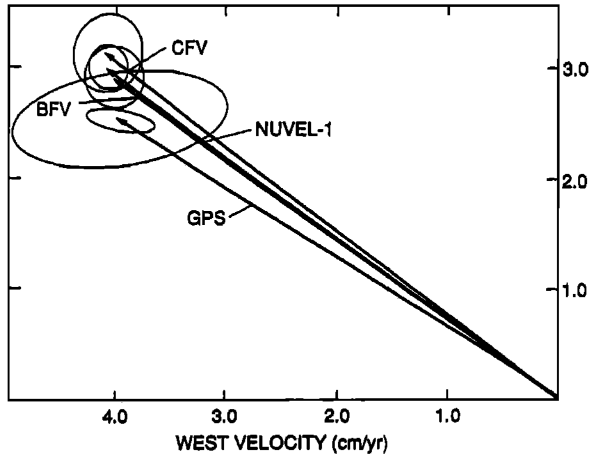

Fig. 2. Vector diagram summarizing relative motion of Pacific plate (at Cabo San Lucas) with respect to North America, based on GPS (this study), and NUVEL-1 global vector, closure fitting vector (CFV) and best fitting vector (BFV)[DeMets et al., 1990]. Error ellipses are 1σ. GPS ellipses based on formal error (smaller ellipse) and total error (larger ellipse) (Table 3).

TABLE 5: Predicted Motion of Cabo San Lucas Relative to North America

	GPS[1]	VLBI[2]	NUV[3]	BFV[3]	CFV[3]
Rate (mm/yr)	47.3	48.1	51.1	49.9	52.0
	±6.5	±1.6	±1.3	±3.2	±2.2
Azimuth (°West	57.4	52.7	53.8	54.1	52.5
of North)	±6.2	±3.2	±1.5	±2.0	±2.7

1. GPS vector based on Mazatlan-Cabo San Lucas data.
2. VLBI from Argus and Gordon [1990].
3. NUV=NUVEL-1 global vector, BFV=best fitting NUVEL vector, CFV=closure fitting NUVEL vector, from DeMets et al. [1990] and DeMets (personal communication).

(Table 5). Third, some geodetic measurements in the vicinity of the central San Andreas fault show fault-normal compression similar to the 7mm/yr predicted by the NUVEL-1 model [Harris and Segall, 1987; Feigl et al., 1990]. Fourth, the GPS-based vector is displaced from the NUVEL-1 global vector in the same direction as is the NUVEL-1 best-fitting vector (Figure 2), suggesting consistency in the local data over a large range of time scales. The difference between the NUVEL-1 global vector and the GPS-based vector, or the smaller difference between the NUVEL-1 global and best-fitting vectors could be interpreted in terms of a 'Gulf discrepancy,' (a possible indicator of motion on the Tosco-Abreojos fault?). Given the preliminary nature of our data, it is inappropriate to discuss these possibilities in detail. Nevertheless, it is clear that comparative studies involving increasingly accurate global plate models, global space geodetic measurements such as VLBI, and more detailed regional measurements with GPS, have considerable resolving power for complex tectonic problems in this and other regions.

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