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## First GPS Baseline Results from the North Andes

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## FIRST GPS BASELINE RESULTS FROM THE NORTH ANDES

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**Abstract.** The CASA UNO GPS (Global Positioning System) experiment (January-February 1988) has provided the first epoch baseline measurements for the study of plate motions and crustal deformation in and around the North Andes. Two dimensional horizontal baseline repeatabilities are as good as 5 parts in  $10^8$  for short baselines (100 - 1000 km), and better than 3 parts in  $10^8$  for long baselines (>1000 km). Vertical repeatabilities are typically 4-6 cm, with a weak dependence on baseline length. The expected rate of plate convergence across the Colombia Trench is 6-8 cm/yr, which should be detectable by the repeat experiment planned for 1991. Expected deformation rates within the North Andes are of the order of 1 cm/yr, which may be detectable with the 1991 experiment.

## Why Study the North Andean Margin?

Precise geodetic measurements in the tectonically active North Andean margin (Figure 1, Kellogg and Dixon, this issue) will provide constraints on models for convergent boundary tectonic processes. First, an island located just seaward of the Colombia trench provides the opportunity to directly measure subduction rates for the first time across a short baseline (399 km). Second, such measurements will help determine whether aseismic convergence is occurring along the Caribbean - North Andean margin. Deformation of the youngest sediments in the South Caribbean deformed belt suggests active aseismic underthrusting of Caribbean crust beneath the deformed belt [e.g., Ladd et al., 1984]. A poorly defined Benioff Zone [Dewey, 1972; Pennington, 1981] has been interpreted as the result of slow subduction of Caribbean crust beneath the North Andes [Kellogg and Bonini, 1982]. Third, repeated precise geodetic measurements in the North Andes will demonstrate whether strain is confined to the plate boundaries or distributed across a broad zone from the South Caribbean marginal fault to the East Andean fold belt [Jordan, 1975].

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## Rapid Subduction of the Nazca Plate

Active subduction of Nazca oceanic lithosphere under the North Andes at the Colombia trench is indicated by a Benioff zone dipping 30° to the east [Galvis, 1980; Pennington, 1981] and by andesitic volcanism in the Cordillera Central. The rapid subduction is associated with episodic great shallow earthquakes [Pennington, 1981; Kanamori and McNally, 1982]. Between 1899 and 1982 seven large earthquakes ( $M \geq 7.5$ ) occurred in the North Andes, with an average recurrence interval of 13 years [Addicott and Richards, 1984]. All of these were related to subduction of the Nazca plate. Between 1963 and 1981, seventeen earthquakes with  $m_b \geq 6.0$  were detected in the North Andes, with average recurrence interval of one year [NOAA-EDIS Earthquake Data File]. We can therefore expect that at least one more earthquake of  $m_b \geq 6.0$  will occur within the network prior to the CASA DOS reoccupation.

One of the most exciting results anticipated after CASA DOS is the direct measurement of the convergence rates across short baselines for rapidly subducting trenches. We can add the South America - North Andean vector ( $1.0 \pm 0.2$  cm/yr,  $S55^\circ W \pm 5^\circ$ ) [Aggarwal, 1983] and the Nazca - South America vector ( $7.8 \pm 0.5$  cm/yr,  $N80^\circ E \pm 3^\circ$ ; RM2 model of Minster and Jordan [1978] to obtain the Nazca - North Andean vector ( $6.9 \pm 0.7$  cm/yr,  $N83^\circ E \pm 7^\circ$ ) [Kellogg, et al., 1985]. The predicted motion using the NUVEL-1 model [DeMets et al., 1990] is 1 cm/yr slower. Colombia trench-crossing baselines were measured from Malpelo Island to Tumaco (390 km), Buenaventura (510 km), Cali (585 km), Pasto (570 km), and Quito, Ecuador (580 km), and from Baltra in the Galapagos Islands to Tumaco (1170 km) (Figure 1, Kellogg and Dixon, this issue).

## Microplate Boundaries and Intraplate Deformation

There is general agreement that the Caribbean, Nazca, and South America plates are converging, but the directions of relative motion and the locations of the plate boundaries are controversial [e.g., Dewey, 1972; Shagam, 1975; and Aggarwal, 1983]. Kellogg et al. [1985] have interpreted the tectonics in the region by two additional microplates, the Panama and North Andes blocks (Figure 1, Kellogg and Dixon, this issue). The North Andean microplate is bounded by the Colombia Trench and the Panama block on the west and the South Caribbean deformed belt to the north. On the east side of the North Andes, right-lateral movement is taking place on the Bocono-East Andean fault zone (Figure 1, Kellogg and Dixon, this issue). From the short-term seismicity Aggarwal [1983] deduced a seismic-slip rate of  $1 \pm 0.2$  cm/yr. Using a measured 100-m right-lateral offset of glacial moraines, Schubert [1980] estimated a similar average rate of strike slip motion on the fault, 0.8 cm/yr for the last 12,000 years.

The Panama and North Andes microplates are not rigid, however, and are characterized by considerable internal deformation. The shear stresses distributed throughout the two microplates may be related to the attempted subduction of the Carnegie Ridge and buoyant Caribbean crust and collision with Panama [Wadge and Burke, 1983]. The Romeral fault system is still active, for example. A microearthquake seismometer array recorded 94 earthquakes during a 17-month period along the Romeral and Cauca fault zones between  $5^\circ 50'$

Table 1. Estimated station locations and RMS repeatabilities from CASA UNO data. All good days of data are used. Coordinate system is an earth-fixed XYZ based on the Goddard Space Flight Center VLBI solution GLB223, with the motion of North America in the AMO-2 model of Minster and Jordan [1978] subtracted.

Station	X (cm)	Y (cm)	Z (cm)
Baltra	-2882306.5 ± 5.2	-637792712.5 ± 8.5	-5093880.1 ± 5.9
Bogota	174366228.0 ± 5.3	-611441797.5 ± 8.8	53810954.4 ± 2.5
Cali	150189745.2 ± 9.5	-618761494.8 ± 17.7	38732874.7 ± 7.5
Jerusalen	128758355.3 ± 8.6	-624915953.7 ± 11.3	-65914.6 ± 1.8
La Palma	139282548.1 ± 7.1	-620917308.6 ± 25.1	43113619.8 ± 7.1
Malpelo	92884630.6 ± 7.3	-629463755.8 ± 15.0	44220580.3 ± 8.3
Mocoa	147747046.1 ± 8.4	-620410521.0 ± 27.5	10852709.8 ± 4.9
Pasto	140673027.4 ± 8.9	-622241406.0 ± 23.8	13450596.5 ± 5.5
Tumaco	124324540.3 ± 8.9	-625258487.5 ± 19.8	20026645.1 ± 7.6
Villavicencio	181982048.6 ± 5.6	-609671051.2 ± 9.6	44920197.1 ± 2.3

and 7°30'N [Hutchings et al., 1981]. Composite focal mechanism determinations were compatible with left-lateral movement on near-vertical north-south fault planes from the surface to a depth of 36 km. On March 31, 1983, an earthquake along the fault killed between 250 and 350 people in Popayan, Colombia. First motion data for the earthquake is quite sparse, but the data are consistent with left-lateral displacement on the Romeral fault [Needham, personal communication, 1983]. Present left-lateral movement on the fault system may be intraplate shear attributable to northward escape of the North Andean microplate.

#### GPS Data Analysis and General Results

The data was processed at the University of South Carolina and the Jet Propulsion Laboratory (JPL) using the GIPSY software developed at JPL. The method of analysis used for the solutions presented here is described in Freymueller and Kellogg [this issue]. The results shown in this paper are based on a set of single day solutions using the entire CASA UNO extended tracking network. Three stations in North America, with good mutual visibility and proven VLBI-GPS ties, were held fixed to determine the reference frame. No constraints were applied to the positions of the other fiducial stations. Freymueller and Kellogg [this issue] list the stations used in the extended tracking network (Figure 2, Kellogg and Dixon, this issue). The South American stations used in the study are listed in Table 1. Biases were fixed using the method of Blewitt [1989] with a confidence level of 99.5% for having fixed all the biases correctly.

Table 1 shows the estimated station positions for the stations considered in this study, along with the RMS repeatabilities for each component. Table 2 lists baseline lengths and RMS repeatabilities derived from the solutions given in Table 1. The baseline length represents only one of three orthogonal components (length, transverse, vertical) of the GPS vector baseline solution. The repeatability in the baseline length is better than 1 cm for most baselines shorter than 350 km. The largest RMS repeatabilities are for baselines involving Malpelo or La Palma, which had the worst visibility, and Mocoa, which had the worst data outages.

#### Results for Selected Baselines

Figures 1-3 show the initial results for the baseline horizontal components for baselines crossing three important tectonic features. Each figure shows the daily solutions for each baseline, with the formal errors shown as error bars. All solutions are plotted about the weighted mean. The baseline horizontal components are computed in the local East-North-

Vertical coordinate system at the first station listed. The agreement between the daily RMS repeatability and the formal errors is very good.

All baselines studied here are scheduled to be reoccupied during the CASA DOS experiment in January - February 1991, three years after the initial occupation. An important question remains as to the extent repeatability over several days represents the long-term precision of GPS position determinations [Davis et al., 1989]. Previous results from southern California, where very long baseline interferometry measurements are available for comparison, suggest that GPS accuracy

Table 2. Estimated baseline lengths, RMS repeatabilities, and number of days that each baseline was observed. GPS baselines are determined by differencing the station position estimates. Baseline length is only one of three orthogonal baseline components (length, transverse, vertical). Only one day of common data is available between Pasto and Jerusalen, so no repeatability can be given.

Baseline	Estimated Length (cm)	Days
Baltra/Jerusalen	132364487.7 ± 2.7	3
Baltra/Malpelo	108039782.5 ± 3.7	6
Baltra/Tumaco	130267919.2 ± 3.0	6
Bogota/Cali	29418167.6 ± 0.7	5
Bogota/Villavicencio	11839840.9 ± 0.3	5
Cali/Mocoa	28035513.7 ± 1.1	3
Cali/Pasto	27237317.2 ± 1.2	5
Cali/Tumaco	32575187.0 ± 0.9	9
Cali/Villavicencio	33640292.4 ± 0.9	5
La Palma/Cali	11950110.7 ± 1.6	4
La Palma/Tumaco	27849530.3 ± 0.7	3
Malpelo/Bogota	84000096.6 ± 2.0	5
Malpelo/Cali	58553643.9 ± 2.6	10
Malpelo/La Palma	47191465.9 ± 1.7	4
Malpelo/Mocoa	64847988.7 ± 1.2	3
Malpelo/Pasto	57294727.4 ± 1.6	5
Malpelo/Tumaco	39893588.9 ± 2.0	9
Malpelo/Villavicencio	91272063.6 ± 2.4	5
Pasto/Jerusalen	18215611.7 ± ***	1
Pasto/Mocoa	7755187.4 ± 1.7	3
Tumaco/Jerusalen	20578797.4 ± 0.4	3
Tumaco/Mocoa	25617928.6 ± 1.8	3
Tumaco/Pasto	17877935.3 ± 0.4	4

may be comparable to GPS precision [Blewitt, 1989; Dong and Bock, 1989]. Assuming that the results for CASA DOS will be comparable in quality to those from CASA UNO, the uncertainty in the baseline change between the experiments is the square root of 2 times the uncertainty of the CASA UNO baseline. A comparison of this uncertainty to the predicted motion can be used to estimate the likelihood that the predicted tectonic motion will be detectable in the difference between solutions from the two experiments.

Except for the baseline from Malpelo to Tumaco (399 km; Figure 1), all daily solutions for a given baseline have similar

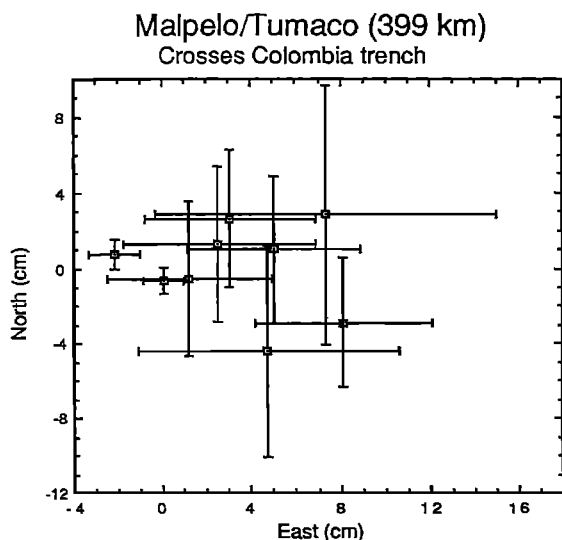


Fig. 1. Daily horizontal baseline solutions for Malpelo to Tumaco (399 km) plotted with respect to their weighted mean. Error bars denote the formal errors (data noise).

formal errors. Two of the daily solutions for the Malpelo to Tumaco baseline have formal errors about one-fourth as large as the other days. On those two days, the observation period was nine hours in length, while the remaining days used a 7.5 hour observation period. This dramatic reduction in formal errors is due to the effect of bias-fixing. On the days with nine hour observation sessions, 62% of the double-differenced carrier phase biases which included Malpelo as one station were resolved, while only 22% of these biases were resolved on the days with the short observation session. There was not a significant change in the percentage of biases fixed over the network as a whole.

The baseline from Malpelo to Tumaco (Figure 1) crosses the Colombia Trench. The predicted convergence rate is approximately 6-8 cm/yr directed east-west. The RMS repeatability in the baseline east component is 2.5 cm. The predicted baseline change of 18-24 cm over 3 years is 5 to 7 times as large as the predicted uncertainty, so it should be detectable if the rate of plate convergence during the three years between experiments is typical of the plate convergence rate averaged over much longer time spans.

The baseline from Bogota to Villavicencio (Figure 2) crosses the East Andean Frontal Fault zone, on which the predicted motion is approximately 1 cm/yr. Overall RMS horizontal repeatabilities are 4 mm in the baseline east component and 3 mm in the baseline north component, for a total two-dimensional uncertainty of 5 mm. The predicted baseline change is approximately three times the predicted uncertainty in the change, so the predicted tectonic motion on this fault is potentially detectable.

The baseline from Bogota to Cali (Figure 3) crosses the Romeral Fault. There is no estimate of the rate of motion along the Romeral Fault. Overall RMS horizontal repeatabilities are 9

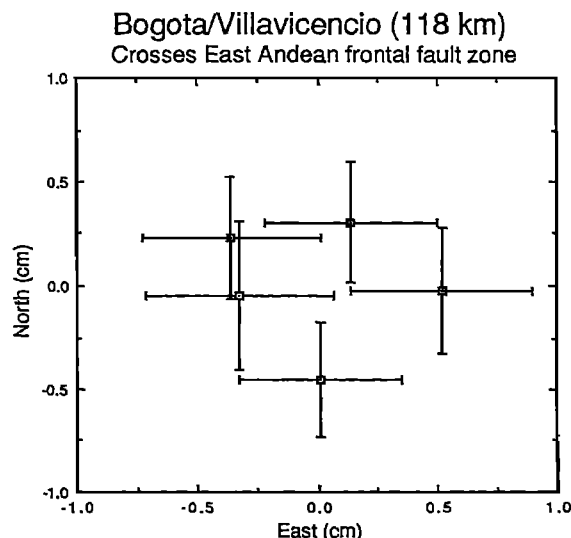


Fig. 2. Daily horizontal baseline solutions for Bogotá to Villavicencio (118km) plotted with respect to their weighted mean. Error bars are the same as in Fig. 1.

mm in the baseline east component and 5 mm in the baseline north component. An observed displacement of more than 25 mm ( $\sim 9$  mm/yr) in the east component or 14 mm ( $\sim 5$  mm/yr) in the north component would represent motion that is significantly different from zero at the two sigma level (approximately 95% confidence).

#### Discussion

Baseline solutions from the CASA UNO experiment establish a set of first epoch measurements for the monitoring of crustal deformation in the North Andes. Two dimensional horizontal baseline repeatabilities are as good as 5 parts in  $10^8$  for short baselines, and better than 3 parts in  $10^8$  for long baselines. Vertical repeatabilities are typically of the order of 4-6 cm, with a weak dependence on baseline length. The quality of solutions from the CASA UNO experiment suggests that convergence across the Colombia Trench will be detectable with the repeat experiment in 1991. The convergence over three years predicted from global plate motion models is several

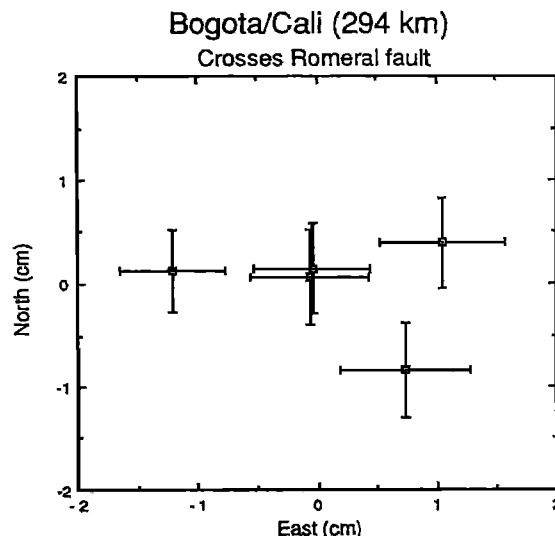


Fig. 3. Daily horizontal baseline solutions for Bogotá to Cali (294 km). Error bars are the same as in Fig. 1.

times the level of repeatability for baselines crossing the trench. On shorter baselines on the continent, intraplate deformation or block motion may be detectable as well. The predicted motion over three years is several times larger than the repeatability of a baseline crossing the East Andean Frontal Fault system.

The importance of the length of data arc on the baseline solutions for Malpelo to Turnaco was greater than that predicted by previous studies [e.g., Golombek et al., 1987; Freymueller and Golombek, 1988]. Due to the isolated location of Malpelo, almost 400 km away from the nearest other station in the network, and possibly due also to the poor satellite constellation and visibility at Malpelo, the longer data arc made bias-fixing possible.

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