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James Kellogg
University of South Carolina

Timothy H. Dixon
California Institute of Technology, thd@usf.edu

R. Neilan
California Institute of Technology

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CASA

Central and South America GPS Geodesy

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James Kellogg

Department of Geological Sciences, University of South Carolina, Columbia

Timothy Dixon and Ruth Neilan

Jet Propulsion Laboratory, California Institute of Technology, Pasadena

Introduction

In January 1988, scientists from over 25 organizations in 13 countries and territories cooperated in the largest Global Positioning System (GPS) campaign in the world to date (Table 1) [Neilan *et al.*, 1988]. From January 18 to February 5, 1988, 43 GPS receivers collected about 590 station-days of data in American Samoa, Australia, Canada, Colombia, Costa Rica, Ecuador, New Zealand, Norway, Panama, Sweden, United States, West Germany, and Venezuela. The experiment was entitled CASA UNO, an acronym for Central and South America—and "uno" is Spanish for "one," designating first-epoch measurements. The CASA UNO experiment was the first civilian effort at implementing an extended GPS satellite-tracking network and established the first major GPS network in the northern Andean margin and the western Caribbean.

By coordinating observations with participating scientific institutions in Europe and the Americas, the number of scientifically interesting baseline measurements was increased, the overall solution improved, and experiment costs minimized. Geophysical and geodetic agencies in the various countries provided logistical support to ensure the success of the experiment. The agencies in Colombia, Costa Rica, Ecuador, Panama and Venezuela are interested in preserving the GPS network as a part of their permanent regional network and supplied geophysical personnel, field vehicles and naval vessel support.

One of the ultimate goals of the project is to measure strain in the northern Andes. On March 5, 1987, the need for strain measurements was tragically dramatized when a large earthquake ($m_b = 6.8$) on the fault system 80 km east of Quito, Ecuador, ruptured the trans-Andean oil pipeline and triggered land-

slides and floods that killed over a thousand people. The epoch measurements of 1988 will be followed by measurements planned in 1990, providing first results on strain in the area. The repeat measurements will monitor convergence rates at the rapidly subducting Colombia (6.4 cm/yr) and Middle America (8 cm/yr) trenches.

GPS System Description

The GPS is a satellite-based positioning system allowing centimeter level geodesy to be performed with low-cost portable receivers. Centimeter level precision has been demonstrated on baselines up to 2000 km in length [e.g., Beutler *et al.*, 1987; Blewitt *et al.*, 1988; Tralli and Dixon, 1988]. Such precise geodetic measurements will allow widespread determinations of plate motion rates within several years of measurements. Slower intraplate strain rates may be measurable over 5- to 10-year intervals. The NAVSTAR GPS satellites are administered by the U.S. Department of Defense, and published ephemerides transmitted by the satellites (the Broadcast Ephemerides) are accurate to a few parts in 10^6 . This is not adequate for high-precision geodesy on long baselines, but the ephemerides can be improved in post processing by employing the "fiducial concept." This approach utilizes simultaneous observation of the satellites at sites whose positions are well known, from Very Long Baseline Interferometry (VLBI) or Satellite Laser Ranging (SLR) stations. While the full system of satellites will

TABLE 1. CASA UNO Participants

Investigator	Institutional Affiliation
	<i>Experiment Manager</i>
Ruth E. Neilan	Jet Propulsion Laboratory/California Institute of Technology, Pasadena, Calif.
	<i>North Andes and Western Caribbean GPS Projects</i>
James N. Kellogg	University of South Carolina, Columbia, S.C.
Timothy H. Dixon	Jet Propulsion Laboratory, Pasadena, Calif.
James Stowell	University NAVSTAR Consortium, Boulder, Colo.
Clemente Ropain U.	Instituto Nacional de Investigaciones Geologico-Mineras, Bogota, Colombia
Sergio Camargo M., Benjamin Fernandez Ch.	Instituto Geografico Agustin Codazzi, Bogota, Colombia
Hugh N. Caddess	Inter-American Geodetic Survey, San Antonio, Tex.
Brian R. Tallman	Defense Mapping Agency HTC/GSGS, Washington, D.C.
Kenneth Barger,	Inter-American Geodetic Survey, Panama City, Panama
Thomas Hughes,	San Jose, Costa Rica
Leonard Leos,	Bogota, Colombia
Vernon Perdue	Quito, Ecuador
Cesar Real R.	Instituto Geografico Militar, Quito, Ecuador
Luis Espin	Escuela Politecnica Nacional, Quito, Ecuador
J. Tejada	Instituto Geografico Nacional Tommy Guardia, Panama City, Panama
C. Vieto	Instituto Geografico Nacional, San Jose, Costa Rica
J. Marino Protti Q.	Universidad Nacional, Heredia, Costa Rica
	<i>Venezuelan Andes GPS Project</i>
Herman Drewes,	Deutsches Geodatisches Forschungsinstitut, Munich, West Germany
Christopher Reigber,	
K. Stuber,	
H. Tremel	
O. Chourio	Direccion de Cartografia Nacional, Caracas, Venezuela
Heinz Henneberg,	La Universidad del Zulia, Maracaibo, Venezuela
Melvin Hoyer	
S. Rekkedal	Statens Kartverk, Honefoss, Norway
	<i>Extended Fiducial Network / Equipment Support</i>
Bill Melbourne	Jet Propulsion Laboratory, Pasadena, Calif.
Gerald L. Mader	National Geodetic Survey, Rockville, Md.
Robert Schutz	Center for Space Research, Austin, Tex.
Bob Russman	Defense Mapping Agency, Washington, D.C.
William H. Prescott,	U.S. Geological Survey, Menlo Park, Calif.,
George Williams	USGS, Reston, Va.
John Hannah	Department Surveys and Land Information, New Zealand
Roger Merrell	Texas Highway Department, Tex.
Russell Crooks	FAA, American Samoa
Jim Lynch	University of Texas at Arlington, Tex.
Josef Popelar	EMR, Canada

Cover. CASA UNO site locations of the first GPS network in the North Andes and Central America. Present-day plate motions (bold arrows) relative to the North Andean block (Cocos plate motion relative to Caribbean) showing average slip rates (in centimeters per year) during the last 5–10 m.y. after *Minster and Jordan* [1978]. See "Central and South America GPS Geodesy," by J. Kellogg, T. Dixon, and R. Neilan, p. 649.

not become fully operational until 1992, geodetic-quality measurements can be made today using the present system configuration of seven operating satellites.

The current Block I GPS satellites orbit at an height of about 20,000 km in 12-hour orbits inclined at 63° to the equator. Each satellite broadcasts on two L-band frequencies, carrier L₁ at 1.57542 GHz and carrier L₂ at 1.2276 GHz. In order to correct for dispersive ionospheric effects, geodetic measurements involve dual frequency observations to determine carrier phase advance and may also use P-code pseudorange measurements to determine the group delay. The P-code is modulated on both carrier frequencies at 10.23 MHz.

Observations consist of simultaneous reception of multiple satellite signals at two or more ground stations. Four or more satellites are required to estimate user position and time. For relative positioning, data are differenced between satellites and ground station receivers to remove errors due to clock offsets and other common mode errors. Atmospheric calibration may be applied to correct the effects of variable nondispersive signal delay through the troposphere.

Scientific Objectives

High-quality geodetic data can yield important constraints on models of plate tectonic processes and behavior at convergent boundaries. For example, measurements along a convergent plate boundary could demonstrate whether the plate motion was episodic and associated with infrequent, large earthquakes. If transmission of such episodic motion is damped out by stress relaxation in a viscous asthenosphere [Bott and Dean, 1973; Berg *et al.*, 1977], determination of the damping wavelength would constrain predictions of asthenosphere viscosity.

How much aseismic slip occurs along plate margins is a second important question that can be answered by precise geodetic measurements. The answer will be particularly relevant to understanding "seismic gaps" and aseismic (?) subduction such as the underthrusting beneath the North American continental margin in Washington and Oregon.

Intraplate deformation is a third basic problem that can be addressed by precise geodetic measurements. The assumption of plate rigidity is a first-order approximation that encounters many exceptions in large oceanic plates [Weissel *et al.*, 1980; Stein and Okal, 1978] and continental plates. Deformation often appears to be distributed over broad zones, especially where plate boundaries involve continental crust [Jordan, 1975; Dixon *et al.*, 1985]. Strain may be spread continuously across a broad zone, or be confined to sub-parallel zones separated by more rigid microplates which may be rotating. Adequate characterization of such complex patterns of crustal strain is necessary for full understanding of the tectonic processes occurring at these boundaries, might aid in the difficult task of earthquake prediction, and may even allow quantification of the frictional forces that resist plate motion.

Precise geodetic measurements in the tectonically active North Andean margin (see cover) would provide valuable constraints on models for the three convergent boundary tectonic processes just discussed. Rapid subduction of Nazca oceanic crust beneath the North Andes [Minster and Jordan, 1978; Kellogg *et al.*, 1985] is associated with episodic great shallow earthquakes [Pennington, 1981]. Malpelo Island, located just seaward of the Colombia trench, about 390 km from the mainland, gives us the opportunity to directly measure Andean subduction rates for the first time. Similar data will accrue from Cocos Island to mainland Costa Rica. Second, the deformation of the most recent sediments in the South Caribbean and North Panama deformed belts suggests active aseismic underthrusting of Caribbean crust beneath the deformed belts [Lu and McMillan, 1982; Lehner *et al.*, 1983; 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, precise geodetic measurements in the North Andes would 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].

The North Andean geodetic field program and the subsequent analyses of the acquired data are directed toward completing the following objectives.

- To obtain critical baseline measurements between several Pacific islands on the Cocos and Nazca plates and Colombia and Middle America that, when compared with future observations, will monitor subduction rates across the trenches and spreading rates across the Galapagos Rise.

- Establish a survey network across the South Caribbean deformed belt that will demonstrate whether or not Caribbean crust is being subducted aseismically beneath the North Andes. If convergence is confirmed by reoccupation of the sites, we will be able to calculate the aseismic slip rate.

- Baseline measurements across the Romeral, Santa-Marta, and Bocono-East Andean fault systems will determine strain distribution across the North Andean continental margin. Although we predict that most of the strain is occurring at the Colombia Trench and South Caribbean deformed belt, we also predict that the attempted rapid subduction of the Carnegie Ridge, slow subduction of buoyant Caribbean crust, and the collision of Panama and the North Andes result in shear strain along the Romeral, Santa-Marta, and Bocono-East Andean fault systems at distances of up to 600 km from the margins.

- To obtain elevation measurements to determine whether the northern Andes are still rising, as suggested by uplifted Pliocene-Quaternary terraces [Page and James, 1981] and first-order leveling [Luschen, 1983]. Although a 10-year interval may be necessary to measure regional uplift, crustal movements associated with large earthquakes, such as the December 12, 1979 ($M = 7.9$) event near Tumaco, Colombia, would be immediately measurable [Luschen, 1983].

- Colocate Doppler and GPS to improve the frame tie between World Geodetic System (WGS) '72 and WGS '84 reference systems in this region.

North Andes and Western Caribbean GPS Network Description

The geometry of the North Andes-CASA UNO GPS network is shown on the cover. All 25 sites are marked by concrete monuments surrounded by several reference markers. The geodetic agencies of Colombia, Costa Rica, Ecuador, Panama, and Venezuela are currently surveying the sites into their national first-order geodetic networks. The initial network in Colombia consists of 13 sites: Bogota, Bucaramanga, Cali, Cartagena, La Palma (Buenaventura), Malpelo Island, Mocoa, Monteria, Pasto, San Andres Island, Tumaco, Valledupar, and Villavicencio. Three sites were observed in Costa Rica: Cocos Island, Liberia, and Limon. In Ecuador, three sites were observed: Baltra Island (Galapagos), Jerusalem (near Quito), and Quito. One site was occupied in Panama near Panama City. The initial network in Venezuela includes five sites: Barinas, El Batey, Merida, Por Fin, and Uribante.

One of the most exciting results anticipated after the second GPS occupation of these sites is the first direct measurement of the convergence rates across short baselines for rapidly subducting trenches. The predicted baseline shortenings of 6.4 cm/yr at the Colombia trench and 8 cm/yr at the Middle America trench are significantly larger than the 2- to 3-cm level of accuracy predicted [Freymueller and Golombek, 1988]. Colombia trench-crossing baselines were measured from Malpelo Island to Tumaco (390 km), Cali (570 km), Pasto (570 km), and Quito, Ecuador (580 km), and from Galapagos to Tumaco (1170 km). Convergence rates across the Middle America trench will be measured from Cocos Island to Liberia (540 km), Limon (620 km), and Farfan (870 km).

The controversial predictions of aseismic subduction of the Caribbean plate beneath the South Caribbean deformed belt will be tested with repeat GPS baseline measurements from San Andres Island to Cartagena (710 km) and Monteria, Colombia (750 km). The predicted shortening of 1.7 +/- 0.7 cm/yr should be detectable over a 3- to 5-year interval.

Attempted subduction of the Carnegie Ridge and buoyant Caribbean crust and collision with Panama may be contributing to distributed shear strain within the North Andean microplate. Eight sites are positioned to measure strain along the Romeral-Cauca fault system: Quito, Tumaco, Pasto, La Palma, Cali, Monteria, Cartagena, and Valledupar. Convergent, divergent, or the predicted strike-slip displacement will be measured across baselines as short as 70 km. Movement along the active Santa Marta-Bucaramanga fault will be monitored between Cartagena, Valledupar, and Bucaramanga.

Offset Pleistocene glacial moraines and seismic slip rate estimates indicate that the North Andes microplate is slipping northeast relative to South America along the Bocono-East Andean frontal fault system at a rate of about 1.0 +/- 0.2 cm/yr [Schubert, 1980; Aggarwal, 1983]. Baselines between the sites in Quito, Mocoa, Pasto, Bogota, Villavicencio, Por Fin, Uribante, El Batey, Merida, and Barinas were measured across the Bocono-East Andean frontal fault system.

Extended Fiducial Network Impact on Baseline Accuracy

During the CASA UNO experiment, most of the GPS receivers were concentrated in Central and South America. During the time frame of the experiment, the visibility of the GPS satellites was limited and less favorable than in North America. Furthermore, the accuracies of the ephemerides degrade in the North Andes region due to the distance from satellite-tracking stations in North America. Therefore the predicted accuracies of baselines recovered for scientific interest in the region was about a factor of 2 worse than for similar baselines located in North America.

The concept of implementing an extended satellite-tracking network to supplement the CASA UNO campaign stems from results of covariance analyses performed by *Freymueller et al.* [1986], *Wu et al.* [1988] and *Freymueller and Golombek* [1988], using the OASIS/GIPSY software developed at the Jet Propulsion Laboratory, Pasadena, Calif. The covariance analysis performed by *Freymueller et al.* [1986] predicted a few parts in 10^8 accuracies for baseline recovery in the North Andes region using the nominal four-station satellite-tracking network in the U.S. at three Polaris sites (Westford, Mass.; Ft. Davis, Tex.; and Richmond, Fla.) and Owens Valley Radio Observatory in California. The *Wu et al.* [1988] analysis found that using an extended network with stations located in Australia, Hawaii and New Zealand could improve GPS orbit accuracy by almost a factor of 3 over the four-station network in the U.S. Covariance analysis by *Freymueller and Golombek* [1988] suggested a significant improvement in accuracy for the CASA UNO baselines with the use of an extended tracking network.

These predictions led to the implementation of a network (Figure 1) that located GPS receivers at Black Birch Observatory, New Zealand; Pago Pago, American Samoa; Kokee Park, Hawaii; and at NASA's Deep Space Network (DSN) station in Canberra, Australia. These supplemented the NGS coordinated tracking stations in Richmond, Fla.; Westford, Mass.; and Mojave, Calif.; as well as Yellowknife, Canada; Tromsø, Norway; Onsala, Sweden; and Wettzell, West Germany.

In choosing the final satellite observation schedule and determining the length of view periods needed for Central and South America, further covariance analysis was performed. A subset of 15 stations was chosen for the analysis, and it was assumed that carrier phase (1-cm data quality) and pseudorange (200-cm data quality) were available at each site. Fiducial station errors were set at 4 cm in each component and treated as systematic (consider) errors in the analysis. Stations whose coordinates were estimated were Galapagos, Cocos, Malpelo, Buenaventura, Pasto, and Tumaco. These stations represent baseline lengths from 100 to 1000 km. Two schedules were examined for the South American sites, with 7-hour and 9-hour observation periods.

The shorter schedule was expected to produce less accurate baselines; however, the longer schedule was considered to pose a risk to the integrity of the data since the demands on the field operators would be severe for a 3-week experiment. Figure 2 plots the averaged standard deviations of the baseline com-

ponents for baselines between the various sites. With either approach, the horizontal errors are 1-2 cm and the vertical error is about 3 cm. Due to the benefit expected with the longer period, it was decided to use a 9-hour schedule for the first session and then a 7.5-hour schedule for the last two sessions of CASA UNO.

1988 Field Campaign

The North Andes GPS epoch measurements were divided into three 5-day sessions. The Pacific coast of northwestern Colombia has one of the highest precipitation rates in the hemisphere, so it was essential that GPS measurements be made during the dry season from December through February to reduce the uncertainties attributable to atmospheric water vapor. Receivers at the sites on Malpelo Island, Panama, and Costa Rica remained fixed for all three sessions. During the first session from January 18 to 22, 9-

hour observations were made in Jerusalem (near Quito), Tumaco, Pasto, Mocoa, La Palma, and Cali, as well as at the fixed sites. In the second session from January 25 to 29, 7.5-hour observations were made at the fixed sites and at Galapagos, Jerusalem, Tumaco, Cali, Bogota, Villavicencio, and Bucaramanga. In the third session, February 1 to 5, 7.5-hour measurements were made at the fixed sites and Quito, Bogota, San Andres Island, Monteria, Cartagena, Bucaramanga, and Valledupar. The five Venezuelan sites were observed in four 2-day and two 3-day discontinuous 6-hour sessions.

About 212 days of GPS data were collected with 16 TI-4100 receivers in the North Andes and Central America. Incredibly, only 2 days of data were lost due to receiver failure. A D-series Water Vapor Radiometer (WVR) recorded data for 3 days at Tumaco prior to failure in heavy rain. Two D-series WVR's in Liberia and Limon, Costa Rica and one R-series WVR in Panama collected data for 19 days during the experiment. An additional 378 days of GPS data were collected with 25

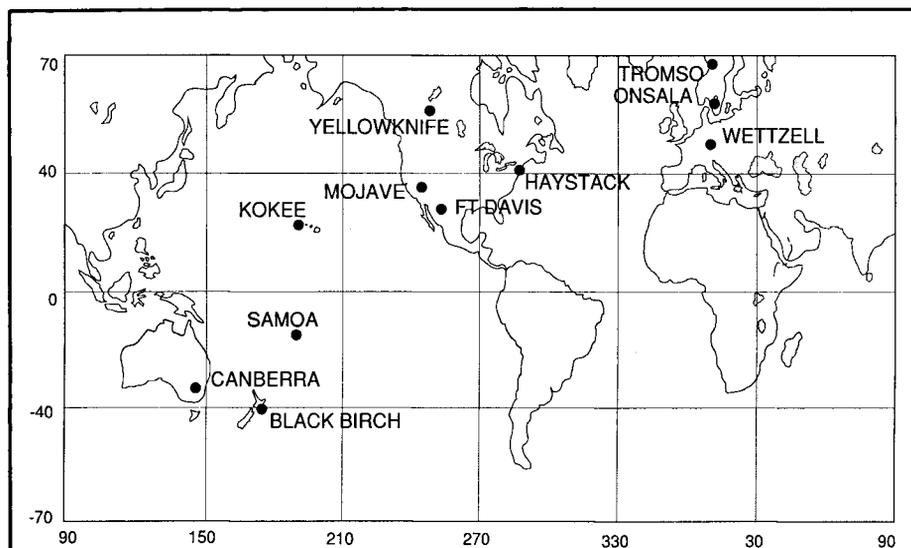


Fig. 1. Extended fiducial network for 1988 CASA UNO campaign.

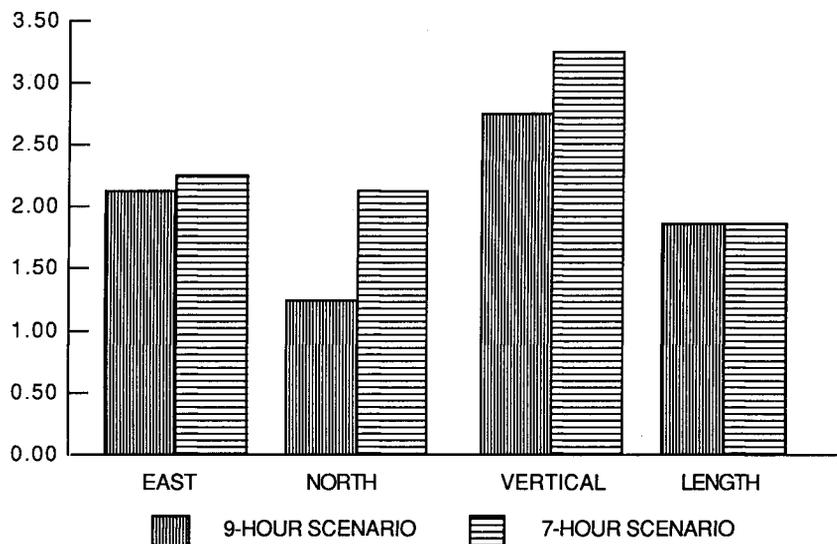


Fig. 2. Average of the considered baseline errors (in centimeters) from seven baselines in Central and South America.

TI-4100 receivers and two new ROGUE receivers in Europe, North America, and the Pacific.

Preliminary Results from 1988 CASA UNO Campaign

The North Andean data have been transferred from cassettes onto 9-track magnetic tape and archived at JPL and at UNAVCO in Boulder, Colo. The data are available for distribution to all participants. Initial baselines are being calculated at JPL, the University of South Carolina (USC), Columbia, and Deutsches Geodatisches Forschungsinstitut (DGFI), Munich, West Germany. Preliminary precise satellite ephemerides have been calculated by the Center for Space Research, Austin, Tex. [Schutz *et al.*, 1988].

Processing of the CASA UNO data set is an ongoing process and is expected to continue up until the second occupation. Data editing and calibration for the troposphere and ionosphere have been completed for most of the CASA UNO data set, including all the data from Central and South America, as well as four tracking stations in North America, two in Europe, two in the Pacific, and two in the Australia/New Zealand area. Two additional tracking stations at high northern latitudes have also been processed but have not yet been used because they suffered from extremely high ionospheric noise. Data recovery rates were better than 90% in South America, and about 75% in the worldwide tracking network.

Drewes *et al.* [1988] successfully used the Bernese software on the 1988 Venezuelan data. Using observational data from the CASA UNO campaign, they calculated a multistation solution for the Venezuelan network. After final cycle slip analysis and ambiguity resolution, they report an internal precision of about 5 mm on baselines of up to 200 km in length.

Although analysis of the CASA UNO GPS experiment is still in progress, preliminary results give some indication of the overall data quality. Although there are no methods to directly test baseline accuracy from this first-time occupation, a good estimate of baseline precision can be obtained from the repeatability of daily baseline solutions, assuming each day is treated independently. Previous results from southern California, where very long baseline interferometry measurements are available for comparison, suggest that GPS accuracy may be comparable to GPS precision [Blewitt *et al.*, 1988; Dong and Bock, 1989]. Figure 3 illustrates the repeatability for 6 days of data for horizontal components of the 270-km baseline from Limon to Liberia, Costa Rica [Kornreich *et al.*, 1988]. Five days of data are plotted in Figure 4 for the 294-km baseline between Bogota and Cali, Colombia [Freymueller and Kellogg, 1988; Kellogg *et al.*, 1988]. These results were obtained using the GIPSY software developed at JPL. Estimated parameters included satellite positions and velocities, station positions for sites in Central America, South America and Europe, carrier phase range ambiguities, and satellite and station clock biases modeled as white noise. The wet and dry zenith tropospheric path delay was modeled as a stochastic process [Tralli *et al.*, 1988]. The positions of three sites in the U.S. were held fixed as

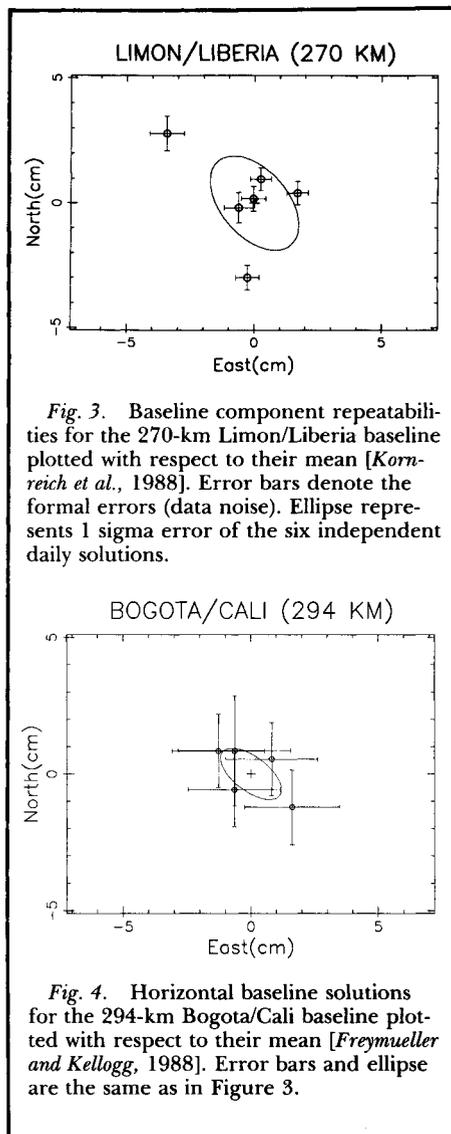


Fig. 3. Baseline component repeatabilities for the 270-km Limon/Liberia baseline plotted with respect to their mean [Kornreich *et al.*, 1988]. Error bars denote the formal errors (data noise). Ellipse represents 1 sigma error of the six independent daily solutions.

Fig. 4. Horizontal baseline solutions for the 294-km Bogota/Cali baseline plotted with respect to their mean [Freymueller and Kellogg, 1988]. Error bars and ellipse are the same as in Figure 3.

fiducial sites to establish a self-consistent reference frame and to constrain satellite ephemerides. Pseudorange data were used and carrier phase cycle ambiguities were fixed where possible [Blewitt, 1989]. Ninety five percent of the cycle ambiguities for the two Costa Rican sites, Limon and Liberia, were fixed successfully.

Repeatabilities of 1.5 cm for the length component and 2.3 cm for the vertical component were achieved on the Limon-Liberia baseline, while 0.7 cm in the length component and 4.6 cm in the vertical component were achieved on the Bogota-Cali baseline. This performance is comparable to the predictions made from covariance analyses prior to the experiment [Freymueller *et al.*, 1986; Freymueller and Golombek, 1988]. Assuming that the accuracy of the final results is no worse than 1 part in 10^7 , this level of performance should be adequate to monitor expected plate velocities (up to 8 cm/yr) with 5 years of observations with an accuracy of better than 1 cm/yr. Analyses are in progress to test the effects of troposphere calibration, cycle ambiguity resolution techniques and various fiducial strategies. It is expected that these results will improve once fiducial stations from outside the U.S. are included in

the analysis, and multiday arc and optimal bias-fixing strategies are employed.

The repeatabilities of daily baseline solutions suggest that adequate baseline accuracies can be obtained with the present satellite configuration. The CASA UNO collaborators, however, agreed to postpone the second campaign until January 1990 to insure an improved satellite constellation. Six Block II satellites are scheduled for launch in 1989. The enthusiasm shown by the 22 cooperating organizations from Latin America, North America, Europe, and the Pacific ensures continued international support for GPS geodesy in this tectonically active part of the world.

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