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TOWARD 10^9 GPS GEODESY: VECTOR BASELINES, EARTH ROTATION AND REFERENCE FRAMES

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INTRODUCTION

Center for Space Research University of Texas efforts under NASA Grant No. NAG-1936 during the period from January 1, 1993 to December 31, 1993 were in the following areas:

. GPS orbit accuracy assessments and efforts to improve the accuracy
. Analysis and effects of GPS receiver antenna phase center variation
. Analysis of global GPS data being collected for the IGS campaign
. Analysis of regional (south west Pacific) campaign data

A brief summary of each of the above activities is presented in the following.

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ACTIVITY SUMMARY

ANALYSIS OF GPS-35 (PRN05)

The launch of the GPS-35 satellite in August 1993 with laser reflectors and the subsequent SLR tracking from a few ground stations has enhanced the analysts ability to assess the accuracy of the GPS orbits and to identify and/or improve the GPS satellite force models. Using November 18, 1993, as a test case due to tracking obtained by five Northern Hemisphere SLR stations (none in Southern Hemisphere available yet), the difference between an SLR-determined orbit and an orbit determined using double differenced phase data from 25 stations of the IGS Network has been found to be at the meter level, with most of the difference being in the along-track direction. For comparison, the orbit based on double-differenced phase differs by 17 cm radial, 27 cm along-track and 21 cm cross-track with the IGS-combined orbit. The next steps in this analysis will be: 1) computing residuals of the SLR data based on various orbits determined from the IGS data and reported by the IGS Analysis Centers, 2) processing other days and 3) processing days with Southern Hemisphere data when they become available.

GPS FORCE MODEL ANALYSIS

Efforts to improve the GPS orbit accuracy have been focused on studies and improvements of the non gravitational force models, since all evidence suggests that the gravitational force models for GPS are adequate. In the non gravitational model, the common approach is to adopt the ROCK4 model (Fliegel et al., 1992) or one of its variants and estimate a scale parameter. However, this adjusted scale parameter combined with an estimated Y-bias parameter, provide an adequate representation of the non gravitational forces. Although the technique of introducing additional adjusted parameters in the form of empirical forces improves the data fitting for short (1 day) and multi-day arcs (3 days) as described in the 1992 Progress report, it does not improve either orbit prediction accuracies or baseline repeatability.

Given the large surface area of the satellite, it is important to know the precise attitude of the satellite for the computation of the solar radiation pressure and the y-bias force. The MSODP1 software assumes a sun-synchronous orientation which exposes the maximum solar panel area to the sun; however, in reality the attitude may be offset during certain times, such as exit from the Earth's shadow. Hence, a major part of the mismodeling of the non gravitational forces could be due to attitude misalignment. To evaluate this conjecture, the empirical forces were modeled with a frequency of one cycle per orbital revolution (once per rev), but a panel-fixed axis system was used in which constant and periodic terms were estimated in this system. Although this alternate empirical model did not produce any appreciable improvement in the orbit prediction or baseline repeatability using short arcs, significant improvements were obtained with long arcs. These improvements occurred in both the data fit RMS and in the orbit prediction accuracy. These results and other related experiments support the notion that a major problem in modeling the non gravitational forces may be due to GPS attitude misalignment and this investigation will benefit from attempts to obtain Air Force agreement to better control the spacecraft attitude. In the coming year, this investigation will continue to examine non gravitational force modeling for the purpose of improving orbit accuracy. Tests of the models will be conducted using a variety of baseline vectors, ranging from a few hundred kilometers to several thousand kilometers.

As part of the tests of force modeling and other error sources that affect the long baseline accuracy, six months of IGS data from 1993 have been processed to support these analyses. As a consequence, the data sets now available at UT/CSR that have been preprocessed are the 90-day set from the 1992 IGS-campaign and the first six months of 1993. The analysis of these data sets has included estimation of Earth rotation parameters, which are one measure of the accuracy of the IGS orbits and other parameters. Using the nominal ROCK4 and Y-bias parameters with one day arcs, the difference between estimated pole position from GPS and Lageos SLR is at the 0.5 mas level for the 1993 data. Analysis of the combined 1992 and 1993 data sets has enabled some long term analyses, even though a data gap of 90 days exists where the data has not been preprocessed (end of 1992). The data set has been used for the study of evolution of the reference frame, including the geocenter variations. Nevertheless, this long term data set has shown the existence of long term effects. In the coming year, the goal is to complete a one year data set which will be used for both improving the satellite force models and to evaluate the quality of orbit and observation modeling in achieving one part per billion accuracy for baseline vectors.

The campaign data from the 1992 Southwest Pacific are being used as an additional means of establishing orbit and baseline accuracy. This campaign is particularly useful in this application because there are no usable SLR/VLBI sites in the area (the American Samoa mark occupied by SLR in the early 1980s is unusable). The analysis of these data has produced repeatability at the few parts per billion level in the horizontal components. Further analysis of the vertical component, especially the contribution of both the orbit and the troposphere, will be examined in the coming year. Results of part of the 1990 campaign were published by Schutz et al. (1993), but the nature of the global tracking network for 1990 will limit their utility in assessment and improvement toward the part per billion level.

RECEIVER TESTS

The electrical phase centers of the received GPS signals on the L1 and L2 frequencies do not coincide with a fixed point on the antenna. Tests by GSFC and JPL using either anechoic chambers or similar controlled environments have show variations depending on the azimuth and elevation of the transmitting antenna with respect to the receiving antenna. The combined effect of such variations on the location of the ionospheric-corrected phase center (L3) is as much as 2 cm or more for some types of antennas, hence this effect cannot be ignored for baseline accuracies at the one part per billion level. Experimental data consisting of the L1 and L2 phase center offsets from a fixed, physical location on the antennas have been analyzed using test data from GSFC (Schupler and Clark) and JPL (Young et al.) for eleven different antennas and/or tests. For example, the L3 phase center location of the Trimble SST antenna shows a constant offset of about 18 mm with amplitude variations up to 4 mm, depending on the azimuth for a fixed elevation of 60 degrees. The measured amplitudes are dependent on elevation. Experience has shown that use of common antenna types in network operations minimize the phase center variations. However when antenna types are mixed, such as Rogue and Trimble antennas, the phase center variations may adversely affect baselines.

The UT/CSR analysis software has been modified to handle phase center variations through a spherical harmonic representation. This approach has been successful in modeling the JPL-determined Rouge antenna phase center variations, however, a different measurement strategy has been used at GSFC using a coarser tabular representation that makes the spherical harmonic approximation more complicated. In the near term, a satisfactory representation of the tabular data for use in data processing will be investigated. Selected portions of the SWP campaign data will be used to evaluate the influence of the phase center modeling.

In addition, controlled tests of various receivers has been performed in October and November 1993. Data on short baselines (10 m) were collected with different combinations of Turbo-Rouge, Ashtech and Trimble receivers. These data are being analyzed.

FUTURE WORK

. Continue analysis of empirical force modeling options and the effects on baseline accuracy.

. SLR data processing for the GPS-35 in order to obtain a more definitive estimate of the computed GPS satellite orbit accuracy.

. Implementation of the antenna phase center variations (as spherical harmonic coefficients or by other appropriate ways) in the routine data processing.

. Analysis of geocenter variation over a long period by continued processing of the IGS data.

MEETING PRESENTATIONS AND PUBLICATIONS

. West Texas FLINN site: Comparison of OMNI, GAMIT, and MSODP Baseline solutions for the 1990 and 1992 GPS Footprint Occupations, AGU Spring Meeting, Baltimore, Maryland, May 24-28, 1993 (R.Gutierrez, C.R.Wilson, and B.E.Schutz).

. Geodetic Observations of Convergence and Back-arc Spreading in the S.W.Pacific (1988-1992), AGU Fall Meeting, San Francisco, California, December 6-10, 1993 (M.Bevis, F.W.Taylor, B.E.Schutz, and S.Calmant).

. Evaluation of GPS Satellite Orbital Error and their Effect on Geodetic Parameter Solution, AGU Fall Meeting, San Francisco, California, December 6-10, 1993 (D.Kuang, B.E.Schutz and P.A.M.Abusali).

. An Efficient Algorithm for Processing Ambiguity Parameters of GPS Phase Measurement, AGU Fall Meeting, San Francisco, California, December 6-10, 1993 (H.J.Rim, B.E.Schutz, and B.D.Tapley).

. The Southwest Pacific GPS Project: Geodetic results from Burst 1 of the 1990 Field Campaign, ***Bulletin Geodesique,*** Vol.67, No.4, 1993 (B.Schutz, M.Bevis, F.Taylor, D.Kuang, P.Abusali, M.Watkins, J.Recy, B.Perin, and O.Peyroux).

. CSR Results from IGS and Epoch-92, ***Proceedings of the 1993 IGS Workshop*** , March 25-26, 1993, University of Berne, Switzerland (B.Schutz, P.Abusali and M.Watkins).

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The Southwest Pacific GPS Project: Geodetic results from Burst 1 of the 1990 Field Campaign

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ABSTRACT: The Southwest Pacific GPS Project (SWP) is using the Global Positioning System (GPS) to monitor crustal motion across and within a plate boundary complex between the Australian and Pacific plates. GPS field campaigns were conducted in 1988, 1989 and 1990, to observe networks of increasing size and complexity. The 1990 campaign consisted of two periods, or "Bursts", and this paper focuses on the analysis of data collected during the nine day Burst 1 in July, 1990, a period in which GPS Selective Availability was activated. During Burst 1, baselines that spanned the Tonga Trench and the Lau Basin were observed, and only one station (Espiritu Santo, Vanuatu) was located west of Fiji in the network. The lengths of the baselines observed fall mainly between 300 km and 1600 km, but some lines are as long as 3500 km. A total of 78 station-days of field site data and approximately 150 station-days of global fiducial data were processed from predominantly codeless receivers. A global fiducial network of 20 sites was used to provide orbit control and accuracy assessment for the 13 available satellites. The daily solutions for 45 baselines between 10 SWP sites have an RMS scatter in the length of 24 mm plus 6 parts per billion. This scatter provides an estimate of baseline precision for the Burst 1 "nominal solution." Experiments were conducted to investigate a variety of possible effects on the SWP Network baseline estimates, including the influence of a reduced global fiducial network for the purpose of assessing the quality of results obtained in 1988 and 1989 in which the fiducial network was smaller than in 1990. These experiments produced results that agreed with the nominal solution at the level of the precision estimate. Furthermore, estimates for selected baselines in Australia, the Central Pacific, North America and Europe, also measured by VLBI and SLR, were used for an external accuracy evaluation. The GPS and VLBI or SLR determinations of length agreed at a level consistent with the nominal solution precision estimate.

1. INTRODUCTION

The Southwest Pacific GPS Project (SWP) is using the Global Positioning System (GPS) to monitor crustal motion across and within a plate boundary complex between the Australian and Pacific plates. In this region (Fig. 1) the relative plate motions are unusually rapid [Pelletier and Louat, 1989]. Two active subduction zones of opposite polarity, associated with the New Hebrides and Tonga Trenches, are separated by a broad interarc region, which includes the North Fiji and Lau Basins, which are undergoing rapid, complex and possibly diffuse deformation as discussed by Hamburger and Isacks [1988]. Because of the fortuitous location of islands on both sides of both trenches, and within the broad interarc region, it is possible to use the GPS satellites to measure inter-island baselines that straddle many of the major tectonic elements of the region (Fig. 2). By repeatedly observing these baselines, the kinematics of plate convergence, back-arc spreading and intra-arc strain can be observed.

An international consortium (Table 1) has been formed to carry out this program of measurements. The first SWP field campaign was mounted in 1988, and observations were obtained at four sites in the vicinity of the Tonga trench (at the islands of Rarotonga, Upolu in W. Samoa, Tongatapu and Vava'u). Preliminary results for the 1988 campaign were reported by Schutz et al. [1989a]. A larger campaign was mounted in 1989; it extended from Rarotonga in the east to New Caledonia in the west. An even larger regional campaign was mounted in 1990 - the geometry is illustrated in Figure 2. This GPS campaign, SWP-90, was divided into two observation periods or "Bursts", each of about one week duration. Roughly speaking, both sites in Fiji (Viti Levu and Vanua Levu) and all sites to the east were observed during Burst 1, and both sites in Fiji and all sites to the west in Burst 2. Actually, Espiritu Santo island was observed during both bursts, and Futuna was observed only during Burst 2.

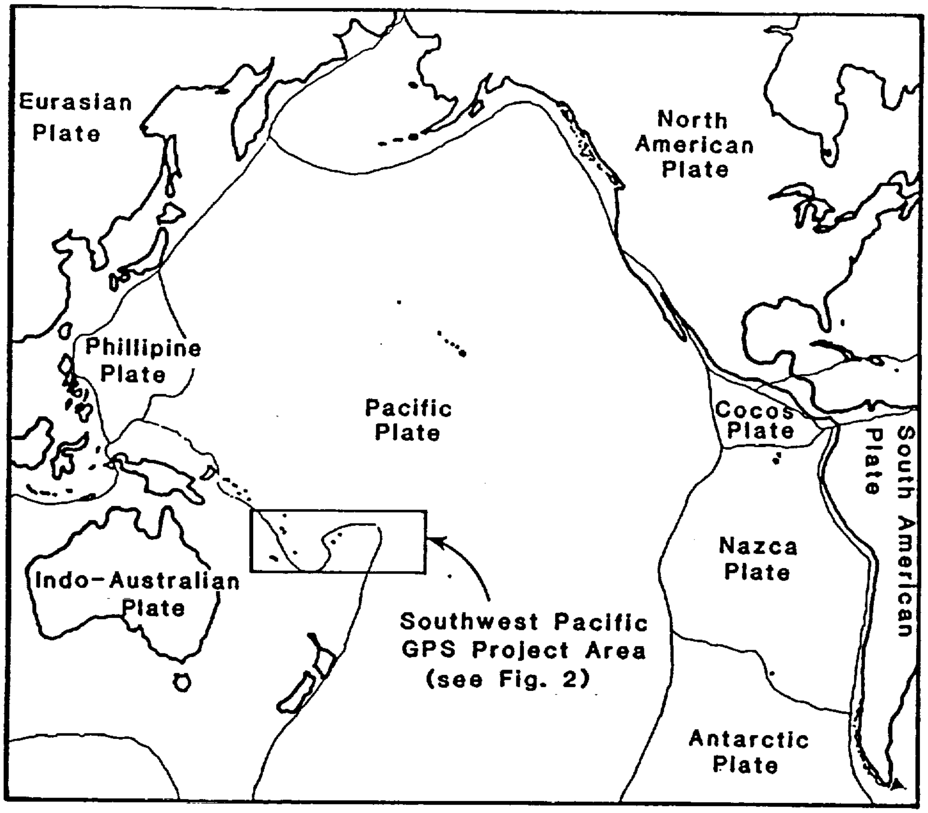

Figure 1. Location of the Southwest Pacific GPS Project

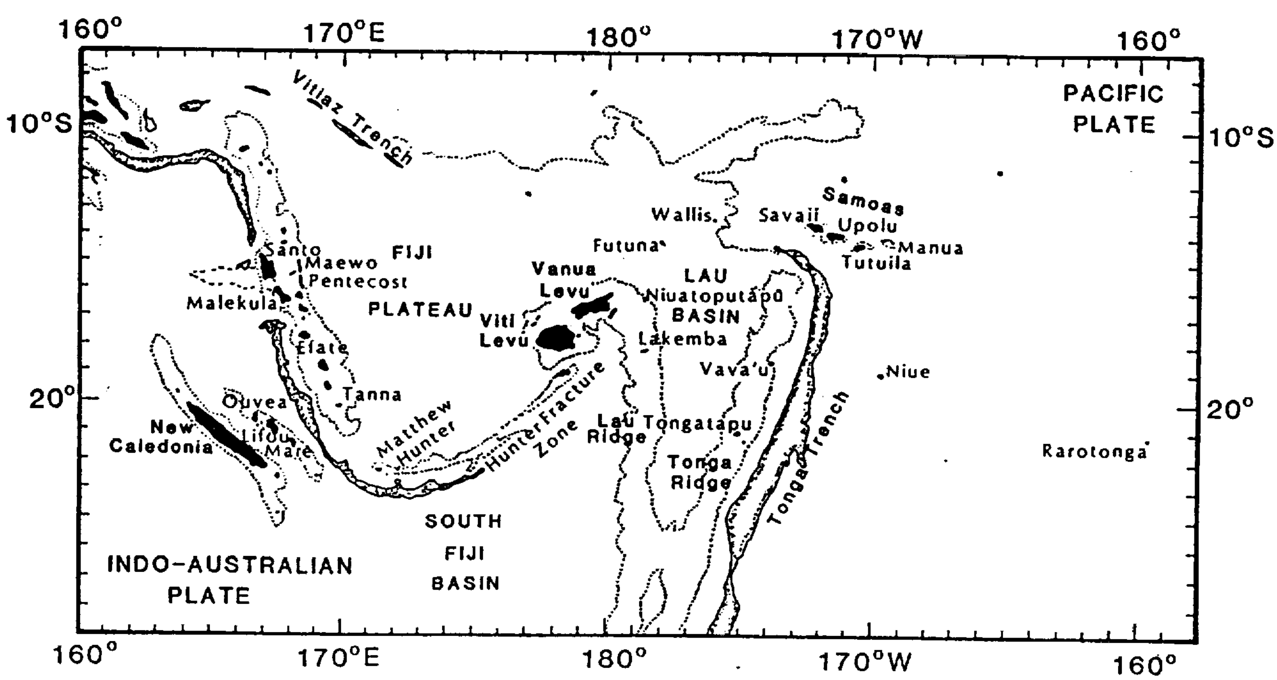

Figure 2. Southwest Pacific GPS Project 1990 Site Locations for Burst 1 and Burst 2
(Burst 1 sites are listed in Table 2)

The purposes of this paper are 1.) to describe the analysis of the 1990 Burst 1 data set and, 2.) describe the results obtained from analyses of the major error sources and their implications for other campaigns in the Southwest Pacific. The collective set of campaign analyses will have geophysical implications. The scientific value of a GPS survey implemented for crustal motion studies tends to increase as time passes and tectonic signals accumulate. But the historical value of these surveys is assured only if each campaign, and its analysis, are adequately documented. This is especially true for campaigns mounted prior to 1992 because of the rapid evolution of GPS receivers, the global tracking network and analysis techniques. The second purpose is to address the level of systematic error affecting the network solutions, particularly the network solutions obtained prior to 1990 when the global tracking system was far weaker than it was in 1990. The results of the error analysis show that the systematic errors in the baseline vectors exceed the formal standard (random) errors. The analysis has produced a novel approach to specifying confidence intervals on the relative network geometry solutions.

2. ANALYSIS SOFTWARE

All software used in the analysis of the SWP-90 data has been developed at the Center for Space Research (CSR) and is known collectively as TEXGAP (TEXas Gps Analysis Programs). The analysis process is divided into a preprocessing component and a geodetic component. In the preprocessing component, the data were reviewed and corrected for cycle slips, erroneous points and general data anomalies. In this process, the time tags of the phase measurements were validated and/or corrected using the L1 C/A pseudorange, or ionosphere-free pseudo-range if the receiver operates with the P-code. Finally, explicit double-differenced, ionospherically corrected measurements were formed for the geodetic processing stage.

The geodetic processing was performed using MSODP (Multi-Satellite Orbit Determination Program). In the general application of MSODP, the GPS epoch orbit elements and selected nongravitational force model parameters (radiation pressure scale and y-bias) were simultaneously estimated with three-dimensional coordinates of the GPS receiver network using the double-difference measurements formed in the first stage. MSODP obtains the GPS ephemerides through numerical integration of the satellite equations of motion. Furthermore, MSODP has made extensive use of satellite force models from its single satellite predecessor, UTOPIA, which has been extensively compared against an independent orbit and geodetic parameter estimation program developed at NASA Goddard Space Flight Center known as GEODYN. Early comparisons were given by Schutz et al. [1980] and current assessments have shown better than centimeter level agreement using all force models expected to be significant for TOPEX/POSEIDON [J. Ries, personal communication, 1991]. Comparisons between

TABLE 1.

INSTITUTIONS AND AGENCIES PARTICIPATING IN THE SW PACIFIC GPS PROJECT

North Carolina State University	USA
University of Texas at Austin	USA
University of Colorado	USA
ORSTOM	France & New Caledonia
Cornell University	USA
Institut Geographique National (IGN)	France
National Geodetic Survey (NGS)	USA
NASA Jet Propulsion Laboratory (JPL)	USA
University of New South Wales	Australia
Australian Surveying & Land Info. Group (AUSLIG)	Australia
Army Survey	Australia
Department of Surveying & Land Info.	New Zealand
Department of Lands and Survey	Western Samoa
Ministry of Lands, Survey & Natural Resources	Tonga
Survey Department	Cook Islands
Lands and Survey Branch	Niue
Mineral Resources Department	Fiji
Survey Department	Fiji
Department of Land Surveys	Vanuatu
Department of Geology, Mines & Rural Water Supply	Vanuatu
Service Topographique	New Caledonia
Geographical Survey Institute (GSI)	Japan
Texas State Department of Highway & Public Transportation	USA
University of Nottingham/ Royal Greenwich Observatory	UK
Institut fur Angewandte Geodasie (IFAG)	Germany
Canadian Geodetic Survey	Canada
Norwegian Geodetic Survey (Statens Kartverk)	Norway
Defense Mapping Agency (DMA)	USA

MSODP and UTOPIA have shown millimeter agreement in the models used for GPS analysis [H. Rim, personal communication, 1991]. UTOPIA has undergone extensive application to high precision orbit determination of Lageos [for example, Tapley et al., 1985] and Starlette [for example, Schutz et al., 1989b, and Cheng et al., 1990] using Satellite Laser Range (SLR) data. The TEXGAP software uses several computers, including VAX computers at the CSR and a Cray YMP8/864 supercomputer at the University of Texas System Center for High Performance Computing.

3. DATA

The SWP-90/Burst 1 was conducted from day 196 (July 15) until day 204 (July 23) in 1990. Days 196-202, coinciding with GPS Week 549, were the primary analysis period for this paper. During this period, there were 13 active GPS satellites: PRN 2, 3, 6, 9, 11, 12, 13, 14, 16, 17, 18, 19, 20. This active constellation consisted of both Block-I satellites (3, 6, 9, 11, 12, 13) and the more recent Block-II satellites. Aside from differences in spacecraft design characteristics, the orbit inclinations are 63 degrees for Block-I and 55 degrees for Block-II. During the period of the SWP experiment, Selective Availability (SA) was activated on the Block-II satellites.

Trimble 4000SST ("codeless") dual frequency receivers were used in the SWP Network at the sites listed in Table 2. Four sites in the SWP Network have been occupied in 1988, 1989 and 1990. Two of the baselines associated with this subnet, Rarotonga-Tongatapu and Rarotonga-Vava'u, will provide the first GPS estimates of the rate of convergence across the Tonga trench through comparison of the year to year baseline results. The mean length of these lines is approximately 1550 km.

All SWP Network sites are located on islands which consist of volcaniclastic sediments and/or coral reef limestone overlying volcanic rocks. At all but one site the geodetic marker which serves as the reference point for repeat measurements is a stainless steel pin which has been friction-fitted and/or cemented into a hole drilled into bedrock. In most cases this rock is either strongly indurated coral reef limestone or hard volcanic rock. However, in the case of Rarotonga a suitable area of rock was not found and a site was chosen on the airport grounds. The airport runway and apron construction areas were originally excavated to a depth of several meters and then filled with crushed coral and sand, which subsequently was compacted.

Since Rarotonga is an important site for the establishment of motion across the Tonga Trench, the SWP geodetic monument on the island has been monitored by the Cook Islands Department of Survey since the first GPS measurements in 1988. A footprint system of four reference monuments was established within 2 km of the primary GPS marker, which has been periodically remeasured with a Geodimeter 14 on the long lines and a Nikon ND20 on the short lines. The primary GPS marker is "Bolt A". One of the footprint markers is on the concrete airport taxiway (marker ARP) and a second marker is set in concrete at the end of the runway (marker PRM). Two additional sites are located in volcanic rock outcrops on ridges approximately 150 m above the airport. The relative positions of the markers are shown in Fig. 3. Repeat measurements between the markers have been made at approximately 12-18 month intervals since November 1988. The repeat measurements are given in Table 3, which shows repeatability over the 1988-1990 period of better than 15 mm (RMS). Since this observed scatter reflects both site stability and instrumental errors, the measurements in Table 3 can be regarded as an upper bound on the horizontal instability of the site over the history of the GPS project.

In general, high quality data were collected at all SWP-90 Network sites during the 1990 campaign. The main problem was an occasional cycle slip on the L2 carrier, which could be readily fixed against the L1 carrier. Other, infrequent data problems did occur, but no significant losses in data occurred at any site. Data were collected at a 15 sec interval to aid the cycle fixing process; however, the data were sampled to 30 sec after cycle fixing for compatibility with the fiducial network. The Ashtech receiver at Wallis recorded data at a 10 sec interval, but the data were sampled to 30 sec. A total of 78 station-days of data were analyzed for this paper from the SWP Network sites.

TABLE 2.

SWP-90/BURST 1 NETWORK SITES

Site	Previous Occupations
Rarotonga (Cook Islands)	1988/1989
Upolu (W.Samoa)	1988/1989
Vava'u (Tonga)	1988/1989
Tongatapu (Tonga)	1988/1989
Niuatoputapu (Tonga)	
Niue	
Lakeba (Fiji)	
Viti Levu (Fiji)	1989
Vanua Levu (Fiji)	
Espiritu Santo (Vanuatu)	1989
Espiritu Santo/Cape Lisburn	
Espiritu Santo/Tasmalum	
Espiritu Santo/Ratard	
Wallis (Ashtech receiver)	

NOTE: All receivers operated with the internal quartz oscillator.
All receivers were Trimble 4000 SST (except Wallis).

The fiducial network consisted of the sites given in Table 4, formed from Cooperative International GPS Network (CIGNET) sites (see, for example, the CSTG GPS Bulletin for July-August, 1990), sites operated for campaign support only (labeled Campaign), and NASA/JPL sites. In most cases, the sites in the fiducial network were located near Very Long Baseline Interferometry (VLBI) or Satellite Laser Ranging (SLR) sites. As evident from Table 4, the fiducial network is dominated by receivers of the dual frequency "codeless" type, namely, Minimac and Trimble units which do not track the GPS P-Code. Most sites in the fiducial network operated satisfactorily, but the TI and Trimble receivers at Kokee Park, operated from a common antenna, had intermittent problems. The CIGNET and Campaign site data in the fiducial network were recorded at a 30 sec interval, on the minute and half minute; however, the TI-4100 data were recorded at 0.92 sec before the minute and half minute, thus requiring procedures for accommodating SA when TI data were combined with data from other receivers. The NASA/JPL sites recorded data at 2 min intervals, with two sites (Tidbinbilla and Madrid) recording data at a time offset by +5 sec from the exact 2 min time mark, thus introducing an SA sensitivity. In spite of these problems, most receivers were synchronized at the millisecond level, and no perceptible SA limitations were encountered, consistent with the results of Rocken and Meertens [1991]. For the few cases in which the Rogue receivers were not synchronized at the millisecond level with the rest of the network, only Block I satellites were used to avoid SA-induced problems. All satellites were used in the analysis from other sites. Approximately 150 station-days of data were processed from the global fiducial network and most receivers were synchronized at the 1 ms level.

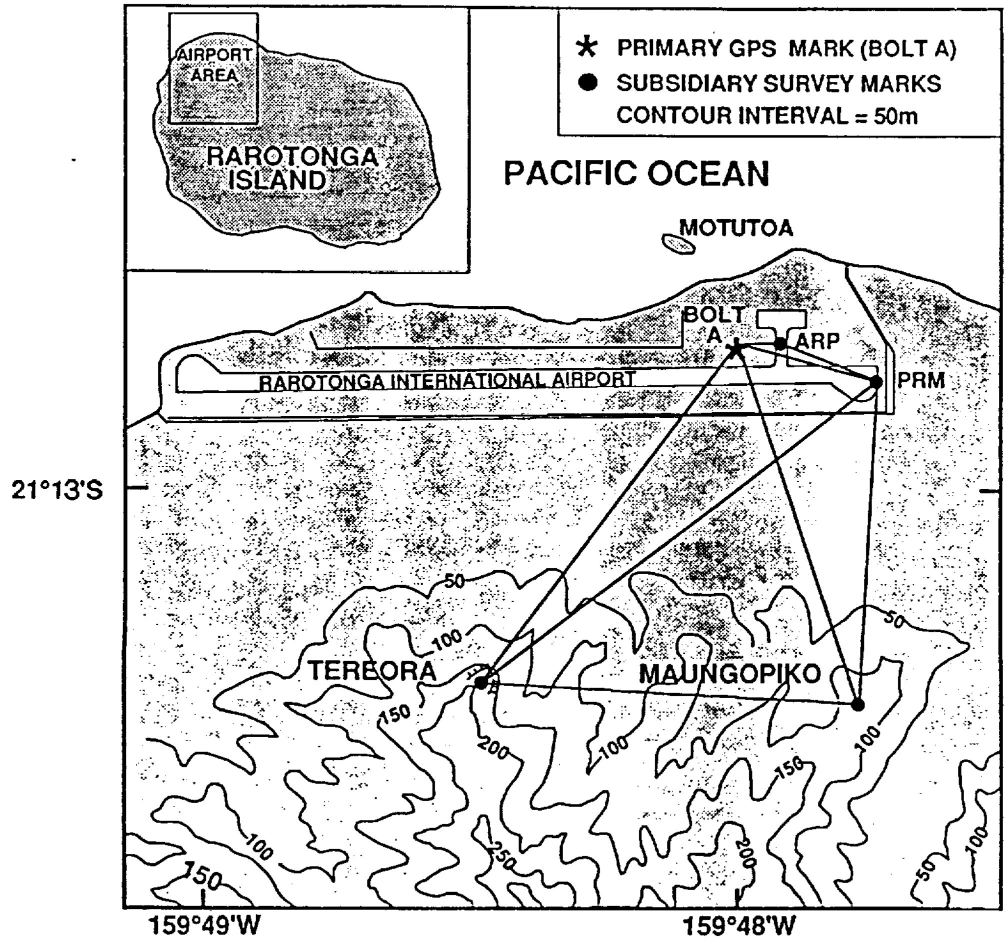

Figure 3. Locations of Rarotonga GPS Mark and Subsidiary Marks

Two receivers were operated at both Kokee Park and Ft. Davis (McDonald Observatory) from a common antenna. In the case of Kokee Park, the antenna was a Trimble; however, the McDonald Observatory antenna was a TI Series 4000. The Kokee Park operation was conducted as part of the phase out of TI-4100 operations and the McDonald operation was conducted as part of a West Texas GPS experiment [C. Wilson, personal communication, 1990]. Analysis of data from both sites was used in the Southwest Pacific data preprocessing to validate receiver time tags and analysis techniques; however, only Trimble data were used from these sites for SWP Network analysis.

TABLE 3.

RAROTONGA FOOTPRINT REPEAT MEASUREMENTS

Distance Measurements (millimeters)

DATE	A to ARP	A to Maungopiko	A to Tereora	A to PRM
July 1988	146762			
Nov. 1988	-	1314472	1370652	
Mar. 1989	146758			558291
Aug. 1989	146745	1314456	1370623	558305
Oct. 1989	146758			558288
Sep. 1990		1314457	1370627	558288
Mean	146756	1314462	1370634	558293
Standard Error	7	9	16	8

A refers to "Bolt A", the marker used for GPS measurements in 1988, 1989 and 1990.

TABLE 4.

FIDUCIAL NETWORK SITES (GPS WEEK 549)

SITE	RECEIVER	REF. OSCILLATOR
Mojave, CA	Minimac 2816AT	Hydrogen maser
Westford, MA	Minimac 2816AT	Hydrogen maser
Richmond, FL	Minimac 2816AT	Hydrogen maser
Wettzell, Germany	Minimac 2816AT	Hydrogen maser
Tsukuba, Japan	Minimac 2816AT	Hydrogen maser
Hobart, Tasmania	Minimac 2816AT	Hydrogen maser
Kokee Park, HI	Trimble 4000SST	Hydrogen maser
Kokee Park, HI	TI-4100	Hydrogen maser
Wellington, NZ	Trimble 4000SST	Cesium
Yellowknife, NWT	TI-4100	Cesium
Onsala, Sweden	TI-4100	Hydrogen maser
Tromso, Norway	TI-4100	Cesium
Orroral, Australia	Trimble 4000SST	Quartz
Kwajalein	Trimble 4000SST	Quartz
Huahine	Trimble 4000SST	Quartz
Ft. Davis, TX	Trimble 4000SST	Cesium
Ft. Davis, TX	TI-4100	Cesium
Goldstone, CA	Rogue	Hydrogen maser
Tidbinbilla Australia	Rogue	Hydrogen maser
Madrid, Spain	Rogue	Hydrogen maser
Fairbanks, AL	Rogue	Hydrogen maser
Usuda, Japan	Rogue	Hydrogen maser

4. MODELS AND REFERENCE FRAME

The satellite force and kinematic models are consistent with the International Earth Rotation Service (IERS) Standards [McCarthy, 1989]. In particular, the Earth gravity field was GEM-T1 [Marsh et al., 1988], truncated to degree and order 8, and GM was adopted to be 398600.440 km^3/s^2 [Ries et al., 1989]. The point mass perturbations of the Moon and the Sun were included, with coordinates obtained from DE-200 [Standish et al., 1982]. General relativity was included, consistent with the description given by Ries et al. [1988]. The solid tide perturbation was included with the Love Number $k_2 = 0.3$, and the Honkasalo correction was accounted for. Ocean tides were not included. Solid Earth tide corrections to station coordinates were applied using $h_2 = 0.609$ and $l_2 = 0.0852$, but ocean loading was not included. The nongravitational force model included a y-bias component and the ROCK4 solar radiation pressure model [Fliegel, et al, 1992]. The Earth orientation was consistent with the IERS Standards, including the short period variations in UT1 [Yoder et al., 1981; McCarthy et al., 1989]. The polar motion and UT1 used in the analysis are given by Eanes et al. [1991] based on analysis of Lageos SLR data.

As noted previously, the SWP Network sites are characterized by island environments; thus the GPS receivers were operated in moderate to high humidity conditions. The Chao [1974] troposphere model, including both wet and dry components, was used to correct the measurements. To accommodate variations that take place over the daily intervals of receiver operation, a new zenith delay for the Chao model was estimated every 2.5 hours for each site in the solution. Water Vapor Radiometer (WVR) measurements were not collected because of the experience of other investigators (for example, Dixon et al., 1991) that show results obtained by estimating a zenith delay are comparable to results obtained using WVR measurements.

Ionospheric corrections were applied using dual frequency phase measurements. In addition, the satellite phase center with respect to the satellite center of mass was x=0.21 m, y=0.0 m and z=0.854 m for the Block I satellites and x=0.2794 m, y=0.0 m and z=1.0229 m for the Block II set, as described in the spacecraft-fixed axes [Fliegel et al., 1992].

The reference frame was based on Lageos SLR analyses performed at UT/CSR. The technique used by Ray et al. [1991] was used. The local geodetic ties between common SLR and VLBI sites were used to determine a set of seven origin translation, rotation and scale parameters. These seven parameters were applied to the VLBI sites, thereby maintaining their internal consistency, but adjusting them into a center of mass reference frame defined by SLR. The VLBI solution was GLB718 from Goddard Space Flight Center [Ma et al., 1991] and the SLR solution was CSR91L03 from UT/CSR [Eanes et al., 1991]. The local surveys for the common sites were given by Ray et al. [1991] and the SLR and VLBI coordinates were weighted according to the information published with the respective solution. After applying the seven parameter transformation, the RMS differences between the 18 common sites was 15 mm in x, 29 mm in y and 31 mm in z at the selected reference epoch of January 1, 1988. The individual site comparisons, after application of the seven parameter transformation, are shown in Table 5. The largest differences (Medicini, Shanghai and Canberra) are believed to be the result of weak solutions or problems with local survey ties. Except as noted, the transformed VLBI sites were usually used in this paper for the fiducial coordinates, thereby maintaining the VLBI relative positioning for the GPS fiducial network.

The seven parameter transformation was applied to VLBI sites of interest for the Southwest Pacific experiment sites, as given in Table 4. The resulting coordinates for the reference epoch were then mapped to the approximate mid-point of Burst 1, day 199 in 1990, using site velocities measured by the respective SLR or VLBI technique. It should be noted that the velocities measured by both SLR and VLBI are in good agreement with the plate motion models of DeMets et al. [1990] for most of the sites of interest located at points distant from the plate boundary. Furthermore, as noted in the next section, all sites within the Pacific basin were allowed to adjust in order to diminish the direct influence of a priori plate motion on the SWP Network results.

The final step in the establishment of the reference frame was the addition of the local GPS antenna vectors, given in Table 6, to the VLBI/SLR coordinates mapped to July, 1990, as described in the preceding paragraph. The resulting GPS coordinates are given in Table 7. These coordinates were used in fixed fiducial site experiments and for the evaluation of fiducial coordinate estimation experiments. These coordinates were applied throughout Burst 1 since the effects of

TABLE 5

COORDINATE DIFFERENCES AFTER APPLICATION OF 7-PARAMETER TRANSFORMATION TO VLBI

Comparison Site	SLR minus Adjusted VLBI (mm)		
	Dx	Dy	Dz
Wettzell, Germany	17	-13	31
Grasse, France	-10	21	-63
Medicini, Italy	-48	84	13
Greenbelt, Maryland	-1	-15	4
Haystack, Massachusetts	-12	-5	-11
Westford, Massachusetts	-8	9	-16
Richmond, Florida	-24	-29	2
Platteville, Colorado	-7	-20	-18
McDonald Observatory, Texas	-19	-30	57
Ft. Davis, Texas	-4	-49	30
Mojave, California	-5	-20	40
Monument Peak, California	5	59	27
Otay Mt., California	23	-43	-1
Owens Valley, California	32	52	17
Quincy, California	14	-33	-52
Maui/Kauai, Hawaii	-36	1	-27
Shanghai, PRC	-42	-71	2
Canberra, Australia	-26	-118	2
Weighted RMS	15	29	31

plate motion over the one week experiment are negligible.

Both L1 and L2 phase data were used to obtain ionospherically corrected measurements. The adopted Minimac L2 location was 15.5 mm below the L1 phase center (CSTG GPS Bulletin v.2, no. 3). The Trimble L2 location was assumed to be 1.5 mm below the L1 phase center (adopted by UNAVCO, based on information provided by R. Hyatt, Trimble Navigation). The TI L2 location was 15 mm below L1, based on experiments performed by Prescott et al. [1989]. The Minimac and Trimble values agree to less than 2 mm with anechoic chamber results obtained by Schupler and Clark [1991]; however, the Schupler results give 24 mm for the TI antenna compared to 15mm obtained by Prescott. The Dorn-Margolin antenna used with the Rogue receivers have an L1 location that is 22 mm below L2, as reported by Schupler and Clark [1991].

5. PROCEDURES

A multi-day analysis strategy was adopted for the analyses described in the following section. Such a strategy has been successfully used in the analysis of Lageos SLR data [Tapley et al., 1985; Smith et al., 1985] and with GPS data [Schutz et al., 1990; Lichten et al., 1990]. For the analysis of the SWP-90 data, an orbital arc length of one week was adopted spanning the complete GPS week 549. The data used in the analysis were double-differenced phase measurements, formed between combinations of satellite pairs and receiver pairs, as described by various investigators, including Remondi [1984, 1985] and Bock et al. [1986].

As described by Bock et al. [1986], if L ground stations simultaneously observe S satellites, there are (L-1)(S-1) double difference combinations for which the observation-state relationships are linearly independent, but correlated. The technique used to transform the measurements into an uncorrelated set was based on the Gram-Schmidt Orthogonalization [e.g., Remondi, 1984], which integrates well with the least squares processing based on the square-root-free Givens technique [Gentleman, 1973] used in MSODP and UTOPIA. Additional information on the MSODP implementation is given by Ho [1990].

The estimated parameters included satellite-dependent quantities, geodetic parameters and measurement parameters. The satellite-dependent parameters were (for each satellite): six epoch (day 196) position and velocity components, one scale parameter for the ROCK4 radiation pressure, and two y-bias parameters. The geodetic parameters included the three position components of each estimated site position. The measurement parameters included a troposphere zenith delay and double difference ambiguity parameters. To accommodate a changing tropical environment, the zenith delay parameters were estimated at 2.5 hour intervals for each site. Unless otherwise stated in the results discussion, the a priori covariance of the estimated parameters was infinite; thus all estimated parameters were unconstrained in their adjustment.

6. RESULTS

Various experiments were conducted to evaluate the sensitivity of the results. The primary purpose of these experiments was to examine the influence of the fiducial network on the estimated baselines, particularly the influence of adopted fixed sites and the number of sites. The specific cases reported in the following sections are:

- Nominal solution: this solution was based on all available data with five fixed sites.
- Alternate fiducial: this solution was based on an alternate selection of fixed fiducial sites.
- Perturbed fiducial: this solution was based on the nominal solution, however, the fixed site coordinates were perturbed by 30 mm (one sigma) Gaussian distributed errors that were introduced to reflect coordinate uncertainty.
- Reduced arc length: this solution was based on the use of two arcs of 3 day and 4 day duration instead of the single 7 day arc of the nominal solution.
- Reduced network: this solution was based on the use of a subset of the complete data set, but with the same fixed sites as the Alternate Fiducial Case. The purpose of this case was to enable an assessment of the quality of the results that can be expected from smaller fiducial and field networks, similar to those used in the Southwest Pacific Experiments in 1988 and 1989.

As discussed by Larsen and Agnew [1991], there have been two approaches commonly used for the specification of errors in network solutions. First, the formal solution standard errors are scaled so that the chi-squared errors equal one and, second, the formal standard errors are ignored, but

TABLE 6.

VECTORS FROM VLBI/SLR TO GPS

Location	VLBI/ SLR Mark	GPS Ref. Point	x	y	z	Reference *
Hobart	7242	MiniMac L1	52453	17009	-25846	v.3#3
Mojave	7222	MiniMac L1	-44870	19372	-14394	v.2#3
Richmond	7219	MiniMac L1	51317	14361	5200	v.2#3
Tsukuba	7311	MiniMac L1	-20826	-46729	24241	v.2#3
Westford	7209	MiniMac L1	26373	42091	32490	v.2#3
Wettzell	7224	MiniMac L1	12450	90532	-40183	v.2#5
Kokee Pk	1311	Trimble L1	27637	-19161	44575	v.3#3
Orroral	7843	NM/C/106	277	-22257	-10423	B.Murphy, 1991
Huahine	7123	RM-1	-18477	5317	26307	C.Boucher, 1989
Onsala	7213	TI4100 L1	53512	-40270	-42446	v.2#3
Tromso	7602	TI4100 L1	37232	-32791	-6524	v.3#3

*Except as noted, all references refer to the CSTG GPS Bulletin, published by NGS; for example, V.2#3 refers to Volume 2, Number 3. Notethat x,y,z are the components of a vector from the VLBI/SLR mark to the GPS reference point (in millimeters).

TABLE 7.

COMBINED VLBI/SLR FRAME: DAY 199, 1990

Site	Ref.	x	y	z
Hobart	L1 PC	-3950184055	2522364524	-4311588685
Mojave	L1 PC	-2356215716	-4646736529	3668456184
Richmond	L1 PC	961309571	-5674075641	2740538943
Westford	L1 PC	1492233184	-4458088370	4296047981
Wettzell	L1 PC	4075552458	931825794	4801589116
Kokee Park	L1 PC	-5543818255	-2054583236	2387858449
Onsala	L1 PC	3370659644	711877210	5349788205
Tromso	L1 PC	2102905660	721613130	5958199963
Ft. Davis	7850	-1330007984	-5328391582	3236502694
Orroral	NM/C/106	-4446476590	2678104639	-3696261926
Huahine	RM-1	-5345885268	-2958242121	-1824597937

Note: x,y,z in millimeters, PC denotes phase center

an estimate of the precision of the solution is obtained from the scatter, or repeatability, of daily solutions (or some other adopted time interval). In the latter case, the level of repeatability is a necessary condition, but not a sufficient condition, to estimate the accuracy of the solution. Such a test reflects the level at which the dominant error sources repeat from day to day. Still other approaches include the use of covariance analysis or a systematic investigation of the influence of expected error sources on the estimates, which are essentially equivalent under appropriate conditions. In this paper, both the daily scatter (repeatability) and numerical experiments of the network estimate sensitivity to various error sources were used to assess the quality of the results.

Additional evaluations were conducted by comparing results with those determined by SLR and/or VLBI. Unfortunately, no precise positioning results from these techniques are available within the SWP Network from which direct comparisons can be made and no definite plans exist to deploy mobile SLR or VLBI to the area. In lieu of sites within the SWP Network, the evaluation sites were in Australia, the Central Pacific, North America and Europe. These sites enabled evaluations of the orbits in areas adjacent to the SWP Network as well as at other, more distant locations.

6.1 Nominal Solution

The data from the fiducial network (Table 4), in combination with the SWP Network data (Table 2), were used to determine the "nominal solution." From the combined fiducial and SWP field sites, over 328,000 double-difference measurements were used in the nominal solution. These double difference measurements were processed by MSODP in which over 3000 parameters were simultaneously estimated. The estimated parameters included over 1700 ambiguity parameters, over 900 zenith delays, over 100 orbit-related parameters and several hundred station coordinates. The double difference measurements were weighted equally at 30 mm and the weighted RMS of the double difference residuals for the one week arc was 27 mm.

In the nominal solution, the following five sites were fixed to the values given in Table 7: Hobart, Mojave, Richmond, Westford and Wettzell. All other site coordinates were estimated, including daily values for all field sites and selected global sites. The five sites chosen to be fixed in the nominal solution provided good geographical distribution, a common receiver type (Minimac 2816 AT), and each site had a good history of VLBI measurements. The transformation of the VLBI coordinates into the SLR reference frame described in "Models and Reference Frame" essentially maintained the internal consistency of the VLBI coordinates since the scale between SLR and VLBI was found to be small. With this set of five fixed sites, only two sites were fixed on the boundary of the Pacific basin (Hobart and Mojave); thus the SWP Network was only very loosely influenced by the plate motion characteristics introduced with the mapping of the fixed site coordinates from the January 1988 epoch to July 1990 using the observed SLR or VLBI rates.

The estimated positions of the Trimble sites in the Southwest Pacific Network are given in Table 8, expressed in the SLR/VLBI reference frame used to describe the fiducial station coordinates (Table 7). These coordinates are primarily determined from baselines that extend from Australia to Santo and Australia to Rarotonga, distances of 2900 km and 5100 km, respectively. To the extent that the RMS scatter of the daily solutions, or repeatability, can be regarded as a measure of precision, the North/South components exhibit the best precision, and the vertical component exhibits the worst.

The nominal solution results for the relative positions within the SWP Network are summarized in Table 9. This table gives the relative baseline vectors in rectangular cartesian coordinates (xyz) for the 10 primary Trimble sites in the SWP Network, including the RMS scatter in the respective daily solutions, referred to here as "repeatability." The (xyz) repeatability components were also transformed into a topocentric coordinate system (North, East, Up/Vertical), or NEU, centered at the tip of the vector (i.e., the station identified in the second column). The repeatability statistics corresponding to Table 9 are as follows, assuming a linear function of the form a + b L, where L represents the distance between the two sites:

North: a = 5 mm, b = 3 ppb (parts per billion)
East: a = 25 mm, b = 9 ppb
Up: a = 39 mm, b = 6 ppb
Length: a= 24 mm, b = 6 ppb

These statistics are in general agreement with those obtained in other networks (e.g., Kellogg et al., 1990; Dixon et al., 1991; Larson and Agnew, 1991], although the individual values of the parameters a and b differ. Detailed comparisons with results obtained in other networks are complicated by several factors, such as the location of the network, the length of the baselines and the proximity of fiducial sites. In the examples cited, only the CASA UNO results of Kellogg et al. [1990] have similar lengths and an equatorial location of the network. The Kellogg results exhibit baseline repeatability of better than 30 ppb for lines exceeding 1000 km, and vertical repeatability of 40-60 mm with a weak dependence on baseline length, comparing favorably with the results given in Table 9. The results of Freymueller [1992] from the CASA UNO experiment also exhibit better repeatability in the North/South direction than in the East-West direction. The North-South quality is associated with the geometrical effect of the satellite motion being somewhat parallel to the baseline, whereas the East-West lines are more orthogonal to the motion.

Additional results, including results for local networks, are given in Table 10. Although some of the sites are within the region of the network, most of the sites are not part of the main network; thus, these sites are not planned for regular reoccupation in future campaigns.

An assessment of the accuracy within the SWP Network is limited by the absence of measurements made by other high precision techniques such as VLBI or SLR. Nevertheless, comparisons can be made outside the SWP Network which enable a partial evaluation of the orbit accuracy, which in turn affects the accuracy of the SWP Network solutions. Table 11 shows comparisons with VLBI and/or SLR using the nominal solution results. Various error sources potentially limit the use of the available external comparison, including 1.) accuracy of local surveys, 2.) level of agreement between SLR and VLBI and 3.) performance of mixed receivers and antennas. Each of the cases shown in Table 10 is worthy of additional discussion.

The Hobart-Orroral baseline shown in Table 11 exhibits very similar characteristics to the difference shown in Table 5 for the comparison of SLR and VLBI. The comparison of VLBI and SLR shown in Table 5 is based on the SLR at Orroral and the VLBI at Tidbinbilla, a distance of approximately 26 km. The Table 5 (xyz) result is -26, -118 and 2 mm, whereas the Table 11 result is -10, -120 and 56. These independent results are remarkably consistent in the (x,y)-components and suggest that the discrepancy between SLR and the GPS result is not an artifact of the GPS analysis. Nevertheless, a more recent comparison of the SLR and VLBI by Himwich et al.[1993] shows the Orroral-Tidbinbilla discrepancy to be at the level of 60-70 mm, which is still larger than the estimated standard error, but smaller than the discrepancy in Table 5. No definite conclusion about an apparent Orroral-Tidbinbilla discrepancy can be drawn at this time. While the GPS solution was obtained using a mixed receiver configuration (Minimac and Trimble), the uncertainty in respective phase center locations is significantly smaller than the observed discrepancy between SLR/VLBI and GPS. In spite of the differences in the compo-

TABLE 8.

SWP-90 TRIMBLE NETWORK COORDINATES (millimeters)

Site	#	x	y	z	RMS Scatter of Daily Solutions N	E	U
Rarotonga	7	-5583136633	-2054237436	-2292187986	7	27	59
W. Samoa	6	-6134394669	-860418930	-1514829459	4	25	96
Vava'u	7	-6012412242	-631999382	-2026504074	8	43	100
Tongatapu	7	-5930280626	-486629241	-2289337906	13	39	103
Niue	7	-5936927505	-1054874495	-2071944014	11	42	84
Niuatoputapu	6	-6097998306	-666372262	-1741074825	10	44	75
Viti Levu	7	-6073527437	276501959	-1921630423	7	44	70
Vanua Levu	7	-6119100702	62728219	-1792700009	6	38	76
Lakeba	4	-6060201967	-129071351	-1978127707	1	19	65
Espiritu Santo	7	-5996538766	1361935340	-1688098970	11	33	24

Site	Geodetic Latitude (degrees-min-sec)			Longitude (degrees-min-sec)			Height (mm)
Rarotonga	-21	12	4.46407	200	12	1.40340	16490
W. Samoa	-13	49	51.07726	187	59	3.48147	51774
Vava 'u	-18	38	51.98026	186	0	2.35456	179344
Tongatapu	-21	10	24.49999	184	41	27.91899	62290
Niue	-19	4	54.70696	190	4	30.64315	87857
Niuatoputapu	-15	56	48.13693	186	14	10.95994	60739
Viti Levu	-17	39	3.32677	177	23	36.11713	86789
Vanua Levu	-16	25	55.92235	179	24	45.60912	166865
Lakeba	-18	11	14.36881	181	13	12.40358	112574
Espiritu Santo	-15	26	57.31117	167	12	14.55054	125161

Reference ellipsoid: R=6378137000 mm, 1/f=298.257
# denotes the number of daily solutions
N, E, U denotes North, East and Up/Vertical components
All coordinates refer to the geodetic marker established at each site.

nents, the 26 mm agreement in baseline length (30 ppb of the baseline length) is compatible with the overall difference between SLR and VLBI as well as the precision estimate of the SWP Network.

The Kokee Park-Huahine baseline comparison in Table 11 shows excellent agreement in all three components. This particular case is the only one in Table 11 that uses compatible receivers and antennas. On the other hand, the VLBI/SLR comparison values are obtained from the VLBI coordinates at Kokee Park (adjusted into the SLR reference frame of Table 7) and SLR coordinates at Huahine. Furthermore, neither Kokee Park or Huahine was fixed, whereas one site was fixed for each of the other three cases given in Table 11. The 8 mm difference in length, or 2 ppb, is a strong indication that very good orbit quality has been achieved in the Central Pacific.

The Mojave-McDonald Observatory baseline, while exhibiting an agreement with SLR/VLBI at the 23 mm level on a 1306 km line (20 ppb), shows an anomalous height of 136 mm. This height discrepancy is not understood, but it should be noted that this case represents a dissimilar mix of receivers and antennas.

The Wettzell-Onsala comparison was limited by SA since the TI receiver at Onsala recorded at a 0.92 second offset with respect to the Wettzell data. To expeditiously circumvent the SA problem, the baseline result for this case was based only on six Block I satellites, thereby limiting the data coverage and viewing geometry. Nevertheless, the GPS-determined baseline length agrees with SLR/VLBI at 30 mm, or 30 ppb.

In summary, the length precision of the SWP Network nominal solution, based on daily repeatability or scatter, is estimated to be 24 mm plus 6 ppb of the baseline length. Comparable precision was obtained in the East-West component, but significantly better precision (5 mm plus 3 ppb of baseline length) was obtained in the North-South components. The vertical components showed 39 mm plus 6 ppb of baseline length. Furthermore, the comparison with external

TABLE 9.

SWP-90 NETWORK:
Nominal Solution (millimeters)

Vector	#	x	y	z	L	RMS Scatter of Daily Solutions x	y	z	L
RARO-VAVA	7	-429275609	1422238053	265683912	1509180761	57	29	19	25
RARO-TGPU	7	-347143993	1567608195	2850080	1605587907	55	24	23	25
RARO-WSAM	6	-551258036	1193818506	777358527	1527538650	68	36	10	28
RARO-NIUE	7	-353790872	999362940	220243972	1082774988	32	23	13	24
RARO-NTPT	6	-514861673	1387865174	551113161	1579549936	41	33	14	31
RARO-VITI	7	-490390804	2330739395	370557563	2410423650	39	33	16	29
RARO-VANU	7	-535964068	2116965654	499487977	2240153857	45	35	18	32
RARO-LLAU	4	-477065334	1925166085	314060279	2008105985	44	55	22	50
RARO-SNTO	7	-413402133	3416172775	604089016	3493717403	24	41	26	38
VAVA-TGPU	7	82131616	145370142	-262833832	311383531	17	13	15	9
VAVA-WSAM	6	-121982427	-228419548	511674616	573468495	38	26	15	17
VAVA-NIUE	7	75484737	-422875113	-45439940	431956126	37	21	13	21
VAVA-NTPT	6	-85586064	-34372880	285429249	299960540	31	15	14	6
VAVA-VITI	7	-61115195	908501341	104873652	916574185	49	40	16	38
VAVA-VANU	7	-106688459	694727601	233804065	740738286	39	42	18	36
VAVA-LLAU	4	-47789725	502928032	48376367	507504420	41	48	15	46
VAVA-SNTO	7	15873476	1993934722	338405104	2022509742	68	42	31	37
TGPU-WSAM	6	-204114043	-373789689	774508447	883880427	35	19	21	24
TGPU-NIUE	7	-6646880	-568245255	217393892	608446345	28	18	12	16
TGPU-NTPT	6	-167717680	-179743021	548263081	600857038	32	13	21	12
TGPU-VITI	7	-143246812	763131200	367707483	859126108	43	29	26	19
TGPU-VANU	7	-188820076	549357459	496637897	764261630	34	31	29	15
TGPU-LLAU	4	-129921341	357557890	311210199	491506854	35	38	26	15
TGPU-SNTO	6	-66258141	1848564581	601238936	1945011416	68	34	43	22
WSAM-NIUE	6	197467164	-194455566	-557114555	622240207	47	32	13	15
WSAM-NTPT	6	36396363	194046668	-226245366	300276157	40	23	8	16
WSAM-VITI	6	60867232	1136920889	-406800964	1209041336	51	35	15	37
WSAM-VANU	6	15293967	923147148	-277870550	964181832	42	35	16	37
WSAM-LLAU	4	74192702	731347579	-463298248	868918354	41	57	25	57
WSAM-SNTO	6	137855902	2222354270	-173269511	2233357355	75	20	22	22
NIUE-NTPT	6	-161070801	388502234	330869189	535118873	32	21	15	17
NIUE-VITI	7	-136599932	1331376454	150313591	1346780227	35	38	19	36
NIUE-VANU	7	-182173196	1117602714	279244005	1166276174	33	44	21	40
NIUE-LLAU	4	-123274462	925803145	93816307	938674361	46	61	23	58
NIUE-SNTO	7	-59611261	2416809835	383845044	2447827669	47	45	33	40
NIUA-VITI	6	24470869	942874221	-180555598	960318147	39	38	18	39
NIUE-VANU	6	-21102396	729100480	-51625184	731230457	36	39	19	40
NIUA-LLAU	4	37796339	537300911	-237052882	588485260	39	70	28	73
NTPT-SNTO	6	101459539	2028307602	52975855	2031534446	51	34	22	32
VITI-VANU	7	-45573264	-213773740	128930414	253769947	16	20	4	19
VITI-LLAU	4	13325470	-405573310	-56497284	409706262	23	23	8	23
VITI-SNTO	7	76988671	1085433381	233531453	1112937473	46	23	21	18
VANU-LLAU	3	58898735	-191799569	-185427698	273202428	20	11	10	8
VANU-SNTO	7	122561935	1299207121	104601039	1309160781	50	29	20	24
LLAU-SNTO	4	63663201	1491006690	290028737	1520286362	39	21	24	22

RARO-Rarotonga
VAVA-Vava'u
WSAM-W. Samoa
TGPU-Tongatapu
NIUE-Niue
NTPT-Niuatoputaopu
VITI-Viti Levu
VANU-Vanua Levu
LLAU-Lakeba
SNTO-Espiritu Santo

Notes:
#denotes the number of daily solutions
For the site combination A-B, the position vector is from A to B
No solutions have been edited

TABLE 10.

OTHER BASELINES:
Nominal Solution (millimeters)

Vector	#	x	y	z	L	RMS Scatter of Daily Solutions x	y	z	L
SANT-CAPE	2	15844527	44484489	-19372156	51041152	6	4	7	8
SANT-TASM	3	11927696	30353386	-17150435	36847461	17	2	8	1
SANT-RATA	1	7232244	10920081	-16428550	21010730	-	-	-	-
VTIL-WALL	4	-121826720	-690307785	467472314	842553827	10	45	4	37
HOBA-TIDB *	3	-510803860	159997702	636962156	832009998	28	61	31	8
HOBA-WELL *	6	-830464717	-2085857511	126148175	2248641049	18	47	21	42

SANT-Espiritu Santo
RATA-Santo/Ratard
HOBA-Hobart
TASL-Santo/Tasmalum
VTIL-Viti Levu
TIDB-Tidbinbilla
CAPE-Santo/Cape Lisburn
WALL-Wallis
WELL-Wellington

* denotes one day was edited

Tidbinbilla and Wellington coordinates refer to ionospherically corrected phase center.

TABLE 11.
COMPARISONS WITH SLR/VLBI: NOMINAL SOLUTION (millimeters)

	x	y	z	L
Hobart (Minimac)- Orroral (Trimble)				
GPS	-496292525	155740235	615326703	805722187
SLR/VLBI	-496292535	155740115	615326759	805722213
Difference (xyz)	-10	-120	56	26
Difference (NEU)	15	108	-76	
Kokee Park(Trimble) - Huahine(Trimble)				
GPS	197932958	-903658877	-4212456398	4312837317
SLR/VLBI	197932987	-903658885	-4212456386	4312837309
Difference (xyz)	31	-8	12	-8
Difference (NEU)	5	22	-26	
Mojave(Minimac) - McDonald Obs.(Trimble w/TI antenna)				
GPS	1026207742	-681654943	-431953572	1305503611
SLR/VLBI	1026207732	-681655053	-431953490	1305503634
Difference (xyz)	-10	-110	82	23
Difference (NEU)	15	17	136	
Wettzell(Minimac) - Onsala(TI)				
GPS	-704892878	-219948514	548199086	919659478
SLR/VLBI	-704892814	-219948584	548199089	919659448
Difference (xyz)	64	-70	3	30
Difference (NEU)	-39	-81	29	

Note: Difference is formed as (SLR/VLBI) minus (GPS)
The SLR/VLBI vectors are consistent with Table 7

determinations suggests that the precision estimates are indicative of the accuracy.

6.2 Alternate Fiducial Network

The same data set used for the nominal solution was processed with an alternate selection of fixed fiducial sites. Four fixed sites were chosen for this experiment: Orroral, Mojave, Westford and Wettzell. The primary difference between the "alternate fiducial" and the nominal fiducial cases is the use of the SLR site at Orroral instead of the VLBI site at Hobart, two sites that are separated by 806 km. The reasons for conducting this experiment were twofold. First, the Orroral site was occupied in 1988 and the Hobart site was not yet installed. Second, there was concern that the 120 mm discrepancy between SLR and VLBI coordinates for Orroral (Table 5) could influence the SWP Network results at a comparable level. The other difference between the alternate fiducial and the nominal fiducial cases concerns Richmond, which was not fixed in the alternate fiducial case. This aspect of the alternate fiducial case was an attempt to mitigate the effect of Richmond on the solution, motivated primarily by the sparse amount of data available in 1988 from this site.

Using the coordinates given in Table 7 for the four sites chosen to be fixed, the results from the alternate fiducial case have similar characteristics to those from the nominal fiducial case. In particular, the repeatability parameters for a + b L are:

North: a = 5 mm, b = 4 ppb
East: a = 25 mm, b= 9 ppb
Up: a = 38 mm, b = 7 ppb
Length: a = 24 mm, b = 6 ppb.

Comparison of the baseline vectors between the nominal and the alternate fiducial solutions shows the following statistics (mean and standard deviation) for the 45 baselines: North (15±13 mm), East (13±10 mm), Up (16±12 mm), Length (-11±12 mm). Individual baselines differ between the two solutions at a level that is generally bounded by the repeatability of the nominal solution in Table 9. Some exceptions to this statement exist; namely, the z-component of the lines involving Rarotonga show differences that are a factor of two times greater than the nominal solution repeatability. However, the baseline length differences are significantly smaller than the nominal solution repeatability.

In summary, the results of the alternate fiducial case exhibit similar repeatability to the nominal fiducial case and the two cases differ by values approximately bounded by the daily scatter in both solutions. Consequently, the apparent discrepancy of the Australian fiducial stations has not influenced the SWP Network results at a comparable magnitude.

6.3 Perturbed Fiducial Network

In both the nominal fiducial and the alternate fiducial cases, Mojave, Westford and Wettzell were fixed at the same values. As noted in Table 5, the overall agreement between SLR and VLBI in a common reference frame is at the level of 30 mm. This difference could be caused by a variety of error sources, even though the internal consistency of the respective techniques is better than 30 mm. Since all of the three fixed sites could be in error, an experiment was conducted to evaluate the propagation of possible errors into the SWP Network. Assuming the 30 mm difference between SLR and VLBI is indicative of the level of error in the fixed sites, perturbations to the fixed coordinates were generated using a Gaussian distribution with 30 mm standard deviation. The resulting perturbations that were added to the respective five nominal fiducial stations are given in Table 12. With the set of perturbed coordinates, the same data set used for the nominal solution was reprocessed.

The repeatability of the 45 baselines in the SWP Network were essentially identical to the nominal fiducial case. When the two sets of vector baselines are compared, the mean and standard errors are subcentimeter for all components, with the largest standard error in the vertical (7 mm). The longer baseline lengths changed by a maximum of 11 mm (Rarotonga/W. Samoa), and the overall length statistics for mean and standard error are -4 mm and 5 mm, respectively. Examination of individual differences between the perturbed fiducial solution and the nominal solution shows differences between the two solutions that are bounded by the nominal solution repeatability in Table 9.

In summary, the experiment with a perturbed set of fixed fiducial stations agrees with the nominal fiducial solution within the daily repeatability or scatter, assuming a 30 mm standard deviation for the perturbation in the experiment. While this is only one case from a very large possible sample, the random nature of the introduced perturbations and the expectation that the introduced perturbation is indicative of the actual errors, the result provides additional support that the daily repeatability of the nominal solution is a measure of the solution precision

TABLE 12.

PERTURBATIONS TO FIDUCIAL COORDINATES:

PERTURBED FIDUCIAL CASE (millimeters)

STATION	x	y	z
Hobart	-28	-10	57
Mojave	-35	28	-64
Westford	-12	21	-51
Richmond	-10	-24	6
Wettzell	43	17	-42

6.4 Reduced Arc Length

It is widely acknowledged that data intervals of short duration, referred to as short arcs, are influenced at a smaller level by model errors, especially force models. While this expectation contains some merit, it also contains some difficulties since an arc length that is too short may not allow adequate separation of some dynamical parameters. With these considerations, a series of arcs with a shorter duration than the nominal solution were computed. These arcs included durations of two, three and four days, with the two-day and three-day cases conducted with the first three days of Week 549 and the four day arc performed using the last four days of the week. Since small differences were observed between the two and three day arcs, only the results from the three day arc are given here.

The results from a three-day arc computed with the first three days of Week 549 and a four-day arc computed with the last four days of Week 549 were combined into a single baseline solution. For these arcs, a single y-bias parameter for each satellite was estimated in each of the arcs. Although two y-bias parameters for each satellite were estimated in the nominal solution, the fundamental difference is that the reduced arc length solutions allow for independent orbits between the three and four day arcs, whereas the nominal solution was a single, continuous arc for seven days.

The combined solution, based on the combination of the three and four day arcs, differs from the nominal solution by the following statistics (mean and standard deviation) computed from the 45 baselines vectors shown in Table 9: North (4±3mm), East (6±5 mm), Up (17±12 mm) and Length (5± 7 mm). These differences are within the precision estimates (repeatability) of the nominal solution. In addition, the repeatability of the combined three and four day solution is:

North: a = 4 mm, b = 3 ppb
East: a = 18 mm, b = 5 ppb
Up: a = 32 mm, b = 5 ppb
Length: a = 19 mm, b = 2 ppb

Comparison of individual vector baseline differences with the nominal solution shows that all are bounded by the repeatability given in Table 9, with the exception of the Viti Levu/Lakeba baseline in which the differences in the x- and z-components exceed the repeatability by a factor of two.

In summary, a solution based on the combination of results from a three-day and a four-day arc, with an overlap between the two arcs, exhibits slightly better repeatability than the nominal solution which was based on a single, continuous seven-day arc. Nevertheless, the differences between the baseline vectors computed from the reduced arc length and those from the nominal solution (Table 9), are generally within the precision estimate (repeatability) of both solutions. This result also suggests that the repeatability of the case selected to represent the "nominal solution" may be a conservative estimate of precision. It should also be noted that a global fiducial network was used in the solution, rather than the commonly used fiducial network at the periphery of the field network. The use of a global fiducial network was motivated by the long baselines in the field network (approximately 1500 km) and the expectation that long-wavelength orbit errors should be controlled for such baselines. As a consequence of these considerations, it is expected that the orbit errors from a global network will be better controlled than the peripheral fiducial network.

6.5 Reduced Fiducial Network

As noted in Table 2, some network sites were observed in 1988 and 1989. Comparison of the baseline results from these sites (Rarotonga, Tongatapu, Vava'u and W. Samoa) between the respective years is expected to yield estimates of the relative motion. In both 1988 and 1989, the global fiducial network was significantly reduced in size from the 1990 network given in Table 4. In addition, only the four primary sites in the Southwest Pacific Network were observed. The 1990 data set offers the opportunity to evaluate the influence of the expanded global network as compared to a network of reduced size, thereby evaluating the robustness of the regional network solution. As a consequence, this experiment was conducted in an attempt to closely duplicate the 1988 tracking configuration using the 1990 data set and to compare the results with the nominal solution. However, no attempt was made to use a reduced satellite constellation, i.e., 1988 had only seven Block I satellites available, but 1990 had a total of 13 satellites.

For this experiment, the following global fiducial sites were chosen: Orroral, Mojave, Westford, Wettzell, Richmond and Onsala, with the first four sites fixed to the coordinates given in Table 7 and corresponding to the selected fixed sites in the alternate fiducial network case in this paper. Orroral was used in this experiment as a fixed site because it was the only Australian site available in 1988. The SWP Network sites were Rarotonga, Tongatapu, Vava'u and W. Samoa. The case produced approximately 137,000 double difference measurements which were fit using the same seven day strategy that was used for the nominal solution and the alternate fiducial solution. The RMS of the double difference residuals was 30 mm, slightly higher than the nominal solution. The reduced network solution, including the daily repeatability, is given in Table 13. The daily repeatabilities are:

North: a =6 mm, b = 3 ppb
East: a = 16 mm, b = 5 ppb
Up: a = 38 mm, b = 23 ppb
Length: 9 mm, b = 13 ppb.

Direct comparison of the (xyz) components between Table 9 and Table 13 show differences that are within the RMS scatter of the nominal solution, except for the z-component of the Rarotonga components. Furthermore, comparison of the reduced network case with the results from the alternate network case show differences that are bounded by the Table 9 RMS scatter in all components, a result that is presumably related to the fact that the fixed fiducial network is the same for both cases.

In summary, a solution based on a reduced fiducial and SWP networks produces results that differ from the nominal solution by values that are within the Table 9 RMS scatter. As in the alternate fiducial case, the exception is the z-component of the Rarotonga lines which exceeds the repeatability by a factor of two. The conclusions drawn in the alternate fiducial network case apply similarly to this case; furthermore, comparison of the reduced network case with the

TABLE 13.

REDUCED NETWORK SOLUTION (millimeters)

Baseline	#	x	y	z	L	RMS Scatter of Daily Solutions x	y	z	L
RARO-VAVA	7	-429275580	1422238067	265683944	1509180771	53	30	18	24
RARO-TGPU	7	-347143970	1567608210	2850116	1605587917	53	29	27	27
RARO-WSAM	6	-551257979	1193818513	777358565	1527538654	72	34	18	25
VAVA-TGPU	7	82131611	145370144	-262833828	311383527	25	21	18	10
VAVA-WSAM	6	-121982399	-228419544	511674621	573468496	47	31	14	11
TGPU-WSAM	6	-204114009	-373789697	774508449	883880424	45	10	20	18

RARO-Rarotonga   VAVA-Vava'u   WSAM-W. Samoa   TGPU-Tongatapu

Notes: # denotes the number of daily solutions
For the site combination A-B under "Baseline", the vector is from A to B
No solutions have been edited

alternate network case shows differences that are bounded by the daily RMS scatter in all components.

7. CONCLUSIONS

Several experiments were conducted with the 1990 Burst 1 data of the Southwest Pacific GPS Project to provide an assessment of the robustness of the solution, as well as the precision and accuracy of the geodetic results. Based on 45 possible baselines between 10 primary sites with Trimble receivers, with baselines ranging from 253 km to 3594 km, a nominal solution was presented in which the full set of global fiducial and project area data were processed in a simultaneous solution. The results show that the daily repeatability, defined as the RMS scatter of the daily solutions at each site of the 45 baselines, can be characterized by the commonly adopted linear function of the form a + b L, where L is the baseline length, with a=24 mm and b=6 ppb for the length. Similar values in the East component and smaller values in the North-component were obtained. Since no baselines within the SWP Network have been measured by other techniques, such as VLBI and SLR, a direct assessment of the accuracy of the 45 baseline estimates cannot be made. However, receivers were operated at other sites, both in the Pacific and elsewhere, that aid an assessment of the accuracy. Four baselines were compared with SLR and VLBI, all of which gave results that are consistent with the SWP Network horizontal repeatability, with the best agreement being achieved on the Kokee Park to Huahine baseline in the Central Pacific, adjacent to the SWP Network.

Other experiments that were conducted include an alternate selection of fixed fiducial sites, perturbing the fixed fiducial coordinates by an amount consistent with VLBI/SLR comparison statistics, using shorter arc lengths and using a reduced set of global fiducial and network data. The respective daily repeatability of each experiment was analyzed and each experiment was compared to the nominal solution. With a small number of exceptions, the differences between each experiment and the nominal solution were within the repeatability of the nominal solution, thus supporting the notion that the repeatability is a measure of precision. Furthermore, the comparisons with SLR and VLBI suggest that the accuracy of the solution is consistent with the estimate of precision.

With the numerical experiments performed to evaluate the sensitivity of the results to potential error sources, it has been found that the effect of these error sources is almost always smaller than the one-sigma scatter in the daily solutions. The observed level, however, is usually larger than the formal standard error, which is the result of remaining unmodeled effects. Such model errors produce systematic errors that are not accommodated in the estimation process. From the point of view of random errors based on the five or more individual daily solutions for each baseline, the one-sigma scatter interval exceeds the formal 95% confidence interval for random error. The one-sigma scatter level from the daily solutions was adopted as the nominal 95% confidence interval on total error, based on the analysis that the combination of both random and systematic errors in the baseline solutions will be bound by the one-sigma scatter about 95% of the time.

Comparison of the results in this paper with those obtained from the smaller campaigns conducted in 1988 and 1989, as well as future campaigns, will provide estimates of relative motions between Rarotonga on the Pacific Plate and sites in the vicinity of the Tonga Trench. Rarotonga is a key site for these comparisons with the earlier data, and measurements were presented in this paper to demonstrate that the local geodetic stability of Rarotonga over the period from 1988 to 1990 is at the centimeter level. Hence, local motions will not be a factor in the geophysical interpretation of the year-to-year comparisons.

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CSR Results from IGS and EPOCH-92

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This paper summarizes the participation of the University of Texas/Center for Space Research (UT/CSR) in the IGS campaign of June 21 to September 21, 1992. The models and parameters used in the regular operations during the IGS are documented. An adjustment to the reference frame and a new polar motion series were derived in a post-campaign analysis mode and preliminary investigations into orbit effects have been conducted. The IGS data and orbits were used to support network solutions during EPOCH-92.

OPERATIONS DURING IGS

The solution approach used explicit double difference ionospherically corrected phase measurements. One-day arcs were used throughout the campaign in which the GPS position and velocity vectors at 00:00 GPS time of each day were estimated, along with daily pole position, selected stations, GPS y-bias and scale parameter for ROCK4, 2.5 hour zenith delays for each station and double difference ambiguity parameters.

The reference frame used for operations during the campaign was based on the VLBI reference frame (GSFC GLB-718; Ma et al., 1991) translated, rotated and scaled into the SLR reference frame (UT/CSR 91 L 03; Eanes et al., 1991). The local ties between SLR, VLBI and GPS were taken from Boucher and Altamimi (1992). In the regular solutions, the following Rogue sites were held fixed: Algonquin, Goldstone, Fairbanks, Kauai, Hartebeestoek, Onsala, Pinyon, Wettzell and Yaragadee. The following Rogue sites were adjusted: Kootwijk, Kourou, Madrid, Mas Palomas, McMurdo, Ny Alesund, Santiago, St. Johns, Tahiti, Taiwan, Tidbinbilla, Usuda, and Yellowknife. The following codeless receivers were used regularly after Anti-Spoofing was activated on August 1: Hobart, Mojave, Townsville and Wellington. Solutions were performed for Day 173 (Week 650) through Day 259 (Week 662), except for some AS days. Solutions were performed on the following days when AS was activated: Days 214-216 and Day 221. The solutions generally used all Block-I and Block-II satellites; furthermore, PRN 26 was included for the first time in Week 659. Apparent thrusts or other anomalies occurred from time to time and these satellites were excluded from the solution on the day of occurrence.

The IERS Standards (McCarthy, 1992) were generally followed. UT1 was not estimated and the Lageos-SLR series was used in the GPS solutions. The software used was the TEXGAP set of programs.

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ADJUSTED REFERENCE FRAME AND POLAR MOTION

A 54-day subset from Weeks 650-662 was used to determine the site positions of all sites, except Wettzell, Kauai and Fairbanks, which were held fixed. In addition, daily GPS position and velocity vectors, force model y-bias and ROCK4 scale, x and y pole position, 2.5 hour zenith delay and ambiguity parameters were estimated. The resulting solution was reported by Watkins et al. in IGS Electronic Report No. 16. A comparison of ITRF91 to the resulting coordinates shows an RMS difference in the adjusted stations of 13 mm in x, 29 mm in y and 43 mm in z. After removing a bias in the x and y polar motion series, the weighted RMS of the new GPS series with respect to the Lageos-SLR series was 0.71 milliarcseconds in x and 0.59 milliarcseconds in y.
Experiments with estimating diurnal and semi-diurnal polar motion and dUT1 were performed using one day arcs. The resulting series for dUT1 shows good agreement with Lageos-derived series (results to be presented at Spring 1993 AGU by M. Watkins).

ORBIT ANALYSIS

Although one-day arcs were used for the operational activities, longer arcs were used to investigate the fidelity of the force and kinematic models. These longer arcs included a 7-day continuous orbital arc with estimation of sub-arc daily polar motion. With a 7-day arc spanning Week 651, each day contained 19-20 of the previously identified station set and contributed about 17,000 to 19,000 double difference measurements at a 2-min interval. For comparison with the 7-day arc, the operational one-day arcs produced double difference RMS values of approximately 12 mm to 18 mm.
Several 7-day arcs were studied, each of which used a different set of estimated parameters. Two cases are presented here:

Case 1) 7-day arc with 12-hr sub-arc parameters of ROCK4 scale and y-bias, daily sub-arc polar motion

Case 2) 7-day arc with empirical once per orbital revolution along track and cross track forces in which amplitude and phase were estimated as daily sub-arc parameters; daily sub-arc polar motion estimated

Approximately 5000 parameters were simultaneously estimated for each case. The double difference RMS of fit for Case 1 was 34 mm and the fit for Case 2 was 14 mm, approximately equivalent to the one-day arc fits. The higher RMS for Case 1 is one indicator of problems with the modeling, presumably errors in the nongravitational modeling are the major contributor. Evidence to support this presumption can be drawn from SLR analyses of the Etalon satellites which have an altitude similar to GPS (except they are not in deep resonance like GPS). The Etalon satellites are spherical with low area-to-mass ratios. The ability of the empirical models to absorb model errors is indicated by the RMS of Case 2.

EPOCH-92

The data and the orbits for Weeks 653-654 were used to support analyses of a Trimble SST network operated in the Southwest Pacific by M. Bevis et al. This network spans the Tonga

Trench and extends to the New Hebrides and includes baselines ranging in length from a few hundred kilometers to 3500 km. The daily repeatability in baseline length (L) for Days 196-203 (just prior to EPOCH-92), represented by a + b L, was a = 9.7 mm and b = 1.3 ppb. Preliminary solutions during EPOCH-92, which included several AS days, tended to produce higher noise in the double differences by a factor of two. These preliminary solutions suggest some degradation in the network solutions caused by AS effects on the global network, however, the analysis is incomplete and a definitive statement cannot yet be made.

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