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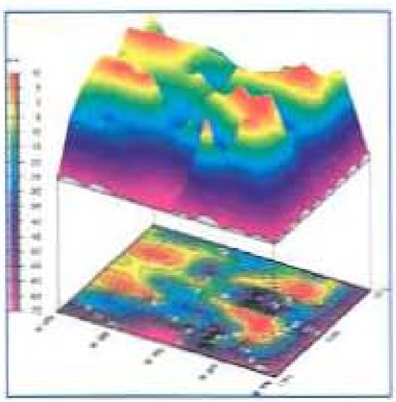

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Establishment of a GPS High Accuracy Reference Geodetic Network in the Caribbean

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ABSTRACT. A practical implementation of a new spatial reference frame throughout the Caribbean was recently completed by the National Geodetic Survey (NGS) of the National Oceanic and Atmospheric Administration (NOAA), using high-accuracy GPS methodology and techniques. The fundamental purpose of the campaign was to establish primary and secondary geodetic control at airports selected by the Federal Aviation Administration (FAA) to improve Area Navigation Approach (ANA) reliability. Eventually, this control can support local densification of geodetic networks to meet future requirements for charting, mapping, and modern geographic information systems (GIS) application. A project of this magnitude would not have been feasible without the cooperation of the International Civil Aviation Organization (ICAO) and several Caribbean-based surveying agencies. This paper addresses the procedures used to process and evaluate GPS observations and the nature of the different types of three-dimensional coordinate systems used in GPS.

Introduction

The National Geodetic Survey (NGS), in cooperation with the International Civil Aviation Organization (ICAO) and various Caribbean-based surveying agencies, conducted a GPS control survey at several Caribbean airports chosen by the Federal Aviation Administration (FAA). The main purpose of the campaign was to establish Primary and Secondary Airport Control Stations (PACS and SACS) and, ultimately, to position runway points in support of ICAO and FAA Area Navigation Approach (ANA) projects following NGS's standard survey procedures.

The GPS processing methodology used in this particular project was applied in two distinct phases. First, A-order stations were established at each airport to provide an accurate geocentric framework. These A-order sites are generally determined using more stringent requirements (FGCS 1989) than is the case for primary control stations (Leigh 1996) but, in the context of the project reported here, the characteristics of A-order and primary airport control stations will be considered similar and interchangeable. After the primary stations were in place, a more dense, localized survey was used to position secondary control stations and other relevant points (bench marks, runway points, etc.) at each individual airport using shorter interstation vectors. This paper will address only the establishment of primary airport control stations.

When GPS data are processed, the term "fiducial station" is loosely applied to describe continuously operating GPS sites whose data are electronically made available to the geodetic surveying community. Generally, the geocentric coordinates of these permanent stations are well known (to ±2 cm in the horizontal component and ±4 cm in height) with respect to a given pre-defined reference frame, and they are often used to propagate coordinates to other arbitrary points either directly or by a "leap-frog" sequence.

All the Caribbean PACS established at the first processing stage were positioned directly from continuously operating GPS receivers. However, as will be explained later, a GPS solution (solution B) was also completed using "hub" stations. A hub site is selected as a possible connecting point because it is occupied by receivers which collect data at that particular site for a number of consecutive days/weeks during the duration of the project. The coordinates of the hub sites are not known in advance and are determined from the fiducial stations during the processing stage. In this particular campaign, two stations—one at Grand Cayman Island (C304) and the other at Trinidad (TTPA)—were selected as hub stations. The Continuously Operating Reference Stations (CORS) MIAMI, in Florida, and ST. CROIX, in the U.S. Virgin Islands, were designated as fiducial stations. As described later, another site, KOUROU, belonging to the International GPS Service for

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Geodynamics (IGS) network (Neilan 1996) was also used as a fiducial station during the analysis of results. The selection of these fiducials was based on availability and geographic proximity to the Caribbean primary airport control stations. Finally, from the newly determined primary control stations, local geocentric geodetic control was subsequently extended to support the high-accuracy ANA surveys of airport features and nearby runway approach obstructions (see pertinent definitions in FAA 1996).

Besides the immediate technological transfer and know-how provided by NGS to local survey authorities, this international cooperative project has established the basis for future surveys related to mapping, charting, navigation, hydrography and, possibly, support scientific studies such as investigating sea-level variations, modeling the geoid, and analyzing deformations of the Caribbean tectonic plate.

Terrestrial Coordinate Systems

Users familiar with GPS technology and methods are aware that the three-dimensional coordinate system to which all reduced vector components refer is determined by the inherent characteristics of the satellite ephemerides employed while processing the observations. In most cases (except when applying orbital relaxation methods), the position of the satellites in their orbits is assumed "true" and fixed (internally) by the reduction software. This technique automatically designates the ephemeris frame as the three-dimensional Cartesian frame in which all resulting coordinates and vector components will be expressed.

A clarification, though, is in order. Because in most GPS geodetic applications a relative (differential) positioning method is used, it is imperative to start with known coordinates of at least one reference (base) station. The positional accuracy extracted from such a relative technique degrades as the distance between the base and "remote" stations increases. Independent of the source of the initial coordinates employed to hold fixed the base station (e.g., NAD 83, ITRF94, etc.), the frame to which the final vector components will be referred is not altered. Invariably, this is the Cartesian reference frame implicit in the ephemeris used to fix the satellite positions.

Fortunately, the differences in orientation and scale between an ephemeris-defined coordinate frame and frames based on modern continental datums (e.g., NAD 83 and EUREF89) are not significant. The more important non-geocentricity of the datum itself plays a minimal role when only dealing with vector components due, in part, to the relative nature of the problem, i.e.,

$$\text{components of vector } \overrightarrow{AB} = \text{coordinates of point B (computed) - coordinates of point A (fixed).}$$

Thus, errors due to geocentric inaccuracies of point A will not affect the vector components between A and B. The coordinates of newly determined "remote" stations (points B, C, etc.) will be propagated on the datum's reference frame (e.g., NAD 83) if GPS vector components (not necessarily on the NAD 83, but close to it) are added to the assumed datum coordinates of point A. This is commonly implemented during the final stages of the network adjustment process. However, mixing datum and precise ephemeris frames is not encouraged when processing GPS data that are expected to have the highest achievable accuracy. Eventually, there may be detectable differences in frame orientation and scale which, although small, may affect the components of long (> 150 km) interstation vectors.

In summary, whenever the GPS differential method is applied, two independent sets of quantities are fixed in a typical processing session:

1) the coordinates of one or more base stations; and

2) the coordinates of the satellites as given by their ephemeris.

If these two groups of required *a priori* values are not referenced to the same coordinate system, errors are introduced into the reduction process. This is so because GPS observables are invariant physical quantities which cannot be changed or modified (only weighted) during processing. However, if the coordinates of the fixed base station(s) and the ephemeris of the satellites refer to different coordinate systems, in essence, the program tries to fit the observations between these fixed points (reference station(s) and satellites positions) the best it can, ignoring that they are defined by sets of coordinates expressed in unrelated coordinate frames. The program always assumes that the coordinates of the base station are in the precise ephemeris frame, which sometimes is incorrect. Theoretically, this could introduce undesirable biases into the observation model, thus affecting the final values of the vector components. This anomalous situation should be avoided when rigorous geodetic results are sought.

In order to produce accurate vectors, the quantities to be fixed, namely, the coordinates of the base station(s) and the ephemeris of the satellites should refer to identical coordinate systems. Should this precaution not be taken the size of the errors introduced would be difficult to predict, ultimately depending on such variables as the magnitude of a 7-parameter transformation between frames, length of the vectors, number of GPS sessions sequentially connected, and type of orbit used (see, e.g., Beutler et al. 1988).

The main point to be emphasized is the obvious one: accurate reduction of vectors can only be accomplished if consistency in all pertinent coordinate systems is enforced. In today's GPS environment, this requirement should be easy to fulfill by the practitioner. With the recent establishment of NGS' CORS network (e.g., Strange 1995), mixing of coordinate frames during GPS processing can be completely avoided.

To the authors' best knowledge, satellite ephemerides are not available anywhere with respect to coordinate frames defined by continental datums, e.g., NAD 83, EUREF89, etc. Yet, to obtain the most accurate results, the base station coordinates used to process GPS surveys should be known in one of the various geocentric coordinate systems employed to disseminate GPS satellite ephemerides. The two immediate choices, in order of preference, that come to mind are precise and broadcast ephemerides.

Broadcast ephemerides are not recommended for geodetic work. However, they are the only ones available on a real-time basis and, consequently, the only possible alternative for any kind of instantaneous navigation using pseudo-ranges and point positioning methods. One of the drawbacks of using broadcast ephemeris is the user's difficulty in estimating its real accuracy, which is needed to assess the overall quality of the more stringent geodetic activities. The primary reason for this is that broadcast ephemerides are predicted before the fact, which entails certain approximations not present in post-fitted precise ephemerides. Comparison of GPS broadcast ephemeris with precise orbital solutions shows discrepancies in the order of 1.3 m, 3.6 m, and 4.7 m along the radial, cross-track, and along-track components, respectively (Zumberge and Bertiger 1996).

The Keplerian elements of the broadcast ephemeris currently available through the navigation message are given since January 29, 1997, in the so-called WGS84 (G873), epoch 1997.0, coordinate frame. This is the latest realization of a series of WGS84 frames implemented by the Defense Mapping Agency (DMA), recently reorganized into the National Imagery and Mapping Agency (NIMA). The WGS84 (G873) frame replaces WGS84 (G730) (Malys and Slater 1994). The letter "G" in G873 stands for "GPS," indicating that archived Doppler data were excluded from the analysis; the "873" indicates the GPS week number (0^h UTC, September 29, 1996) of the starting date when the coordinate frame was implemented in the precise ephemeris (Malys et al. 1997a). Consequently, when broadcast ephemeris are now employed, the components of all the vectors that are determined through the reduction process refer to WGS84 (G873), thereafter simply called WGS84.

Recently, NIMA started to distribute to the general public WGS84 post-fitted precise ephemeris in the standard satellite state vector format—the so-called SP3 format—at intervals of 15 minutes. Unquestionably, this is a step in the right direction to improve the quality of GPS results expressed on WGS84. Nevertheless, there still remains an important logistic problem: the unavailability in North America, or for that matter practically anywhere else, of WGS84 reference sites useful as fiducial stations for differential positioning and point-to-point coordinate propagation of geodetic networks.

Thus, although the coordinate frame WGS84 is accessible through broadcast/precise ephemerides, no access to continuously operating stations expressed on this reference frame is available from which to densify high-accuracy geodetic control. It also should be mentioned that the realization of this military-oriented coordinate frame is not monitored on a regular basis by any international GPS users group; consequently, its day-to-day changes are not publicized and remain unknown to the geodetic community at large. These inconveniences may change in the future, although the great utility of WGS84 essentially resides not in its accuracy, but in its real-time accessibility through the information provided in the broadcast navigation message.

In contrast, one advantage of relying on NGS precise ephemerides (instead of NIMA orbits) or equivalently, any other ephemerides under the auspices of the International GPS Service for Geodynamics (IGS), is the assurance of getting positioning results consistent with the well-known International Earth Rotation Service (IERS) Terrestrial Reference Frame (ITRF). The ITRF frame is a conventional frame created under international sponsorship in order to satisfy the accuracy requirements of various modern space techniques (Feissel and Gambis 1993).

The origin, coordinate axes orientation, and scale of the ITRF frames are implicitly defined by the coordinates adopted for the worldwide tracking sites (VLBI, SLR, DORIS, and GPS) involved in each IERS yearly global solution. Related to each ITRF frame is an associated velocity field (not known for the WGS84). For instance, each station has a velocity vector indicating its time-dependent absolute displacement associated with plate tectonics and other types of crustal motion. These secular displacements can be approximated anywhere on the earth's crust by geophysical "no net rotation" models such as NNR NUVEL1A (McCarthy 1996, p. 14).

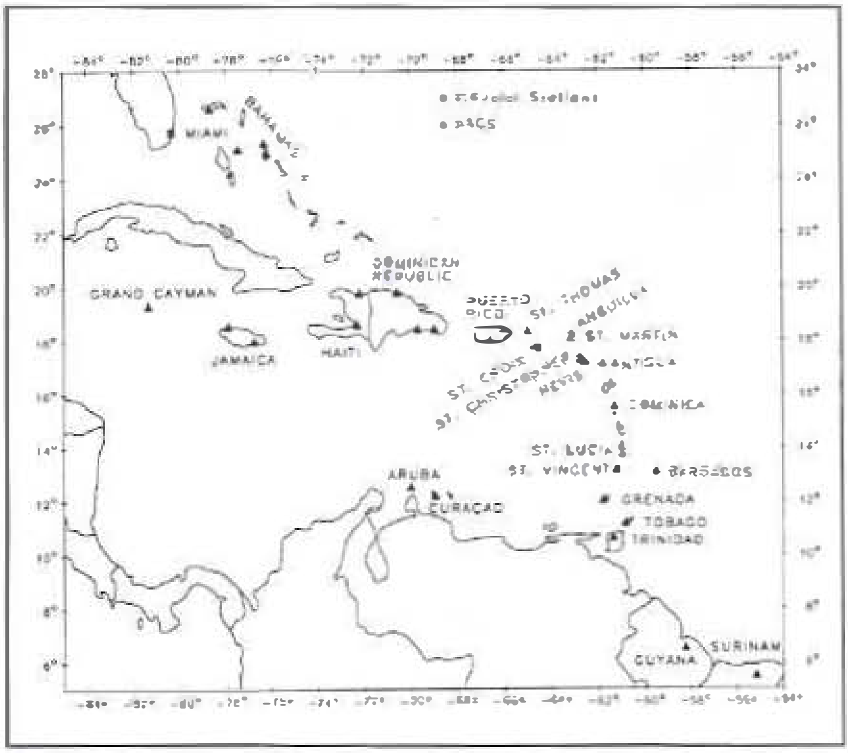

Figure 1. Geographic location of primary airport control stations positioned during the Caribbean campaign.

The National Geodetic Survey began releasing precise weekly ephemeris to the general public on a regular basis in July 1991 (GPS week 602). Daily orbit production began on February 26, 1992 (week 633). The quality of the NGS ephemeris has improved consistently over the years (Mader et al. 1995). The ephemerides from NGS have always referred to frames of the ITRF family, adopting the year of the latest IERS published solution and epoch. These dates change periodically to take advantage of newer observations and refinements to the software. The National Geodetic Survey disseminates precise GPS satellite ephemerides as well as CORS antenna positions and velocities for about 1120 stations in the U.S.

These data are consistent with the currently (August 1997) published IERS solution ITRF94 (IERS 1995); the chosen epoch is 1996.0. This epoch denotes the date for which the estimated positions correspond. This reference date is used to update station coordinates at any other observation time by taking into account the station' velocities and correcting the site by the absolute displacements caused by plate tectonics. Through the combination of CORS GPS data, site information, and IGS or NGS precise ephemerides, any interested GPS researcher or practitioner can rigorously determine vector components between stations and, therefore, propagate coordinates referred to an accurately defined geocentric ITRF coordinate frame.

The relationship between the WGS84 (G873) and ITRF94 was given in Malys et al. (1997b). The shifts between these two frames reached a maximum of 1 dm, making either one of them equally suitable for mapping or GIS applications. Considering that the Caribbean and the North American plates move independently, and because satellite positions of the IGS and/or NGS precise orbits and fiducial stations are expressed in ITRF coordinates, ITRF was the frame of choice to process the Caribbean GPS data.

Data Collection and Processing

A total of 32 primary airport control stations were surveyed during the Caribbean campaign. Figure 1 depicts the approximate geographic locations of the stations positioned. Table 1 shows the name of the sites, their 4-character IDs, the 1996 day of year (doy) the observations were taken, the receiver manufacturer (TR=Trimble), and the antenna model used. All GPS primary control station data were processed at NGS headquarters in Silver Spring, Maryland, using the PAGE4 program (Schenewerk 1993) which runs on UNIX-type HP9000/700 series workstations.

The PAGE4 program is a new-generation program used to process GPS RINEX data in the static mode. It replaces OMNI, the original NGS vector processor software (Hilla and Schenewerk 1992). Among the improvements incorporated in the PAGE4 software are:

- Generation of an optimal satellite reference scenario;
- Better ability to detect cycle slips;
- Better outlier detection and automatic removal routines; and
- Application of antenna/elevation-dependent phase corrections —a must when an observing session involves stations having different types of antennas.

When compared to OMNI, the main advantages of PAGE4 are the ability to solve tropospheric biases for several intervals of time (instead of one bias per

Geographic Location	Station Name	4-Char. ID	Observing Sessions (doy, 1996)	Antenna Model
Anguilla	TQPF A: Waublake Airport	QPFA	108,109,110	TR#9-22020-00
Antigua	TAPA A: V.C. Bird Airport	TAPA	113,114,115,116	TR#9-22020-00
Aruba	TNCA A: Reina Beatrix Airport	TNCA	103, 104, 106	TR#10-14532-00
Bahamas	MYEM B: Governors Harbour Airport	MYEB	099,100,101*	TR#9-22020-00
	MYER A: Rock Sound Int'l Airport	MYER	099,100,101	TR#9-22020-00
	MYGF A: Freeport Int'l Airport	MYGA	099,100,101	TR#9-22020-00
	MYNN A: New Providence Island	YNNA	099,100,101	TR#9-22020-00
Barbados	TBPB A: Grantly Adams Int'l Airport	TBPA	117,118,120	TR#9-22020-00
Curacao	TNCC A: Hato International Airport	NCCA	103,104,106	TR#9-22020-00
Dominica	TDPD A: Melville Hass Airport	DPDA	113*,114,115	TR#10-14532-00
Dominican Republic	MDPP A: Puerto Plata Int'l Airport MDSD A: De las Américas Int'l Airport	MDPA MDSA	113,114,115 113,104,106*	TR#9-22020-00 TR#9-22020-00
	MDLR A: Punta de Águila La Romana	MDLA	108,109,110	TR#9-22020-00
Grand Cayman	C 304: Owen Roberts Int'l Airport	C304	099 through101,106,108,109	TR#10-14532-00
Grenada	TGPY A: Point Salines Int'l Airport	TGPA	117,118,120	TR#10-14532-00
Guyana	SYTM A: Timehri Airport	YTMA	117,118,120*	TR#9-22020-00
Haiti	MTPP A: Port-Au-Prince Int'l Airport	TPPA	103*,104,106	TR#10-14532-00
	MTCH A: Cap-Haitien Int'l Airport	TCHA	108,109,110	TR#10-14532-00
Jamaica	MKJP A: Norman Manley Int'l Airport	KJPA	099,100,101,102	TR#9-22020-00
	MKJS A: Sangster Int'l Airport	KJSA	102,103,104,106*	TR#9-22020-00
Nevis	TKPN B: Newcastle Airport	TKNB	113,114,115	TR#10-14532-00
Puerto Rico	PSE E: Mercedita Int'l Airport	PSEE	115,116	TR#9-22020-00
	ZSU A: San Juan, Puerto Rico Cerap	ZSUA	113,114*,115,116, 117*,118,120	TR#10-14532-00
St. Christopher	TKPK A: Robert L. Bradshaw Int'l Airport	TKPA	108,109,110	TR#10-14532-00
St. Lucia	TLPC A: Vigie Airport	LPCA	113,114,116,118	TR#9- 22020-00
	TLPL S: Hewanorra Airport	LPLA	115,116,117	TR#9-22020-00
St. Martin	TNCM A: Princess Juliana Int'l Airport	NCMA	108,109,110*	TR#9-22020-00
St. Thomas	STT E: Cyril E. King Airport	STTE	108,109	TR#10-14532-00
St. Vincent	TVSV A: Et Joshua Airport	VSVA	113,114*,115	TR#9-22020-00
Surinam	ZANDERIJ CBL P4: Johan A. Pengal Airport	ZBP4	117,118,120	TR#9-22020-00
Tobago	TTCP B: Crown Point Int'l Airport	TTCB	117,118,120	TR#9-22020-00
Trinidad	TTPP A: Piarco Airport	TTPA	103*,104*,106*,113,114*,115,	TR#9-22020-00
			117*,118,120	
*Rejected observations.				

Table 1. Stations participating in the Caribbean project.

session as OMNI currently does) and to fix more than one station simultaneously, as well as allocate hub stations to propagate vectors. New consolidated advantages of PAGE4 are: improved mathematical models for the observables, flexible strategies for estimating unknowns and, if desired, the possibility of performing hands-off (batch) processing of sessions involving several days/weeks of data.

GPS data were collected during a 6^h observation window (approximately: 17^h UTC to 23^h UTC). All 25 operational satellites in the GPS constellation at the time of processing were used in the reductions of each individual day-session. At any given time, a minimum of four and a maximum of seven satellites were simultaneously visible above the horizon. Although raw data were collected at 15-second intervals, the selected sampling rate to reduce the observations of this project was set at 30 seconds, a restriction imposed by the data collection interval at the fiducial stations. A minimum elevation angle of 20° was chosen as the cut-off angle for all carrier phase observables during the processing stage.

At the time the GPS observations were collected (April 1996), NGS' precise ephemerides were expressed in ITRF93, epoch 1995.0 (abbreviated for simplicity ITRF93-95). This implies that all components of the vectors originally processed in the GPS Caribbean project "nominally" refer to ITRF93. The reference frame for disseminating IGS and NGS precise ephemerides was changed to ITRF94, epoch 1996.0 (ITRF94-96) on June 30, 1996, GPS week 860. Since 0h UTC March 1, 1998, IGS and NGS precise ephemerides are referred to as the ITRF96, epoch 1997.0 frame (ITRF96-97).

The adopted coordinates for the fiducial stations used in the reductions described herein are consistent with the frame of the precise satellite ephemeris employed. At the time of processing, these coordinates were known on the ITRF93-95 frame. However, because observations were collected on April 1996, before the processing of GPS observations was begun, PAGE4 applies the ITRF velocity field to update the coordinates of the fiducial stations (available at epoch 1995.0) to the average epoch of each individual observing session. As a result of this precaution, the components of all determined vectors are, in a sense, "instantaneous" and refer to ITRF93 (the ephemeris frame) and a variable epoch which is determined by the time at which the observations were actually taken (e.g., April = 9 day-of-year 100 = epoch 1996.27, etc.). This ITRF frame and epoch identification tag become crucial in case the processed vectors are used for future scientific applications.

Only static, multi-station, relative GPS procedures between selected "base" and "remote" stations were implemented. When all non-automatically corrected data outliers and cycle slips, if any, on frequencies L1 and L2 were manually accounted for (relying on post-fitted residual plots for quality control), final solutions were determined using double-difference carrier phase measurements, and the ionosphere-free linear combination of the L1 and L2 model (Leick 1995, p. 306). A zenith tropospheric scale factor was estimated for every 3 hours. Considering the average length (830 km) of the vectors involved, no attempt was made to fix ambiguity biases.

At the time the Caribbean project was being observed, the IGS just started trial operations of station ST. CROIX in the U.S. Virgin Islands. However, accurate coordinates for this site in the ITRF frame were not yet computed and officially published. Because this station is centrally located in the Caribbean island arch (see Figure 1) and because NGS was planning to include it in its CORS network, station ST. CROIX was selected as a fiducial site in conjunction with MIAMI. To speed up the process as much as possible, the approximate (to a few centimeters) geocentric coordinates of ST. CROIX were initially determined using four other known fiducials (MIAMI and EGMONT KEY, Florida; KOUROU, French Guiana; and CHETUMAL, Mexico.)

With the values of the coordinates of ST. CROIX determined, processing was started using exclusively MIAMI and ST. CROIX (KOUROU was added later) as the selected fiducials in the Caribbean project. Since September 1996, new coordinates were computed for ST. CROIX, consistent with the CORS network, and posted on NGS' Web home page (http://www.ngs.noaa.gov). These new values for ST. CROIX were used to recompute the components of all observed vectors.

Antenna Height Measurements

One of the most important operations performed in the field during GPS surveys relates to determining the exact spatial relationship between antenna phase centers L1 and L2 and a designated physical point or reference mark. Proper time and concentration should always be devoted to achieve this important task. The situation is even more serious when crustal motion is being investigated and unknown systematic errors, introduced by careless setting of the antenna (centering and height measuring errors) could be incorrectly interpreted at the analysis stage as possible displacements caused by nonexistent geophysical phenomena.

For archival purposes, each GPS survey site must have a unique, well defined point to which to assign all processed vector components and/or coordinates. This "station reference point" (SRP) could be defined differently, depending on the particular properties and requirements of the tracking station, e.g., CORS (geodetic surveying applications), IGS (GPS precise orbit generation), NGS' ANA projects (FAA airport surveys), etc.

Another commonly used word in standard surveying practice is that of "monument," usually a brass disk at ground level. This term often alludes to the center of the physical disk attached to a metallic rod buried in concrete in the ground and used to permanently mark the location of the station. In classical geodesy and/or surveying, the SRP is traditionally the monument. This is a logical choice considering that it is the only remaining permanent marker once the observations are completed. The same restriction does not apply to continuously operating GPS receivers.

Most IGS stations have as the station reference point the so-called antenna reference point (ARP) which is located at the center of the bottom surface of the antenna. Emphasis should be placed on the differences between antenna and monument reference points. The former is a point on the antenna's body and will change if the antenna is replaced. In the case of ST. CROIX, and owing to unpredictable seasonal hurricane threats, a compromise exception was made prior to the processing of the Caribbean data. To have a future permanent physical point as origin for all vector components determined from this site, the monument ground mark was selected as SRP. This logic was followed for all other stations except MIAMI, where the L1 phase center was retained as the station reference point because of the absence of a physical mark to which coordinates could be rigorously assigned.

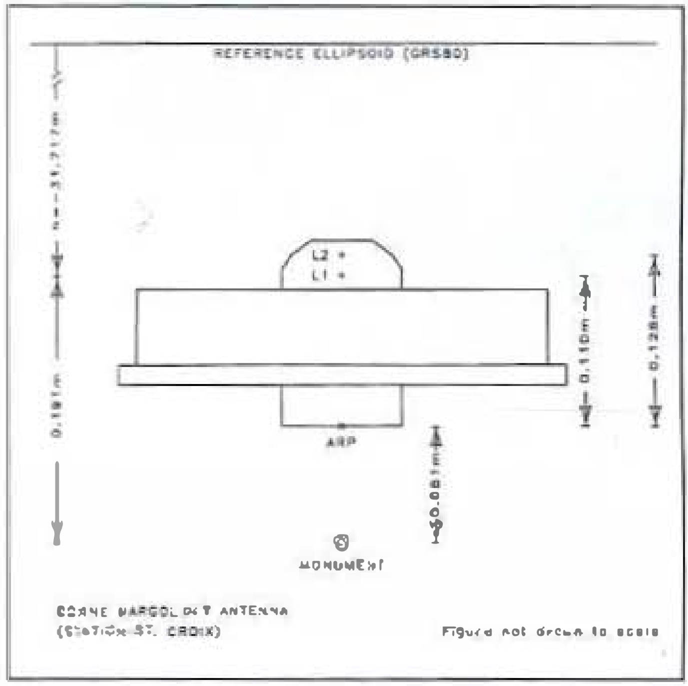

Figure 2. Antenna parameters at fiducial station ST. CROIX.

Figure 2 depicts the antenna type at ST. CROIX and the relationship of its various constants. With this information, if desired, transformations between L1 phase center, ARP, and monument could be easily accomplished. Notice one well known characteristic of Dorne Margolin T model antennas: the L2 phase center is above the L1 phase center. This sketch is also consistent with a negative value of the ellipsoid height h for all points located in the Caribbean basin. In this particular region, the surface of the geocentric GSR80 reference ellipsoid is not, as usual, below the station monument, but above it, thus $h<0$. Consequently, the value of the ellipsoid (geodetic) height as given in the CORS database for the L1 phase center of the antenna at ST. CROIX reduces to h = -31.908 m, if referred to the monument (see Figure 2).

One word of caution, mixing antenna types can lead to errors of up to 10 cm in height unless the antenna-phase-center variation is properly modeled (Meertens et al. 1996). The modeling of individual antenna phase patterns is imperative in any modern GPS vector-processing software which aims to obtain accurate results and should not be ignored.

Results

As previously described, for the Caribbean project, the coordinates of the fiducial stations and the resultant processed vector components refer to the same frame as the precise ephemeris available at the time the observations were taken, that is, ITRF93. For the analysis of results, several solutions were computed and compared (Table 2).

In solution A, PACS coordinates were determined as two independent solutions, with vectors radiating from MIAMI and ST. CROIX, respectively. Thus, no points are common to either network. This is schematically represented by two non-overlapping limiting blocks in Figures 4 through 7 which contain the stations processed from each fiducial.

In solution B, three fiducial stations were used (KOUROU was added). Two hubs, one in Grand Cayman and the other in

Solution	Fiducial Stations	Hubs	Type of Solution
A	MIAMI and ST. CROIX	None	Independent
B	MIAMI, ST.CROIX, and KOUROU	Grand Cayman and Trinidad	Simultaneous
C	MIAMI and ST.CROIX	None	Simultaneous
D	MIAMI and ST.CROIX	None	Made independent of results for C

Table 2. Processing strategies investigated.

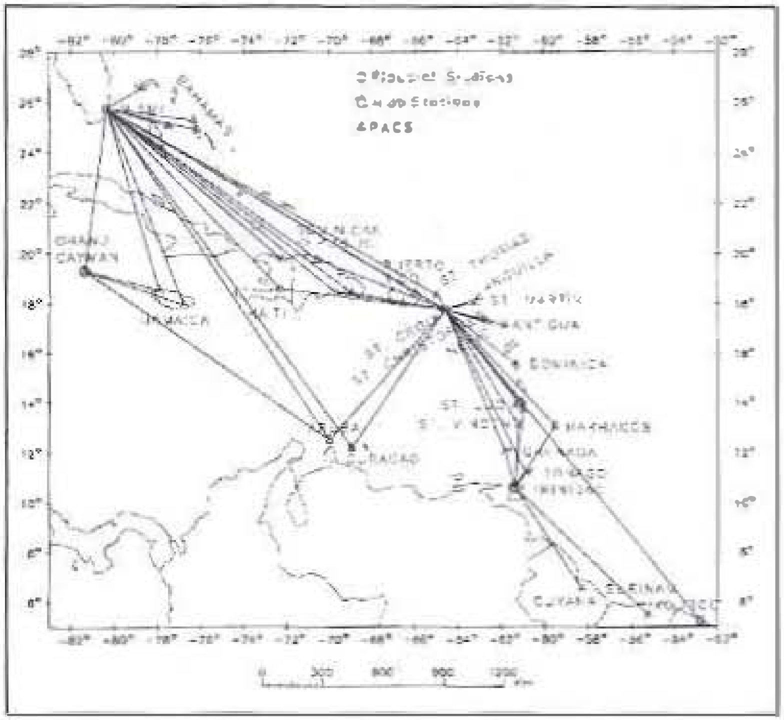

Figure 3. The network used in solution B, consisting of three fiducial stations (MIAMI, ST. CROIX, and KOUROU) and two "hub" stations (GRAND CAYMAN and TRINIDAD).

Trinidad, were introduced. When hubs are incorporated into any network design, the PAGE4 software determines the opti- mum combination of vectors connecting the hubs to other stations and internally selects them without further intervention. However, it is also possible to select an interactive processing technique where the operator can specify, *a priori*, the desired geometric arrangement of vectors between stations.

Figure 3 graphically depicts the set of vectors (i.e., baselines) selected automatically by PAGE4 in solution B which includes stations C304 (Grand Cayman) and TTPA (Trinidad) as hubs. As expected, some vectors are forced by the software to pass through the two selected hubs.

Solution C replaced the hub option in favor of a single simultaneous solution, holding fixed only MIAMI and ST. CROIX. Notice that this solution is not equivalent to solution A, because in solution A the two fiducial stations were not fixed simultaneously in a unique GPS network arrangement. In other words, the vectors connecting the two fiducial stations were not computed. Interfiducial vectors that are present in solutions B and C are all identical and strictly obtained from the values used to constrain the coordinates of MIAMI and ST. CROIX. Although PAGE4 could assign variable sigmas to the coordinates of the fiducial stations, this option was not implemented. Instead we followed the established practice of fixing fiducial points absolutely so as to guarantee a constant reference to which to compare future results.

Finally, a modification to solution C (referred here as solution D) was implemented. Solution D reuses all the vectors already determined in solution C, except that the vectors connecting the two fiducial stations are discarded. This alternative requires the modification of the standard NGS' G-File (Yeager 1994) produced by solution C, to ensure that the correlations between the remaining vector components are not corrupted by the deletion in each session of the interfiducial vectors. For each GPS session the G-File contains the three components of the non-trivial (independent) vectors, their standard errors, and the correlations between all components.

Coordinates for all primary airport control stations were determined by executing four three-dimensional least squares adjustments—constraining MIAMI and ST. CROIX—using as observations the components of all processed vectors obtained through solutions A, B, C, and D. The *a posteriori* standard deviations of unit weight for the four adjustments were 6.0, 11.9, 11.8, and 7.6. These moderately high values of an *a posteriori* standard deviation of unit weight reinforce the theory that statistics resulting from GPS reduction software are optimistic, thus they underestimate "true errors" affecting carrier phase observations caused by unmodeled effects.

The coordinates from the solution with a minimum *a posteriori* variance of unit weight were then compared against the other three solutions. Figures 4 and 5 depict horizontal (latitude and longitude) and vertical (ellipsoid height) differences between curvilinear geodetic coordinates resulting from solutions A and B. It can easily be seen that the displayed vector differences show excellent agreement in latitude. While the disagreement in longitude is larger than in latitude, the differences still remain within the requirements of this type of project. Recall that, e.g., an error of 3 cm for any point on the surface of the Earth is equivalent to a relative geocentric error of 4.7 ppb (parts per billion = 10^{-9}). This uncertainty is more than acceptable for most geodetic work and exceeds all types of mapping and/or GIS requirements.

However, Figure 4 also shows that the larger disagreements are somewhat peculiarly located. A closer scrutiny indicates that they correspond mostly to points determined from hub stations and/or points simultaneously determined from vectors originating at MIAMI and ST. CROIX. Solution C, which eliminates the possible propagation of errors through the hub alternative, improved the horizontal differences for Jamaica, Tobago, and Barbados, although due to space restrictions the figure depicting them is not reproduced here. However, this performance could be visualized by observing the coordinate differences between solutions A and D (D is a byproduct of C) which are represented in Figures 6 and 7.

By comparing Figures 4 and 5 with 6 and 7, several conclusions can be reached. One is that the inclusion of hub stations may not always be the best alternative, particularly when the quality of the observed raw data at the hub is suspicious. Undefined data errors at the hub point could be propagated to nearby connected stations. This problem is certainly more critical at hub sites than at fiducial stations because they are selected to run for relatively short periods of time, and unsuspected error sources (multipath effects, radio frequency interferences) are not known in advance. Once the data have been collected with errors, the glitches create noise which is almost impossible to correct during processing. Apparently, this was the case for station TTPA in Trinidad where, for yet unexplained reasons, five days of observation were rejected from a total of nine days, because of poor data quality.

The other obvious conclusion from the present investigation appears to be that the values used to fix the coordinates of the fiducial stations (MIAMI and ST. CROIX) do not seem to belong to a common conventional terrestrial frame. This hypothesis is supported by the higher than usual coordinate differences encountered at some of the stations simultaneously determined from the two fiducial stations. In this respect, note that MIAMI and ST. CROIX are located on two different plates—North America and the Caribbean, respectively.

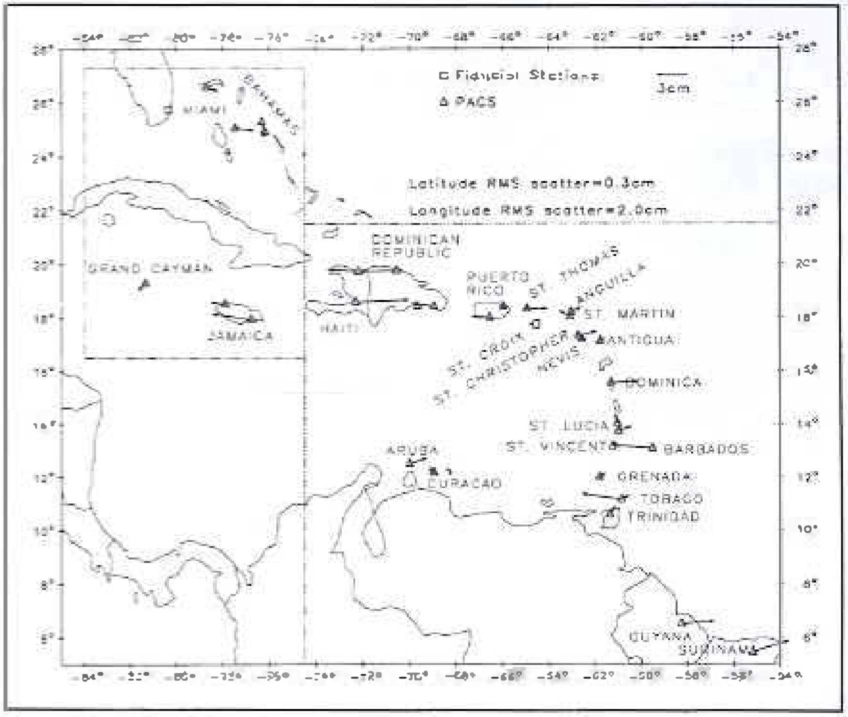

Figure 4. Horizontal differences (solution B minus solution A) when MIAMI and ST. CROIX are constrained in the network adjustment.

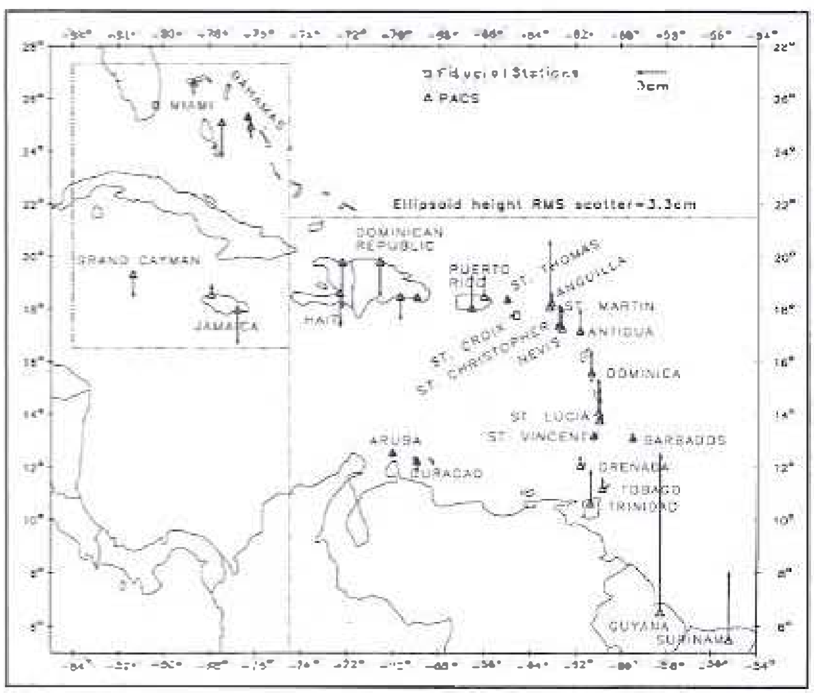

Figure 5. Ellipsoid height differences (solution B minus solution A) when MIAMI and ST. CROIX are constrained in the network adjustment.

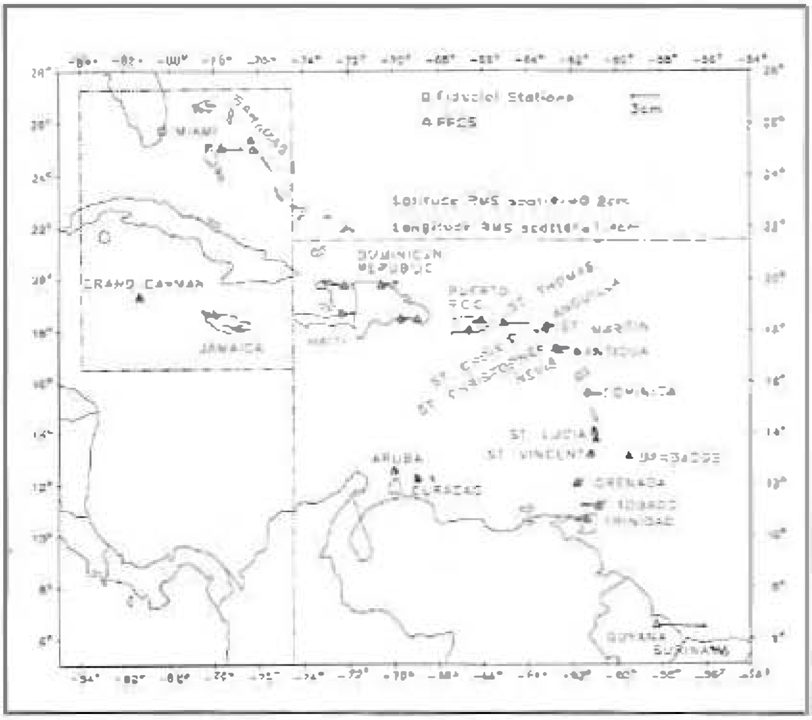

Figure 6. Horizontal differences (solution D minus solution A) when MIAMI and ST. CROIX are constrained in the network adjustment.

Furthermore, ST. CROIX is a relatively new station with a short history of collected GPS data. Consequently, small systematic errors of two types could be present. First, its geocentric coordinates may not as yet be very accurate and second, the plate rotation angular velocities applied to bring these coordinates to the epoch of observation are only poor approximations, based strictly on geophysical models.

These position uncertainties could explain the improvement in the detected differences when solutions A and D are contrasted (see Figures 6 and 7). Notice the overall RMS scatter improvement in longitude from 2.0 cm to 1.4 cm (see Figures 4 and 6) and, more significantly, in ellipsoidal height from 3.3 cm to 1.7 cm (see Figures 5 and 7). Notice that solutions A and D are independent and do not include direct vectors connecting MIAMI and ST. CROIX which, presumably, were determined from fiducial coordinates referred to two slightly different frames, as solutions B and C tend to prove.

It is estimated that, after a rigorous analysis is finished and the ties to the local points have been completed, the final primary and secondary airport control station coordinates uploaded into NGS' database would be geocentrically accurate to at least 2-3 cm in latitude and longitude and about twice that amount in ellipsoid height. One more indication of the quality of the results is presented in Figures 8 and 9 which depict all adjustment residuals from solution A projected on the planes of the geodetic horizon (east versus north) and prime vertical (east versus ellipsoid height = up).

Pertinent definitions and geocentric-to-local coordinate transformations are given in Soler and Hothem (1988). The GRS80 ellipsoid was used for these calculations. The plots in Figures 8 and 9s present each observation residual as obtained from the least squares network adjustment. Notice, for example, that no horizontal observation residual exceeds 2 cm and 5 cm in latitude and longitude, respectively. However, the RMS of the scatter of all residuals are only 0.47 cm and 1.94 cm. The large error in longitude arises from model errors related

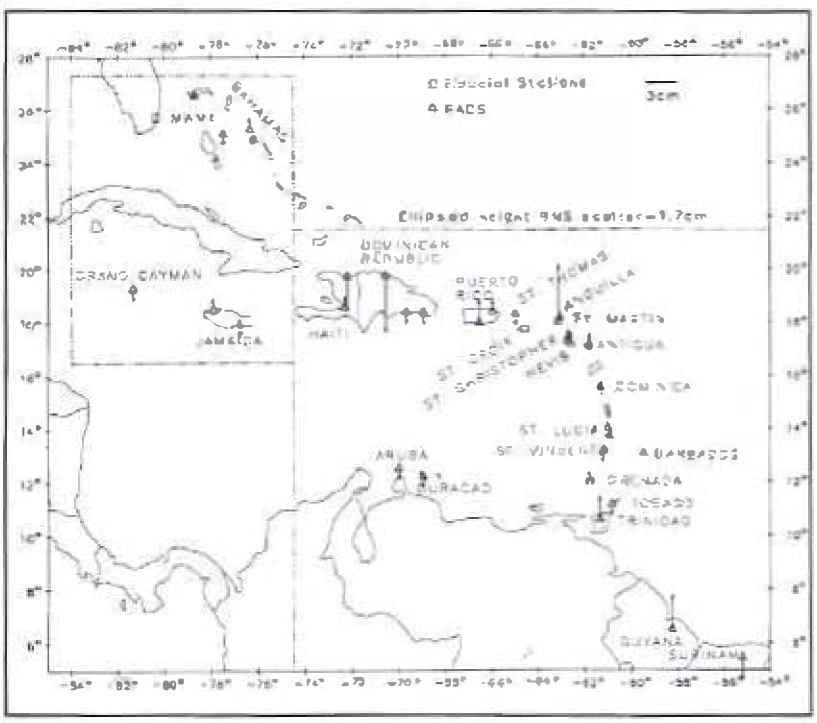

Figure 7. Ellipsoid height differences (solution D minus solution A) when MIAMI and ST. CROIX are constrained in the network adjustment.

to timing, which are reflected in longitude due to variations in the rotation of the earth and the peculiar GPS satellite ground-track coverage.

Vertical uncertainties are consistent with the difficulty in modeling the atmospheric refraction (ionosphere and troposphere). The magnitudes of the vertical and horizontal errors are not necessarily correlated, although a systematic degradation in the order latitude, longitude, and height is prevalent and has been known since the introduction of GPS in geodetic operations (see, e.g., Soler et al. 1991). Nevertheless, it is surprising that the magnitude of the RMS for the vertical component when contrasted with previous A-order projects was not larger. This may indicate a significant progress in the modeling of phase-center incompatibilities between antennas, which was an unknown problem a few yearsago.

The plotted residuals are practically invariant with respect to the choice of fixed station, but they are significantly influenced by the unmodeled errors intrinsic in the observations of each particular session. Thus, they reflect a better measure of dispersion for each observable than the formal errors generated by the GPS vector processing software. Large residuals are generally correlated with unmodeled conditions at the observation sites, e.g., high humidity, passing storm fronts, multipath effects, or ionospheric activity. Conceptually, they indicate how consistently each observation fits its average value which, presumably, represents the outcome of ideal standard observing conditions.

Another factor to consider when GPS networks are adjusted is that reduced GPS vector components (the observables) have implicit definition of scale and orientation. Consequently, only three degrees of freedom specifying the origin (i.e., three coordinates = one site position) remain to be defined to account for the required minimal set of geometric constraints. Thus, no information about the origin of the GPS network is known in advance and an accurate coordinate frame (the same to which the vector components are referred, e.g., ITRF93) should be used to fix a minimum of one station. Once coordinates are known in a rigorous geocentric coordinate frame, final transformations to other continental datums (e.g., NAD 83, EUREF89) could be implemented (Soler and Hall, 1995).

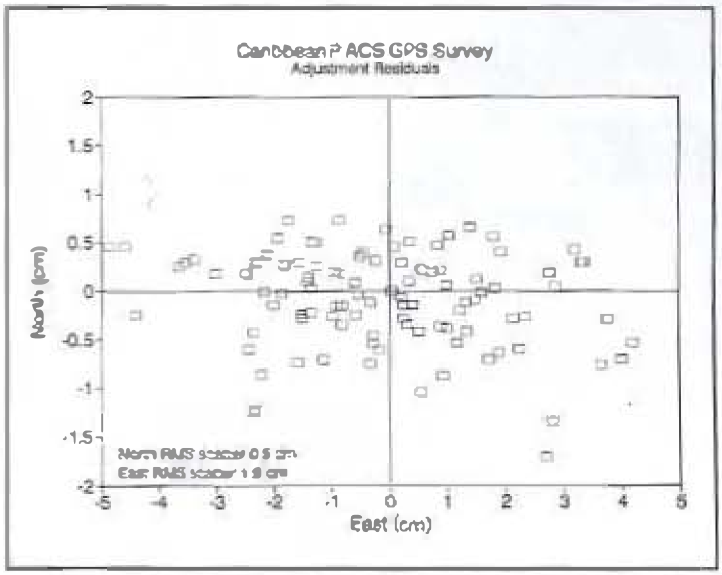

Figure 8. Adjustment residuals of solution A plotted on the geodetic horizont plane.

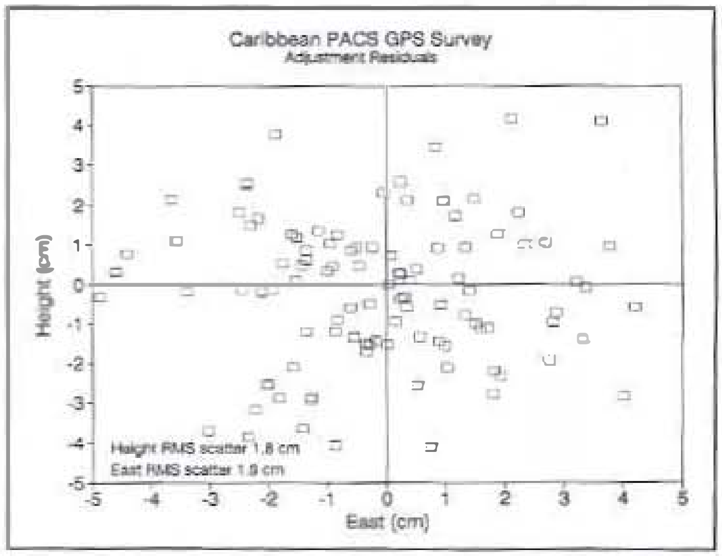

Figure 9. Adjustment residuals of solution A plotted on the prime vertical plane.

Conclusions

Considering the quality of the results obtained by employing advanced GPS technology and methods, NCS' objectives with respect to the Caribbean FAA project have been fully accomplished. The National Geodetic Survey has put in place an accurate set of primary airport control stations, which secures accurate geocentric positions for 32 airports. The degree of accuracy ensures that other future geodetic and cartographic operations in the region can meet the most stringent geodetic and mapping requirements. This is only the first step in the arduous task to follow. Now, individual Caribbean geodetic surveying agencies are left with the challenge of adding supplemental GPS points to densify their own geodetic networks. Only then can all activities related to geodesy, cadastre, cartography, and GIS in the region be expressed in an accurate, commonly defined spatial framework. Final coordinates for all stations involved in this project are available on request from NGS' Observation and Analysis Division.

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