GPS RESULTS FROM STATEWIDE HIGH PRECISION NETWORKS IN THE UNITED STATES

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ABSTRACT

The Global Positioning System (GPS) is being used at NOAA's National Geodetic Survey (NGS) to establish very precise geodetic networks with relative accuracies ranging between 0.1 ppm (A-order) and 1 ppm (B-order). The final quality of these GPS networks is investigated by analyzing their "internal" as well as "external" consistencies. The latter, or "absolute", accuracy is determined by connecting preselected (A-order) marks to known Cooperative International GPS Network (CIGNET) fiducial points whose coordinates are rigorously known in the International Earth Rotation Service (IERS) terrestrial reference frame ITRF 89. Double-difference observables collected from this A-order reference framework are reduced applying orbital improvement techniques based on precise ephemerides. Finally, comparisons of Cartesian coordinates between A-order points collocated with an independent set of VLBI antennas, give an estimate of the accuracy presently attainable with GPS procedures. This accuracy, in turn, is propagated to the statewide B-order networks through a constrained least squares adjustment fixing the common A- and B-order points to the A-order coordinates. Updated results, procedures, and the high levels of precision and accuracy of several regional and statewide networks are presented.

1. INTRODUCTION

A significant breakthrough in the fields of geodesy and surveying was accomplished with the introduction of the technology and methods of the Global Positioning System (GPS). The capability of determining three-dimensional coordinates at a level of accuracy not previously achievable, is revolutionizing research in many scientific disciplines, from geodynamics to oceanography. The National Geodetic Survey (NGS) recognized the implications and promise of GPS in its early stages of development and embarked on the promotion and adaptation of GPS methods to improve the National Geodetic Reference System (NGRS). By working cooperatively with state and other Federal agencies, NGS is in the process of establishing a nationwide GPS high-accuracy reference network (HARN) that will define the fundamental framework enhancing future geodetic work for years to come [Strange and Love, 1992]. Embedded into a primary A-order network of 0.1 parts per million (ppm) relative accuracy, is a secondary, denser, but less stringent B-order (1 ppm relative accuracy) cluster of points. Their main objective is to provide regional (statewide) reference control needed in a vast assortment of engineering and mapping projects (e.g., airport and highway construction, GIS/LIS, and photogrammetric surveys).

Coordinates of the primary A-order points are determined at NGS by exploiting the most advanced GPS methodologies. For example, permanent trackers of the Cooperative International GPS Network (CIGNET) [Chin, 1992] are used as fiducial stations. These points are rigorously known in a well-defined geocentric coordinate system, such as the International Earth Rotation Service (IERS) terrestrial reference frame of 1989 (ITRF 89) [Boucher and Altamimi, 1989]. Simultaneous observations are collected spanning a time window of about 6 hours to optimize the visible spatial satellite geometry and to overcome the effect of multipath. The GPS processing software invokes orbital relaxation methods where Keplerian elements for each satellite arc are introduced as parameters to be adjusted. As a result of these demanding procedures, relative accuracies between points on the order of 0.1 ppm can be realized. More specialized surveys (e.g., geodynamics, subsidence, etc.) can sometimes surpass this precision threshold reaching a maximum relative precision of 0.01 ppm [Geometric, 1989].

The three-dimensional location of the A-order stations represents the most accurate set of geocentric geodetic positions currently computed at NGS. Absolute accuracy of some of these points has been individually investigated by comparing their geocentric GPS coordinates to the known coordinates of very long baseline interferometry (VLBI) stations collocated with the GPS marks [Soler et al., 1992]. The worst disagreement was only 6 parts per billion (ppb). A 1 ppb "absolute accuracy" would be equivalent to determining an absolute position on the surface of the earth to approximately 6 mm.

2. RESULTS FROM A-ORDER NETWORKS

The establishment of a nationwide A-order framework was initiated as early as 1987 during a GPS campaign originally intended to define an accurate strain network covering the eastern half of the United States. Most of this network was resurveyed during 1990. Subsequent additions confined to specific states were incorporated in 1990 in Wisconsin and in 1991 in Maryland-Delaware. An expansion to the west started in 1989 with the Oregon survey and in 1990-91 with the Washington project, later followed by the Colorado, Montana-Idaho and California surveys [Hilla and Schenewerk, 1992]. A variety of state and local organizations were involved in the preparation and development of these projects. In particular, credit should be given to the Texas Department of Highway and Public Transportation, New Mexico Highway and Transportation Department, Wisconsin Department of Transportation, and Maryland Department of Transportation for their assistance in collecting pertinent field information and GPS data. This collaboration took on an international scope when Instituto Nacional de Estadística Geografía e Infomática (INEGI), the organization in charge of all geodetic work in Mexico, recently coparticipated with NGS in defining accurate A-order points in neighboring Mexico [Álvarez-García et al., 1992].

A combined least squares adjustment, using observations from all of the above processed campaigns, was recently performed at NGS. Furthermore, as a side investigation, the newly determined GPS coordinates were contrasted to known VLBI values and the results published elsewhere [Soler et al., 1992]. In this investigation, two independently collected, reduced, and adjusted GPS and VLBI sets of solutions were analyzed. There were a total of ten collocated stations (GPS and VLBI) whose coordinates were compared producing results nothing less than

TABLE 1. Coordinate differences de, dn, du, in a local geodetic coordinate system (east, north, up) given in the sense GPS - VLBI. After [Soler et al., 1992].

Location	Stat. ID	NGS No.	GPS Ant.	VLBI Type	de mm	dn mm	du mm	Total, ds mm	ds/R ppb	Stat. Tied	GPS Vectors	
											From	To
Austin (TX)	AUST	5966	TR	M	-11	33	2	35	5	1	0	3
Blomington (IN)	BLOO	1192	TI&TR	M	8	-3	4	9	1	10	23	2
Carrolton (GA)	CARR	9449	TI&TR	M	-1	0	0	1	0.3	18	52	1
Fort Davis (TX)	HAR4	8727	TI	F	-4	12	-3	13	2	14	40	0
Green Bank (WV)	T007	8440	TI&TR	F	13	6	-15	21	3	5	4	6
Leonard (OK)	LEON	9437	TI&TR	M	-15	4	17	23	4	12	26	3
Maryland Point (MD)	MDPT	5009	TI&TR	F	8	-8	-34	36	6	9	22	1
Miles City (MT)	MILE	9433	TI&TR	M	-1	14	5	15	2	2	0	6
Platteville (CO)	PLAT	6614	TI&TR	M	4	14	-3	15	2	12	18	4
Richmond (FL)	RICH	9721	MM	F	0	0	0	0	0	5	5	0

Notes: MM = Mini-Mac; TI = Texas Instruments; TR = Trimble; M = mobile; F = fixed; R = mean Earth's radius = 6371 km.

TABLE 2. Transformation parameters between NGS VLBI (10-01-90) and ITRF 89. After [Soler et al., 1992]

From	To	No. of Sta.	Number of Observations		RMS	Translations			Rotations			Scale
			Input	Used	mm	Δx mm	Δy mm	Δz mm	$\delta\epsilon$ mas	$\delta\psi$ mas	$\delta\omega$ mas	δs $\times 10^{-8}$
NGS VLBI 90	ITRF 89	65	195	179	14	-23.9 ±3.3	-13.7 ±3.3	-3.6 ±3.0	-4.9 ±0.1	10.2 ±0.1	-1.0 ±0.1	0.38 ±0.05

spectacular. Absolute differences ranging from 0.3 to 6 ppb were obtained. As Table 1 shows, the agreement between these two independent space techniques is remarkable. Minor discrepancies undoubtedly demonstrate the capabilities of commercial dual-frequency GPS receivers to perform geodetic work at the highest available accuracies. Differences are due to the particular error budget influencing either one of the two methodologies. Nevertheless, at this moment, it is premature to pinpoint with certainty the individual error sources attributable to each technique, although deficient survey ties between VLBI and GPS marks seem to be an obvious explanation for the largest discrepancies appearing in Table 1.

The present study departs from the previously mentioned investigation in that an adjustment of all GPS observables was performed, but every GPS station at known VLBI locations were constrained to their VLBI-derived coordinates. In essence, this implies that VLBI values have better geocentric accuracy than GPS-determined results. Although this assumption may be controversial and should not be extrapolated to every situation, there are various reasons supporting the conjecture. For example, VLBI observables are independent of satellite orbital dynamic problems such as errors introduced by approximating the Earth's gravity field, or remaining unmodeled effects due to solar radiation pressure, atmospheric drag, etc. The VLBI methods have an added advantage: the availability of highly sophisticated *in situ* atomic clocks at most VLBI observatories. The largest uncertainty is caused by atmospheric (tropospheric and ionospheric) refraction, which affects both techniques, primarily along the vertical component. Attempts to correct for the wet component of the tropospheric path delay are under way using experimental water vapor radiometers (WVR), although most current GPS software packages depend exclusively on robust unsophisticated atmospheric modeling subroutines.

The coordinates of every VLBI station (fixed and mobile) were transformed from the original system to which they referred, specifically the NGS VLBI 10/01/1990 [M. Abell, personal communication, 1990], to the more universal and accessible ITRF 1989. The seven parameters of the similarity transformation relating the two frames are given in Table 2. Once each collocated VLBI/GPS station was known in ITRF 89, the VLBI transformed coordinates were used to fix the fiducials and the *a priori* selected "base" station of each multistation GPS session. Hence, as previously indicated, this approach assumes that the VLBI coordinates in the ITRF 89 system represent the "ground truth," speculating that they are more accurate than their GPS-determined counterparts. Thus, they are viewed as ideal "true" quantities in sharp contrast with the procedure followed before in Soler et al. [1992], where uncorrelated VLBI and GPS solutions were compared. Then, only one station (Richmond, FL) was assumed to have identical coordinates in both systems and was the only one fixed in the minimally constrained GPS adjustment.

The main logic behind the new overconstrained procedure described herein is to obtain the "best" possible set of geocentric coordinates for the A-order points, by relying on "calibration standards" defined by a proven more accurate space-based geodetic technique such as VLBI. A rigorous set of GPS-determined geocentric coordinates for all presently established and processed A-order stations was determined this way, and is available on request to any interested. These stations are depicted in Fig. 1 with NGS's four character station name abbreviation.

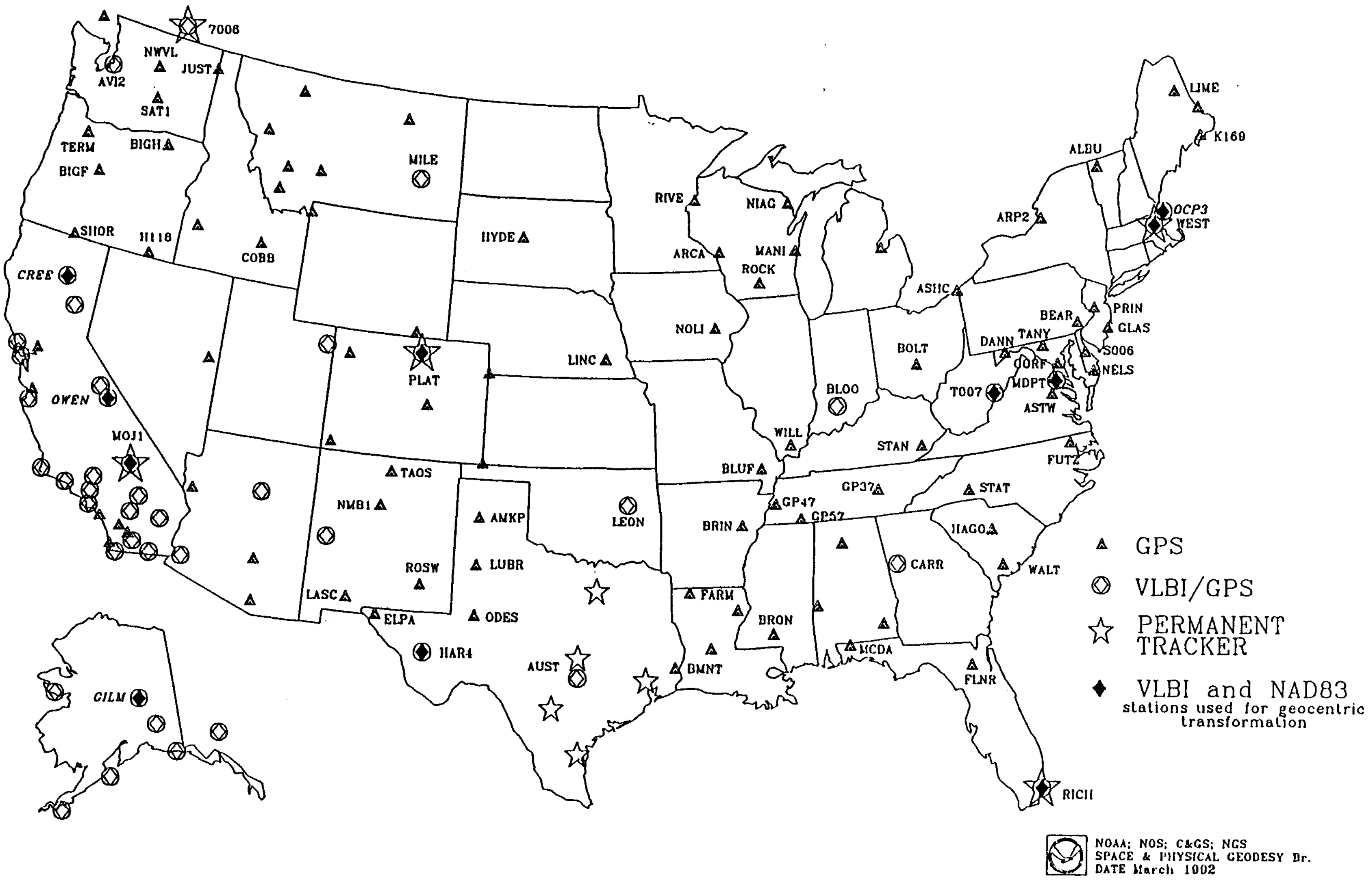

Figure 1. A-order sites in the High Accuracy Reference Network (HARN) already occupied. Adjusted stations are shown with names.

TABLE 3. Transformation parameters between NAD 83 (1991) and ITRF 89 (GPS) [Washington & Oregon]

			Number of Observations			Translations			Rotations			Scale
From	To	No. of Sta.	Input	Used	RMS cm	Δx cm	Δy cm	Δz cm	$\delta\epsilon$ mas	$\delta\psi$ mas	$\delta\omega$ mas	δs $\times 10^{-6}$
NAD 83 (1991)	ITRF 89	9	27	27	21	-97.4 ±32.8	194.2 ±27.8	51.7 ±19.8	-16.1 ±8.4	0.7 ±8.4	-2.9 ±9.6	1.34 ±2.86

TABLE 4. Adopted transformation parameters between NAD 83 (1986) and ITRF 89 (VLBI) [11 points in USA]

			Number of Observations			Translations			Rotations			Scale
From	To	No. of Sta.	Input	Used	RMS cm	Δx cm	Δy cm	Δz cm	$\delta\epsilon$ mas	$\delta\psi$ mas	$\delta\omega$ mas	δs $\times 10^{-6}$
NAD 83 (1986)	ITRF 89	11	33	33	17	-91.9 ±2.3	201.8 ±2.4	48.4 ±2.6	-27.5 ±1.0	-15.5 ±0.7	-10.7 ±0.6	0.00 ±0.28

In order to know the relationship between the A-order geocentric GPS (ITRF 89) coordinates and the published values of the same stations in NAD 83 (1991), a seven-parameter similarity transformation was derived. The NAD 83 (1991) coordinates were retrieved from the NGS Geodetic Data Base. The date in parenthesis indicates the year that the classical observations were adjusted to the statewide HARN, generally, by blocks of statewide size. However, note that the reference datum is still NAD 83. The geographic region selected for this test comprises the states of Washington and Oregon. The results are presented in Table 3. The values clearly show, as expected, the non-geocentricity of NAD 83 at the 2 m level. Previously, NGS adopted the values given in Table 4 as the parameters to transform from the NAD 83 (1986) to a geocentric ITRF 89 (VLBI) defined coordinate system. The adopted transformation parameters were determined using 11 geocentric VLBI stations located in the U.S. (one is in Alaska) whose positions are also known in the NAD 83 (1986) datum. They are shown with a black diamond in Fig. 1.

Because every coordinate published by NGS refers to the NAD 83 (1986) datum, it should be realized that these coordinates are not truly geocentric, as the test in Washington-Oregon verifies. Notice also that the seven transformation parameters for this region are not exactly equal to the adopted ones, given in Table 4, although they are very close (a maximum shift of 7 cm in Δy) to them. The main reason for the discrepancies is not only the constraint enforcing that the NAD 83 (1986) and VLBI scales must be equal, but also the fact that the ten VLBI points in the conterminous U.S. were primarily located in northeastern and southern states (see Fig. 1) and not well distributed over the whole datum. For example, coordinates of geocentric VLBI stations in the Washington-Oregon area were not available at the time the transformation parameters were adopted, and, therefore, were not taken into consideration. Consequently, the set of adopted parameters may not fit geocentric coordinates equally well for every region of the USA.

These transformations become mandatory when rigorous geocentric coordinates are required. For example, and in order to emphasize the problem, Fig. 2 depicts the differences (horizontal and height components) between the NGS published values and the "best" available set of geocentric coordinates for the same points. Although the horizontal differences are clearly systematic and will not affect relative GPS results at an instrument's noise level, nevertheless, it can be noticed that there is a bias of about one half meter in the height component. This may

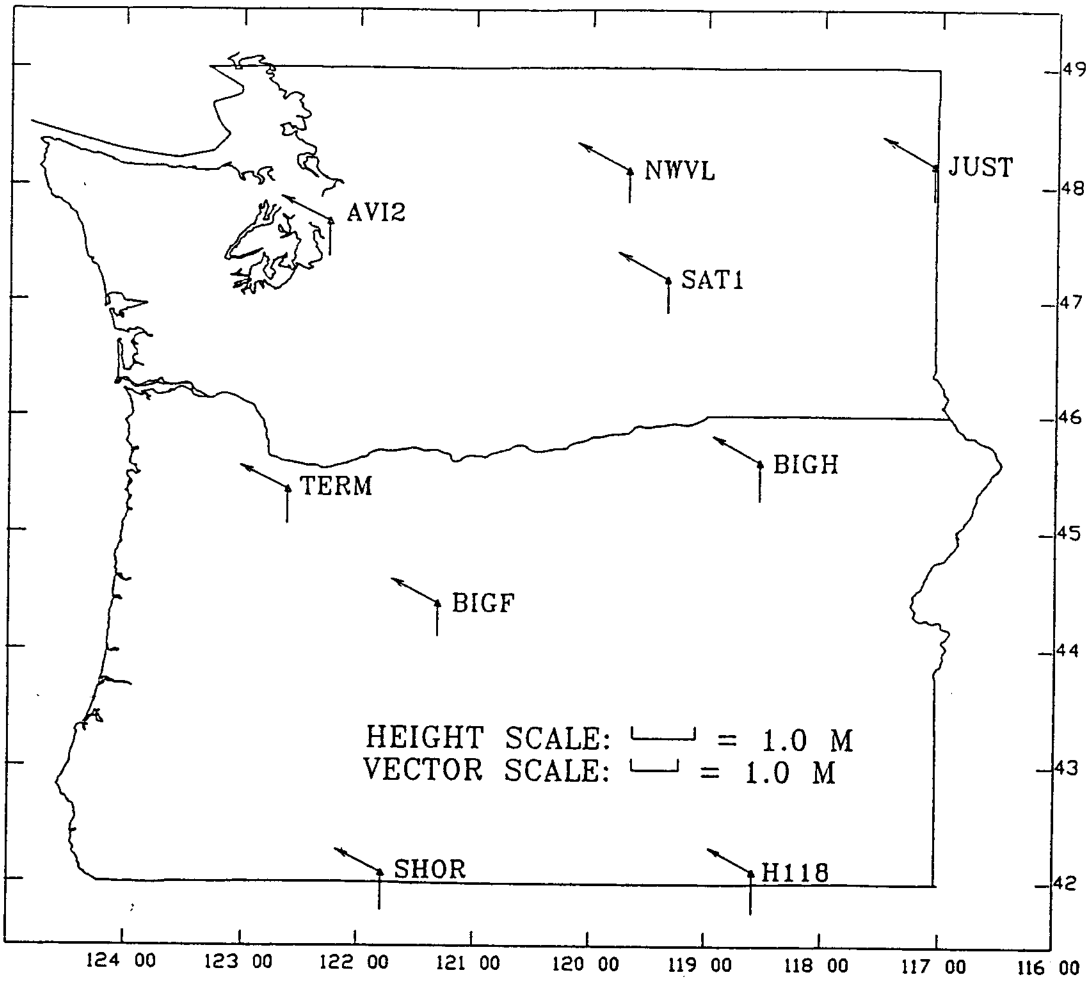

Figure 2. Horizontal and ellipsoidal height differences [ITRF 89 - NAD 83 (1991)]. The GRS 80 ellipsoid was assumed in both cases.

confuse some users interested in "true" ellipsoidal heights needed to determine accurate orthometric or geoid heights.

3. RESULTS FROM B-ORDER NETWORKS

Table 5 shows a comparison of different statewide networks which were planned, designed, observed, processed, and analyzed by NGS. The heading ID(NRC) represents a regional survey around the area of station COBB in Idaho (see Fig. 1) which was contracted by the Nuclear Regulatory Commission. In contrast with the procedures followed with the A-order network, no orbit improvement methods are implemented. Consequently, the stringent presumption that the precise ephemeris is without error characterizes more than anything else the differences between A- and B-order procedural approaches. By fixing the coordinates of the satellites to given state vector values, extra rigidity is introduced into the geometry of the least squares model and final results may converge to less accurate coordinates. Although in all the cases described in Table 5, Department of Defense (DoD) post-fit precise GPS ephemerides (referred to WGS 84) were used, in the immediate future NGS determined precise ephemerides, now available to the civilian GPS sector, will be applied in all NGS data processing. For a more detailed description of the history, status, availability, data formats, and accuracy of NGS' ephemerides, consult Spofford et al., [1992].

TABLE 5. B-order High Precision GPS Network Comparisons

	FL	OR	ID (NRC)	WA	MD/DE
Receiver	TI4100	TI4100	4000SST	4000SST	4000SST
Average Vector Length (km)	42	68	75	50	43
No. of Sessions	156	99	32	152	45
No. of Stations	252	136	35	220	85
A-order stations	3	5	1	7	8
B-order stations	170	106	35	211	85
No. of Indep. Vectors	400	305	80	431	206
Ratio: Vectors/B-Stations	2.35	2.87	2.29	2.04	2.42
Rejected vectors (%)	11(2.75)	9(2.95)	2(2.5)	30(6.96)	28(13.5)
Adj. std. dev. of unit weight	4.87	6.09	18.20	11.00	14.22
Residuals' RMS East (cm)	0.59	0.61	1.53	1.09	1.14
North (cm)	0.49	0.60	0.69	0.96	0.75
Up (cm)	5.26	3.66	4.02	2.68	3.83

A striking feature in Table 5 is the difference in magnitude of the adjusted standard deviation of unit weight (σ_0) depending on the type of dual-frequency receiver employed: Texas Instruments TI4100 (four-channel) or Trimble 4000SST (eight-channel). The tabulated statistics are the outcome of minimally constrained adjustments where one A-order station (preferably collocated with VLBI) in each particular network was fixed. It should be mentioned that NGS software OMNI [Mader, et al., 1991] was used exclusively to process all GPS measurements. Consequently, the same *a priori* estimates for the uncertainties of each phase observation were applied during the processing of the various networks involved. However, the subroutines used to transform observed raw data into OMNI readable format are different and inconsistencies in this area should not be ignored.

The results are very intriguing, because they appear to indicate that the P-code TI4100 observables may be of better quality than those of the C/A code 4000SST. Although the networks discussed here were not simultaneously observed with both types of receivers, nevertheless they have common characteristics (e.g., average vector length and repeatability) and some broad conclusions can be drawn. The *a posteriori* standard deviation of unit weight σ_0 is larger by a factor of about three for the networks observed with 4000SST. This implies than the initial standard errors assumed for the observables (σ_ϕ) are more optimistic in the case of Trimble's observed phases. Thus, it can be concluded that the adopted initial standard error σ_ϕ which was applied equally to all phase observations is more realistic for the TI observables, and presumably too small (optimistic) for the Trimble data; in another words, the TI observations appear more precise than their Trimble counterparts, at least for this examples.

The reader should be cautioned that these inferences are unconfirmed and based exclusively on the data sets available to us. As always, generalizations deduced from small samples are risky or plainly erroneous, and this premise should always be kept in mind. However, the evidence seems to be conclusive, and is partially supported by the magnitude of the residual's root mean square (RMS) about the mean on the east, north, and up directions. Notice that the values along the east component for the Trimble receivers is clearly larger than for the TI4100. Eventually it may be argued that the TI41000 clocks' stability is better (i.e., causes less jitter in tracking loops)

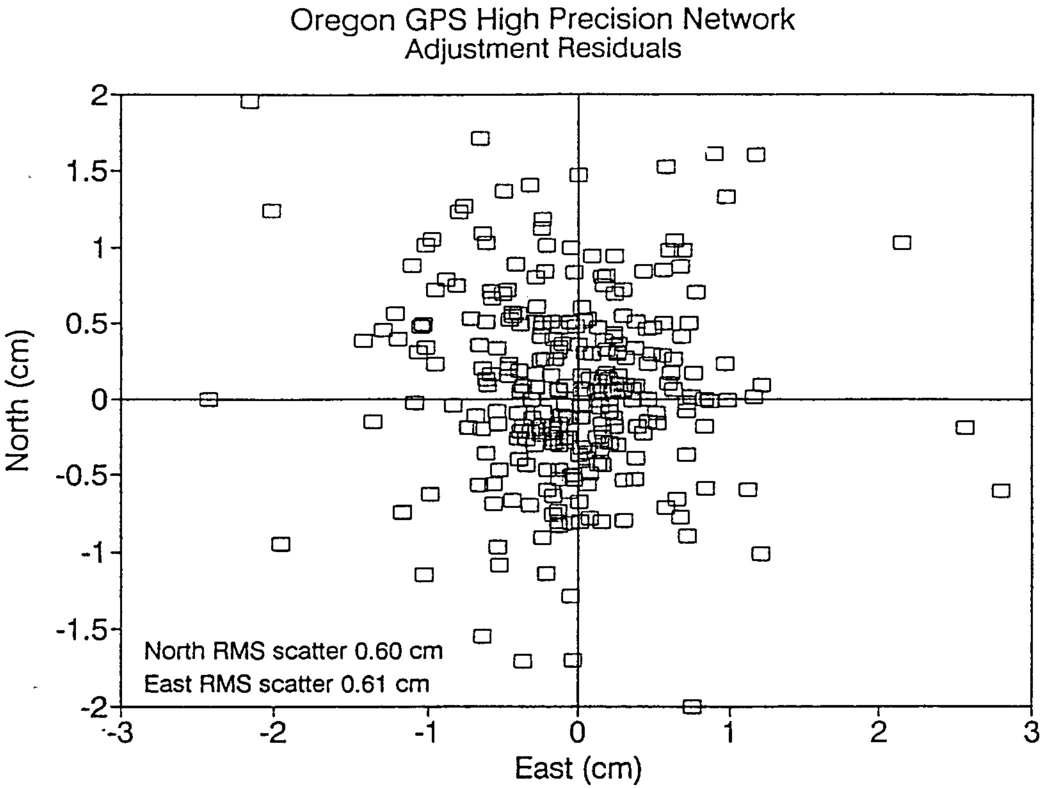

Figure 3. Residual scatter obtained in the Oregon network using TI4100.

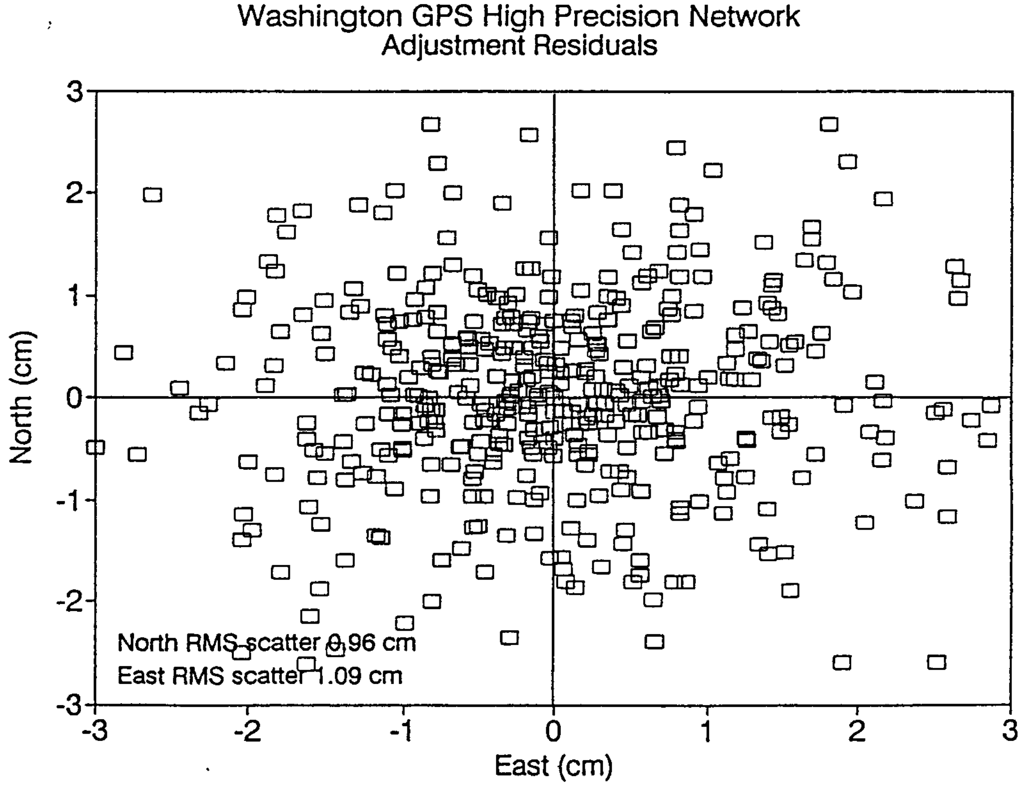

Figure 4. Residual scatter obtained in the Washington network using Trimble 4000SST.

than for the 4000SST. Alternatively, the P-code signal strength of the TI instrument generates more accurate pseudoranges and, therefore, better time tags can be computed. Even after differencing the observables, small uncorrected timing errors will introduce uncertainties into the Earth's rotation definition, and, consequently, will affect the orientation of the vectors along the east-west component. See, for example the difference in the scatter patterns in Figs. 3 and 4. The plots show less dispersion for the adjusted residuals of the Oregon network where TI receivers were used. Plots similar to that of Fig. 3 for the Florida network were previously published in Soler et al., [1991].

Furthermore, the number of rejected observations serves as an independent corroboration of the noisier Trimble data. Mainly, these are points falling outside the stipulated figure plotting range. Larger noise in the east component, visible when comparing Figs. 3 and 4, translates into difficulty in properly fixing ambiguity biases, further complicating a procedure which is inherently more difficult with the Trimble receivers because of the possibility of creating half cycle slips (~ 12 cm) in L2. Again, errors in sampling time will generate incorrect float integers that, when fixed to the nearest whole number (by simple rounding off), will deteriorate instead of helping the final solution. NGS is still trying to evaluate these inconsistencies, although as clearly shown by the table, this only impacts the east component at the subcentimeter level and does not affect the overall final quality of the B-order networks.

4. SUMMARY

Modern GPS technology and methods were implemented at NGS from the very early stages of GPS development. Strategies presently applied at NGS to obtain the high accurate reference networks (HARN) were covered. Emphasis was placed in the accuracy and precision of the resulting coordinates and how statistical measures of dispersion are obtained. As a consequence, two major types of geodetic networks are currently established by NGS. They are referred to as A-order and B-order, depending on the relative accuracy of the points involved. More stringent procedures are used for the A-order networks, whose points could attain absolute accuracies better than 6 ppb. In return, this provides the possibility of obtaining geocentric coordinates with accuracies below 5 cm. The relationship between these geocentric coordinates and NAD 83 coordinates was discussed. Finally, still unexplained differences between the precision of data collected with TI4100 and 4000SST receivers were presented.

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