GPS HIGH ACCURACY GEODETIC NETWORKS IN MEXICO

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ABSTRACT: Recently, Mexico's *Instituto Nacional de Estadística, Geografía e Informática* (INEGI) adopted a geocentric three-dimensional coordinate system as the basis for all its national geodetic and mapping needs. The selected frame is the International Earth Rotation Service (IERS) Terrestrial Reference Frame of year 1992 (ITRF92), epoch 1988.0. The geometric surface of choice is the ellipsoid of the Geodetic Reference System of 1980 (GRS80). The implementation of this geocentric datum permits the integration of all geodesy, engineering surveys, mapping, and land information systems of Mexico into a modern framework consistent with present accuracies obtainable through the global positioning system (GPS). The practical realization of the spatial reference system was done in cooperation with the National Oceanic and Atmospheric Administration's (NOAA) National Geodetic Survey (NGS) through a series of coordinated GPS projects. As a result, Mexico established 14 permanent GPS trackers (A-order stations) from which the less accurate B-order GPS network was propagated. With this implementation, INEGI assures that the requirements of modern geodetic and cartographic operations in Mexico will be met for many years to come. Updated results, procedures, and data analysis are presented here.

INTRODUCTION

Up to 1993, all Mexican geodetic and cartographic products were referred to the North American Datum of 1927 (NAD 27). Radical advances in global positioning system (GPS) technology accomplished during the last decade, along with the spectacular improvements in computer hardware and software, advocated the prompt incorporation of new satellite methods and techniques to geodetic/mapping operations. In close cooperation with the National Oceanic and Atmospheric Administration's (NOAA) National Geodetic Survey (NGS) and from 1991 onwards, Mexico's *Instituto Nacional de Estadística, Geografía e Informática* (INEGI) has transitioned from the classical, mainly two-dimensional methods to the more accurate three-dimensional GPS-based satellite methodologies. The *Dirección General de Geografía* (DGG) is the office in INEGI responsible, among other duties, for the establishment, maintenance, and densification of the national geodetic network. DGG is also in charge of producing the Mexican cartography, primarily maps at 1:50,000, which provide the backbone of the country's natural resources inventory. DGG evolved from several departments committed to geodesy and mapping

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including *Comisión de Estudios del Territorio Nacional* (CETENAL), founded in 1968 (Villasana 1974), and its successors *Dirección de Estudios del Territorio Nacional* (DETENAL) and *Dirección General de Geografía del Territorio Nacional* (DGGTENAL).

To implement a national cadastral system, which is already at a very advanced stage, INEGI created in 1993 the new *Dirección General de Cartografía Catastral* (DGCC). The specific role of DGCC is to identify, locate, delineate borders, and measure every parcel of land and/or community farm (*ejidal*, in Spanish), while generating pertinent cartographic evidence to support the legal transfer of ownership rights to interested Mexican peasants or farm operators.

The joint effort of DGG and DGCC is crystallizing toward a smooth transition of Mexican cartography, bringing it into the realm of sophistication comparable to the most advanced international organizations working in this field. To push this endeavor to the limit, INEGI acquired about 500 GPS receivers of all types. Among them, 181 Ashtech P-XIIs; 60 of the newest Ashtech Z-XIIs; eight Trimble receivers; and two Leica system 2000. The number of SOKKIA total stations purchased was 280 SET2 and 400 ELTA3 instruments. INEGI also owns a respectable air fleet including two Lear jets, three Cessna aircrafts, and two Bell helicopters—all of them equipped with exterior GPS antennas to do photogrammetry with minimum ground control. This wealth of support makes INEGI a powerful cartographic center focused on the production of accurate mapping by consciously exploiting the most current technology.

GPS OBSERVING CAMPAIGNS

Between 1992 and 1994 and through various campaigns coordinated with NGS, INEGI's DGG positioned several Mexican points to the most stringent accuracies possible by relying exclusively on GPS instrumentation and methods. Simultaneous observations between Mexican and American stations began in February 1992. This initial participation was planned in conjunction with the Arizona high accuracy reference network (HARN) and the collaboration of other U.S. federal and state agencies, such as the Texas Department of Highways and Public Transportation (TDHPT), New Mexico State Highway and Transportation Department (NMSHTD), and U.S. Army Yuma Proving Grounds (YPG). The main purpose of this combined survey was to accurately connect several sites in adjacent southwestern states including the contiguous Mexican republic.

As in any HARN project, the procedures followed two distinct phases. First, an extensive regional A-order network determined to relative accuracies of 0.5 mm + 1:10,000,000 (i.e., 5 mm + 0.1 ppm) is completed. The absolute accuracy of NGS' A-order points in the United States has been estimated to be better than 5 parts per billion (ppb). An error of 1 ppb in the coordinates of a point on the Earth's surface is equivalent to positioning the absolute location of that point within 6 mm. These results have been corroborated (Soler et al. 1992a) by comparing an intricate A-order GPS network with values obtained from more reliable space geodesy data collected by very long baseline interferometry (VLBI) radiotelescopes, which have the disadvantage of depending on more expensive and cumbersome hardware-software technology. However, GPS positioning has improved recently due to significant refinements in orbit accuracies (Kouba and Popelar 1994) and the incorporation of new vector-reduction software developments. The end to this spectacular progress of GPS innovations can only be speculated; these unprecedented advancements continue as we write.

After the A-order network is in place, a more dense and localized B-order (8 mm + 1 ppm) survey covering the area in question is tied to the A-order points. Major differences between these two well-differentiated observational stages include the number of independent occupations at each site (minimum of three and two for A- and B-order, respectively), lasting at least 6 h each, and some stability restrictions imposed on the ground monumentation.

Successful discussions with NGS afforded INEGI the opportunity to originate what was going to develop into a fruitful cooperation beneficial to both agencies. As a result, coobservations with five Mexican points (DIAZ, INEGI, LOMA, RIO VERDE, and XICO) took place during four days in February 1992 [day of year (doy), 034-037], coinciding with the NGS GPS survey of the Arizona HARN.

The same year (doy: 076-079) and in conjunction with the Louisiana HARN network, which was planned and designed by NGS in coordination with the Louisiana Department of Transportation and Development (LADOTD), two more points (CINVESTAV and JOCOTITLAN) were added to the Mexican GPS network. As before, TDHPT, YPG, and NMSHTD were also involved in this project (Love et al. 1993).

Simultaneous observations with NGS at 14 more Mexican points (ALTAMIRA, CHETUMAL, CHIHUAHUA, COLIMA, CULIACAN, VG16, HERMOSILLO, LA PAZ, MERIDA, MEXICALI, MONTERREY, OAXACA, TOLUCA, and VILLAHERMOSA) well-distributed throughout the country occurred during the Puerto Rico-Virgin Islands campaign, Feb. 22–25, 1993 (doy: 053-056). Coparticipants in the project were the Florida Department of Natural Resources (FDNR), Louisiana State University (LSU), the Jet Propulsion Laboratory (JPL), and, as in preceding occasions, TDHPT, YPG, and NMSHTD.

In mid-1993, INEGI decided to deploy a nationwide geodetic array of permanent GPS trackers [*Red Geodésica Nacional Activa*, (RGNA)] paralleling NGS' commitment to the continuously operating reference stations (CORS) (Strange 1995). A total of 14 receivers observing 24 h a day form part of this permanent GPS tracking arrangement. All stations in the network except one (TAMPICO) were previously surveyed in the A-order projects described. Three of them (LA PAZ, CHETUMAL, and CHIHUAHUA) were relocated after discovering technical glitches of various sources (radio interferences, excessive multipath, etc.) affecting the gathering of data at the old locations. The coordinates of all stations completing the Mexican active GPS network were recomputed jointly by INEGI and NGS in 1994 using a new set of observations collected the same year (doy: 032, 060, 091, 121, and 152). Fig. 1 schematically depicts the distribution in Mexico of every A-order site, including the INEGI-managed 14 continuously operating RGNA stations.

TERRESTRIAL COORDINATE SYSTEMS

Until now INEGI has used NAD 27 as the reference datum for all its maps (Hernández-Navarro 1993). With the advent of GPS, the possibility of obtaining accurate geocentric coordinates has drastically revolutionized not only the discipline of geodesy, but also many others. Present earth-satellite GPS techniques are capable of consistently determining geocentric coordinates below the 3-cm level when pertinent precautions are enforced.

INEGI's staff carefully considered the option of transferring all its cartographic databases to the continental NAD 83 datum to remain entirely compatible with the NGS and U.S. Geological Survey (USGS) products. How-

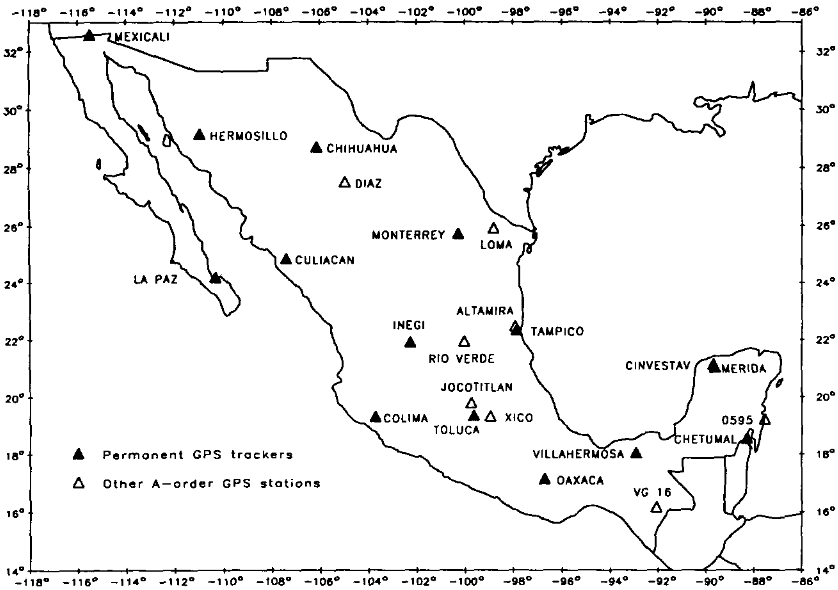

FIG. 1. INEGI's A-Order Stations in Mexico

ever, INEGI finally decided, as a pragmatic solution, to capitalize on the best geocentric coordinate system presently at its disposal.

The new reference datum surface for all INEGI map products will be the biaxial ellipsoid of the Geodetic Reference System (GRS) 1980 (GRS80) as adopted at the XVII General Assembly of the International Union of Geodesy and Geophysics (IUGG) held in Canberra, Australia (December, 1979). See Moritz (1992) for the definition of adopted and derived GRS80 ellipsoidal parameters.

The foregoing ellipsoid of revolution is centered and oriented with respect to the International Earth Rotation Service (IERS) Terrestrial Reference Frame (ITRF) 1992, epoch 1988.0 (IERS 1993). The ITRF92 is a geocentric coordinate frame implemented by the IERS, Paris, France (Feissel and Gambis 1993), that works in close cooperation with several international organizations and academic research centers.

INEGI's primary reasons, among others, for preferring the ITRF coordinate system were the following:

1. NAD 83 is a horizontal datum fundamentally established before the GPS era, although Doppler observations were included. Its coordinate frame is related to the geocenter by 11 VLBI stations connected with NAD 83 points at the time the transformation parameters were originally computed. None of the NAD 83 sites were GPS-determined and because of the requirement of being near VLBI observatories, their distribution across the continental United States was less than ideal, e.g., one of them is in Alaska. Furthermore, none of these points are in Mexico and, consequently, it can be conjectured that although the transformation may fit the classical geodetic observations adequately in the conterminous United States, this fitting may not be nearly as good with

respect to the conventional observations available in Mexico. In fact, INEGI is ignoring its archival geodetic data (including Doppler) to define the geocentricity of its high-accuracy reference frame and, instead, is depending exclusively on up-to-date three-dimensional GPS methods and techniques.

2. The seven parameters adopted by NGS for the transformation between a geocentric coordinate system and NAD 83 (solution 1986) are given in Table 1. These are "average values" in a least-squares sense (Soler et al. 1992b). The actual values may be slightly different from one section of the United States to another. The maximum shift reaches 2 m in the y-component. This quantity in INEGI's judgement was considered well above the noise level of present GPS observations. Also compare in Table 1 the values between INEGI's selection of reference frame (ITRF92) and the IERS most recently published coordinate system (ITRF93) (Boucher et al. 1994).
3. INEGI is in the process of revamping all its digitized cartographic databases; consequently, there are plans to revise the publication of future maps encompassing the full spectrum of scales, from topographic quads to thematic representations. Considering the amount of work involved in the creation and revision of such geospacial databases, the conclusion was reached to pursue the best possible currently existing geocentric reference system. This will be a reference frame compatible with the accuracy of near-real-time GPS observations. INEGI is involved in an ambitious campaign that began in 1992 (Álvarez-García et al. 1992) to cover the whole country with GPS points to a densification convenient for cadastral and GIS applications. Use of the ITRF frame will provide INEGI with the best geocentric coordinate system that GPS can directly realize.
4. During the *Federation International de Géomètres* (FIG) Congress, held in Helsinki in June 1990, a resolution was passed encouraging member countries (e.g., Mexico) to consider adopting the ITRF geocentric system when planning to update their datums. Other Latin American interests, e.g., *Sistema Internacional de Referencia Geodésico para América del Sur* (SIRGAS) searching for an improved South American datum have supported a similar resolution advocating the use of a coordinate system compatible with GPS and ITRF (Souto-Fortes et al. 1995). This appears to be the worldwide trend as the high accuracies of GPS techniques are maturing. Further, the almost absolute geocentricity of ITRF makes such a coordinate system valuable for other kinds of scientific research. This matter is of great concern in Mexico, where the National Aeronautics and Space Administration (NASA) has four monumented satellite laser ranging (SLR) points; the French have installed one Doris tracking station; and American, French, and Mexican university groups are investigating crustal deformations in Baja California and other tectonically active regions. INEGI wants to avoid a duality of geodetic frameworks: one for navigation, surveying, and mapping; the other for scientific applications (geodesy, geophysics, oceanography, etc.) constrained by more stringent coordinate system definition requirements.
5. INEGI has established a network [*Red Geodésica Nacional Activa* (RGNA)] of 14 continuously operating GPS trackers uniformly spaced across the country (see Fig. 1). INEGI is interested in providing a wide

TABLE 1. Transformation Parameters between Selected Reference Frames

Transformation type (1)	Translations			Rotations			Scale
	Δx (cm) (2)	Δy (cm) (3)	Δz (cm) (4)	$\delta\varepsilon$ (mas) (5)	$\delta\psi$ (mas) (6)	$\delta\omega$ (mas) (7)	δs ($\times 10^{-8}$) (8)
NAD 83 (1986) → ITRF89	−91.9 ± 2.3	201.8 ± 2.4	48.4 ± 2.6	−27.50 ± 1.00	−15.50 ± 0.70	−10.70 ± 0.60	0.00 ± 0.28
ITRF93 → ITRF92	0.2 ± 0.1	0.7 ± 0.1	0.7 ± 0.1	−0.39 ± 0.06	0.80 ± 0.05	−0.96 ± 0.04	−0.12 ± 0.02
WGS84 (GPS) → ITRF92	−4.0 ± 0.1	−1.0 ± 0.1	−28.0 ± 0.1	4.20 ± 0.06	−4.00 ± 0.05	−15.60 ± 0.04	−21.80 ± 0.02
WGS84 (G730) → ITRF92	0.0 ± 0.1	3.0 ± 0.1	4.0 ± 0.1	−2.60 ± 0.06	−2.50 ± 0.05	−0.40 ± 0.04	0.00 ± 0.02

Note: 1 mas = 1 milliarc second.

range of Mexican GPS users with high-quality geocentric coordinates. This is consistent with accuracies that GPS receivers can achieve in conjunction with the caliber of GPS orbital data readily accessible via various independent sources. Shifting or transforming these coordinates to a second pseudogeocentric coordinate system was considered unnecessary. The selection of ITRF will assure that observations from the permanent trackers in Mexico will be directly referred to an accurate geocentric spatial reference frame of international acceptance. In essence, this is the standard frame for fiducial stations placed around the globe pertaining to the International GPS Service (IGS) for Geodynamics network in which INEGI hopes to become an active member.

6. In conclusion, today's GPS technology is capable of determining geocentric coordinates to only a few centimeters in accuracy and INEGI did not want to ignore the reality of this premise. In the final evaluation, ITRF was considered a comprehensive, internationally well-known reference frame boasting several advantages over NAD 83. However, it should be stressed that the differences between ITRF and NAD 83 inherently defined coordinate frames are negligible at the mapping scales currently used in border areas overlapping the United States and Mexico (Álvarez et al. 1994), implying that present and/or future strategies to publish topographic quads will not be affected.

DATA PROCESSING AND ANALYSIS

A-Order Network

The processing of GPS observations involving A-order vectors was completed at NOAA's NGS headquarters in Silver Spring, Maryland, following two alternative procedures, which were controlled by the a priori stipulated accuracy of the available precise postfitted ephemeris.

NGS began releasing precise weekly ephemeris to the general public 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. Fig. 2 shows recent comparisons with the orbits computed by the Jet Propulsion Laboratory (JPL) for IGS (Mader et al. 1995). NGS' ephemeris have always referred to frames of the ITRF series, adopting the year of the IERS published solutions and epochs, which may have changed sporadically to take advantage of newer observations and refinements to the software.

Before April 1993 orbit relaxation solutions [Leick (1994), p. 396] were invoked in A-order vector processing done at NGS to account for unknown but plausible errors in satellite positions. In this methodology, IGS fiducial stations [formerly the Cooperative International GPS Network (CIGNET)] are fixed to known values in the ITRF reference frame. The coordinates of the rest of the sites are estimated in a simultaneous least-squares adjustment also containing as parameters five Keplerian orbital elements for each satellite arc plus the usual clock terms, ambiguities, tropospheric biases, etc. This extra orbital refinement was discontinued when meliorations in the precise ephemerides materialized.

Thus, from the second quarter of 1993 onward, when the accuracy of the precise ephemeris was well-confirmed, the satellite positions are routinely fixed to the values given by their state vectors. Recent empirical analyses showed, as expected, that coordinates obtained using the orbit relaxation method were slightly less accurate (particularly in the longitude and vertical

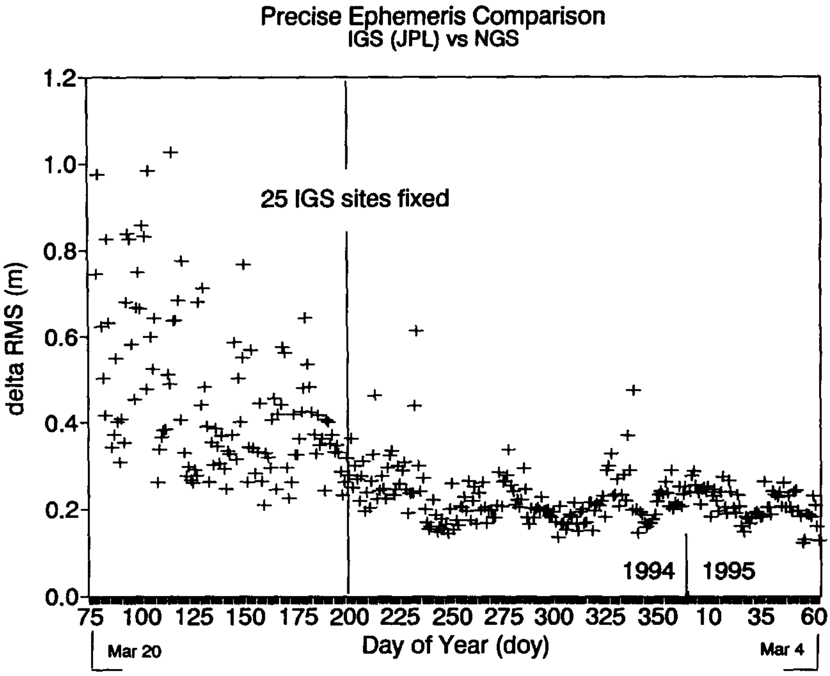

FIG. 2. Comparison between NGS and JPL Precise Ephemerides

components) than more updated reductions fixing the satellites to the latest improved satellite ephemeris. In all A-order projects discussed here, the coordinates of the fiducial stations and the satellite positions are in a consistent geocentric ITRF frame and, obviously, the determined coordinates of the sought stations are (as well) referred to an equivalent type of frame.

It was also clear after INEGI started operating its RGNA permanent GPS array, that the need to establish more A-order stations was unnecessary. Any point inside Mexican borders is less than 300 km from at least one of the GPS continuously operating stations. Consequently, precise coordinates are readily available at any point by using daily archived data from the reference trackers. However, densification of the B-order network may still be required for detailed investigations about countrywide geoid modeling or to support the pivotal cadastral effort.

To get the best possible set of geocentric coordinates for the 14 Mexican permanent trackers, only the five 24-h sessions collected in 1994 with a new, improved vector-reduction program (MGPS) were used. Also, the old orbital relaxation procedure was replaced by a standard relative positioning methodology fixing the satellites according to NGS precise ephemerides, referred to the frame ITRF92, epoch 1994.0. Three stations (MDO1, RCM5, and WES2) from the IGS network known in the ITRF93, epoch 1993, were used as fiducials in the reduction process. However, before processing started, the original coordinates of the IGS points were rotated to the average epoch of the observations (i.e., 1994.25) using the geophysical model NUVEL NNR-1 and its set of tectonic plate angular velocities [e.g., McCarthy (1992), p. 21]. Initially, the coordinates of station INEGI, which is centrally located in

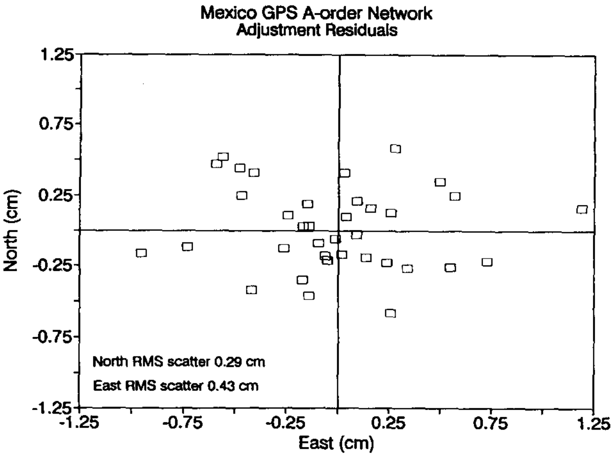

FIG. 3. A-Order Adjustment Residuals Plotted on Geodetic Horizon Plane

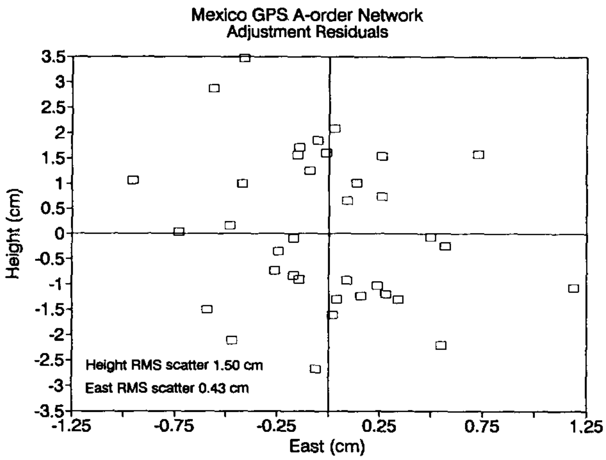

FIG. 4. A-Order Adjustment Residuals Plotted on Geodetic Meridian Plane

Aguascalientes, Mexico, were determined holding fixed the coordinates of fiducial stations to the IERS rotated values.

Once the coordinates of the mark at INEGI were known in the ITRF93, epoch 1994.25, a minimally constrained least-squares adjustment fixing INEGI was implemented to solve for the coordinates of the other permanent A-order GPS sites. In this adjustment, components of the vectors (also determined using MGPS) connecting INEGI's site to the remaining 13 stations were used as observables. The raw residuals of each observation included in the adjustment, projected along the geodetic horizon and meridian planes, respectively, are displayed in Figs. 3 and 4. After the coordinates for all stations in the ITRF93, epoch 1994.25 were obtained, they were rotated back to epoch 1988.0, taking into consideration the rotation of the North American plate according to the same geophysical model used earlier. Finally, a similarity transformation in the sense ITRF93 → ITRF92 (both 1988.0 epochs) using

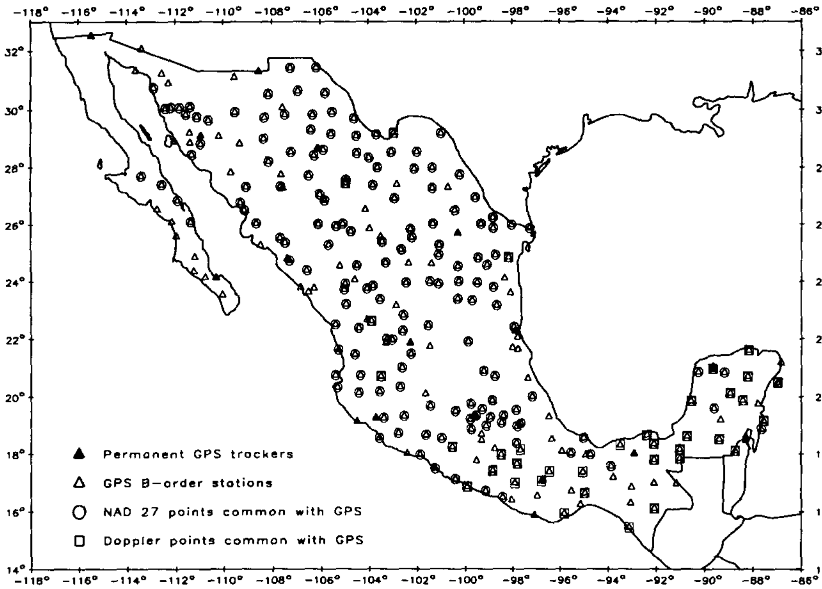

FIG. 5. Mexico's B-Order Geodetic Network (as of June, 1995)

the seven parameters given in Table 1 was applied to get the final set of coordinates in a common ITRF92, epoch 1988.0. The obtained values were used to constrain the B-order network and force all results to a common ITRF frame and epoch.

B-Order Network

The nationwide Mexican B-order network consists (as of June, 1995) of 290 GPS geodetic stations (see Fig. 5); 27 of these points were planned for cadastral support and were visited only once. Consequently, possible field errors (misreading of antenna heights, etc.) could not be checked at these sites and their positions should not be used to propagate coordinates to nearby points. During INEGI's GPS B-order campaign, a total of 175 existing NAD 27 marks, and 36 Doppler stations were occupied. Most of the Doppler points are common to NAD 27 stations, and they are concentrated along the southern jungle regions, where classical horizontal geodetic control was weak and sparse at the time Doppler satellite receivers were introduced.

INEGI's GPS field operations began on March 18, 1992, and were completed by May 12 of the same year. GPS observations pertaining to the B-order network were processed in their entirety by DGG's staff at INEGI's headquarters in Aguascalientes. Broadcast ephemerides referred to the WGS84 frame and Trimvec and Prism software were used in all vector reductions. The total number of vectors processed was 1,077.

A constrained least-squares adjustment was implemented where the coordinates of all A-order permanent trackers were held fixed to their ITRF92, epoch 1988.0 positions already independently determined with NGS' program MGPS. The resulting a posteriori standard deviation of unit weight was 2.36. The residuals of all observations are presented in Fig. 6 and Fig. 7. To have a grasp of the dispersions involved, it could be said that the average position standard error for the B-order stations was 2.2, 1.5, and 3.1 cm in

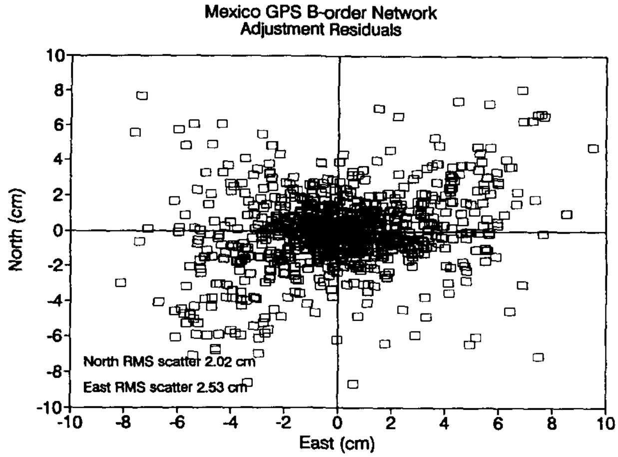

FIG. 6. B-Order Adjustment Residuals Plotted on Geodetic Horizon Plane

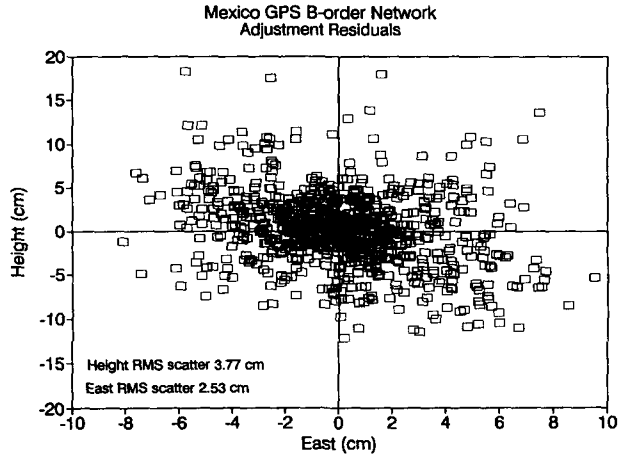

FIG. 7. B-Order Adjustment Residuals Plotted on Geodetic Meridian Plane

longitude, latitude, and ellipsoidal height, respectively. These results are sure to be improved in the future when new sets of observations and vector reductions—performed using precise orbits—are incorporated into the adjustment. At that time, old less-precise observations can be discarded and replaced by the new ones and, as a result, the coordinates of the B-order points could be determined with even greater accuracy. In this manner, their current position standard error will be further reduced while the actual coordinates of the point may not change by much. Changes at the level of a few centimeters (≤5 cm), until convergency to a final unique value is achieved, should be of no concern for mapping and GIS applications, and should be accepted as part of a progressive geodetic refinement.

Although postfit precise satellite ephemerides are currently the most accurate and readily available from various sources, recently the Defense Mapping Agency (DMA) drastically improved the accuracy of the coordinate system to which GPS broadcast orbits are referred (Malys and Slater 1994). This new frame is termed WGS84 (G730) and was introduced into the broadcast ephemeris message on June 1, 1994. For completeness, the relationship between the old and new DMA WGS84 coordinate systems is also given in Table 1.

Without a doubt, the results from the adjustment of the B-order network in Mexico show a substantial improvement over what was available before. At this level of positioning uncertainties (obviously), all geodetic and engineering surveys, mapping, and GIS data gathering and operations could be efficiently exchanged, and the goal of defining a unique geospacial reference frame may be considered accomplished. More precise GPS observations in the future will replace old ones, and the definition of the basic reference frame should be consolidated to accuracies impossible to attain with any other technology as cheaply and as fast as GPS. Thus, uncertainties in the position of the points should shrink further and the usefulness of the results could be extrapolated beyond the geodetic and cartographic applications, reaching specifications required by precise studies of crustal motion and other multidisciplinary scientific uses. INEGI's GPS involvement has just started, but the potential of GPS methods is fully recognized and utilized in many different areas such as geodesy, engineering surveys, cadastre, photogrammetry without ground control, mapping, sea-level investigations, and geoid analyses.

GPS Network Comparison with Doppler and NAD 27 Frames

As a scientific curiosity, and in order to know the authentic relationship between the newly adopted ITRF92 and the old Doppler and NAD 27 geodetic frames previously used in Mexico, the transformation parameters between them were investigated. The results are shown in Table 2. Although the large discrepancies relating the classical NAD 27 horizontal datum and the ITRF92 were expected, one striking feature from the tabulated results is the magnitude of the transformation parameters that relate ITRF with the Doppler system.

It should be remembered that during the 1970s, when some Mexican geodetic stations were positioned using Doppler space technology and methods, unreliable "ground truth" was at the scientists' disposition to compare with Doppler results. Then, since Doppler was the most sophisticated geodetic method known at the time, empirical analyses based strictly on the repeatability of measurements under different conditions were, generally, the primary source of information to determine an accuracy estimate. As a general rule, it was assumed that geocentric coordinates could be determined with Doppler to about 2 m in either three-dimensional component, and, in the worst possible scenario, it could contain errors as large as 5 m. The results presented here, which apply exclusively to the particular case of Mexican stations, shows that the geocentricity of the Doppler-defined NSWC9Z frame has shifts of about 15 m in the x- and z-components when compared to a better defined frame such as ITRF92. These larger than usual discrepancies can be explained by several reasons: the reduced regional nature of the survey; the fact that all Doppler determinations were point solutions and translocation methods were not applied; and, finally, the small number of satellite passes used in the reductions.

These results emphasize, once more, the importance of being conservative when quoting geocentric accuracies when no independent "control" measurement system is available as a calibration standard. Fortunately for GPS, the same situation is not repeated now. In today's technological environment,

TABLE 2. Transformations (in Mexico) between ITRF92, Epoch 1988.0, and Older Geodetic Datums

Transformation type (1)	Number of stations (2)	Number of Observations			Translations			Rotations			Scale
		Input (3)	Used (4)	RMS (m) (5)	Δx (m) (6)	Δy (m) (7)	Δz (m) (8)	$\delta\varepsilon$ (arc sec.) (9)	$\delta\psi$ (arc sec.) (10)	$\delta\omega$ (arc sec.) (11)	δs ($\times 10^{-6}$) (12)
NAD 27 → ITRF92	175	525	367	2.7	−60.2 ± 3.8	141.5 ± 2.2	158.2 ± 4.4	1.04 ± 0.1	0.22 ± 0.1	−1.97 ± 0.1	−0.13 ± 0.28
NSWC9Z → ITRF92	36	108	94	0.8	14.5 ± 2.2	3.2 ± 1.7	15.5 ± 2.9	−0.46 ± 0.1	0.28 ± 0.1	−0.39 ± 0.2	0.54 ± 0.22

GPS positioning can be contrasted with supposedly more accurate VLBI and LAGEOS results, corroborating an overall global agreement of about 3 cm (Zumberge et al. 1994). Consequently, the results presented here imply that the coordinates of the stations recently established in Mexico are now at a level of geocentricity consistent with GPS technology, which should satisfy any geodetic and mapping requirement during the foreseeable future.

Currently, INEGI has underway an elaborate effort to transform all national topographic maps from the outdated NAD 27 datum to the GRS80 ellipsoid and ITRF 92 coordinate system. It appears that Mexico will be the first country whose digital cartographic information will be completely revamped and published using a homogeneous geospacial framework based exclusively on an internationally recognized geocentric frame of the ITRF series.

CONCLUSIONS

Mexico's INEGI, assisted by NOAA's NGS, has put in place a national GPS high-accuracy geodetic reference network referred to the frame ITRF. Overall, the coordinates of these points are conservatively estimated to be geocentrically accurate within ±5 cm; the relative accuracy between points could be much less. This implies that all activities related to geodesy, cadastre, cartography, and geographic information systems can be related to a unique, commonly defined spatial framework. Consequently, digital geodatabases could be effectively exchanged without expecting coordinate incompatibilities. Among the provisions implicitly defined by this coordinate system is the possibility of rigorously positioning any point in Mexico, using relative methods in conjunction with near-real-time GPS data from a set of 14 receivers permanently operated by INEGI. This information should be meaningful to a wide range of users interested in all types of surveying, GIS, cadastral, and mapping applications, but equally valuable to American and Mexican investigators researching time-dependent phenomena in fields such as geophysics and oceanography.

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