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GUIDELINES FOR ESTABLISHING GPS-DERIVED ELLIPSOID HEIGHTS
(STANDARDS: 2 CM AND 5 CM)
VERSION 4.3

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Preface:

The following guidelines were developed by the National Geodetic Survey (NGS) for performing Global Positioning System (GPS) surveys that are intended to achieve ellipsoid height network accuracies of 5 cm at the 95 percent confidence level, as well as ellipsoid height local accuracies of 2 cm and 5 cm, also at the 95 percent confidence level. See Appendix A for information about local and relative accuracies. These guidelines were developed in a partnership with Federal, state, and local government agencies, academia, and private surveyors and are the result of processing various test data sets and having extensive discussions with various GPS users groups.

We are confident that these guidelines, if followed, will result in achieving the intended accuracy. Additional tests may show that some of these guidelines can be relaxed. These guidelines are intended for establishing geometric vertical control networks.

These guidelines will be expanded in the future to include the establishment of GPS-derived orthometric heights that approach these same accuracies, 2 cm and 5 cm. The slight differences between the accuracies of GPS-derived ellipsoid heights and GPS-derived orthometric heights will be generally due to the accuracy of the geoid model and published orthometric heights used to evaluate the differences between the three height systems, i.e., ellipsoid, geoid, and orthometric heights.

Note: these guidelines assume that for the survey project area in question, NGS has completed the establishment of a high accuracy reference network at 100-kilometer spacing or that a state-wide High Accuracy Reference Network (HARN) has been established, i.e., there are A- or B-order stations distributed throughout the state at an approximate spacing of 50 km or else there are Federal HARN stations or GPS Continuously Operating Reference Station (CORS) sites located within 75 km of the project area.

An effort should be made to connect to stations which were previously determined using these guidelines (or equivalent).

Introduction:

Accurate connections to the control stations cited in the Observations section on the next page must be made in the International Terrestrial Reference Frame (ITRF) coordinate system. (See Appendix C for more information on ITRF.) This is accomplished by simultaneous observations between selected A-order (5 mm + 1:10,000,000 accuracy standards) stations of the International GPS Service for Geodynamics (IGS) and/or NGS CORS or NGS-approved CORS within about 75 km of the project. NGS-approved CORS are those which NGS has positioned or approved with respect to the ITRF/NAD 83 coordinate systems. If there are none available, B-order (8 mm + 1:1,000,000 accuracy standards) stations within about 75 km of the project may be substituted. However, it must be noted that the use of some of the B-order stations may mean that the network accuracy of +/- 5 cm will not be achieved.

These IGS stations and CORS sites are located throughout the United States. The IGS stations or CORS sites located closest to the project must be used. The following commands are used to access the NGS CORS system:

```
Ftp cors.ngs.noaa.gov
login: anonymous
Password: your complete e-mail address
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The same files are accessible with Web browers (i.e., Mosaic, Netscape, Internet Explorer). The NGS home page is at http://www.ngs.noaa.gov

"Information about A- and B-order stations is given on five sets of CD-ROMs covering the United States." The particular CD-ROM that covers the project area in question can be obtained by contacting NGS' Information Services Branch, 1315 East-West Highway, Silver Spring, Maryland 20910, (301) 713-3242 (voice), (301) 713-4172 (Fax). A limited amount of this information, i.e., the 100 closest stations of any type, can be retrieved from the NGS world wide web site. The electronic bulletin board system and/or web site usually contain new stations that have been added after the CD-ROM was produced.

Analysis of the quality of project data shall be based on repeatability of measurements, adjustment residuals, and analysis of loop misclosures. Please be aware that repeatability and loop misclosures do not disclose all problems.

Observations:

The following requirements are for both 2-centimeter and 5-centimeter standards, unless otherwise stated.

1. Dual-frequency, full-wavelength GPS receivers are required for base lines greater than 10 km and are the preferred type of GPS receiver for all observations, regardless of base-line distance. Geodetic-quality antennas with ground planes are required. Whenever possible, antennas used during a project should be identical; otherwise corrections must be made for antenna phase patterns. Different makes and models of antennas have different antenna phase patterns. If antenna phase patterns are not accounted for, mixing different antennas in a project can cause vertical discrepancies of as much as 10 cm. Some manufacturers are including software packages which correct for the use of different antennas. (It should be noted that choke ring antennas help reduce the effect of multipath and are highly recommended.)

The manufacturer, model, and complete serial numbers of all receivers and antennas must be included on each station Session Observation Log.

2. The survey shall be referenced to at least three existing National Spatial Reference System A- or B-order three-dimensional control stations near the project area. The survey will also consist of at least three primary base stations that are referenced to the three control stations and interspersed throughout the project. The survey will also include secondary base stations and local network stations to meet the spacing requirements in item 5., below. Primary and secondary base stations can be newly established stations in this project.

A sample project with observing scheme is depicted in figure 1 located at the end of the section. A summary of the guidelines is provided in table 1 located at the end of the vector processing section. See Appendix A for more information about control, base, and local network stations.

3. For control stations and primary base stations, receivers shall collect data continuously and simultaneously for at least three, 5-hour sessions on 3 different days during the project.

4. Observation periods for stations other than control stations and primary base stations are as follows:

a. For the 2-Centimeter Standard: Each base line (adjacent station pair) must be occupied for a minimum of 30 minutes per session.

b. For the 5-Centimeter Standard: Observations between primary and secondary base stations must be for a minimum of 30 minutes per session. While there is no minimum observation time for local network stations, each base line (adjacent station pair) must be occupied long enough in each session to ensure that all integers are fixed and the RMS for the base line solution does not exceed 1.5 cm.

5. The observing scheme is based on the GPS survey of marks spaced as indicated below for 2- and 5-centimeter standards. Stations in the scheme

are noted as either control, primary base station, secondary base station, or local network stations. (The observing scheme chosen for a sample project is depicted in figure 1, page 7.)

For the 2-Centimeter Standard: Spacing between local network stations cannot exceed 10 km; the average spacing must be less than or equal to 7 km. Spacing between primary base stations cannot exceed 40 km and spacing between primary and secondary base stations cannot exceed 15 km.

For the 5-Centimeter Standard: Spacing between local network stations cannot exceed 20 km; the average spacing must be less than or equal to 10 km. Spacing between primary base stations cannot exceed 50 km and spacing between primary and secondary base stations cannot exceed 20 km. (Note that secondary base stations may not be required in projects of small areal extent. See Item 2. above.)

6. The observing scheme for all primary base stations requires that each primary base station must be connected to at least its nearest primary base station neighbor and nearest control station according to the observing procedures stated in item 3., above. Primary base stations must be traceable back to two control stations along independent paths.

In addition to this requirement for primary base stations, the observing scheme for all base stations (primary and secondary) requires that each base station be connected with at least its two nearest primary or secondary base station neighbors according to observing procedures stated in item 4., above. For secondary base stations, one of these connections must be to its nearest primary base station neighbor. Secondary base stations must be traceable back to two primary base stations along independent paths.

Local network stations must be traceable back to two base stations along independent paths.

The observing scheme for all stations requires that all adjacent stations (base lines) be observed at least twice on 2 different days and at two different times of the day according to observing procedures shown in item 4. on the previous page. The purpose is to ensure different atmospheric conditions (different days) and significantly different satellite geometry (different times) for the two base line measurements.

Observations on the second day should be completed between 27 and 33 hours after the completion of the first day's observations if the first day's observations were begun prior to 12:00 noon. Or, the observations should be completed between 15 and 21 hours after the completion of the first day's observations if the first day's observations were begun after 12:00 noon. This is necessary since the satellite constellation geometry repeats itself every 12 hours.

Examples:	First-day observations Begun during:	Second-day observations Completed anytime between:
	8:00 a.m. to 8:30 a.m.	11:30 a.m. and 5:30 p.m.
	10:30 a.m. to 11:00 a.m.	2:00 p.m. and 8:00 p.m.
	1:00 p.m. to 1:30 p.m.	4:30 a.m. and 10:00 a.m.
	3:30 p.m. to 4:00 p.m.	7:00 a.m. and 12:30 p.m.

(Note that the second day of observations does not need to follow immediately after the first day. Satellite geometry moves ahead, or precesses, 4 minutes per day. If the second observations are not performed within 1 week of the first, this daily 4-minute change must be accounted for when meeting the different satellite geometry requirement.)

7. Selection of primary and secondary base stations in order of most-to-least- preferred are: 1. High Precision Geodetic Network (HPGN)/HARN (either Federal Base Network (FBN) or Cooperative Base Network (CBN) stations which have level ties to bench marks of A- or B-stability quality during this project; 2. bench marks of A- or B-stability quality or HPGN/HARN stations which were previously tied to bench marks of A- or B-stability quality; 3. User Densification Network (UDN)stations which have level ties made during this project; or 4. bench marks of C stability quality. In areas of known or suspected subsidence or uplift, special guidelines may need to be followed.

8. Data should be collected during periods when the Vertical Dilution of Precision (VDOP) is less than 6 for at least 90 percent of each 30-minute, or longer, observing period. For shorter observing periods, as in some projects where the 5-centimeter standard is the goal, a VDOP greater than 6 should be avoided entirely. Travel between stations could be scheduled during large VDOP periods.

9. For sessions greater than 30 minutes, collect data at 15-second epoch intervals, starting at an even minute. For sessions less than 30 minutes, collect data at 5-second intervals.

10. Track satellites down to at least a 10-degree elevation angle. (Note that tracking below 15 degrees may be helpful during processing when collecting data for less than 30 minutes.)

11. If possible, coordinate observations with local, existing CORS which are collecting phase data with dual-frequency receivers.

12. Meteorological data must be collected at the control stations and primary and secondary base stations. Weather data consist of wet- and dry-bulb temperatures (or dry-bulb temperature and relative humidity) and atmospheric pressure. For sessions greater than 2 hours, record weather data at the beginning, middle, and end of each session. For sessions that are less than 2 hours in length, but more than 30 minutes, record weather data at the beginning and end of each session. For sessions that are less than 30 minutes in length, collect data at the mid-point of the session. Meteorological data shall also be collected immediately after an obvious weather front passes during a session and also immediately before it passes, if possible. Atmospheric pressure measurements must be made at approximately the same height as the GPS antenna phase center. Record on the observing log the time and where the weather data were gathered, and any abnormal weather conditions.

(Note that even though all of these data may not used in the vector processing, they may be helpful during the analysis of the results and in future reprocessing with more robust software.)

Before taking weather observations, the meteorological instruments should be allowed ample time (approximately 10 minutes) to stabilize to ambient conditions. Observations of wet- and dry-bulb temperatures must be observed and recorded to at least the nearest 1 degree Celsius. Barometric readings must be observed and recorded to at least the nearest 1 millibar. Meteorological data should be collected at or near the antenna phase center. All equipment must be checked for proper calibration.

13. Antenna set-up is critical to the success of the project. Plumbing bubbles on the antenna pole of the fixed-height tripod must be shaded when plumbing is performed. Plumbing bubbles must be shaded for at least 3 minutes before checking and/or re-plumbing. The perpendicularity of the poles must be checked at the beginning of the project and any other time there is suspicion of a problem.

For the 2-Centimeter Standard: Fixed-height tripods are required for all receivers.

For the 5-Centimeter Standard: Fixed-height tripods are preferred for all receivers. When a fixed-height tripod is not used, the height of the antenna must be carefully measured to prevent station set-up blunders. Tribrachs used for these set-ups must be checked and adjusted when necessary. Totally independent measurements of the antenna height above mark in both metric units and English units must be made before and after each session. Someone other than the observer must check the measurement computations by carefully comparing measurements and then entering his/her initials on the log.

14. A rubbing of the mark must be made at each occupation of a station. When not feasible to make the required rubbing, a plan sketch of the mark must be substituted, accurately recording all markings.

```
Control Station 1                                   Control Station 2
             Primary Base 1                 Primary Base 3

                LNS 1                              LNS 12

                 LNS 2                            LNS 11

                  LNS 3                          LNS 10

               Secondary Base 1             Secondary Base 2

                    LNS 4                      LNS 9

                     LNS 5                    LNS 8

                      LNS 6                  LNS 7
                               Primary Base 2

                             Control Station 3
```

6 Receivers 3 Control Stations (CS) 3 Primary Base Stations (PBS) 2 Secondary Base Stations (SBS) 12 Local Network Stations (LNS)	**********	One Week of Observations (1 hour travel time)

CS1, CS2, CS3, PBS1, PBS2, PBS3	Days 1,2, and 3 5-hour sessions (8 a.m.- 1 p.m.)
PBS1, LNS1, LNS2, LNS3, SBS1, LNS4	Day 4 30-minute session (8 am - 8:30 am)
SBS1, LNS4, LNS5, LNS6, PBS2, LNS7	Day 4 30-minute session (9:30 am - 10 am)
PBS2, LNS7, LNS8, LNS9, PBS3, LNS10	Day 4 30-minute session (11 am - 11:30am)
PBS3, LNS10, LNS11, LNS12, SBS2, PBS1	Day 4 30-minute session (12:30 pm - 1 pm)
PBS1, LNS1, LNS2, LNS3, SBS1, LNS4	Day 5 30-minute session (12 pm - 12:30 am)
SBS1, LNS4, LNS5, LNS6, PBS2, LNS7	Day 5 30-minute session (1:30 pm - 2 pm)
PBS2, LNS7, LNS8, LNS9, PBS3, LNS10	Day 5 30-minute session (3 pm - 3:30 pm)
PBS3, LNS10, LNS11, LNS12, SBS2, PBS1	Day 5 30-minute session (4:30 pm - 5 pm)

Figure 1.--Sample project observing scheme.

Vector Processing:

The following requirements are for both 2-centimeter and 5-centimeter standards unless otherwise stated. A summary of the guidelines is listed in table 1 at the end of this section.

1. Final vector processing and quality review of collected data shall be accomplished using NGS' program OMNI or other interactive, graphics-producing software which produces results equivalent to OMNI. The vector between adjacent GPS-occupied stations shall be processed using the multi-station processing technique which includes double-difference phase corelations (or equivalent) with a selection of a reference station that minimizes vector lengths.

2. Use precise ephemerides. NGS' precise ephemerides are available from the U.S. Coast Guard Bulletin Board System or the NGS world wide web site. The Coast Guard Bulletin Board System number is (703)313-5910 and the NGS web site address is http://www.ngs.noaa.gov The USCG web site address is http://www.navcen.uscg.mil/navcen.htm

3. For sessions greater than 30 minutes, process data using 30-second epoch intervals. (Note that using a smaller epoch interval may improve ease of data processing.) For sessions less than 30 minutes, process data using 5-second epoch intervals.

4. For sessions greater than 30 minutes, use only satellite data tracked above the 15-degree elevation angle. For sessions less than 30 minutes, use satellite data tracked above the 15-degree elevation angle; data collected below the 15 degree elevation angle should only be used if required to derive a successful solution.

5. Final processing shall consist of fixing all integers for each vector for all sessions except to some control sites. For short base lines, under 10 km, the L1 fixed solution may be the best choice. For vectors greater than 40 km to control sites, a session may consist of a set of partially or completely fixed vectors and in the worst possible scenario may also include float solutions where no integers could be fixed.

A model to account for tropospheric effects must be used. The project report must state which model was used. Measured meterological data should be used only when it has been determined that the instruments have been properly calibrated and the measurements accurately represent the current atmospheric conditions at the station. If standard meteorological data are used instead of actual measured values, the processing software must account for changes in standard default values due to the station's location and height above the vertical datum. For base lines greater than 15 kilometers or with "large" height differences, a relative tropospheric scale parameter should be solved for, along with the base line vector components.

6. The quality of collected data shall be determined from the double-difference residual plots and RMS values. Final coordinates and their quality assessment shall be determined by using least-squares adjustment software and by analysis of repeated vectors and free-adjustment residuals and loop misclosures (most loops consisting of repeated vectors).

7. RMS values for each computed base line (adjacent station pairs) must not exceed 1.5 cm.

8. Reobservation criteria:

For the 2-Centimeter Standard: For local network requirements, must reobserve any base line (adjacent station pair) where the difference in ellipsoid height between the repeat observations exceeds 2.0 cm. For station pairs involving control stations, must reobserve any control station base line where the ellipsoid height difference between the repeat observations exceeds 5.0 cm.

For the 5-Centimeter Standard: Must reobserve any base line (adjacent station pair) or control station pair where the ellipsoid height difference between the repeat observations exceeds 5.0 cm.

When reobserving base lines that exceed tolerance values, the new observation must agree with an old base line which was observed using the criteria in number 6. of the Observations section above, i.e., the two base line measurements must contain significantly different satellite geometry.

Table 1. -- Summary of Guidelines.

	Control 2 and 5 cm	Primary Base 2 cm	Primary Base 5 cm	Secondary Base 2 cm	Secondary Base 5 cm	Local Network 2 cm	Local Network 5 cm
Dual Frequency Required	Yes, if base line is greater than 10 km	Yes, if base line is greater than 10 km	Yes, if base line is greater than 10 km	Yes, if base line is greater than 10 km	Yes, if base line is greater than 10 km	Yes, if base line is greater than 10 km	Yes, if base line is greater than 10 km
Geodetic Quality Antenna with Ground Plane	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Min. Number of Stations	3	3	3	No Minimum	No Minimum	No Minimum	No Minimum
Occupation Time	5 Hours	5 Hours	5 Hours	30 Minutes 1	30 Minutes 1	30 Minutes 1	No Minimum 1
Number of Days Station is Occupied	3	3	3	2 2	2 2	2 2	2 2
Max. Distance Between Same or Higher-Order Stations	75 km	40 km	50 km	15 km	20 km	10 km	20 km
Average Distance Between Stations	No Maximum	No Maximum	No Maximum	No Maximum	No Maximum	7 km	10 km
Repeat "Base Line"	YES 3	YES 3	YES 3	YES 3	YES 3	YES 3	YES 3
Collect Met Data	Yes	Yes	Yes	Yes	Yes	No	No
Fixed Height Pole	Yes	Yes	No	Yes	No	Yes	No
Rubbing of Mark	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Precise Ephemerides	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Fix Integers	Yes 4	Yes 5	Yes 5	Yes	Yes	Yes	Yes

Notes for Table of Summary of Guidelines:

1 Analyses have indicated that when following all guidelines in this document, 30 minutes of observations over base lines that are typically less than 10 kilometers will meet the standards. For base lines greater than 10 km, but less than 15 km, 1 hour sessions should meet the standards. For observing sessions greater than 30 minutes, collect data at 15-second epoch interval. For sessions less than 30 minutes, collect data at 5-second epoch interval. Track satellites down to at least 10-degree elevation cut-off.

2 Base lines must be reobserved on different days with significantly different satellite geometry.

3 The observing scheme requires that all adjacent stations have base lines observed at least twice on two different days with significantly different geometry.

4 If base line is greater than 40 kilometers, a partially fixed or float solution is permitted.

Data Submission to NGS:

1. The project accession number is of the form GPS-xxx. (The project accession number will be assigned by NGS when draft project plans are submitted to NGS for evaluation prior to the start of the project.)

2. A project report and the data elements listed in Appendix L of "Input Formats and Specifications of the NGS Data Base" must be transmitted to NGS. Quality checks for conformance to NGS format standards shall be performed using software programs COMPGB and OBSDES.

3. Latitude, longitude, and ellipsoid heights, as well as X, Y, and Z coordinates shall be provided in both NAD 83 and ITRF coordinate systems. See Appendix C for more information on transformation parameters and related information.

Guideline Updates:

These Guidelines will be updated as the results of future projects and other procedures are reviewed. There are other procedures that will also achieve the standards. The user should note which procedures in this document were not followed and note how errors and systematic biases were detected, reduced, or eliminated by the new procedure. NGS welcomes the opportunity to examine alternate procedures and supporting data that demonstrate the ability to achieve the accuracy standards stated in this document. If you have such data or would like to comment, please contact Dave Zilkoski or Steve Frakes, telephone 301-713-3191, or write:

National Geodetic Survey, N/NGS2
NOAA, 1315 East-West Highway
Silver Spring, Maryland 20910-3282
email: davez@ngs.noaa.gov or
steve@ngs.noaa.gov

Appendix A. -- Definitions

Accuracy

Local Accuracy - The local accuracy of a control point is a value expressed in cm that represents the uncertainty in the coordinates of the control point relative to the coordinates of the other directly connected, adjacent control points at the 95 percent confidence level. The reported local accuracy is an approximate average of the individual local accuracy values between this control point and other observed control points used to establish the coordinates of the control point.

Network Accuracy - The network accuracy of a control point is a value expressed in cm that represents the uncertainty in the coordinates of the control point with respect to the geodetic datum at the 95 percent confidence level. For National Spatial Reference System (NSRS) network accuracy classification, the datum is considered to be best supported by NGS. By this definition, the local and network accuracy values at CORS sites are considered to be infinitesimal, i.e., to approach zero.

Stations

Base Stations

Primary - Stations evenly distributed that surround the local network. These stations relate the local network to NSRS to the 5-cm, or better, standard through simultaneous observations with control stations. They can be newly established stations and be part of the local network.

Secondary - Stations evenly distributed throughout the local network that ensure that the local network does not contain a significant medium wavelength (20-30 km) ellipsoid height error through simultaneous observations with primary base stations. These stations may be newly established stations and are part of the local network. They are located between Primary Base Stations.

Control Stations

A- or B-order three-dimensional stations that surround the project area in at least three different quadrants. These stations relate the local network to the National Spatial Reference System through simultaneous observations with primary base stations. They must be referenced to NSRS and they provide the network accuracy. They may be newly established stations in the survey project if A- or B-order specifications and procedures are used to establish them. These procedures are not covered in this document, please contact NGS for additional information.

Local Network Stations

These stations include all other stations that are not base (primary or secondary) or control stations. They are part of the local network. They provide the local accuracy standard through simultaneous observations between adjacent stations.

Appendix B. -- GPS Ellipsoid Height Hierarchy and Basic Requirements for 2-cm standard

HARN/Control Stations

(75 km)

Primary Base

(40 km)

Secondary Base

(15 km)

Local Network Stations

(7 to 10 km)

HARN/Control Stations

O CS1

O CS2 <--------------------75 km------------------> O CS3

Primary Base Stations

O CS1

PB1

PB2 <----------------------40 km--------------------->PB3

O CS2 CS3 O

Basic Requirements

- o 5 Hour Sessions / 3 Days
- o Spacing between primary base stations cannot exceed 40 km.
- o Each primary base station must be connected to at least its nearest primary base station neighbor and nearest control station.
- o Primary base stations must be traceable back to 2 control stations along independent paths; i.e, base lines PB1 - CS1 and PB1 - PB2 plus PB2 -CS2, or PB1 - CS1 and PB1 - PB3 plus PB3 - CS3.

Secondary Base Stations

O

PB1

SB1 SB2

SB3 <---------- 15 km ---------- > SB4

PB2 PB3

O O

Basic Requirements

- o 30 Minute Sessions / 2 Days / Different times of the day
- o Spacing between secondary base stations (or between primary and secondary base stations)cannot exceed 15 km.
- o All base stations (primary and secondary) must be connected to at least its two nearest primary or secondary base station neighbors.
- o Secondary base stations must be traceable back to 2 primary base stations along independent paths; i.e., SB1- PB1 and SB1- SB3 plus SB3 - PB2, or SB1 - PB1 and SB1 - SB4 plus SB4 - PB3.
- o Secondary base stations need not be established in surveys of small areal extent.

```
                    Local Network Stations

                             O

                            PB1

                            LN1

                SB1         LN2      LN3         SB2

                LN4                              LN5

                         LN6<--7 km -> LN7
                SB3                              SB4

          PB2                                          PB3

      0                                                      0
```

Basic Requirements

- o 30 Minute Sessions / 2 Days / Different times of the day
- o Spacing between local network stations stations (or between base stations and local network stations) cannot exceed 10 km.
- o All local network stations must be connected to at least its two nearest neighbors.
- o Local network stations must be traceable back to 2 primary base stations along independent paths; i.e., LN1 - PB1 and LN1 - LN2, plus LN2 - SB1, plus SB1 - SB3 plus SB3 - PB2, or LN1 - PB1 and LN1 -LN3, plus LN3 - SB2 plus SB2 - SB4 plus SB4 - PB3.

APPENDIX C.--ITRF TO NAD 83 TRANSFORMATION PARAMETERS

Introduction

The International Earth Rotation Service Terrestrial Reference Frame (ITRF) has become an important coordinate system for users of Global Positioning System (GPS) technology. Both GPS and ITRF are global, geocentric coordinate systems. The ITRF coordinate system supports GPS orbit computations and provides a basis for more precise GPS data reduction computations. Also, for many applications it is necessary to use a coordinate system such as ITRF to account for the motions of the Earth's crust. Published ITRF solutions provide not only coordinate values at a particular epoch in time, but station velocities as well. Thus, up-to-date ITRF station coordinate values can be computed for future epochs in time after the original solution.

The North American Datum of 1983 (NAD 83), on the other hand, has the advantage of being fixed and stable relative to the North American tectonic plate. Additionally, NAD 83 has been officially adopted by the Federal government as the coordinate system for mapping and charting in the Unites States. Therefore, the relationship of ITRF to regional or continental datums like NAD 83 is of utmost importance to GPS users.

The following background information on NAD 83 should help understanding the differences, systematic and otherwise, between ITRF and NAD 83.

NAD 83 Datum Definition

The NAD 83 adjustment combined terrestrial data (distances, azimuths, and direction observations) with space-based data, such as 3-D positions derived from satellite Doppler observations and 3-D inter-station vectors obtained from Very Long Baseline Interferometry (VLBI).

Along with these data, and equally important, was a set of implied constraints that defined the scale and orientation of NAD 83. Also included in the NAD 83 adjustment was a set of global parameters that allowed the implied constraints to have complete influence. An example would be that of a distance observation which has implied scale, but if a global scale parameter is included in its observation equation, it allows the scale to be determined elsewhere. Table 1 shows the global parameters for the NAD 83 adjustment:

Table 1.--Global parameters - NAD 83 adjustment.

Parameter	Terrestrial	Doppler	VLBI
X Shift		F	
Y Shift		F	
Z Shift		F	
X Rotation		F	A
Y Rotation		F	A
Z Rotation	F	A	A
Scale	A	F	A

F=fixed parameter
A=estimated parameter

The above table shows that the 3-D positions derived from Doppler observations defined the geocentricity, scale, and the major part of the orientation of the NAD 83 datum.

The VLBI vectors are very important for several reasons. To begin with, the VLBI vectors are extremely precise. These vectors span the continent and are found to be internally consistent at the 2-3 cm level. Second, the VLBI stations and data are an integral part of the ITRF solutions and thus provide a link between NAD 83 and ITRF. Third, although the VLBI vectors were not used to help define the NAD 83 scale and orientation, the adjusted values for global parameters associated with the VLBI vectors tell how they were changed. This provides a quantitative measure of the systematic difference between NAD 83 and coordinate systems based on VLBI.

Table 2.--Adjusted values for VLBI global parameters.

Parameter	Value
X Rotation	0.022 arc seconds
Y Rotation	0.026 are seconds
Z Rotation*	0.010 arc seconds*
Scale Change	-0.075 ppm

*The actual adjusted value of the Z rotation was 0.375 arc seconds, however there was a post-adjustment correction of 0.365 arc seconds applied, resulting in the 0.010 arc seconds shown above. In effect the coordinate system was rotated to be more consistent with the VLBI observations.

NAD 83 Upgrade Surveys

In 1988, the National Geodetic Survey (NGS) began to upgrade the NAD 83 coordinates by performing high accuracy reference network (HARN) GPS surveys. This is being done on a state-by-state basis. The strategy for determining the control for these upgrades follows. First consider the following (X, Y, Z) transformation, designated equation 1:

$$Xn = Tx + (1 + S)Xi + RzYi - RyZi$$

$$Yn = Ty - RzXi + (1 + S)Yi + RxZi$$

$$Zn = Tz + RyXi - RxYi + (1 + S)Zi$$

This equation defines a seven-parameter transformation from ITRF to NAD 83, where (Xi, Yi, Zi) denote geocentric cartesian coordinates in ITRF and (Xn, Yn, Zn) denote geocentric cartesian coordinates in NAD 83.

In order to establish control stations for the new HARN GPS surveys, NGS completed the following:

1. NGS used a set of 12 VLBI stations located in North America to determine a seven-parameter transformation (equation 1) from ITRF89 (epoch 1988.0) to NAD 83 (see table 3).

2. NGS decided to accept the scale of ITRF89 as being closer to the true value.

3. The derived transformation parameters, translations, and rotations, but NOT scale, were applied to the complete set of ITRF89 positions to get NAD 83 values with corrected scale. A comparison with the original NAD 83 coordinates showed a change in ellipsoid height of 0.6 meters, which was caused by scale differences.

Table 3.--Transformation parameters, ITRF89 (Epoch 1988.0) to NAD 83.

Parameter	Value
Tx = X Shift	0.9191 meters
Ty = Y Shift	-2.0182 meters
Tz = Z Shift	-0.4835 meters
Rx = X Rotation	0.0275 arc seconds
Ry = Y Rotation	0.0155 arc seconds
Rz = Z Rotation	0.0107 arc seconds
S = Scale Change	-0.0871 ppm [See item 3) above.

Apparent in Table 3 is the similarity of the values for the rotations and scale with those in Table 2. This indicates that the coordinate system of the original VLBI vectors is very similar to ITRF.

Computations of GPS Data in ITRF

Several other solutions of ITRF have been computed by the International Earth Rotation Service since the publication of ITRF89. As more and more data have been collected and included in the ITRF solutions, the resulting coordinates and velocities have increased in accuracy. Confidence in ITRF has grown to the point that most geodetic organizations throughout the world now use ITRF as a basis for GPS orbit computations.

An important concept for the GPS user community to understand is that since GPS precise orbits are referred to ITRF, fixed orbit solutions of GPS produce vectors that are oriented in the ITRF coordinate system. However, most of the user community is working in NAD 83. The systematic differences between ITRF and NAD 83 must be accounted for, if high accuracy is to be maintained.

Since we are dealing with inter-station vector components, instead of positional coordinates, we need not worry about X, Y, Z shifts. Also, recall that the scale of NAD 83 was corrected when the high accuracy GPS survey began. But the X, Y, Z rotations between ITRF and NAD 83 must be accounted for. NGS adjustment software ADJUST does just that. ADJUST accepts GPS vectors expressed in ITRF as well as other coordinate systems as input, then, internal to the program, applies the X, Y, Z rotations to convert to NAD 83.

Table 4 describes transformation parameters between NAD 83 and some more recent solutions of ITRF.

Table 4.--Transformation parameters: ITRF solutions to NAD 83.

Parameter	ITRF93 (Epoch 1995.0)	ITRF94 (Epoch = E, in years)
Tx = X Shift	0.9769	0.9738 meters
Ty = Y Shift	-1.9392	-1.9353 meters
Tz = Z Shift	-0.5461	-0.5486 meters
Rx = X Rotation	0.0264	0.02755 + 0.00009(E-1996.0) arc sec
Ry = Y Rotation	0.0101	0.01005 - 0.00077(E-1996.0) arc sec
Rz = Z Rotation	0.0103	0.01136 + 0.00002(E-1996.0) arc sec
S = Scale Change	0.0	0.0 ppm

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