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## Guidelines for Establishing GPS-Derived Orthometric Heights

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# Contents

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Version 1.5

## Preface

In November 1997, the National Geodetic Survey (NGS) published guidelines for performing Global Positioning System (GPS) surveys intended to achieve **ellipsoid height *network* accuracies** of 5 cm and **ellipsoid height *local* accuracies** of 2 cm or 5 cm (Zilkoski et al. 1997). The official definitions of "local" and "network" accuracy as used here, are those adopted by the Federal Geodetic Control Subcommittee (FGCS, 1998) of the Federal Geographic Data Committee,

NGS developed the following guidelines for performing GPS surveys intended to achieve **orthometric height *network* accuracies** of 5 cm and **orthometric height *local* accuracies** of 2 cm or 5 cm. The guidelines were developed in partnership with Federal, state, and local government agencies, academia, and independent surveyors.

Unlike the guidelines for establishing ellipsoid heights (Zilkoski et al. 1997), this document must be more "loose" in its tone, as there are no requirements, mandates, or standards. The reasons there are no standards are as follows:

1) This document is not founded on a comprehensive scientific study, but rather on the expertise of many individuals within NGS who have processed GPS-derived orthometric height projects.
2) The "validation" of the North American Vertical Datum of 1988 (NAVD 88) heights may be called into question because:
    a. The realization of NAVD 88 exists exclusively on passive marks not tracked regularly in time (unlike CORS).
    b. The gravity field of Earth changes over time, so even if NAVD 88 benchmark re-leveling was regularly performed, the use of aged gravity data to compute orthometric corrections would have errors dependent on the local change of gravity since 1988.
    c. Benchmarks disappear due to widespread construction.

Nonetheless, general methodologies for performing campaign-style GPS surveys for the distribution of NAVD 88 orthometric heights have been in existence for years, and this document seeks to codify some *general rules* on those surveys.

Readers may rightly ask why campaign-style guidelines are needed in an era when NGS' Online Positioning User Service (OPUS) yields "peak-to-peak" consistency in ellipsoid heights at the 2-3 cm level, with as little as 15 minutes of GPS data (roughly equal to a network accuracy of 4-6 cm), and the latest hybrid geoid models of NGS have "local accuracies" as small as 1 cm over 10 km in some states. The answer is simply that using tools such as OPUS and hybrid geoids to achieve NAVD 88 Helmert orthometric heights will achieve 5-cm network accuracies only *rarely*, and 2-5 cm local accuracies *occasionally* (due to the combined errors of both the GPS and geoid). In contrast, the campaign-style guidelines contained in this document are intended to achieve those accuracies *almost always*. When tools such as OPUS and hybrid geoid models can single-handedly achieve a similar success rate, these guidelines should certainly be modified to reflect those results.

These guidelines were designed to assist in establishing *vertical control networks on passive geodetic marks*. Following the guidelines may produce the intended accuracies, however the intended accuracies may be achieved with less effort than these guidelines suggest. Ultimately, the baseline comparison and adjustment results will confirm proof of accomplishment.

If, after performing a survey, a surveyor wishes to submit data to NGS for consideration of its inclusion in the NGS Integrated Database (NGS IDB), detailed discussion of field and office procedures should be documented in the project report provided with the data submissions. The documentation will provide the additional advantage of enabling NGS to analyze procedures and results meriting modifications to the guidelines.

## Introduction

Since 1983, NGS has performed control survey projects in the United States using GPS surveying techniques. Analysis of the survey data has shown that GPS can be used to establish precise relative positions in a three-dimensional, Earth-centered coordinate system. GPS carrier-phase measurements are used to determine vector base lines in space, where the components of the base line are expressed in terms of Cartesian coordinate differences ($\Delta x$, $\Delta y$, and $\Delta z$) (Remondi 1984). The vector base lines can be converted to ellipsoidal coordinate (latitude, longitude and height) differences ($\Delta \phi$, $\Delta \lambda$ and $\Delta h$) relative to a defined reference ellipsoid.

When the use of GPS technology began, project results clearly showed that GPS survey methods could replace classical horizontal control terrestrial survey methods. There was a problem, however, in obtaining sufficiently accurate geoid heights to convert GPS-derived ellipsoid height differences to accurate GPS-derived orthometric height differences (Zilkoski and Hothem 1989, Hajela 1990, Milbert 1991). The interest in obtaining accurate GPS-derived orthometric heights has increased in the last decade (Parks and Milbert 1995, Kuang et al. 1996, Satalich 1996, Zilkoski and D'Onofrio 1996, Henning et al. 1998, Martin 1998). Simultaneously, research at NGS began concentrating on customizing geoid models specifically for use as a converter between the North American Datum of 1983 (NAD 83) ellipsoid heights and NAVD 88 Helmert orthometric heights (Smith and Milbert 1999, Smith and Roman 2001).

*With the improvement in both GPS-derived ellipsoid heights and geoid models, the driving question at NGS became "Can the accuracies achieved for GPS-derived* ***orthometric*** *height differences now provide a viable alternative to classical geodetic leveling techniques?"* With the completion of the general adjustment of the North American Vertical Datum of 1988 (NAVD 88) (Zilkoski et al. 1992), computation of an accurate national high-resolution geoid model (currently GEOID03, with new models under development) (Roman et al. 2004), and publication of NGS' Guidelines for Establishing GPS-Derived Ellipsoid Heights (Standards: 2 cm and 5 cm) (Zilkoski et al. 1997), the answer was yes! GPS-derived orthometric heights can provide a viable alternative to classical geodetic leveling techniques for many applications.

Orthometric heights (H) are defined as the geometric distance, measured along the plumb line, from the geoid to a point of interest above. Ellipsoid heights (h) are defined as the geometric distance, measured along a normal straight line to a reference ellipsoid, from the reference ellipsoid to a point of interest above. The geoid height (or geoid undulation, N) is defined as the geometric distance, measured along a normal straight line to a reference ellipsoid, from the reference ellipsoid to a point on the geoid above. See Figure 1 for an example of these three quantities.

Although the plumb line and ellipsoidal normal do not perfectly coincide in space, the non-coincidence is negligible at the sub-millimeter level for heights within the United States, and an equation relating ellipsoid height, orthometric height, and geoid height (to sub-millimeter accuracy) may be written as:

$$h \approx H + N \qquad (1)$$

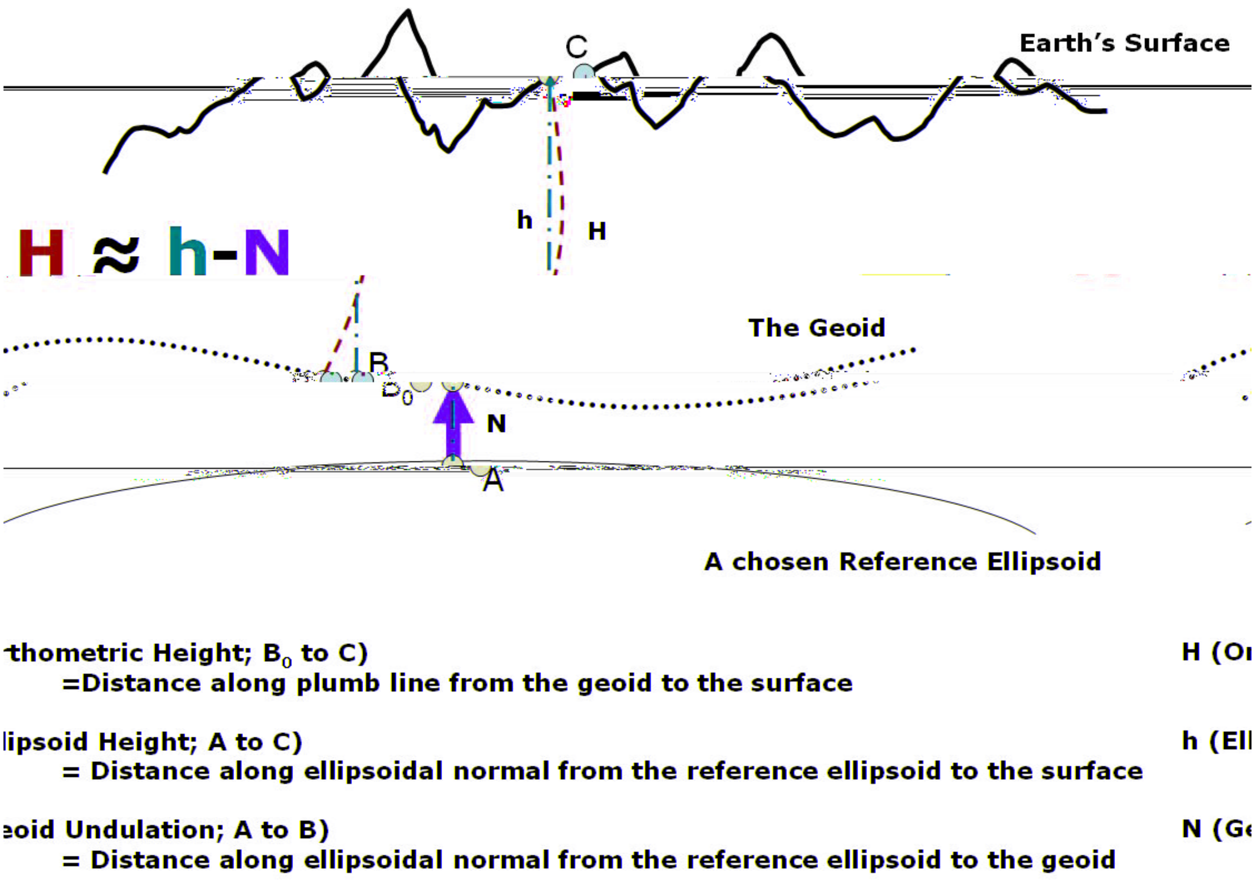


**Figure 1: Relationship between Orthometric, Ellipsoid and Geoid Heights**

Several error sources affecting the accuracy of orthometric, ellipsoid, and geoid height values are generally common to points near one another. Because the error sources are in common, the uncertainty of height differences between nearby points is significantly smaller than the uncertainty of the *absolute* heights of each point.

Orthometric height differences ($\Delta H$) can be obtained from ellipsoid height differences ($\Delta h$), by subtracting the geoid height differences ($\Delta N$):

$$\Delta H \approx \Delta h - \Delta N \qquad (2)$$

Adhering to NGS' earlier guidelines, ellipsoid height differences ($\Delta h$) over short base lines, i.e., not more than 10 km, can now be determined to better than +/- 2 cm (at the 95% confidence level) from GPS carrier phase measurements. This accuracy is possible because of the availability of a greater number of satellites; more accurate satellite orbits; dual-frequency carrier phase data; improved antenna designs; more continuously operating reference stations (CORS) serving as geodetic control; and improved data processing techniques.

The GPS-derived ellipsoid height guidelines (Zilkoski et al. 1997) were intentionally designed to produce ellipsoid heights better than 2 cm, i.e. approximately 1.4 cm, so they could also be used to generate 2 cm

GPS-derived orthometric heights. If the spacing between local network stations is kept under 10 km, this helps keep the relative error in geoid height small; i.e., typically less than 0.5 cm.
See figure 2.

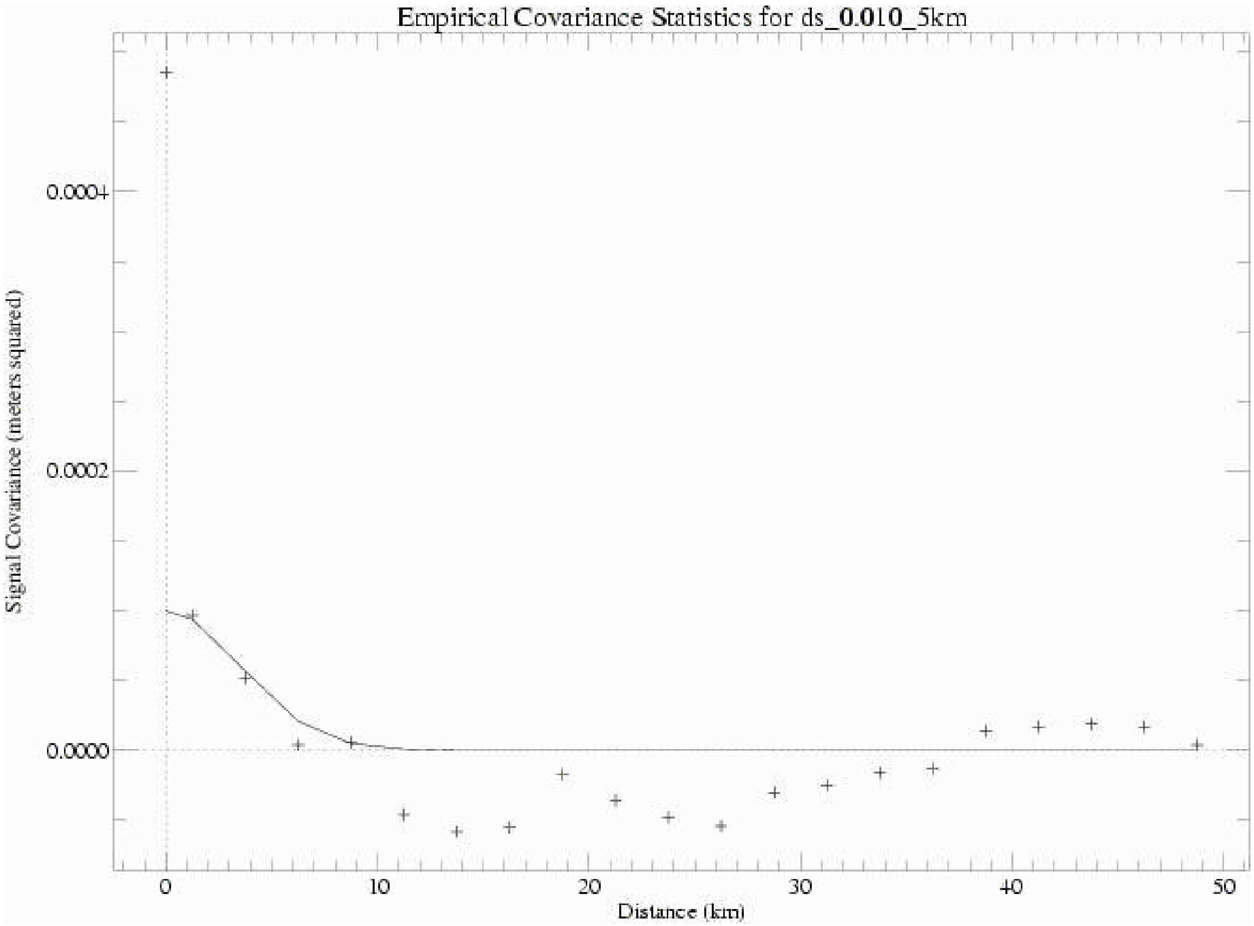


**Figure 2: Empirical and Modeled Residual Error for GEOID03, showing de-correlation at 10 km.**

Adding a small error for the uncertainty of geoid height differences and controlling remaining systematic differences between the three height systems will typically produce a GPS-derived orthometric height with +/- 2 cm local accuracy.

Geoid height differences can be determined (in select areas nationally) with uncertainties typically better than 1 cm for distances up to 20 km, and less than 2-3 cm for distances between 20 and 50 km (Zilkoski and D'Onofrio 1996, and Henning et al. 1999). Small values for the differential geoid height uncertainties have been demonstrated in tests in several regions of the United States. Larger uncertainties can be expected in other areas, depending on the density of the observed gravity network, uncertainties in the determination of gravity anomalies, and errors inherent in geoid computational theory. Determining uncertainties in geoid height differences, through a comparison of leveled and GPS height differences, depends on the error sources in the leveled and GPS height differences (and any correlations between the two). That is, applying error propagation to equation 2, the errors in differential geoid undulations computed directly from differential GPS derived ellipsoid heights and differential orthometric heights is:

$$\sigma_{\Delta N}^2 = \sigma_{\Delta h}^2 + \sigma_{\Delta H}^2 - 2\sigma_{\Delta H,\Delta h} \quad (3)$$

The covariance between differential orthometric and differential ellipsoid heights are often considered zero in the above equation.

The NGS guidelines allow the user to estimate a-posteriori GPS-derived ellipsoid height errors (Zilkoski et al. 1997). Analysis of the leveling and geoid errors is more complex and must be addressed on a case-by-case basis. With a high resolution geoid model, currently GEOID03, and valid (having a publishable height in the NGS IDB) NAVD 88 heights, surveys in most non-mountainous regions of the conterminous United States will produce sub-decimeter results when these GPS-derived orthometric height guidelines are followed.

**Note: The term "user" in this document refers to a person using geodetic quality GPS surveying techniques and/or analysis of GPS data to determine height and position information.**

When high-accuracy field procedures for precise geodetic leveling are used, Helmert orthometric height differences can be computed with an uncertainty of less than 1 cm over a 50-kilometer distance. Depending on the accuracy requirements, GPS surveys and current high-resolution geoid models can be used instead of classical leveling methods. In the past, the primary limiting factor was the accuracy of estimating geoid height differences; with the computation of the latest national high-resolution hybrid geoid model (currently GEOID03), and the development of the 2- and 5-cm guidelines for estimating GPS-derived ellipsoid heights (Zilkoski et al. 1997), the limiting factor is often the lack of valid NAVD 88 Helmert orthometric heights available for vertical control. Strategically, occupying (with GPS) bench marks having valid NAVD 88 Helmert orthometric height values is critical to detecting, reducing, and/or eliminating blunders and systematic errors between the three height systems.

## The 3-4-5 System

There are three basic rules, four control suggestions, and five procedures necessary for estimating GPS-derived orthometric heights. Detailed explanations can be found in the referenced reports.

### Three Basic Rules

**Rule 1**: Follow NGS' guidelines for establishing GPS-derived ellipsoid heights when performing the GPS survey (Zilkoski et al. 1997). Follow the specific guidelines for **desired orthometric heights**. For example, use the guidelines for achieving **2 cm** GPS-derived ellipsoid heights for 2 cm orthometric heights, and the guidelines for **5 cm** GPS-derived ellipsoid heights for 5 cm orthometric heights.

**Rule 2**: Use NGS' latest national hybrid geoid model, currently GEOID03 (Roman et al. 2004), when computing GPS-derived orthometric heights.

**Rule 3**: Use the latest National Vertical Datum, i.e., NAVD 88, height values to control the project's adjusted orthometric heights (Zilkoski, et al. 1992).

### Four Basic Control Suggestions

**Suggestion 1**: Occupy stations with ***valid*** NAVD 88 orthometric heights. Stations should be evenly distributed throughout the project. A previously determined GPS-derived orthometric height, accurate to

2 cm, *is* considered a 'valid' NAVD 88 height, if it has a publishable Helmert orthometric height in the NGS database.

**Suggestion 2**: For project areas less than 20 km on a side, surround project with **valid** NAVD 88 bench marks, i.e., with a minimum of four stations, with one in each corner of project.

**Note: The project area may need to be enlarged to occupy a sufficient number of bench marks, even if the area extends beyond the original area of interest.**

**Suggestion 3**: For project areas greater than 20 km on a side, keep distances between **valid** GPS-occupied NAVD 88 bench marks to less than 20 km.

**Note: When possible, occupy extra NAVD 88 bench marks for redundancy checks.**

**Suggestion 4**: For projects located in mountainous regions, occupy **valid** bench marks that are at both the lowest elevation and the highest elevation in the area, even if the distance is less than 20 km. Consider adding additional bench marks to get a good range of elevation change.

**Five Basic Procedures**

**Procedure 1**: Perform a 3-D, minimum-constraint, least squares adjustment (of Helmert orthometric heights) for the GPS survey project, i.e., constrain the latitude and longitude of one NSRS control station and one Helmert orthometric height value.

**Procedure 2**: Detect and remove all data outliers, i.e., "high" residuals, for a base line using the results from the adjustment in procedure 1 above.

**Note: The user should repeat procedures 1 and 2 until all data outliers are removed.**

**Procedure 3**: Compute differences between the set of GPS-derived orthometric heights from the minimum constraint adjustment (using the latest national geoid model, currently GEOID03), from procedure 2 above and published NAVD 88 orthometric heights.

**Procedure 4**: Using the results from procedure 3 above, the user should determine which NAVD 88 control stations have residuals small enough to be considered ***"valid"*** for the purposes of their survey. This is the most important step of the process. Determining which bench marks have valid heights is critical to computing accurate GPS-derived orthometric heights.

All differences between GPS observations on valid bench marks need to agree within 2 cm for 2-cm surveys and 5 cm for 5-cm surveys.

**Note: For most small area projects, (e.g., 20 km by 20 km, in the conterminous United States) using NGS' latest hybrid geoid model should produce satisfactory results (see Henning et al. 1998).**

Large areas (i.e. 50 km by 50 km) may have a systematic tilt, possibly caused by a difference between the hybrid geoid model and local NAVD 88 control. However, the purpose of these procedures is to disseminate NAVD 88 Helmert orthometric heights constrained to local control, so the reason behind the tilt is immaterial to this process.The simple removal of such a plane will allow a better fit to local control, but it does not necessarily guarantee anything more than values which fit locally. No guarantees regarding absolute accuracy can be made in such a procedure. However, for detecting NAVD 88 height outliers, the user should estimate local systematic differences between GPS-derived heights and leveling-derived heights by solving and removing the systematic difference *[See Vincenty (1987) and Zilkoski (1993)]*.

**Procedure 5**: Using the results from procedure 4 above, perform a constrained orthometric height adjustment by fixing the latitude and longitude of one NAD 83 control station and all "***valid***" NAVD 88 heights.

The user should always ensure that the final set of heights is not overly distorted by the adjustment process. Distortions of this nature should not occur if the procedures outlined above are followed, however if they are, NGS should be contacted in case discrepancies in the local control are the root cause.

To check the influence of additional constraints on the network, compute the differences between the fully-constrained set of GPS-derived orthometric heights from procedure 5 and the minimally constrained set of heights from procedure 2. The comparison of the two sets of orthometric height differences between neighboring stations should not have large (i.e. > 1 cm) differences (see Henning et al. 1998). If the differences exceed 2 cm, it is possible an incorrect or invalid vertical control value was held fixed.

NGS has prepared several reports describing the procedures in more detail (Zilkoski and Hothem 1989; Zilkoski 1990a; Zilkoski 1990b; Zilkoski 1993; and Henning, et al. 1998). The reports are available from NGS' Web site at www.ngs.noaa.gov/PUBS_LIB/pub_index.html.

Due to improvements in high resolution geoid models, implementation of the full constellation of GPS, completion of the NAVD 88 project, improvements in GPS equipment and processing software, and the development of guidelines for estimating GPS-derived ellipsoid heights, the steps outlined in the above reports need to be considered **only** when a problem is detected during the performance of the five procedures. However, the reports, although slightly outdated (because of improvements in geoid models and technology), should provide the necessary information for the user to understand how to perform the five procedures stated in these guidelines. In particular, the report titled "NGS/Caltrans San Diego GPS-Derived Orthometric Height Cooperative Project" (Zilkoski, 1993) demonstrates the minimum steps required to estimate and evaluate a GPS-derived orthometric height project. Today, the ten steps are simplified into five procedures, but they may still need to be considered for some projects.

## Guideline Updates

These Guidelines are likely to be updated as results from future projects and other (modified) procedures are reviewed. Other procedures may also achieve the standards. The contributor should note which procedures in this document were not followed and how errors and systematic biases were detected, reduced, or eliminated by the alternate procedure. NGS welcomes the opportunity to examine alternate procedures and supporting data demonstrating the ability to achieve the accuracy standards stated in this document. If you have such data or would like to discuss alternative procedures, please contact Dave Zilkoski, Edward Carlson, or Curt Smith.

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**State Geodetic Advisors**

Many states have a geodetic advisor whose objective is to enable others to contribute data to, and utilize data of, the NSRS. Because they may be aware of problematical vertical control areas within their jurisdiction, it can be productive to engage in discussions with the advisor. To locate an advisor near your area of interest, refer to www.ngs.noaa.gov/ADVISORS/AdvisorsIndex.shtml.

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# Appendix A: Definitions

## Stations

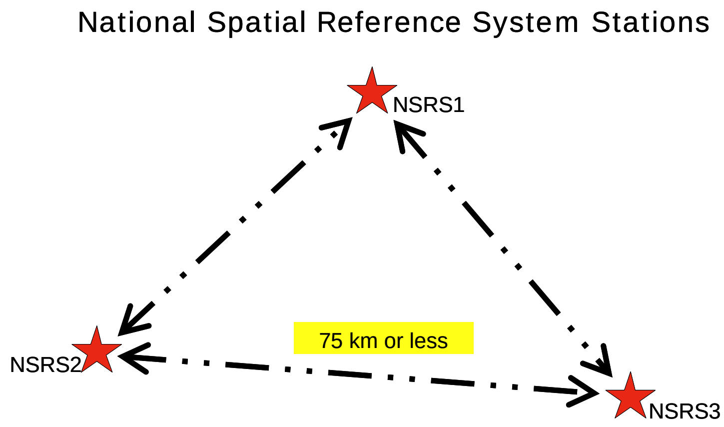
**NSRS Stations**
(~75 km spacing) High accuracy NAD 83 three-dimensional stations (CORS, FBN, HARN stations) surrounding the project area in a minimum of three different quadrants. Stations assist in providing the network accuracy, and they may be newly established stations in the survey project, if specifications and procedures are used to establish them. These procedures are not covered in this document.

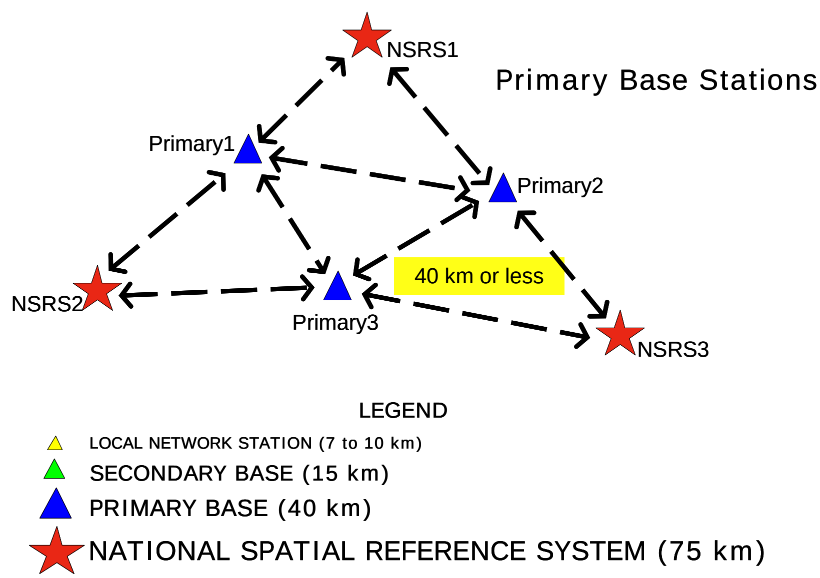
**Primary Base Stations**
(~40 km spacing) Evenly distributed stations surrounding the local survey. These stations relate the local network to NSRS to the 5-cm, or better, standard through simultaneous observations with NSRS control stations. They may be newly established stations, and they may be part of the local network.

**Secondary Base Stations**
(~15 km) Stations are evenly distributed throughout the local network to ensure 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.

**Local Network Stations**
(<10 km) Stations that are not primary or secondary base stations, but 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 Guidelines



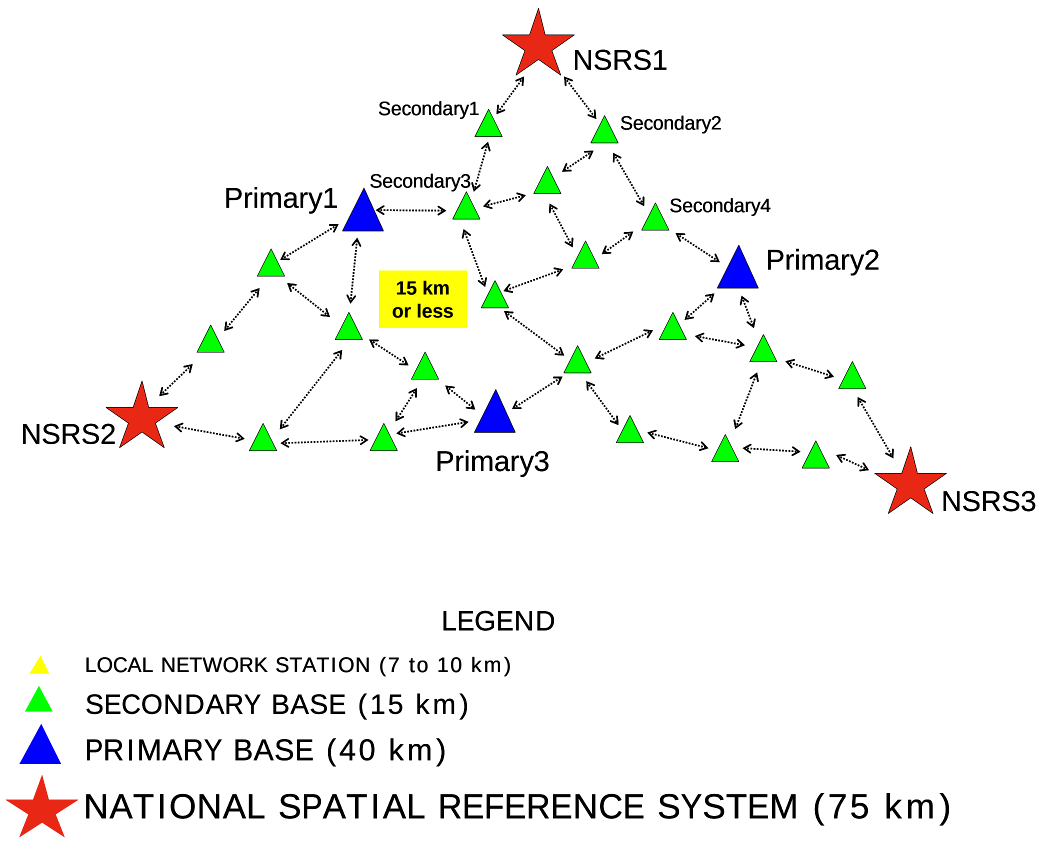




**Basic Guidelines for Establishing Primary Base Stations:**

- 5 hour sessions for three days
- Spacing between primary base stations should not exceed 40 km.
- Each primary base station should have observational vectors connecting it to at least its nearest primary base station neighbor and nearest NSRS control station.

  Primary base stations should be traceable back to two NSRS control stations along completely independent paths; i.e, base lines **Primary1-NSRS1** and **Primary1-NSRS2**, or **Primary1-Primary2 plus Primary2-NSRS3**.

## Secondary Base Stations




**Basic Guidelines for Establishing Secondary Base Stations:**

- 30 minute sessions / 2 days / significantly different satellite geometry.

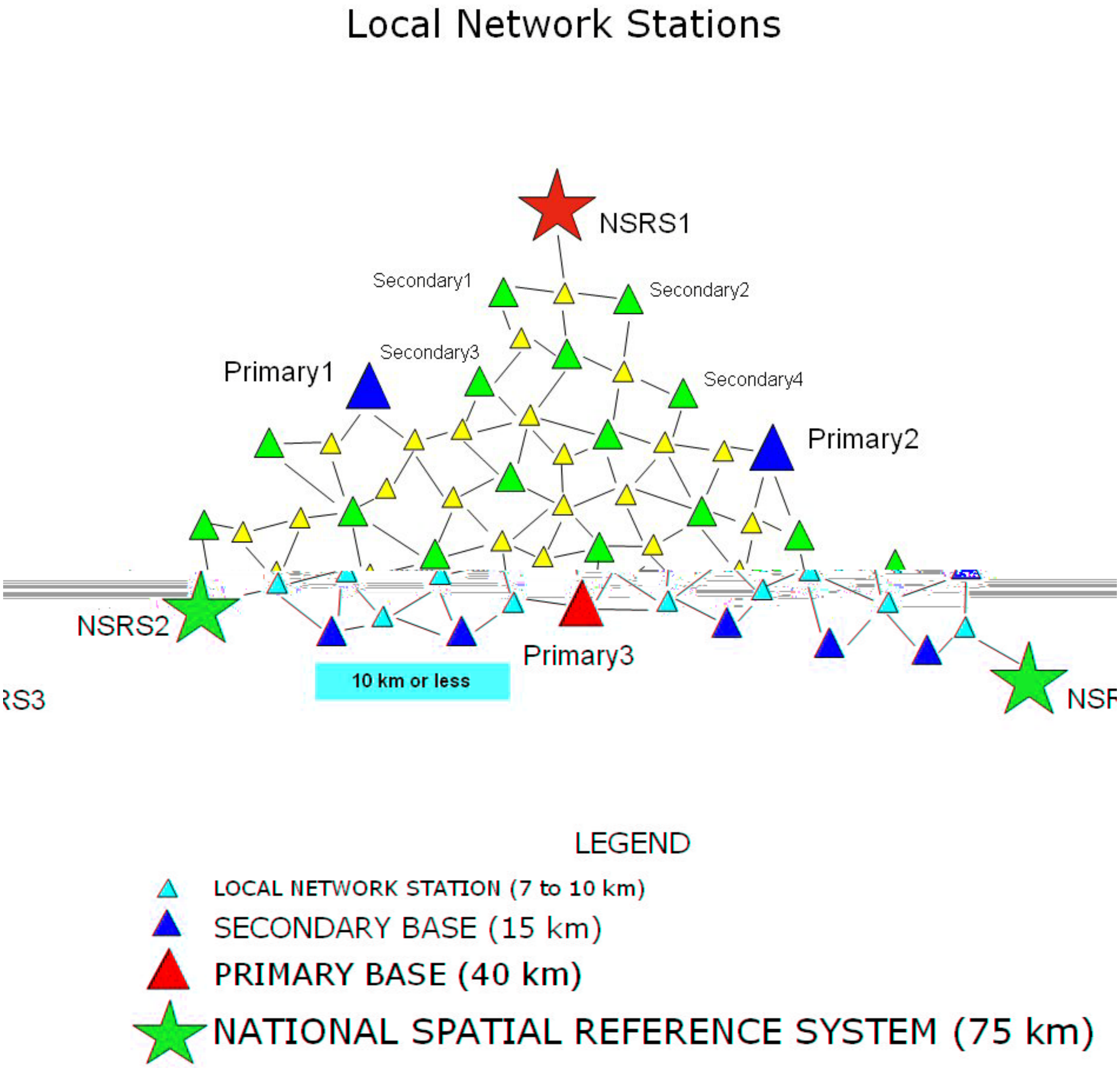
  **Note: 30 minute sessions should be the minimum. In some locations, due to abnormal atmospheric conditions, poor satellite geometry, and local multipath effects, it may be necessary to collect more than 30 minutes of data to meet the 2-cm repeat base line requirement.**

- Spacing between secondary base stations (or between primary and secondary base stations) should not exceed 15 km.

- All base stations (primary and secondary) must be connected to at least the two nearest primary or secondary base station neighbors.

- Secondary base stations should be traceable back to two primary or NSRS base stations along independent paths; i.e., **Secondary1-NSRS1** and **Secondary1-Secondary3 plus Secondary3-Primary1**.

- Secondary base stations need not be established in “small” area surveys.




**Basic Guidelines for Establishing Local Network Stations:**

- 30 minute sessions / 2 days / significantly different satellite geometry

  **Note: 30 minute sessions should be the minimum. In some locations, due to abnormal atmospheric conditions, poor satellite geometry, and local multipath effects, it may be necessary to collect more than 30 minutes of data to meet the 2-cm repeat base line requirement.**

- Spacing between local network stations (or between base stations and local network stations) should not exceed 10 km.

- All local network stations should be connected to at least its two nearest neighbors.

- Local network stations should be traceable back to two primary base stations along independent paths.