Height Modernization Program and Subsidence Study in Northern Ohio

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16. Abstract

This study is an initiative focused on establishing accurate, reliable heights using Global Navigation Satellite System (GNSS) technology in conjunction with traditional leveling, gravity, and modern remote sensing information. The traditional method for determining the elevation of these vertical benchmarks is differential leveling, but the advanced technology of Global Navigation Satellite System (GNSS) and other modern positioning technologies have begun to replace this classical technique of vertical measurement in many situations.

The primary goal of this research was to contribute to the improvement of height estimation using GPS that supports the goals of the National Height Modernization project led by NGS. This was attained by investigating the required baseline length to de-correlate the tropospheric corrections at individual stations, as well as to determine the optimal network design. In order to perform these experiments, three different networks were formed: the single, the double, and the multiple base station approaches. The comparison of these three approaches concluded that the multiple base approach (combination of CORS and IGS stations) is the optimal network, which improved the estimation of the tropospheric corrections, the quality of the processing results, and the positioning accuracy, especially in the height component. This configuration reduced the possible errors associated with the base station, provides reliable tropospheric corrections and improved the accuracy of the ellipsoidal heights. These test cases also illustrated that a longer session provides higher accuracy and reliable ellipsoidal heights. Based on the results in this study, at least a two-hour data span should be used to determine the ellipsoidal heights accurately in OPUS-Projects. Additionally, a second independent observation should be used to increase the confidence in the processing results. In order to maximize independence of the observations, the second observation should be obtained on a different day and at a different time of day.

This project is closely related to project 134692, Impact of Lakeside Subsidence on Benchmark Reliability.

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List of Abbreviation

IPW .... Integrated Precipitable Water

GEOID12 .... Hybrid Geoid Model of 2012

GMF... Global Mapping Functions

GNSS .... Global Navigation Satellite Systems

GPS .... Global Positioning Systems

GPS-IPW .... GPS-Integrated Precipitable Water

GPT.. Global Pressure and Temperature

IGS... International Global Navigation Satellite Systems Service

IGLD.. International Great Lake Datum

NGS .... National Geodetic Survey

NHMP.. National Height Modernization Program

NSRS .... National Spatial Reference System

NOAA.. National Oceanic and Atmospheric Administration

OPUS .... Online Positioning User Service

PAGES... Program for the Adjustment of GPS Ephemerides

ZHD .... Zenith Hydrostatic Delay

ZWD .... Zenith Non-Hydrostatic (Wet) Delay

ZTD.. Zenith Tropospheric Delay

1 Introduction

Height Modernization is an initiative focused on establishing accurate, reliable heights using Global Navigation Satellite System (GNSS) technology in conjunction with traditional leveling, gravity, and modern remote sensing information. The traditional method for determining the elevation of these vertical bench marks is differential leveling, but the advanced technology of Global Navigation Satellite System (GNSS) and other modern positioning technology have begun to replace this classical technique of vertical measurement in many situations.

The National Height Modernization Program (NHMP) is an initiative designed and implemented to improve the vertical component of the National Spatial Reference System (NSRS). This program is overseen by the National Geodetic Survey (NGS), part of the National Oceanic and Atmospheric Administration (NOAA). The main objective of the NHMP is the development and maintenance of an accurate, reliable and readily accessible height reference system nationally, utilizing the availability and accuracy of GNSS technology (Veilleux, 2013). The program also focuses on the development of standards that are consistent across the nation; providing data, technology, and tools that yield consistent results regardless of terrain and circumstances.

The Height Modernization Program has been implemented on a state-by-state basis. This implementation strategy has allowed for the focus on the needs of the individual users and the states while NGS provides technical expertise and support. Additional coordination is ongoing at a regional level to the point that states with similar needs and challenges are being more collaborative and extending their resources to promote the creation of stronger regional networks. The Height Modernization implementation strategy has been crucial in allowing the program to address a variety of needs for an accurate height reference system throughout the country.

This report has been formulated to support some of the processes in which Ohio Department of Transportation may have to engage in with regards to Height Modernization matters related to the state of Ohio. As accurate heights are required in the support of:

- Mapping and construction engineering
- Transportation and navigation applications
- Disaster preparedness and management (e.g. evacuation route surveys, flood mapping)

- Measuring, monitoring, and modeling crustal motion, subsidence, glacial isostatic adjustment (GIA) and seasonal changes like frost heave.
- Precision farming

As mentioned above, with the advancement GNSS technology, GPS surveying has been used extensively for the production of ellipsoidal heights, called GPS-derived ellipsoidal heights. In order for GPS-derived ellipsoidal heights to have any physical meaning in a surveying or engineering application, the ellipsoidal heights must be transformed to orthometric heights. The derivation of orthometric heights from GPS ellipsoidal heights typically involves measuring ellipsoidal heights first, and then applying some form of a geoid model to determine the orthometric heights with respect to the existing vertical datum (Roman & Weston, 2011).

As part of the NHMP, NGS has been developing gravimetric geoid models to enable the determination of orthometric heights (H) since the 1990s. Since 1996, these gravimetric models have been combined with GPS and leveling information on known benchmarks to create a second type of models known as hybrid models. Hybrid models provide a practical and accurate transformation from GPS-derived ellipsoid heights to orthometric heights, called GPS-derived orthometric heights or GPS leveling. The accurate determination of GPS-derived ellipsoidal heights is one of the most critical components in the implementation of a precise hybrid geoid model, however the GPS-derived ellipsoidal heights are also subject to potentially significant error sources (Roman & Weston, 2011). To this end this study in conjunction with the independent study of the Impact of Lakeside Subsidence on Benchmark Reliability focused on methods aimed at improving the accuracy of GPS-derived ellipsoid heights. The results of the latter were overviewed in Section 10 if this document.

2 Research Objectives

The main objectives of this project were (1) to reprocess and re-adjust the three International Great Lakes Datum of 1985 (IGLD) Height Modernization projects (1997, 2005, and 2010) using consistent reference frame and GPS orbits and absolute antenna models, and (2) use the results of objective (1) to help update and combine NGS-58 and NGS-59, and provide guidelines on best practices in height data processing and adjustment procedures. Note: the documents listed above are, (a) NOAA Technical Memorandum NOS NGS-58 "Guidelines For Establishing GPS-Derived Ellipsoid Heights" and (b) NOAA Technical Memorandum NOS NGS-59 "Guidelines for Establishing GPS-Derived Orthometric Heights."

3 General Description of Research

This Height Modernization and Subsidence study consists of the following sections:

1. Determining the dependency of GNSS vertical coordinate accuracy on different parameters and conditions to assure 2-5 cm accuracy of ellipsoidal heights:
   - GPS session durations
   - Network Configuration
   - Baseline lengths
   - tropospheric modeling
   - Single vs dual frequency data used
2. Reprocessing and re-adjustment of the International Great Lakes Datum of 1985 (IGLD 85) Height Modernization projects (1997, 2005, and 2010)

A more comprehensive description of each segment of the study is outlined below.

3.1 Determining the dependency of GPS vertical coordinate accuracy on different parameters and conditions

3.1.1 Background: The GPS System

The NAVSTAR Global Positioning and Satellite System (GPS) is a satellite-based radio-positioning and time transfer system, designed, financed, deployed, and operated by the U.S. Department of Defense (DoD). It was designed to be an all-weather, continuous, global radio navigation system (Wooden, 1985). The configuration of the satellite orbits was established to allow visibility of at least four satellites at all times from most of the Earth, provided that the environment is open enough; that is, the signal is not being obstructed by natural or manmade artifacts such as trees, tall buildings, etc. that may block out large portions of the sky. It takes a minimum of four observed satellites to determine a unique position with GPS. Each of these satellites broadcasts two separate navigation messages: the L1 (1575.42 MHz) and the L2 (1227.60 MHz) microwave carrier signals. The L1 and L2 signals are derived from the fundamental L band frequency (10.23 MHz). The signals also transmit the satellite clock corrections, ephemeris, and pseudorandom noise codes: the Coarse/Acquisition-code (C/A-code) and the Precision-code (P-code) (Leick, 2004).

Modern GPS receivers utilize two types of measurements: pseudorange and carrier phase measurements. A pseudorange is the measure of the geometric range between the transmitting satellite and the antenna of a GPS receiver. This range can be obtained by multiplying the speed of light with time difference between the epoch the signal is transmitted by the satellite's antenna and the epoch it is received by the receiver's antenna. However, the satellite and receiver clocks are not perfectly synchronized, thus a clock delay error enters into the pseudorange observation. Pseudorange observations can be as accurate as the centimeter level if the precision code is used or accurate to a few meters if Coarse/Acquisition (C/A) code is used.

A carrier phase measurement is the difference between the phase of a carrier signal received from a spacecraft and a reference signal generated by the receiver's internal oscillator. A carrier phase range can be determined by multiplying the measured carrier phase by the wavelength of the signal's intensity. The carrier phase observable is the sum of the number full cycles and a fractional part [Leick, 2004].

The observation equations for pseudorange and carrier phase GPS measurements are given below. These measurements are developed between antenna i and satellite k in Figure 3.1 below and apply to the measurements from all visible satellites at a particular instance.

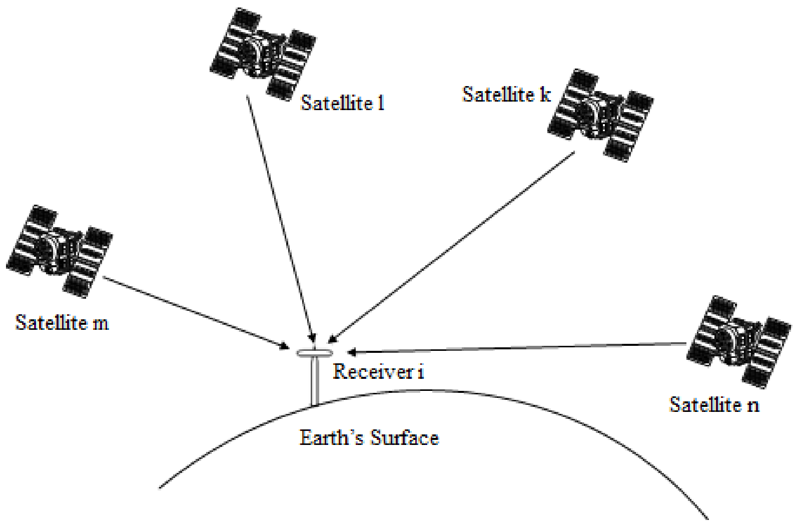

Figure 3-1 - *Depiction of the relationship between receiver i and satellite k that is considered for the GPS observable equations below.*

$$P_{i,1}^{k} = \rho_i^k + d\rho^k + I_{i,1}^{k} + T_i^k + c(dt_i - dt^k) + b_{i,2} + M_{i,1}^{k} + e_{i,1}^{k} \quad 3.1$$

$$P_{i,2}^{k} = \rho_i^k + d\rho^k + I_{i,2}^{k} + T_i^k + c(dt_i - dt^k) + b_{i,3} + M_{i,1}^{k} + e_{i,2}^{k} \quad 3.2$$

$$\phi_{i,1}^{k} = \rho_i^k + d\rho^k - I_{i,1}^{k} + T_i^k + \lambda_1 N_{i,1}^{k} + c(dt_i - dt^k) + \lambda_1\left(\varphi_{0,1}^{k} - \varphi_{i_0,1}\right) + m_{i,1}^{k} + \varepsilon_{i,1}^{k} \quad 3.3$$

$$\phi_{i,2}^{k} = \rho_i^k + d\rho^k - I_{i,2}^{k} + T_i^k + \lambda_2 N_{i,2}^{k} + c(dt_i - dt^k) + b_{i,1} + \lambda_2\left(\varphi_{0,2}^{k} - \varphi_{i_0,2}\right) + m_{i,2}^{k} + \varepsilon_{i,2}^{k} \quad 3.4$$

Where

$\rho_i^k = \sqrt{(X^k - X_i)^2 + (Y^k - Y_i)^2 + (Z^k - Z_i)^2}$ is the geometric range between receiver i and satellite k.

X_i, Y_i, and Z_i are the unknown coordinates of the receiver

$P_{i,1}^{k}$, $P_{i,2}^{k}$ are the pseudorange measurements between receiver i and satellite k for the L1 and L2 frequencies respectively

$\phi_{i,1}^{k}$, $\phi_{i,2}^{k}$ are the carrier phase measurements between receiver i and satellite k for the L1 and L2 frequencies respectively

ρ_i^k is the geometric distance between receiver i and satellite k for the L1 and L2 frequencies respectively

$I_{i,1}^{k}$, $I_{i,2}^{k}$ are the ionospheric delays between receiver i and satellite k for the L1 and L2 frequencies respectively

T_i^k is the tropospheric delay between receiver i and satellite k c is the speed of light in vacuum

dt_i, dt^k are the receiver and satellite clock errors respectively

$M_{i,1}^k$, $M_{i,2}^k$, $m_{i,1}^k$, $m_{i,2}^k$ are the multipath error for the L1 and L2 frequencies for the pseudoranges and carrier phase ranges respectively

$e_{i,1}^k$, $e_{i,2}^k$, $\varepsilon_{i,1}^k$, $\varepsilon_{i,2}^k$ are the measurement noise for the L1 and L2 frequencies for the pseudoranges and carrier phase ranges respectively

λ_1, λ_2 are the wavelengths of the L1 and L2 phases respectively

$N_{i,1}^k$, $N_{i,2}^k$ are the integer ambiguities associated with the L1 and L2 carrier phase measurements respectively

$\varphi_{i_0,1}$, $\varphi_{i_0,2}$ are the initial fractional phases at the receiver i on the L1 and L2 frequencies respectively

$\varphi_{0,1}^k$, $\varphi_{0,2}^k$ are the initial fractional phases at the satellite k on the L1 and L2 frequencies respectively

$d\rho^k$ is the orbital error of satellite k

$b_{i,1}$ is the interchannel bias between $\phi_{i,1}^k$ and $\phi_{i,1}^k$

$b_{i,2}$, $b_{i,3}$ are the interchannel biases between $\phi_{i,1}^k$ and $P_{i,1}^k$ and $\phi_{i,1}^k$ and $P_{i,2}^k$ respectively

3.1.2 GPS Error Sources

From the equations for the code and phase measurements for a single frequency in the equations above, GPS observables contain much more than the range measurement between the visible satellites and an observing antenna. Each of these terms will result in additional errors in the GPS measurements if not accounted for. These error sources include: satellite and receiver clock errors, satellite orbit errors, atmospheric effects caused by the ionosphere and troposphere, multipath, antenna phase center, and receiver biases.

The satellite and receiver clock errors occur due to a lack of synchronization between the precise atomic clocks of the satellites and the lower grade receiver clocks. Satellite orbit errors occur when the course of a satellite deviates from its predicted course in a GPS almanac, used by receivers to predict the position of a satellite at a particular instance in time. These errors can be corrected with precise orbit files for all satellites on a given day. As a GPS signal passes through the atmosphere it is slowed down and refracted by the charged particles of the ionosphere and the water vapor in the troposphere. This causes slight deviations to the path of the signal and increases the travel time, resulting in distances that appear larger than they actually are. Multipath error occurs when a signal arrives at a receiver through an indirect path, such as by reflectance from the ground or a building. Additional errors are caused by phase center variations, which cause a variation in the point that the signal is being measured to within the antenna as the satellite changes in elevation and azimuth with respect to the antenna. There are also biases inherent to receivers. GPS observations collected from different receivers or even the same kind of receivers receiving a signal from the same antenna may result in slightly different positions for a point. High accuracy GPS positions can only be obtained by mitigating the impact of these error sources.

Some errors can be removed or mitigated from a posteriori information and modeling. For instance, precise satellite orbits are calculated to remove the error caused by deviations in satellite position. Ionospheric and tropospheric error can be mitigated with different types of modeling and corrected for with known values. The effects of phase center variations can be mitigated through antenna calibration. More troublesome, are the effects of multipath, which cannot be removed through modeling. Some receivers utilize built in multipath mitigation techniques, which help reduce the effects of multipath but do not fully remove it from the observables. Antenna ground planes and choke-rings are also employed to mitigate the effects of multipath. Multipath can also result in unpredicted phase center variation (PCV), which can be mitigated through an in-situ, or environmental specific, antenna calibration. Additionally, error sources over short baselines can be removed through the use of differential GPS. An additional error source not listed in the equations above that must be accounted for is antenna phase center variation (PCV), in which the phase center or signal reception point changes as a function of the elevation and azimuth angle of the incoming signal. A summary of the magnitudes of the different GPS error sources is given in Table 3.1 below.

Table 3-1 – Summary of GPS error sources and their magnitudes

Summary of GPS Error Sources [m]	
Satellite Clocks	2.0
Orbit Errors	2.1
Ionosphere	5.0
Troposphere	0.5 (model)
Receiver Noise	0.3
Multipath	1.0
Phase Center Variation	0.1

Note that the phase center variation listed here is only the variation seen in heights.

At this point the focus is place on the atmospheric effects (or signal propagation errors). As mentioned above Global Positioning System (GPS) is based on the technology of radio navigation. A radio signal encounters different atmospheric conditions as it travels from the radio source (satellite) to the receiver (Figure 3.2)

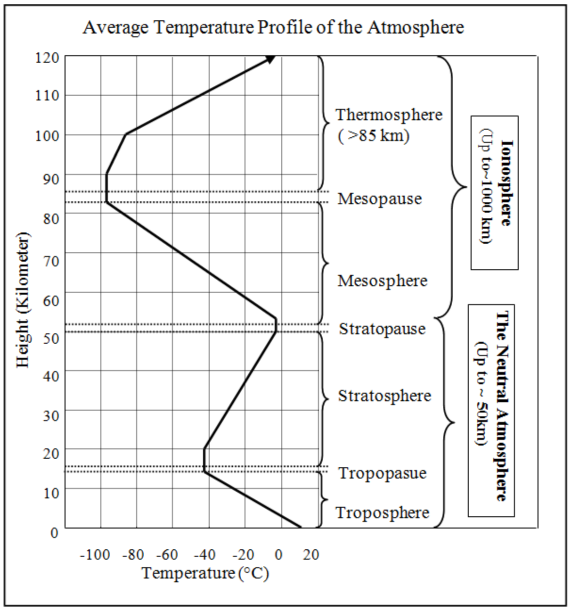

Figure 3-2 - Atmosphere Profile

The atmosphere affects the traveling signal through the change of direction and speed of propagation of the signal. These effects introduce some delay in the arrival time of the signal, and bend the signal, depending on the refractive index of various atmospheric layers along the actual path (Davis et al.1985; Mendes, 1999). Additionally, the atmosphere can also be divided into two main regions (Figure 3-2), based on the ionization: the ionosphere, for the ionized region with the presence of free electrons, and the neutral atmosphere for the electrically neutral region (Mendes, 1999). The ionosphere and the neutral atmosphere are two of the most important sources of errors in modern space based geodetic systems, and have a direct impact on the measurements.

The ionosphere causes phase advance in carrier phase and group delay pseudo-range measurements by the same amount (El-Rabbany, 2002). In other words, pseudo-range is measured longer and carrier phase range is measured shorter than the true range. Because of the dispersive nature of the ionosphere, the ionospheric delay can be determined and removed with high accuracy (up to cm level) for long baselines by using dual-frequency receivers that allow formulation of ionosphere-free linear combinations (El-Rabbany, 2002). Alternatively the troposphere causes a transmission delay of GPS signals and is a source of errors in GPS measurements both through signal path bending and the alteration of the electromagnetic wave velocity. The magnitudes of these effects are a function of satellite elevation and atmospheric conditions such as temperature, pressure and relative humidity during signal propagation (Brunner & Welsch 1993). If not compensated for the total tropospheric delay can induce pseudo-range and carrier-phase errors from about 2 m in the zenith direction and increases to more than 20 m for satellites near the horizon (10° elevation) (Leick 2004).

Improving the accuracy of the GPS-derived ellipsoidal height involves addressing the effects of neutral atmospheric (tropospheric) delay on ellipsoidal height.

3.1.2.1 Tropospheric Delay

The troposphere is the lower part of the atmosphere extending from the Earth's surface to a height of approximately 15 km, composed of dry gases and water vapor. The troposphere is non-dispersive for GPS frequencies, which indicates that the tropospheric range errors are not frequency dependent and therefore cannot be cancelled through the use of dual-frequency measurements, like its counterpart ionospheric effect. Accurate estimation of atmospheric path delay in GPS signals is necessary for high-accuracy positioning (Leick 2004).

The refractivity of the troposphere can be divided into hydrostatic and wet components. The refractive index can be expressed as the sum of the hydrostatic or 'dry' and non-hydrostatic or 'wet' components (Hofmann-Wellenhof et al., 2001). The sum is represented by the follow equation:

$$N^{Tropo} = N_d^{Tropo} + N_w^{Tropo}$$

$$\Delta^{Tropo} = 10^{-6} \int N_d^{Tropo} + \int N_w^{Tropo} \, dw$$

These two components effect on the propagation of the GPS signal are different. The hydrostatic component which accounts for 90% of total tropospheric delay consists of mostly dry gases and can be computed from temperature and pressure measured at the receiver. The variation of water vapor in the atmosphere varies greatly spatially and temporally, making the wet component difficult to model efficiently. As most of the water vapor in the atmosphere occurs at heights less than 4 km, signals from low elevation satellites, which have a longer propagation path length through the troposphere, are most affected. The wet delay contributes only 10% to the total tropospheric delay (Hofmann-Wellenhof et al., 2001; Leick, 2004).

The Effect of Tropospheric Refraction

The impact of errors in the troposphere delay modeling on a baseline can be divided into two parts (Beutler et al. 1988; Rothacher 2001):

1. Relative troposphere biases caused by errors of tropospheric refraction at one endpoint of a baseline relative to the other endpoint.
2. Absolute troposphere biases caused by errors of tropospheric refraction common to both endpoints of a baseline.

The Relative troposphere biases are considered a Class 2 bias in GPS, and leads primarily to a biased station height. The general estimate of the station height bias due to a relative troposphere error may be computed as (Beutler et al. 1988; Rothacher 2001):

$$\Delta h = \frac{\Delta \rho_r^0}{\cos z_{max}}$$

Where:

Δh - is the induced station height bias,

$\Delta \rho_r^0$ - is the relative tropospheric zenith delay error

z_{max} - is the maximum zenith angle of the observation scenario (cutoff)

The above equation indicates that a relative troposphere bias of only 1 cm leads to an error of approximately 3.9 cm in the estimated relative station height for an elevation cutoff angle of 15^o. This error increases in magnitude as the elevation cutoff angle decreases. The absolute troposphere biases alternatively are Class 1 biases and are not critical for heights. However, a bias of 10 cm in the troposphere zenith delay at both stations induces a scale bias of 0.05ppm for an elevation cutoff angle of 20^o. This is a relatively small effect compared to the height error caused by a relative troposphere bias.

There are two alternatives that can be used to reduce tropospheric delay errors (Rothacher 2001):

1. Model tropospheric refraction without using the GPS observable (e.g., by using standard atmosphere, ground meteorological measurements or water vapor radiometers data).
2. Estimate troposphere parameters (e.g., zenith path delays) in the general GPS parameter estimation process.

To this end, for accurate positioning with GPS over long baselines, there is a need to estimate tropospheric corrections at both ends of the baseline if the duration of session and the length of the baseline are suitable. Test cases were developed testing different baseline lengths to find the relation between the baseline length and the tropospheric corrections quality in OPUS-Projects by using several CORS stations in the Ohio network. The experiments designed attempts to investigate the required baseline length to de-correlate the tropospheric corrections as well as to determine the optimal network design, which will improve the estimation of the tropospheric corrections and the quality of the processing results, and the positioning accuracy, especially in the height component.

3.2 Reprocessing and re-adjustment of the International Great Lakes Datum of 1985 (IGLD 85) Height Modernization projects (1997, 2005, and 2010)

The purpose of these surveys was to monitor elevation changes across the Great Lakes to facilitate the development of the International Great Lakes Datum (IGLD) to be released in 2015.

These surveys were conducted in 1997, 2005 and 2010. The project areas included, the entire Great Lakes Region, from Minnesota and Lake Superior eastward to the St Lawrence Seaway in New York.

The existing problem for The Great Lakes and St. Lawrence River region are the post glacial rebound or glacial isostatic adjustment effect, fluctuations on a short-term, seasonal, and long-term basis (Zilkoski, 1991; GLC 2010). These effects causes a gradual uplift of the crust and changes in the water level respectively. As such, there is a need to update or develop a new datum for this region that will reflect continuous and differential changes in land surface elevations across the region. The upcoming vertical datum for the Great Lakes region should serve both countries and all agencies' necessities in this region (GLC 2010).

These three (3) surveys were conducted to ensure 2-centimeter or better local accuracy for the ellipsoid heights. Since these GPS survey were conducted to monitor small changes in the vertical component, the longest sessions possible were observed. Therefore the adopted observation procedure included session lengths of 24 hours at stations that were secured and permitted use of unattended equipment and 8 hours at stations that were unsecured. All sessions, 24-hour and 8-hour had the same start times and every station was occupied at least twice. Meteorological data were not collected.

Figure 3-4 to Figure 3-6, shows the spatial locations of the benchmarks for three (3) IGLD surveys.

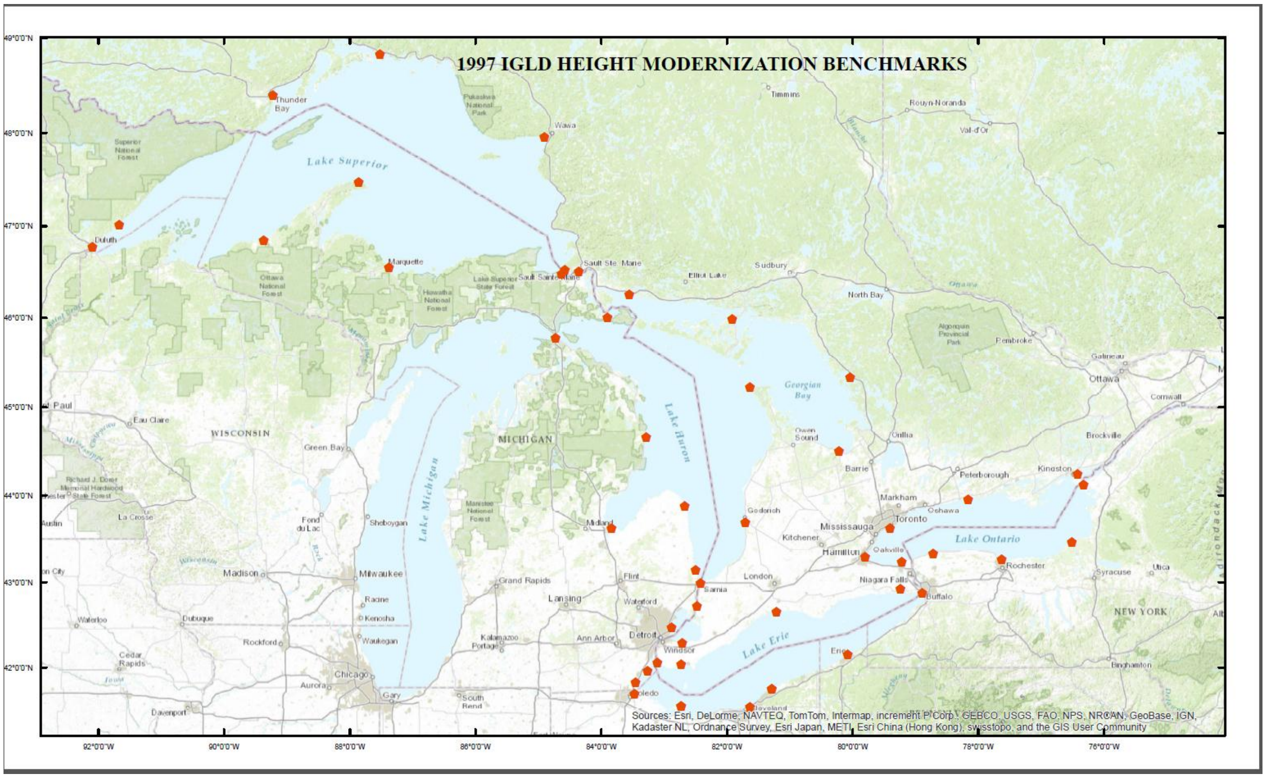

Figure 3-3 - IGLD Height Modernization Benchmarks 1997;

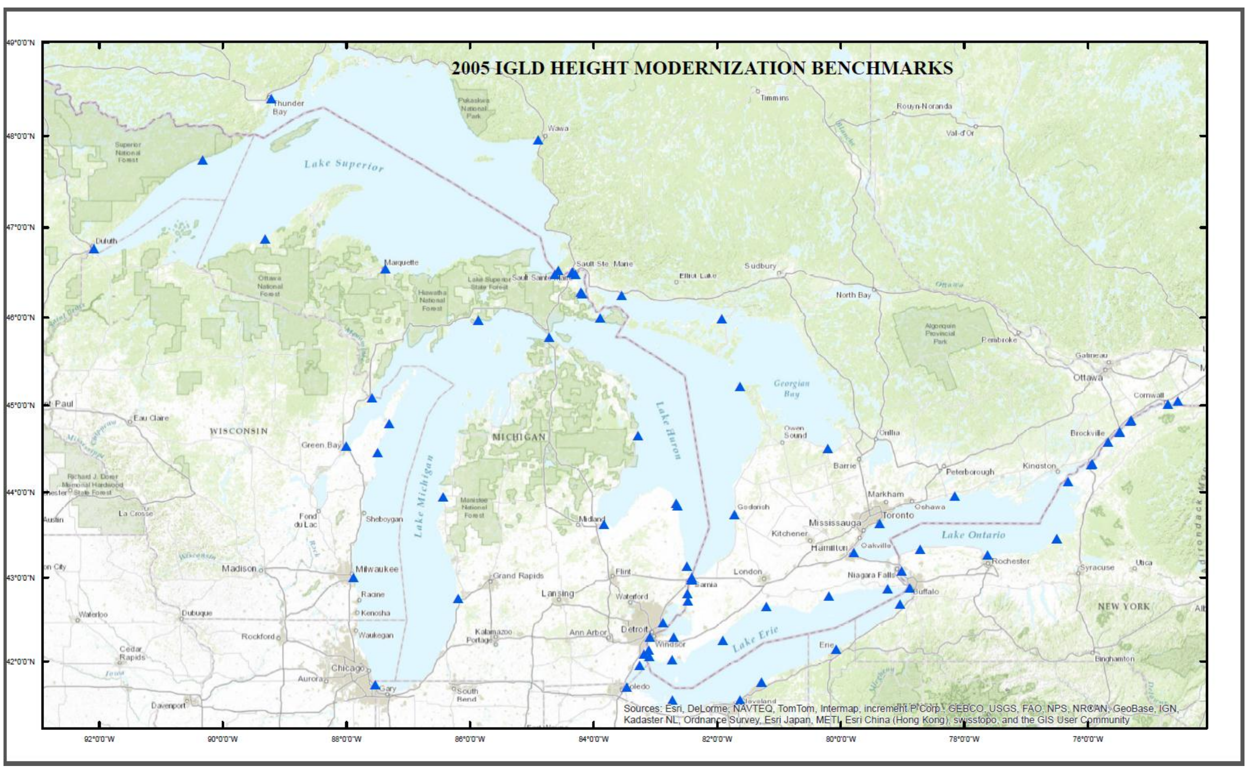

Figure 3-4 - IGLD Height Modernization Benchmarks 2005

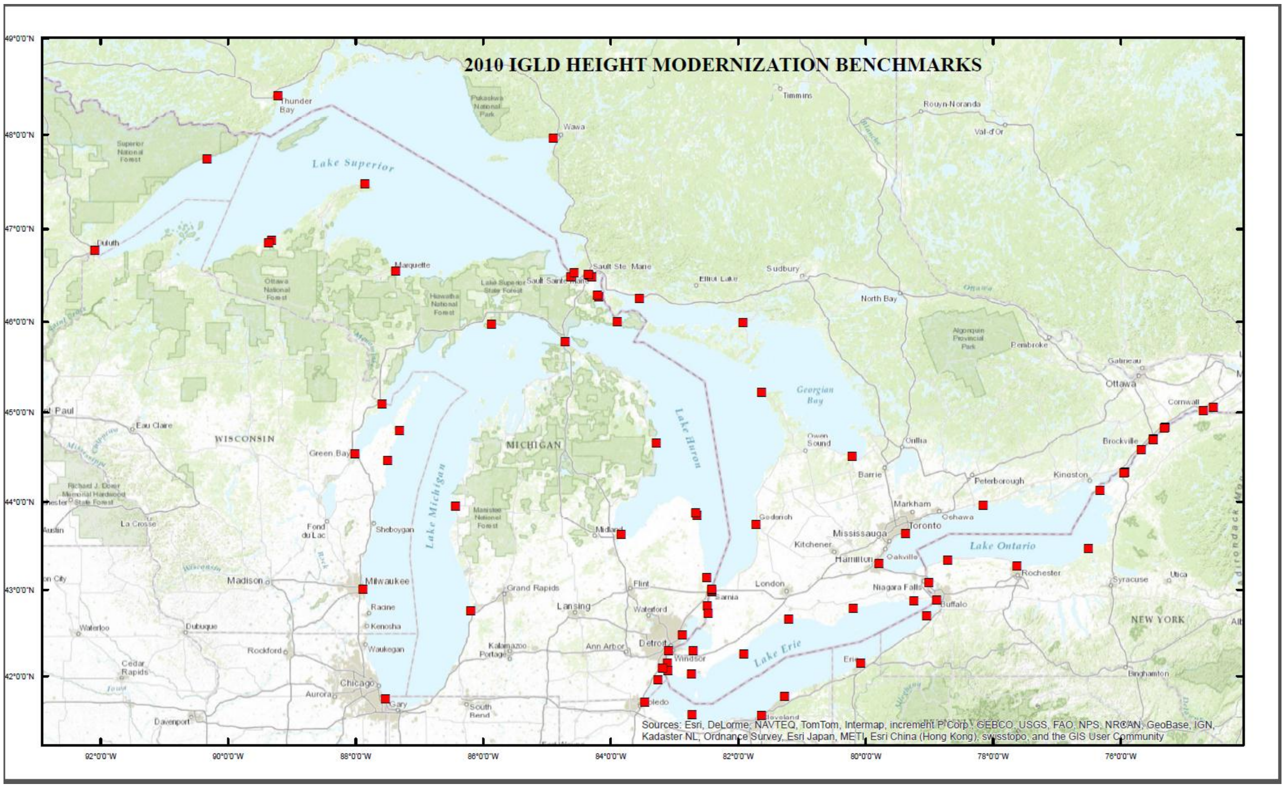

Figure 3-5 – IGLD Height Modernization Benchmarks 2010

With the use of both OPUS-Projects and PAGES/ADJUST, the purpose of this task was, firstly to reprocess and adjust the original data from the three IGLD projects using OPUS-PROJECT in a consistent reference frame at the epoch of each survey. This allowed for the observation of any changes over time, without including either changes in reference frame or processing software/algorithms. This activity assured a modern, up-to-date evaluation of real movement in the Great Lakes region and facilitated a comparison with the velocities derived by the Canadian partners of NGS on the IGLD project.

Secondly, it allowed for a comprehensive comparison of the new OPUS-Project and PAGES/ADJUST approach to data processing and adjustment. These tasks would include the determination of the ellipsoid and GPS-derived orthometric heights, consequently since some of the stations observed were leveled vertical controls, it will allow for the assessment of the ability of GPS to duplicate the orthometric height.

4 GPS Data Processing Tools

One of the NHMP goals is the availability of data, technology, and tools that yield consistent results regardless of terrain and circumstances. NGS has developed a series of online processing tools, to facilitate this; these tools have been used throughout this research. The subsequent subsections describe the software packages in some detail.

4.1 Online Positioning User Service (OPUS)

NGS's Online Position User Service (OPUS) is a web-based application for static data processing that enables access to the high accuracy NSRS coordinates (NGS, 2013). OPUS provides a fully automated and accurate GPS data processing service for an individual GPS session. This processing service provides a solution after five (5) user inputs which are: (1) Dual Frequency (L_1 + L_2) data, (2) the antenna type, (3) the antenna height of the Antenna Reference Point (ARP), and (4) the user's email address (to receive the solution report), (5) selection of a processing option. Figure 4-1 below shows the form used to upload data to OPUS located at http://www.ngs.noaa.gov/OPUS/.

Figure 4-1 - The NGS's Online User Positioning Service (OPUS) web application used for submitting static GPS observation files to OPUS for processing

The first step is uploading a GPS observation file. This can either be in a RINEX 2.x format or it can be almost any of the raw data formats used by the different GPS companies. Currently, OPUS is equipped to only handle dual-frequency (L1 and L2) and static observations. As such, OPUS will return a single coordinate for the entire observation time. Additional requirements are that the observation session duration range from 15 minutes to 48 hours and that the observation rate must be one, two, three, five, ten, fifteen, or thirty seconds.

Secondly, the antenna type used can be selected from the antenna type dropdown list. This list is kept up-to-date with all available antennas on the market. This information must be provided so that antenna calibration information can be used. This will detail how the phase centers changes as the satellites move through the sky and is needed for high accuracy coordinates.

The antenna height is simply the height from the point on the ground being surveyed to the antenna reference point (ARP). The ARP is a point on the antenna, typically on the base plane at the bottom of the threads, where the offsets to the phase center are measured from. When processing, OPUS will use a height entered here to reduce the height measured to the antenna phase center to the ground. If a value of zero is entered here, the solution returned will be to the antenna base plane.

The fourth step is entering an e-mail address for OPUS to send the solution. The Final step requires the user to select a processing mode: "Upload to Rapid-Static", or "Upload to Static". A rapid-static solution is for GPS observations between 15 minutes and 2 hours and a static solution is for GPS observations between 2 hours and 48 hours.

Static solutions submitted to OPUS are processed using the **PAGES** software. The computed coordinates will be the averaged coordinates from three independent, single-baseline solutions, each computed by double-differenced carrier phase measurements from nearby CORS (NGS, 2013). Nearby IGS stations may also be selected for processing in addition to the CORS. Static solutions will attempt to use the three nearest CORS/IGS stations, but will expand the search space for additional CORS/IGS stations for each of the single-baseline solutions from PAGES that fails to meet a quality threshold (Mader et al, 2003).

Rapid-static solutions submitted to OPUS are processed using the RSGPS rapid-static software. The RSGPS software applies more aggressive algorithms to resolve carrier phase ambiguities than in the static processing. However, there are also stricter requirements on data continuity and geometry than for static processing, which may limit the ability to perform rapid-static processing in remote areas of the country (NGS, 2013). The rapid-static algorithm begins be selecting CORS/IGS stations until either six stations have been selected or the distance of a station from the user's position exceeds two hundred kilometers. A solution will then only process if the user's station is inside the polygon formed by the selected reference station or no more than fifty kilometers outside of it (Martin, 2007). RSGPS is then run twice to determine a solution. The first run only uses the selected reference stations in a network mode to resolve the integer ambiguities and solve for the ionospheric and tropospheric delays. RSGPS is next run while treating the position of the user's station as a rover. This will incorporate the ionospheric and tropospheric delays solved for in the previous network solution to estimate the delays at the rover. Afterwards, a full network solution is computed for the user's station, instead of an average from single-baselines.

4.2 OPUS-Projects

OPUS was designed for user simplicity, in that it requires minimum user input and it decide how best to process the data. The user has retained some flexibility in that they can choose the three reference stations that OPUS will use for processing. If the user specifies fewer than three, OPUS will choose the remaining reference stations (Mader et al, 2003). Other than the choice of reference stations, the user does not have any control over the rest of the processing parameters to be used, including elevation angle and atmospheric models for the troposphere and ionosphere delays.

OPUS-Projects was developed as a natural extension of OPUS and further enhances the capability of processing geodetic networks by offering the public a GNSS network adjustment package with web-based access to simple visualization, management, and processing tools for multiple marks and multiple occupations (Armstrong, 2013). Some of the advantages of OPUS-Projects include:

- Data uploading through OPUS
- Coordinate results aligned through the NSRS
- Processing using the PAGES and GPSCOM software
- Graphical visualization and management aids including interactive maps powered by Google Maps mapping service

OPUS-Projects differ significantly from OPUS in that the user has the ability to customize data processing. This includes the user's ability to customize the reference stations used, which can include any operating CORS/IGS stations from the date the GPS data was collected, to the customization of network designs to better meet the accuracy requirements of a particular project (Armstrong, 2013). Additionally, users have the ability to customize processing threshold parameters to regulate the accuracy of a solution.

OPUS-Projects is currently in a beta version, where it is still undergoing development and revision. A flowchart of the basic processing procedures of OPUS-Projects is presented in Figure 4-2 below.

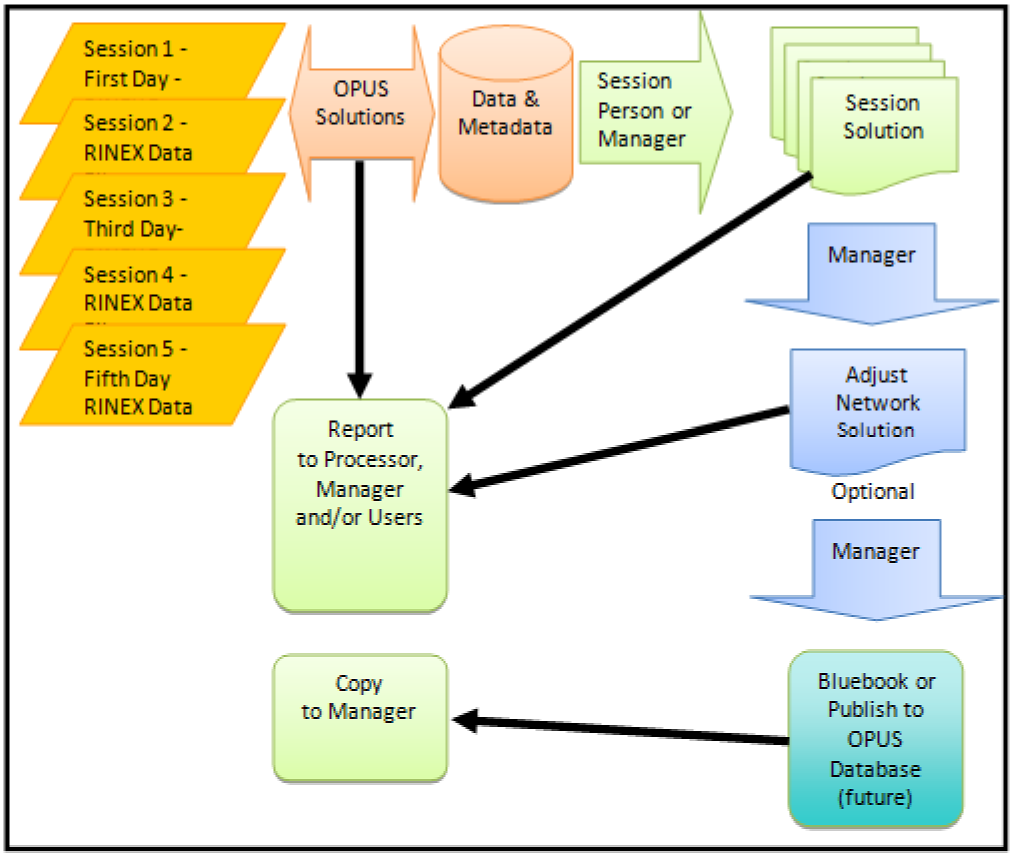

Figure 4-2 - Flowchart of the processing procedures employed in OPUS-Projects (Armstrong, 2013)

To create a new project, a certified project manager will need to go to the OPUS-Projects webpage at http://www.ngs.noaa.gov/OPUSI/OpusProjects.html and click the create button. The manager will then need to fill in their e-mail address, enter a project title, select the project type (height modernization, FAA, or other), enter the approximate latitude and longitude of the project, enter the anticipated start date, and provide the approximate number of stations and duration of the project in the form on the next page. Once all of this information is completed, the user must click the create button and the new project will be created.

Before uploading data to a project, the project manager should review the project preferences and adjust them as needed. There are four general types of preferences the user will need to specify: data and solution quality thresholds, data processing defaults, session definition, mark co-location definition. The OPUS-Project default parameters for these preferences are shown in Appendix A and explained in more detail where appropriate.

Once the processing parameters are set (see Appendix A), GPS observations can be uploaded to the project. Uploading data to a project is done through the OPUS webpage. The user must select an observation file to upload, specify an antenna model used, enter an antenna offset, and provide their e-mail. The user must also click the Options button and enter the project identifier sent to the project manager when the project was created in the Project ID field and then click upload to static. The point will be uploaded to the project after processing in OPUS and an extended OPUS report will be sent to the user with additional details about the baselines and coordinates of the reference stations used in addition to the coordinates of the point uploaded. Since OPUS is used to upload GPS data, OPUS-Projects has the same restrictions on observation files as mentioned in section 4.2. Upon uploading, the user will have the option of creating a monument description, which will include a unique four character monument name that cannot be the name of an existing reference station as well as specifying the type of monument used. If the user chooses to skip this step the first four letters of the filename of the uploaded file will be used as the monuments name.

After the data has been loaded, the user can select a session to process data for. Within a session, the user should review the available CORS and IGS stations in OPUS-Projects. Like OPUS, OPUS-Projects will default to using the nearest CORS to each point and these will be the only ones loading into the project. The user can add CORS to the project by selecting the Add CORS button and either entering the unique four character ID of a CORS station to add or by selecting the desired station from the interactive map.

Once the user is satisfied with the available CORS stations, they can select the Set up Processing button. This will bring up a new menu that will allow the user to determine which GPS points and reference stations to use in the processing. Additionally, the user will have control over the elevation angle and how loosely or tightly each of the points will be constrained. The user will be able to control the processing strategy with the check boxes next to each of the GPS points and reference stations used to turn on/off only the desired ones, the hub station check boxes next to each one to determine the hub station strategy, and well as constraint boxes next to each of the marks. For the CORS and reference stations it is recommended that these be left to a 3-D constraint, whereas the GPS points should be given no constraint. The user will simultaneously be able to see a map of the session solution strategy as they are customizing it in another window. The user needs to click on the Perform Processing button to process the session solution when they are satisfied with the network configuration.

This process can then be repeated for each session in the project and for a final network adjustment using data from all of the session solutions. After each solution of adjustment is generated, OPUS-Projects will store solution reports related to the session or adjustment as well as sending them to the manager’s e-mail. These reports contain statistical summary information about the solution, such as the computed coordinates, RMS, uncertainties in positioning, and tropospheric corrections.

OPUS-Projects will be used in the data processing of certain scenarios in this research. It should be assumed that the default parameters presented here were used unless otherwise stated.

4.3 PAGES and ADJUST

4.3.1 PAGES

Program for Adjustment of GPS EphemerideS (**PAGES**), is orbit/baseline estimation software, which uses double-differenced phase as its observable. A variety of parameter types can be estimated including tropospheric corrections, station coordinates and linear velocities, satellite state vectors and polar motion. **PAGES** runs using the ion-free phase combination, but optionally L1 only, L2 only, or two wide-lane phase combinations can be used. These, in turn, can be used to create partially or completely bias fixed solutions. PAGES is the processing backbone for both OPUS and OPUS-Projects software previous discussed.

4.3.2 ADJUST

ADJUST software is a series of programs and utilities used to perform least squares adjustment on horizontal, vertical angle, and/or GPS observations. Additionally data checking programs are also included. ADJUST software uses specific files such as:

- Adjustment Parameter File (A-file) - contains information on the adjustment constraints and processing options
- Blue Book Format (BBOOK/B-File) – contains information from observation logs, equipment codes, station designations, horizontal positions and heights
- GPS Vectors (G-file) – contains information of the processed GPS vectors and the related statisitics

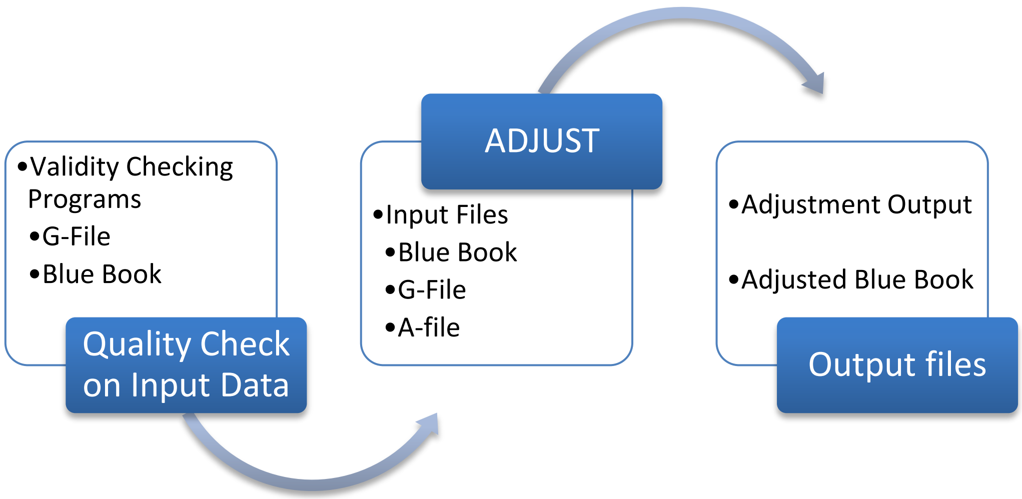

Figure 4-3 – ADJUST – Adjustment Flow

5 Study Area and Methodology for determining the dependency of GPS vertical coordinate accuracy on different parameters and conditions

The experiments are designed to discover the relation between the GPS duration of a session and the positioning accuracy with respect to the network configurations. This is done to determine the shortest possible baseline(s) length required to estimate the tropospheric corrections accurately. Also, this relation will define the best configurations to assure the quality of tropospheric corrections as well as the required duration of session that can provide high-accuracy positioning. The following network configurations are tested, Figure 5.1 illustrates these configuration and further details of these test are given in Section 6 below.

- Single base approach
- Double (dual) base approach
- Multiple base approach

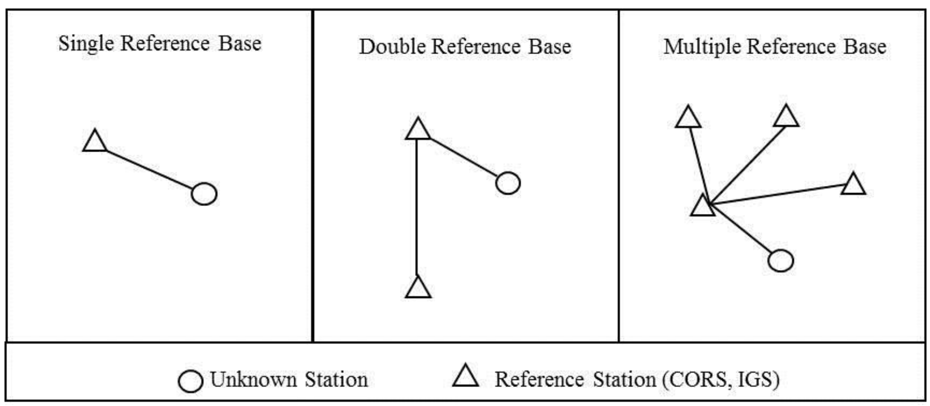

Figure 5-1 - Sample Network Configuration

5.1 Station and Data Selection

A total of ten Continuously Operating Reference Stations (CORS) were selected from the Ohio network, and in the subsequent experiments have been treated as "unknown (user) stations"; hereafter these stations will be called unknown stations, as shown in Figure5-1. Since these stations have known coordinates, they were treated here as "ground truth" to test the accuracy of the results produced from the experiments. Since the study used OPUS and OPUS-Projects as the processing tool, the GPS data obtained were to be dual frequency ($L_1 + L_2$). In this study, CORS and International GNSS Service (IGS) stations were used as the reference stations in the network configuration to facilitate the data processing.

Figure 5-2 - Distribution of CORS Stations used in the study

OPUS-Projects uses the Global Temperature and Pressure model (GPT) as a default model to obtain the temperature and pressure as given by Boehm et al. (2007). In Figure 5-2, the magenta stations are GPS-Integrated Perceptible Water (GPS-IPW) project stations, which contain meteorological data. Therefore, these stations were used for the comparison between the surface measurements from GPS-IPW data and GPT based on the temperature, pressure and the relative humidity profiles. These comparisons can show whether there were any unusual weather conditions during the time selected for the experiments. Furthermore, the comparisons will provide an approximate trend for the zenith tropospheric corrections.

COLB and DEFI are GPS-IPW project stations selected for the comparison. The temperature, pressure, and relative humidity values of these stations were obtained from GPS-IPW project data and GPT for the first week of June 2012. The collected data was plotted and presented in Figure 5-3 to 5-5. The experiments were done in the time period, marked in the figures below by the two vertical dashed red lines (marked as “start/end” in the figures), on June 3, 2012, since this day did not exhibit any unusual weather conditions, since the surface measurements do not change radically.

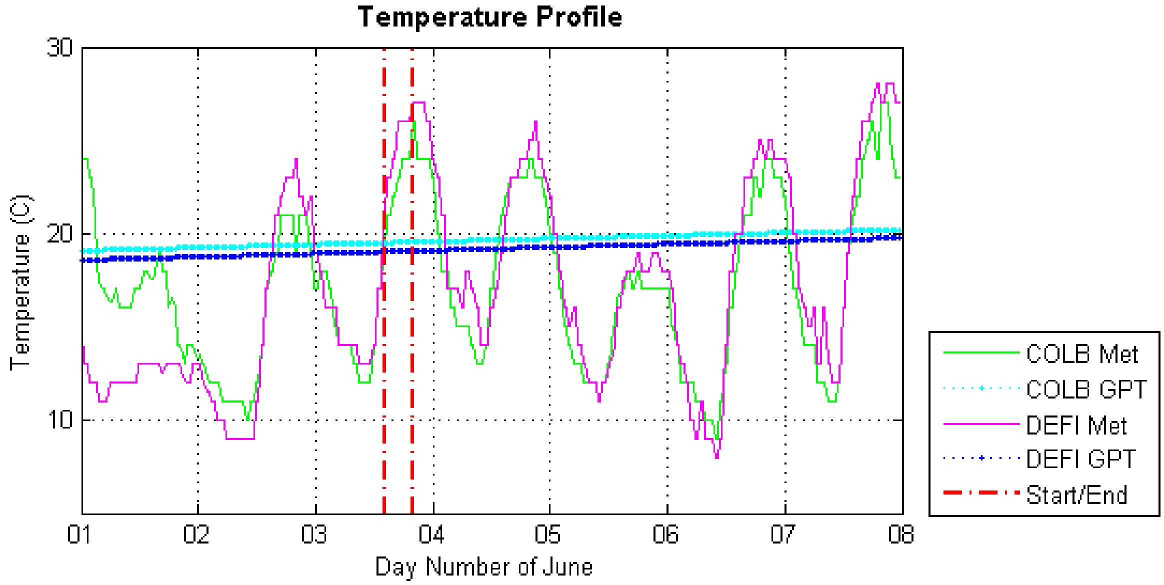

Figure 5-3 – The Temperature Profiles of COLB and DEFI Stations; Start/End denote the time period analyzed in this study

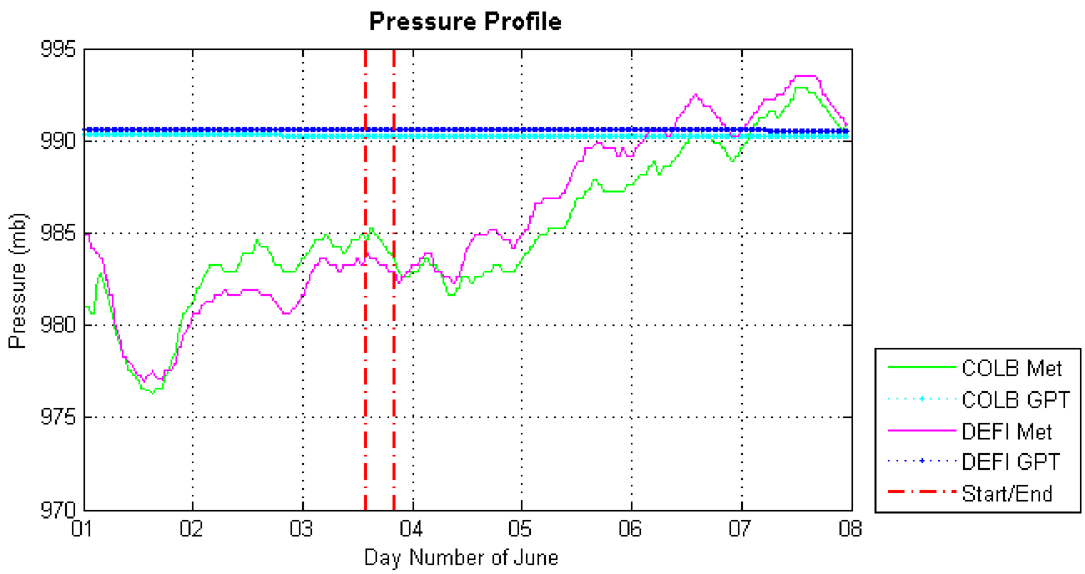

Figure 5-4 – The Pressure Profiles of COLB and DEFI Stations; Start/End denote the time period analyzed in this study

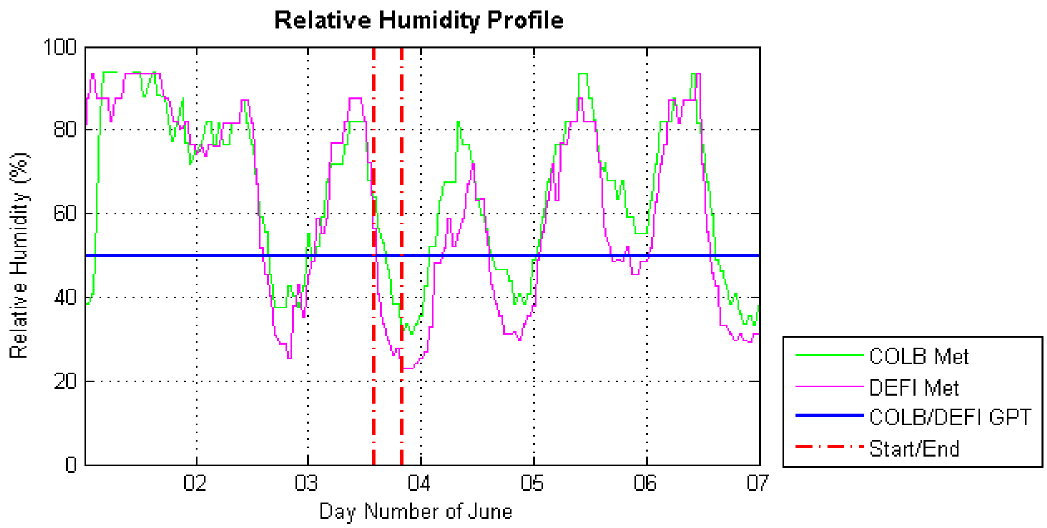

Figure 5-5 – The Relative Humidity Profiles of COLB and DEFI Stations; Start/End denote the time period analyzed in this study

Figures 5-3, 5-4, and 5-5, illustrate that the GPT does not show the variability, compared to the surface measurements, but it still fits the profiles with acceptable accuracy. Therefore, the tested network configuration should provide a smooth trend, and should not contain any peaks in the tropospheric corrections. It is necessary to note that GPT is a global model, and therefore it does not reflect local variability.

The selected GPS observation data for the stations were downloaded from NGS web page (http://www.geodesy.noaa.gov/CORS/) for June 3, 2012 (Day of Year, 155). A set of various data spans was used to determine the relation between the duration of the sessions and the tropospheric corrections.

The time intervals of the data processing sessions were thirty (30) minutes, one (1) hour, two (2) hours, four (4) hours, and six (6) hours. The middle of the data spans takes place around noon local time (5 pm UTC). It is important to note that the data spans of 30 minutes and 1 hour are of rapid static sessions, but in this experiment, they were treated as static sessions for experimental purposes since OPUS-Projects does not offer the option to process in the rapid static mode.

5.2 The Methodology of Determining Tropospheric Corrections and Solution Reports of OPUS-Projects

In data processing, OPUS-Projects use the following procedure to determine and model the tropospheric delay. As the first step, OPUS-Projects computes the zenith hydrostatic delay (ZHD) and zenith wet delay (ZWD) based on the Saastamoinen model (1972) as a priori values. The Saastamoinen model requires some meteorological data, which are temperature, pressure and partial pressure of water vapor (National Geodetic Survey, 2012). OPUS-Projects obtain the temperature and pressure from the synthesized climate model according to Boehm et al. (2007); this model is called the Global Temperature and Pressure model (GPT). The relative humidity is set to 50% to determine the partial pressure due to water vapor (National Geodetic Survey, 2012).

For the illustration of the a priori values, the zenith delays are computed from the Saastamoinen model for the selected five unknown stations, as shown in Figure 4.13. The meteorological inputs are obtained from GPT for the corresponding data span, during June 3, 2012. Based on Figure 5-6, the a priori delays are relatively constant for a specific station and do not vary during the time-span of the session because GPT is used to obtain the meteorological inputs. It is necessary to note that GPT is a global model, therefore it does not reflect local variability, as shown earlier in Figures 5-3 to 5-5.

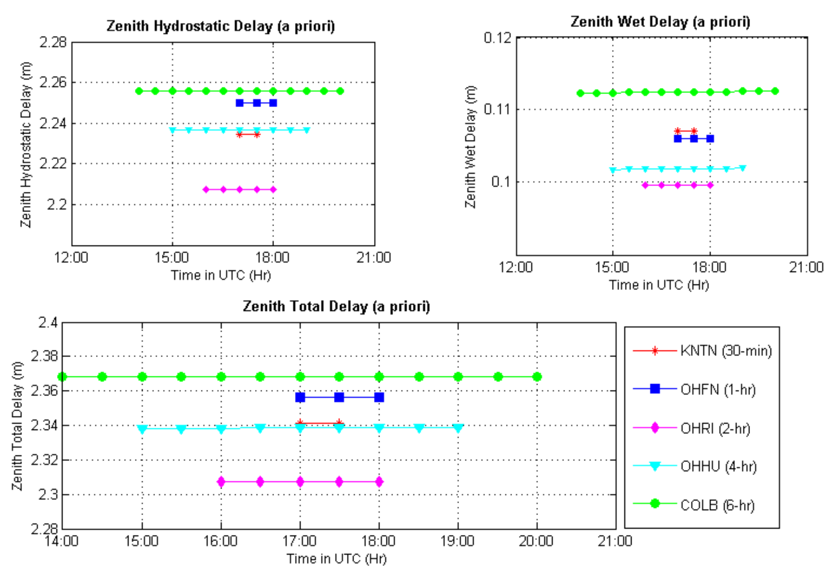

Figure 5-6 - A priori values for the Zenith Hydrostatic, Wet and Total Delays of the 5 unknown stations

Before analyzing the processing results of various solutions, it is important to discuss the processing reports that OPUS-projects generates for every solution. The related information is extracted from the reports, such as: the zenith wet corrections, the computed ellipsoidal height, and the peak-to-peak error associated with ellipsoidal height. Namely, these reports are the "Log File" and the "Summary File".

5.3 OPUS-Projects Processing Settings and Data Upload

Once a project is created in OPUS-Projects, there are some settings the user sets based on desired preferences, such as solution quality thresholds and data processing settings (as discussed in Section 4.2 above). Table 5.1 presents the specific quality thresholds and processing settings used great details of these indicators are discussed in Appendix A.

Table 5-1 - Quality Indicators and Processing Settings used in GPS Data Processing

The Quality Indicators and Data Processing Settings				
Data & Solution Quality Thresholds			Data Processing Settings	
Precise Ephemeris	Best Available		Output Ref Frame	IGS08
Minimum Observations Used	80 (%)		Output Geoid Model	GEOID09
Minimum Ambiguities Fixed	80 (%)		GNSS	GPS-Only
Maximum Solution RMS	0.025 (m)		Troposphere Model	Piecewise Linear
Maximum Height Uncertainty	0.020 (m)		Troposphere Interval	1800 (s)
Maximum Latitude Uncertainty	0.020 (m)		Elevation Cutoff	15 (degree)
Maximum Longitude Uncertainty	0.020 (m)		Constraint Weights	Normal
			Network Design	USER

The percentage of observations used and ambiguities fixed are critical for the short data spans. As an example, if the percentage of observation used is 50% for a two-hour GPS data span, then the solution is generated based on one-hour data rather than two-hours. These experiments attempt to keep the percentage of observations used and ambiguities fixed values as high as possible, thus the threshold preference was given at 80% for these experiments.

The solution RMS value is related to the baseline length. The RMS value should be as low as possible in a solution. The maximum RMS value was set to 2.5 cm in these experiments.

The uncertainties describe the quality of the coordinates determined by the solution. The minimum uncertainties were set to 2 cm for the height component and 2.0 cm for the horizontal components. In the data processing setting, IGS08 was selected as the output reference frame. The output geoid model was selected “GEOID09”. GEOID09 is a hybrid geoid model and used by OPUS-Projects to convert the ellipsoidal heights to orthometric height. This model was the most recent model available when these experiments were performed.

Currently, OPUS-Projects can only process GPS data, it does not have the capabilities to process data from GLONASS or GALILEO satellites.
For modeling the troposphere, OPUS-Projects gives two options: (1) piecewise linear and (2) step-offset. Even though these techniques are named “troposphere model” in the preferences of OPUS-Projects, actually these are the estimation techniques for the zenith wet tropospheric corrections. The piecewise linear estimations technique was used in these experiment (based on personal communication with Gerald Mader from the Geosciences Research Division of National Geodetic Survey).

The interval to estimate zenith wet tropospheric corrections was set to 30-minutes, which is recommended as the minimum time interval to estimate the tropospheric corrections by OPUS-Projects. Since the tested data spans are relatively short, the minimum time interval is selected to obtain larger number of estimated tropospheric corrections.

The option for constraint weights is selected as ‘normal’. That corresponds to ~3 cm. This level of constraints is very acceptable, because CORS stations might move up to 4 cm from the published coordinates.

Table 5.2 presents the session details of the data uploaded to be used for the data processing.

Table 5-2 - Session Details for the Unknown Stations

Session Details for CORS Stations Used (June 3rd , 2012)				
Station Name	Duration (Hour)	Start and End Time (Eastern Time)	New Name	Antenna Type
COLB	6	9 am - 3 pm	COL6	TRM55971.00 NONE
DEFI	6	9 am - 3 pm	DEF6	TRM29659.00 UNAV
KNTN	0.5	12 am - 12:30 pm	KNT0	TRM57971.00 NONE
OHFN	1	12 am - 1 pm	OHF1	TRM57971.00 NONE
OHHA	2	11 am - 1 pm	OHH2	TRM55971.00 NONE
OHHU	4	10 am - 2 pm	OHH4	TRM57971.00 NONE
OHUN	0.5	12 am - 12:30 pm	OHU0	TRM55971.00 NONE
OHMH	1	12 am - 1 pm	OHM1	TRM41249.00 TZGD
OHRI	2	11 am - 1 pm	OHR2	TRM57971.00 NONE
WOOS	4	10 am - 2 pm	WOO4	TRM57971.00 NONE

Note that the actual CORS names of the stations are in column 1, while the adopted names of the stations in OPUS-Projects are listed in column 4.

6 Results and Analysis

6.1 Testing the Network Configurations

This section presents the details of the selected experiments and their corresponding results for the extracted zenith wet corrections and the computed height residuals for each of the network configurations. It should be noted that the 30-min and 1-hour GPS data spans are not presented here, since these spans were determined to be too short to properly capture the zenith corrections

6.1.1 Single Reference Base Approach

The single base station approach was designed by creating single baselines between the unknown stations and a base station from the CORS network Figure 6-1. The CORS station is selected as the base and constrained in the data processing since OPUS-Project requires at least one constrained station. In this experiment the CORS station TIFF was constrained.

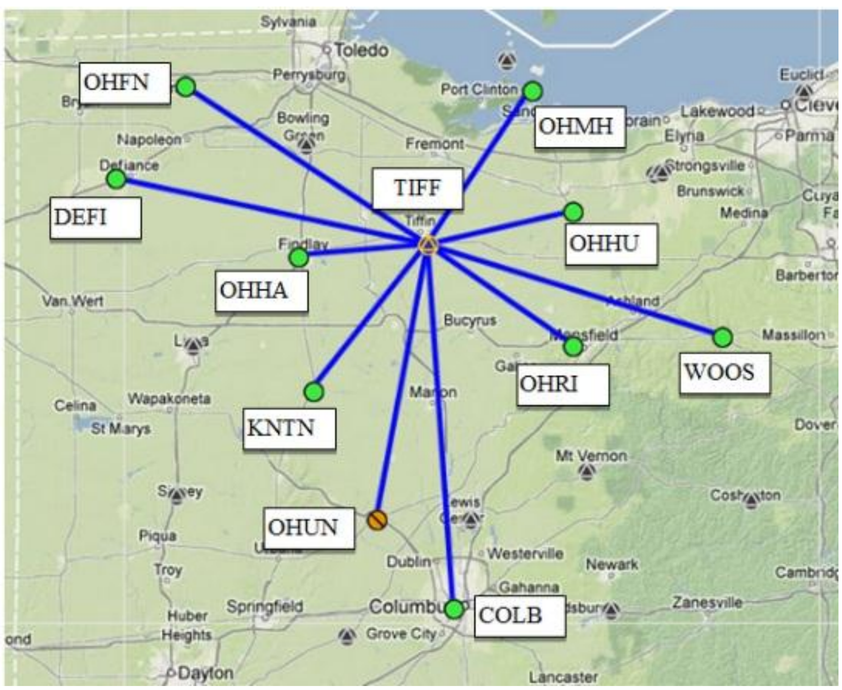

Figure 6-1 – The First Six Single Base Approach Solutions

Additionally, the base stations were moved within the network of the unknown stations up to eight hundred kilometers outside the network to monitor the quality of the estimated tropospheric corrections. This test provided six different solutions and facilitated the possibility of investigating the required baseline length to de-correlate the tropospheric corrections. Table 6-1, shows the base stations and the baseline length between base stations and the corresponding station for the six solutions.

In the analysis of the results for the single base approach, a selection of the unknown stations will be illustrated in the figures. The stations, OHRI (2-hr), OHHU (4-hr) and COLB (6-hr) were randomly selected, also these data spans showed the most details and significant changes.

Table 6-1 - The Base Stations, and Baseline Lengths in the Single Base Approach Solutions: SB1-SB6

Station Name	Time (hrs)	Single Base Solution Number					
		SB1	SB2	SB3	SB4	SB5	SB6
		The Base Station Used and Baseline Length (km)					
		TIFF	SIDN	LEBA	KYTD	TN32	AL20
COLB	6	124	103	121	351	492	711
DEFI	6	108	109	205	417	568	782
KNTN	0.5	63	60	145	380	529	747
OHFN	1	98	138	236	454	605	820
OHHA	2	44	91	186	417	567	784
OHHU	4	50	166	243	480	626	845
OHUN	0.5	95	69	119	356	502	720
OHMH	1	63	183	270	505	653	872
OHRI	2	60	145	209	445	590	808
WOOS	4	105	194	249	481	623	841

Based on the results generated for the 2hr, 4hr and 6hr time spans using the single reference base approach, the tropospheric corrections followed a smooth and comparable trend for the baselines longer than approximately 250 km. However, the corrections estimated with long baselines (>250 km) may differ, from the observed trend as can be seen with baselines 590km, 626 km and 496km in Figures 6-2 to 6-4 respectively.

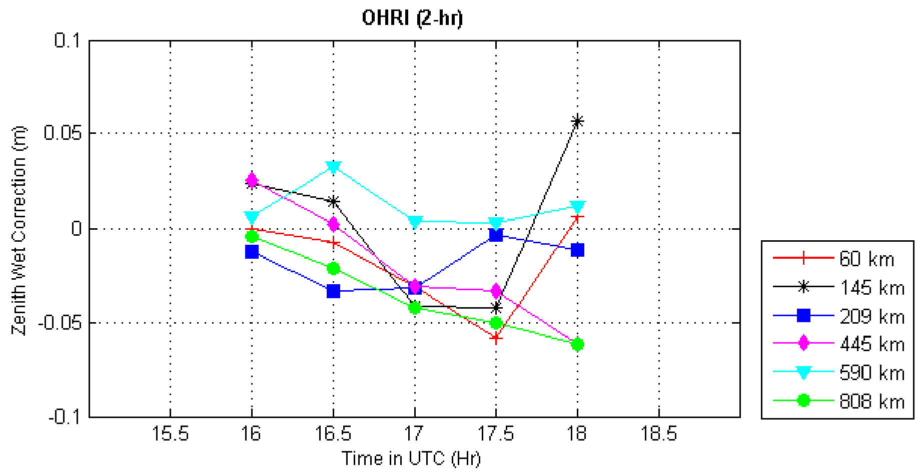

Figure 6-2- Zenith Wet Corrections of OHRI Station from the Single Base Approach - Session Duration 2 hours

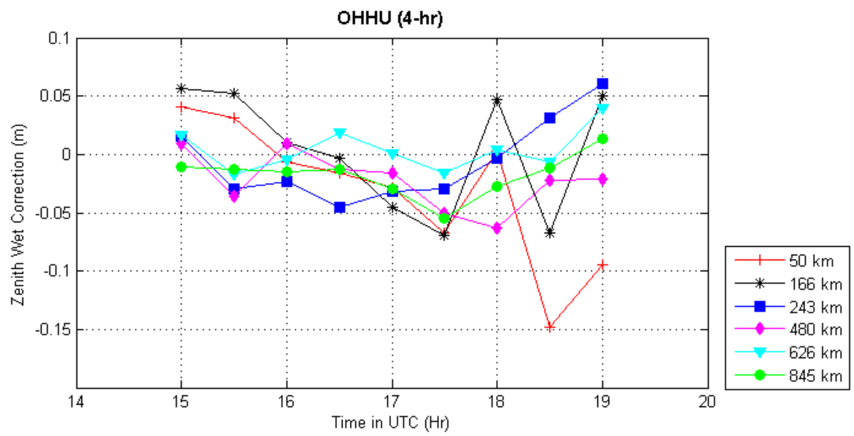

Figure 6-3 - Zenith Wet Corrections of OHHU Station from the Single Base Approach - Session Duration 4 hours

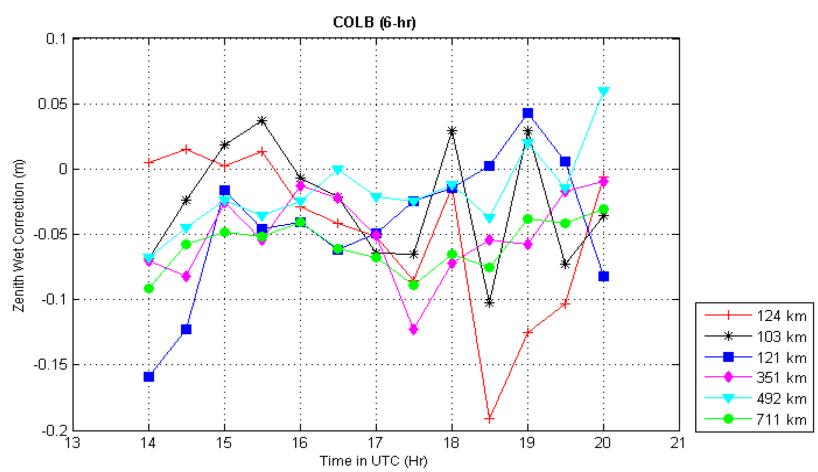

Figure 6-4 - Zenith Wet Corrections of COLB Station from the Single Base Approach - Session Duration 6 hours

The height differences were also analyzed by computing the height residuals. The height residuals were obtained by subtracting the published ellipsoidal heights obtained from the NGS coordinate file of the corresponding station from ellipsoidal heights obtained from the experimental solutions. The published ellipsoidal heights are obtained from the NGS coordinate file of the corresponding station. The calculated residuals show that there were considerable improvements in the height residuals when the duration of sessions was longer that one hour. For the 4-hour and 6-hour data spans, the height residuals were < 2.5cm, as compared to the shorter GPS data spans.

The mean and standard deviation of the height residuals of the unknown stations were calculated for the GPS data spans tested: 1-hour, 2-hour, 4-hour and 6-hour, seen in Tables 6-2 to 6-5 below. These calculations showed that the overall mean and standard deviation decreased as the data span increased. It is also, generally, smaller for baselines grouped together in two categories, approximately up to 250 km (left side of Tables), and approximately over 250 km (right side of Tables).

Table 6-2 - The Mean and Standard Deviation of the Heights Residuals of OHFN and OHMH Stations – 1 hour data span

Solution No.	SB1	SB2	SB3	SB4	SB5	SB6
Base Station	TIFF	SIDN	LEBA	KYTD	TN32	AL20
OHFN (1-hour)						
Baseline Length (km)	98	138	236	454	605	820
Height Residual (m)	0.025	-0.041	0.006	-0.022	0.005	-0.061
	Mean = 0.003m Std. Deviation = 0.034m			Mean (m) = -0.026 Std. Deviation = 0.033m		
Overall Mean (m) = -0.015			**Overall Standard Deviation (m) = 0.033**			
OHMH (1-hour)						
Baseline Length (km)	63	183	270	505	653	872
Height Residual (m)	0.072	0.015	0.038	0.107	0.046	0.187
	Mean = 0.042 m Std. Deviation = 0.029m			Mean = 0.113m Std. Deviation = 0.071m		
Overall Mean (m) = 0.077			**Overall Standard Deviation (m) = 0.062**			

Table 6-3 - The Mean and Standard Deviation of the Heights Residuals of OHRI and OHHA Stations – 2 hour data span

Solution No.	SB1	SB2	SB3	SB4	SB5	SB6
Base Station	TIFF	SIDN	LEBA	KYTD	TN32	AL20
OHRI (2-hour)						
Baseline Length (km)	60	145	209	445	590	808
Height Residual (m)	-0.007	-0.026	-0.017	-0.020	-0.029	-0.044
	Mean (m) = -0.017 Std. Deviation = 0.010m			Mean (m) = -0.031 Std. Deviation = 0.012m		
Overall Mean (m)= -0.024				**Overall Standard Deviation (m)= 0.013**		
OHHA (2-hour)						
Baseline Length (km)	44	91	186	417	567	784
Height Residual (m)	-0.013	-0.036	-0.031	-0.031	0.013	-0.038
	Mean = -0.027m Std. Deviation = 0.012m			Mean = -0.019m Std. Deviation = 0.028m		
Overall Mean (m) = -0.023				**Overall Standard Deviation (m) = 0.020**		

Table 6-4 - The Mean and Standard Deviation of the Heights Residuals of OHHU Station – 4 hour data span

Solution Number	SB1	SB2	SB3	SB4	SB5	SB6
Base Station	TIFF	SIDN	LEBA	KYTD	TN32	AL20
OHHU (4-hour)						
Baseline Length (km)	50	166	243	480	626	845
Height Residual (m)	0.009	0.009	0.008	0.014	0.004	-0.053
	Mean = 0.009 m Std. Deviation = 0.001m			Mean = -0.012 m Std. Deviation = 0.036m		
Overall Mean (m) = -0.001 **Overall Standard Deviation (m) = 0.025**						

Table 6-5 - The Mean and Standard Deviation of the Heights Residuals of COLB Station – 6 hour data span

Solution Number	SB1	SB2	SB3	SB4	SB5	SB6
Base Station	TIFF	SIDN	LEBA	KYTD	TN32	AL20
COLB (6-hour)						
Baseline Length (km)	124	103	121	351	492	711
Height Residual (m)	0.005	-0.009	-0.016	-0.003	-0.008	-0.018
	Mean = -0.007m Std. Deviation = 0.011m			Mean = -0.010 m Std. Deviation = 0.008m		
Overall Mean (m)= -0.008 **Overall Standard Deviation (m)= 0.008**						

Based on these results, the single base approach provides mostly consistent height residuals if the GPS data span is equal or longer than 2-hour. However, it can still introduce some biases in the ellipsoidal height even with 4-hour data span (the sixth solution in Table 6-4), depending on the reference station.

In the next section, an alternative network configuration was tested to evaluate whether any improvements were obtained.

6.1.2 Double Reference Base Approach

The double reference base approach included two reference stations from the CORS network in the data processing, where one CORS station was located near and the other located distant (remote) from the unknown stations. As seen in Figure 6-5, the distant CORS station was selected from the Mississippi network (MSPH), which is approximately one thousand kilometers away from the base station TIFF. It is expected that the distant CORS station, MSPH, would improve the tropospheric correction estimation at the base station TIFF as well as at the unknown stations.

As discussed in the previous experiment, the usage of long baseline may reduce the quality for short data spans. In this approach, the long baseline is created by using two CORS stations, therefore the long baseline shown in Figure 4.31 is processed for 24-hour. This way, the long baseline would not reduce the quality of the solution.

The solution for the double base approach is based on the same preferences for the quality indicators and data processing settings given in Table 5-1

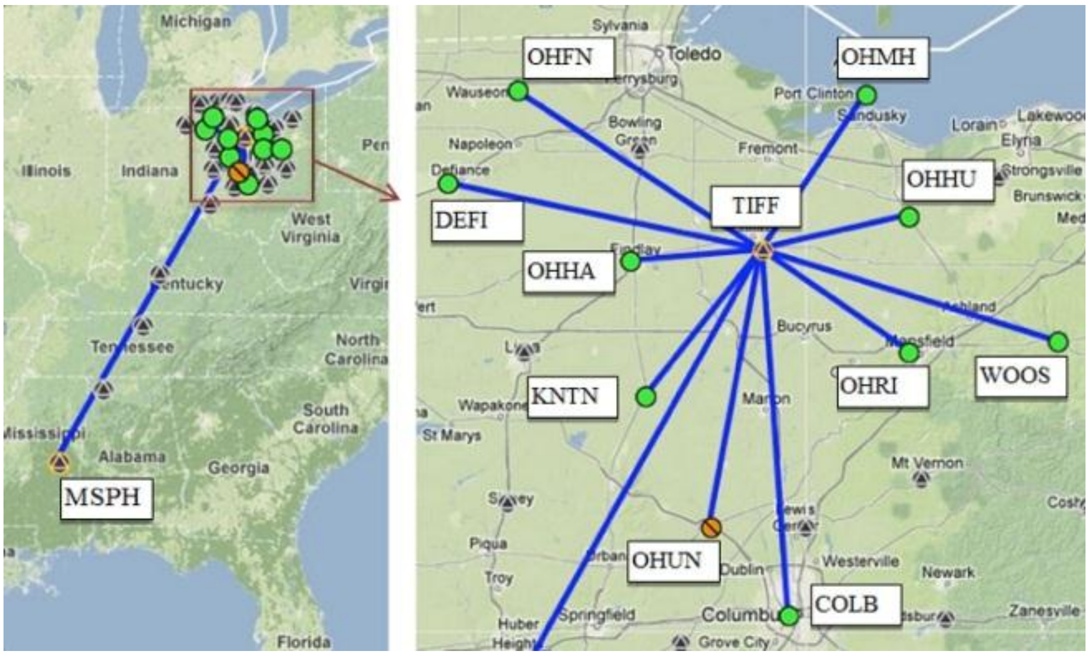

Figure 6-5 - The Network Configuration of the Double Base Approach

The results obtained from the double reference approached, indicated that there were minor improvement over the single base solution for the zenith wet correction estimation. However, the height residuals are almost the same in the case of 6-hour GPS data span.

The zenith corrections of double base solution Figure 6-6 to 6-8, for the 2hr, 4hr and 6hr time spans follow smoother trend, than that of single reference base solution and display a better agreement with the meteorological profiles. Based on these results, it can be stated that the double base solution provides a more realistic zenith wet corrections. Also the use of a remote reference base station did not reduce the quality of the user solutions.

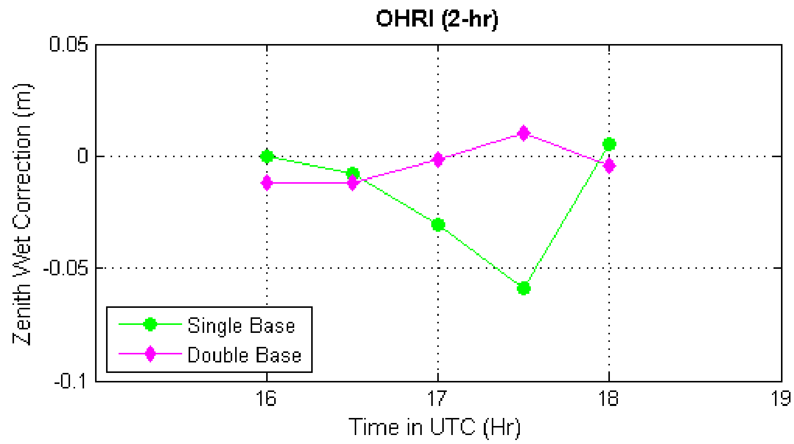

Figure 6-6 - Zenith Wet Corrections for OHRI Station from the Double Base Solution - Session Duration 2 hours

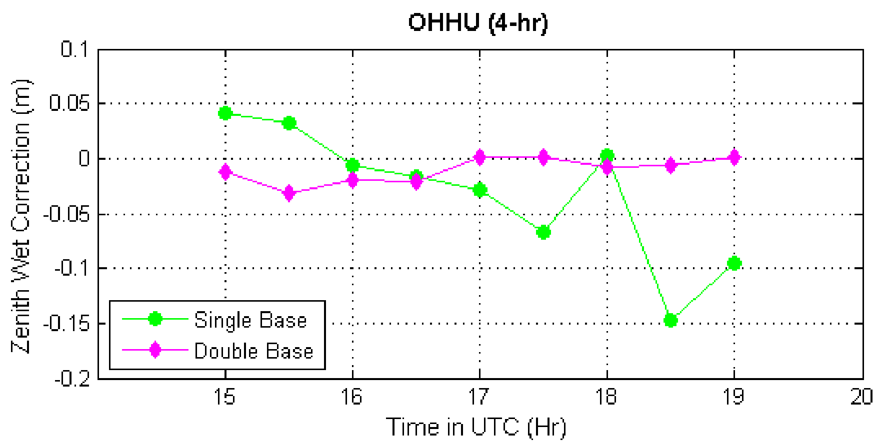

Figure 6-7 - Zenith Wet Corrections for OHHU Station from the Double Base Solution - Session Duration 4 hours

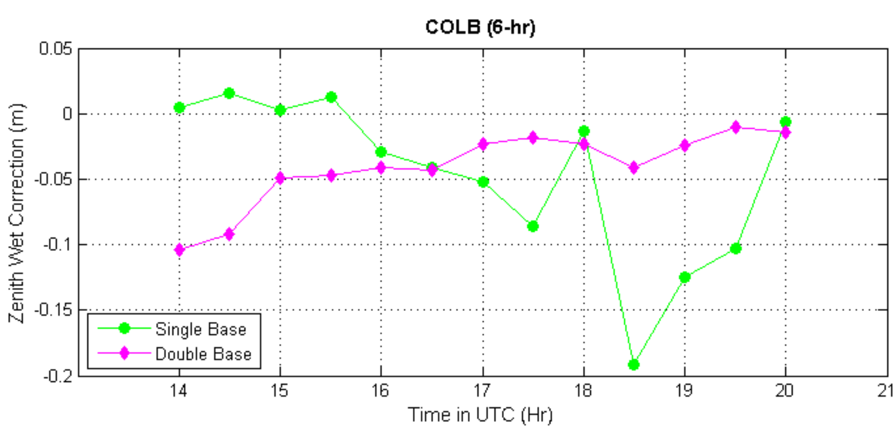

Figure 6-8 - Zenith Wet Corrections for COLB Station from the Double Base Solution - Session Duration 6 hours

In the next section, an alternative network configuration with multiple base stations was tested to evaluate whether any improvements over the double base approach can be achieved especially for the GPS data spans shorter than 2 hour.

6.1.3 Multiple Reference Base Approach

The results of the double base approach indicated that the additional distant base station improved the estimated tropospheric corrections and the quality of the solution. In this approach, four base stations are included in the data processing Figure 6-9. The configuration comprised of four reference station, where one station is located near the unknown stations, and the remaining three stations located distant from the core network.

These four stations can be selected from either the CORS or IGS networks. In this configuration, the CORS station TIFF was selected as the close station to the unknown station COLB. Additionally, three IGS stations were selected from the IGS network: ALGO from Ontario, Canada, DUBO from Manitoba, Canada, and GODE from Maryland in the United States of America. Since the distant stations were selected from the IGS network and their coordinates were tightly constrained, this technique defines the local network in the IGS frame, which is considered the most precise reference frame in geodetic applications.

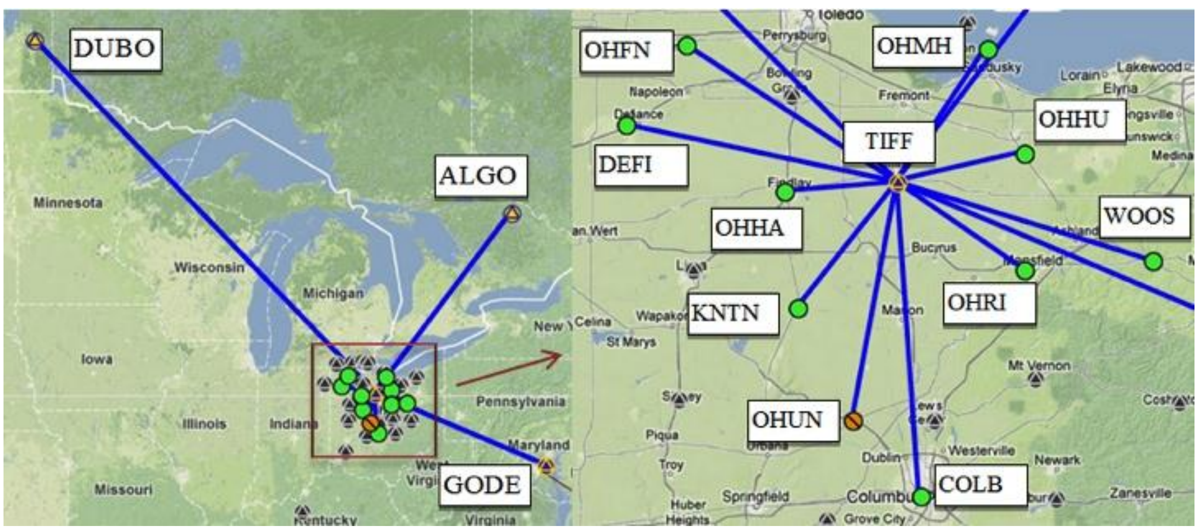

Figure 6-9 - The Network Configuration of the Multiple Base Approach

Finally, the multiple reference base solution is generated by the addition of three distant station. It was observed that with the inclusion of IGS stations in this approach the solution provided a more realistic zenith wet corrections, as compared to the single and double base solutions, Figure 6-10 to 6-12. Also the zenith total delay from the multiple reference base solution agrees with the Ground-Based GPS-IPW delay better than the single base and double base solutions, this is further discussed in Section 6.1.4, below. The results, the height residuals of the stations (except OHMH (1-hr)) were under 2.5 cm, and agreed with the published ellipsoidal heights.

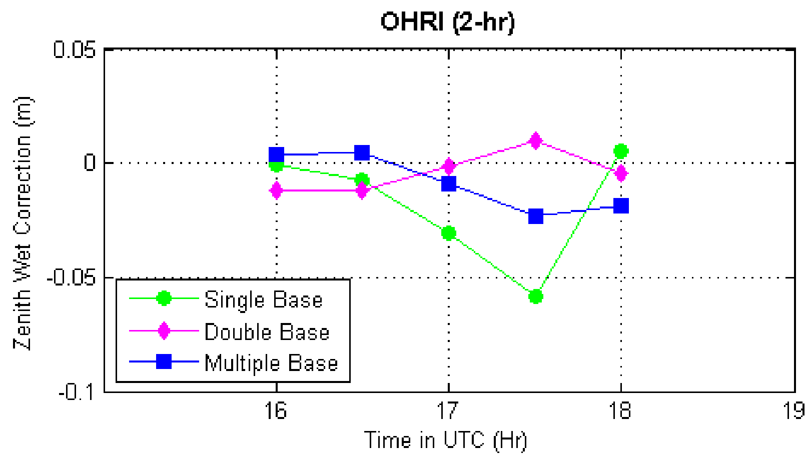

Figure 6-10 - Zenith Wet Corrections of COLB Station from the Multiple Base Approach - Session Duration 2 hours

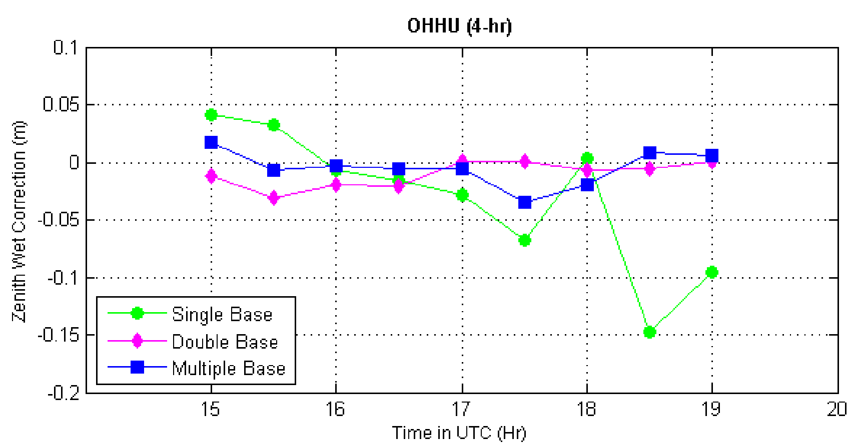

Figure 6-11 - Zenith Wet Corrections of OHHU Station from the Multiple Base Approach - Session Duration 4 hours

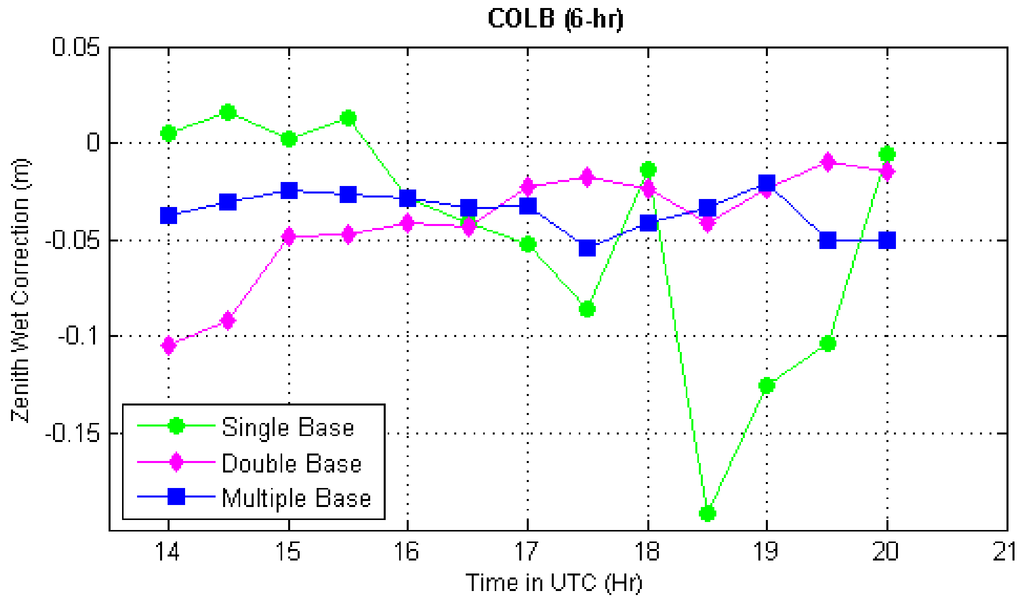

Figure 6-12 - Zenith Wet Corrections of COLB Station from the Multiple Base Approach - Session Duration 6 hours

6.1.4 Zenith Tropospheric Delay Comparison

Zenith tropospheric delay for COLB was extracted from the GPS-IPW project and used as reference to compare to the zenith wet corrections determined from the single base, double base, and multiple base solutions, Figure 6-13.

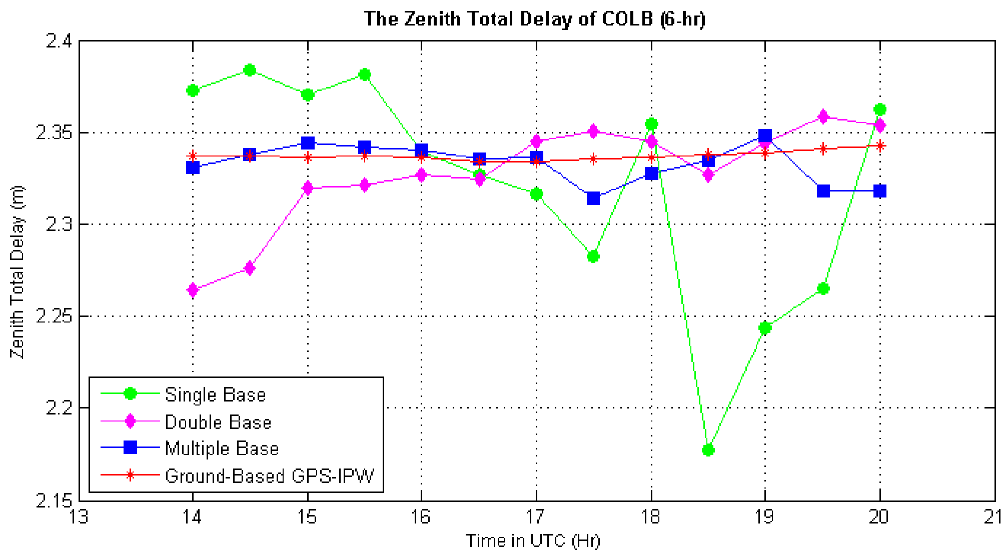

Figure 6-13 - Zenith Total (Tropospheric) Delay of COLB Station – Session Duration 6 hours

Figure 6.13, shows that the zenith tropospheric delays from the multiple reference base approach agreed with the Ground-Based GPS-IPW results better than the single and double base solutions, especially at the beginning of the session. The mean and standard deviation of the zenith tropospheric delay were also computed and the results in Table 6-6, verifies the results of the comparison.

Table 6-6 - The Mean and Standard Deviation of Zenith Tropospheric Delays of COLB Station

The Mean and Standard Deviations of Zenith Tropospheric Delays of COLB		
Solutions Name	Mean (m)	Standard Deviation (m)
Single Reference Base Solution	2.321	0.063
Double Reference Base Solution	2.328	0.029
Multiple Reference Base Solution	2.333	0.011
GPS-IPW	2.337	0.003

Based on Table 6-6 above, the mean of zenith tropospheric delays were very close to each other. The highest difference was between the Ground-Based GPS-IPW and the single base solution, which was ~1.6 cm; the single base solution also had the highest standard deviation, 6 cm, as compared to the other solutions. The best agreement was between the multiple base approach and the Ground-Based GPS-IPW in terms of the means and the standard deviations of the zenith tropospheric delays.

6.1.5 Overall Height Residuals Comparison

The published ellipsoidal heights were obtained from the NGS coordinate file of the corresponding station. These heights were subtracted from the heights obtained from the first single base, double base, and the multiple base solutions to compute the height residuals for the unknown stations, Figure 6-14.

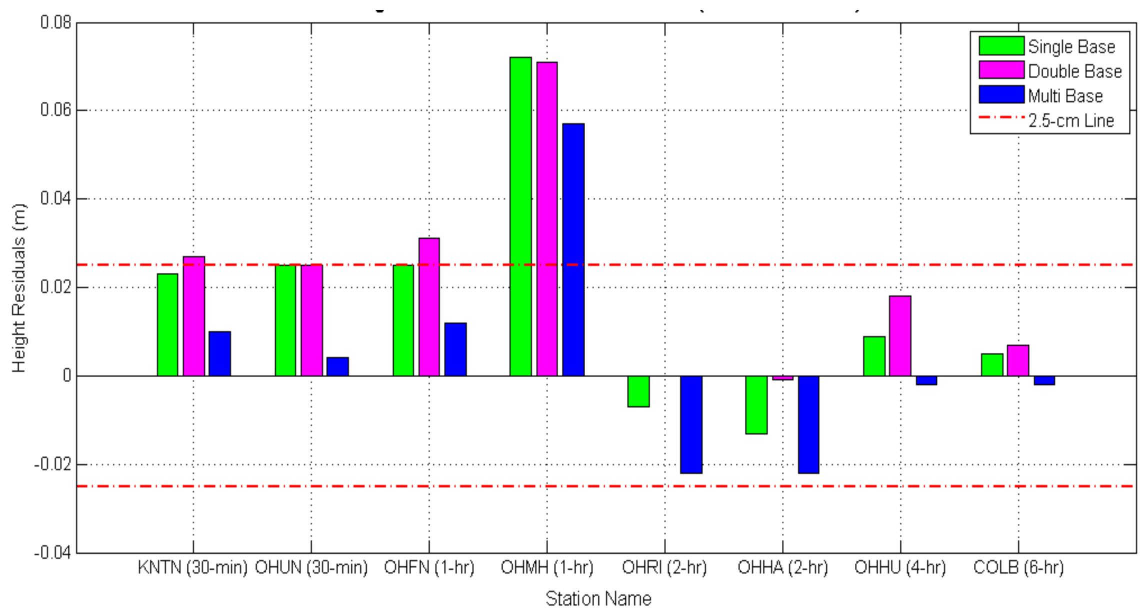

Figure 6-14 - The Height Residuals of the Stations from all the Network Configuration

The computation illustrated in Figure 6-14, indicate that the 1-hour GPS data span, the multiple base solution shows slight improvements in the case of OHFN and OHMH. However, three solutions did not provide a good agreement with the published ellipsoidal height of OHMH. The reason for this phenomenon for OHMH remains unknown, and thus, can be considered as an outlier.

However the height residuals for the 4-hour and 6-hour GPS spans were very low for all the solutions, and showed an agreement with the published ellipsoidal heights. The multiple reference base solution provided the lowest residuals in the case of OHHU and COLB.

6.1.6 Testing the Impact of Data Span

This experiment was executed to determine the changes in tropospheric corrections, and ellipsoidal height estimation with respect to different times of day, and GPS data spans. The CORS station COLB is selected from the Ohio network treated as “unknown station”. In order to avoid any possible gaps in the GPS data, the day of June 5, 2012 (DoY 157) was selected as upon investigation of the data availability this data show continuous data collection throughout the entire day.

In order to test various GPS data spans, the selected time intervals of the sessions are 2 hours, 4 hours, 6hours, and the 24 hours. In order to split the 24-hour GPS data, the daily set is divided by 6-hour sliding window with the 2-hour overlaps, as shown in Figure 6-15.

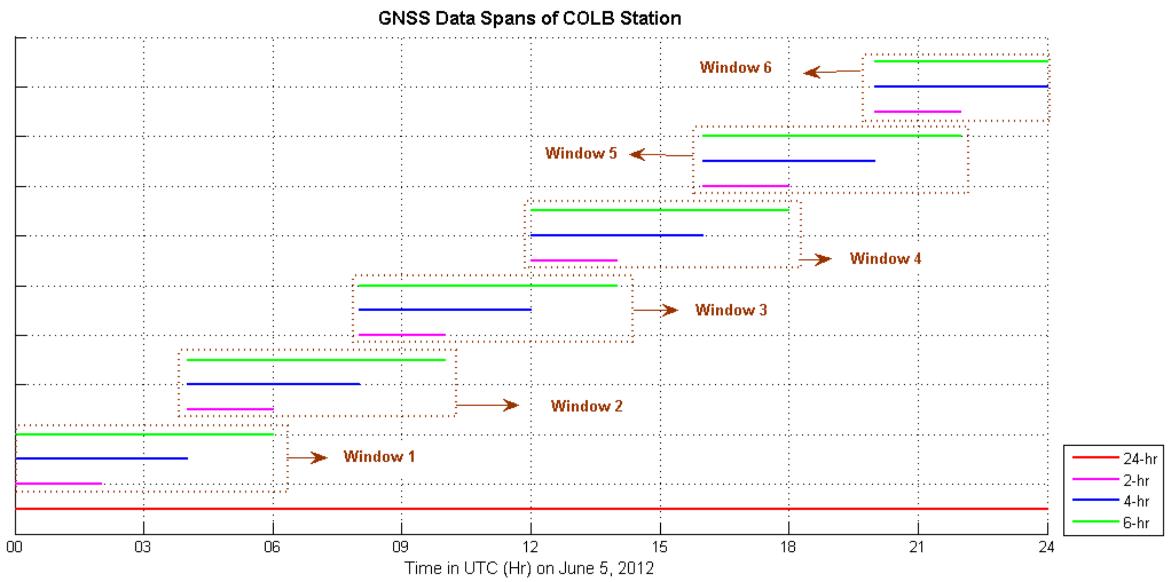

Figure 6-15 - Tested GPS Data Spans of COLB Station and Window Numbers

There are total of 19 GPS data tested: six of 2-hour, six of 4-hour, six of 6-hour, and finally one 24-hour GPS data spans.

As mentioned previously and presented in Figure 4.9, the COLB station is one of the Ground-Based GPS-IPW stations, and has meteorological data. Therefore, this station would enable the comparison between the surface measurements from GPS-IPW data, and GPT. The temperature, pressure, and relative humidity values of COLB station are obtained from the GPS-IPW project and the GPT for the day of June 5, 2012, as shown in Figure 6.16.

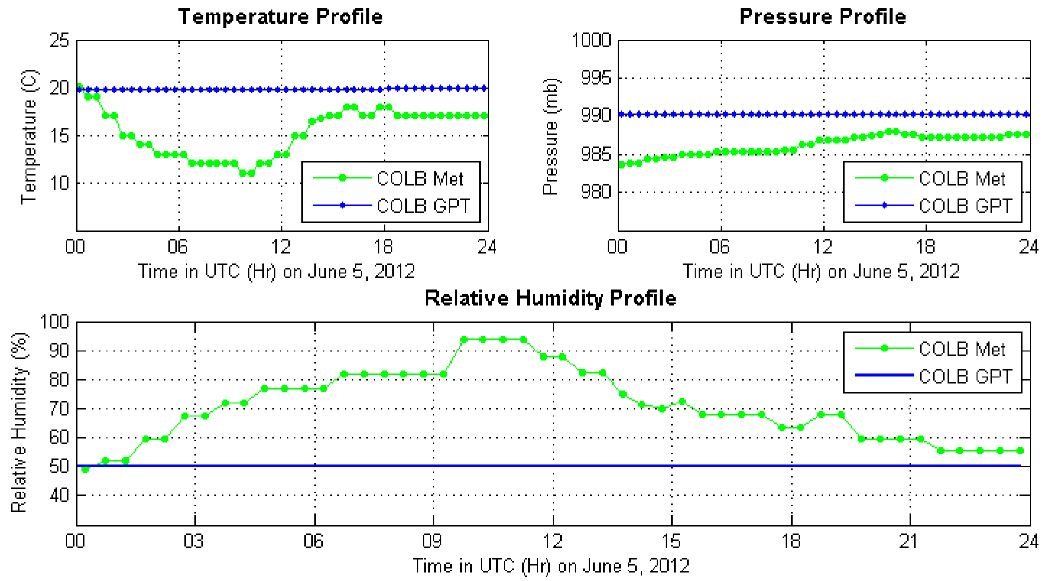

Figure 6-16 : The Temperature, Pressure, and Relative Humidity Profiles of COLB Station. In the legend of plot, COLB Met (green) represents the temperature, pressure, and relative humidity profiles from the Ground-Based GPS-IPW project, while COLB GPT (blue) represents those profiles from the GPT.

Based on Figure 6.16, the selected day does not have any unusual weather conditions, since the surface measurements do not change radically. Figure 6.16 also illustrates that the GPT does not show the variability, as compared to the surface measurements, but it still fits the profiles with an acceptable accuracy. Therefore, it is expected that the zenith wet corrections from the solution(s) should provide a smooth trend without major peaks.

The required GPS data sessions of COLB, presented in Figure 6-15, were downloaded from the NGS web page (http://www.geodesy.noaa.gov/CORS/) for June 5, 2012 (DoY, 157). Then, the corresponding GPS data spans were uploaded through the traditional OPUS web page to the created project.

Based on the processing settings in Table 5-1 in Section 5.1.1 above, the double and multiple base network configurations were tested to investigate the changes in tropospheric corrections as well as the ellipsoidal heights for the corresponding GPS data spans of the COLB station.

6.1.6.1 ***The Double Base Approach***

In this experiment, TIFF is selected as the close base station with ~120 km baseline length to the user, and MSPH is selected as the distant base station with ~1000 km baseline length, as shown in Figure 6-17. The extracted zenith wet corrections and the computed height residuals are presented in the following figures for all the generated solutions.

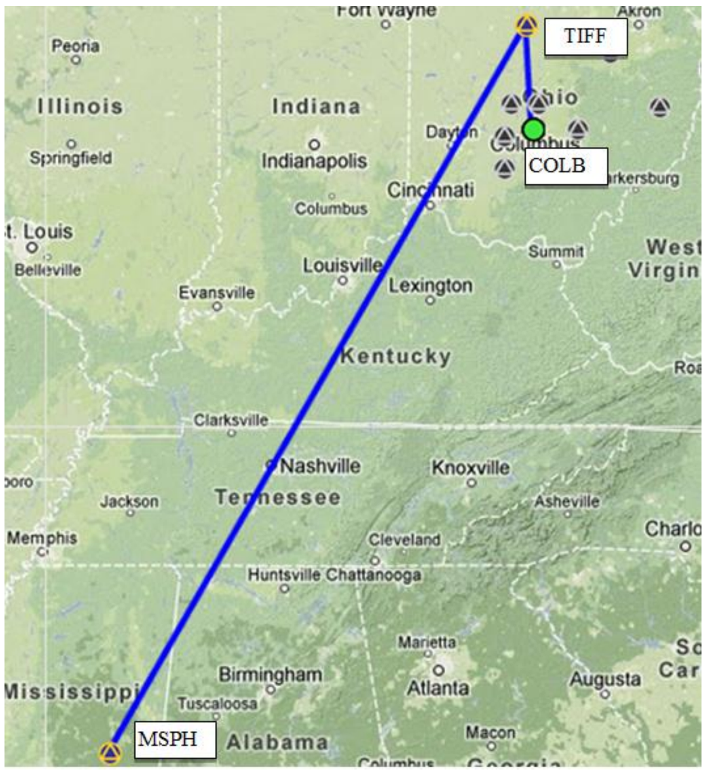

Figure 6-17 - The Network Configuration of the Double Base Approach

The extracted zenith wet corrections and the computed height residuals are presented in the following figures for all the generated solutions.

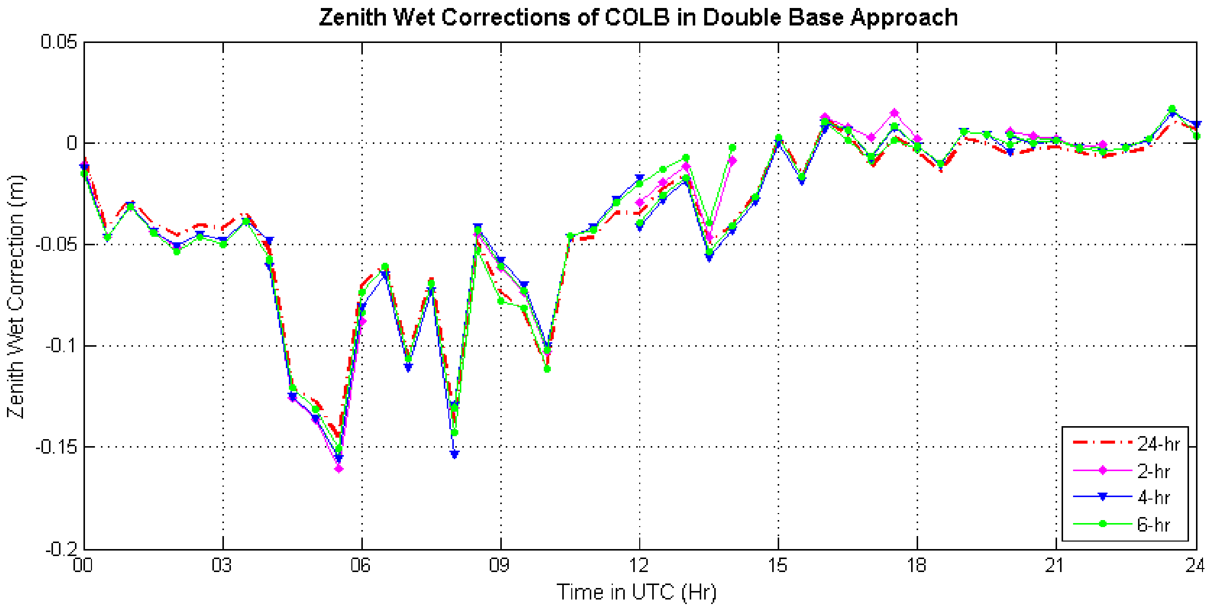

Figure 6-18 - Zenith Wet Corrections of COLB Station from the Double Base Solutions

Figure 6-18 shows that the zenith wet corrections of 2-hour, 4-hour, and 6-hour GPS data spans agree with the 24-hour data solution. However, the 6-hour span from the time window 3 and the 2-hour span from the time window 4 deviate from the trend at ~14:00 UTC. These deviations might introduce high residual in the height component estimated from the corresponding GPS data spans.

Figure 6-19 - The Height Residuals of COLB Station from the Double Base Solutions

In Figure 6-19, the majority of the height residuals are less than 2.5 cm, therefore most of the solutions from the double base approach agree with the published ellipsoidal height of the COLB station. However, the time windows 2, 3, and 4 contain some higher height residuals, as compared to the other windows.

Table 6-7 - The Mean and Standard Deviation of the Heights Residuals of COLB Station from the Double Base Solutions

The Mean and Standard Deviation of the Heights Residuals					
Window Number	GPS Data Spans			**Mean**	**Standard Deviation**
	2 hour	4 hour	6 hour		
1	0.004	0.002	0.006	**0.004**	**0.002**
2	0.008	0.003	-0.013	**-0.001**	**0.011**
3	-0.042	-0.048	-0.041	**-0.044**	**0.004**
4	-0.020	0.009	0.002	**-0.003**	**0.015**
5	-0.014	-0.009	-0.012	**-0.012**	**0.003**
6	-0.017	-0.011	-0.014	**-0.014**	**0.003**

Furthermore the Mean and Standard Deviation of the height Residuals were computed and are shown in Table 6-7. From the table, the time window 3 provides the highest mean of -4.4 cm. The time windows 2 and 4 have the highest standard deviations; because some part of these windows contain higher residuals, as shown in Figure 6-19.

Even though the most of the height residuals are less than 2.5 cm, there are some higher values in the time windows 2, 3, and 4 in Figure 6-19. These high residuals agree with the unexpected tropospheric correction peaks in Figure 6-18, since they are in the same time of the day.

Therefore, from this experiment, the double base approach does not provide consistent results for all GPS data spans tested in terms of both ellipsoidal heights, and zenith wet corrections. Hence, the multiple base approach was evaluated.

6.1.6.2 The Multiple Base Approach

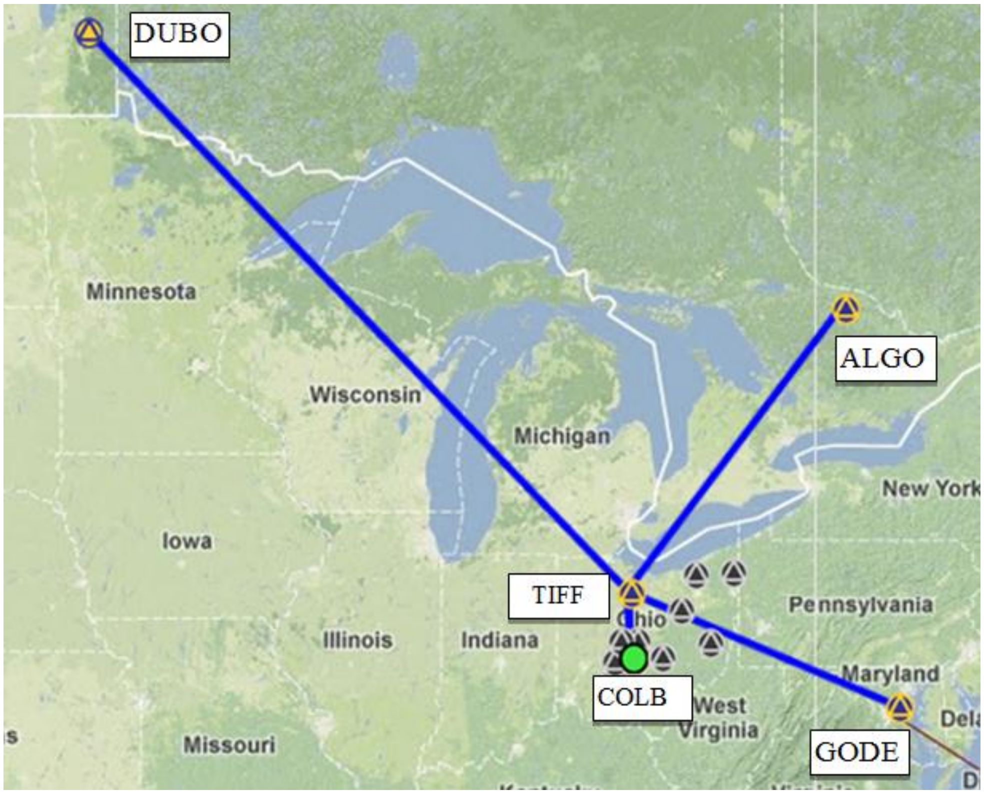

Figure 6-20 - The Network Configuration of the Multiple Base Approach with TIFF

The multiple base approach has four base stations in its network configurations, as previously described in Section 6.1.3. The extracted zenith wet corrections and the computed height residuals are presented in the following figures for all the generated solutions.

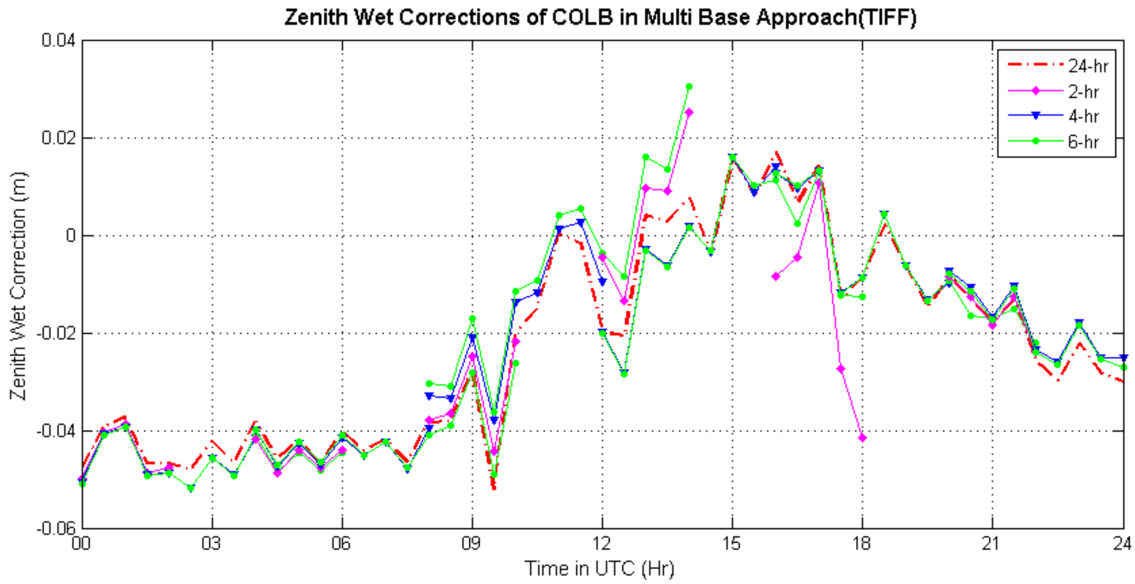

Figure 6-21 - Zenith Wet Corrections of COLB Station from the Multiple Base Approach with TIFF

Figure 6-20, shows that the zenith wet corrections of the 2-hour, 4-hour, and 6-hour GPS data spans mostly follow similar trend with the 24-hour solution. Even though the trend of the zenith corrections contains some peaks between ~9:00 and ~18:00 UTC, the magnitudes of these peaks do not deviate from the trend as much as the ones in the double base approach.

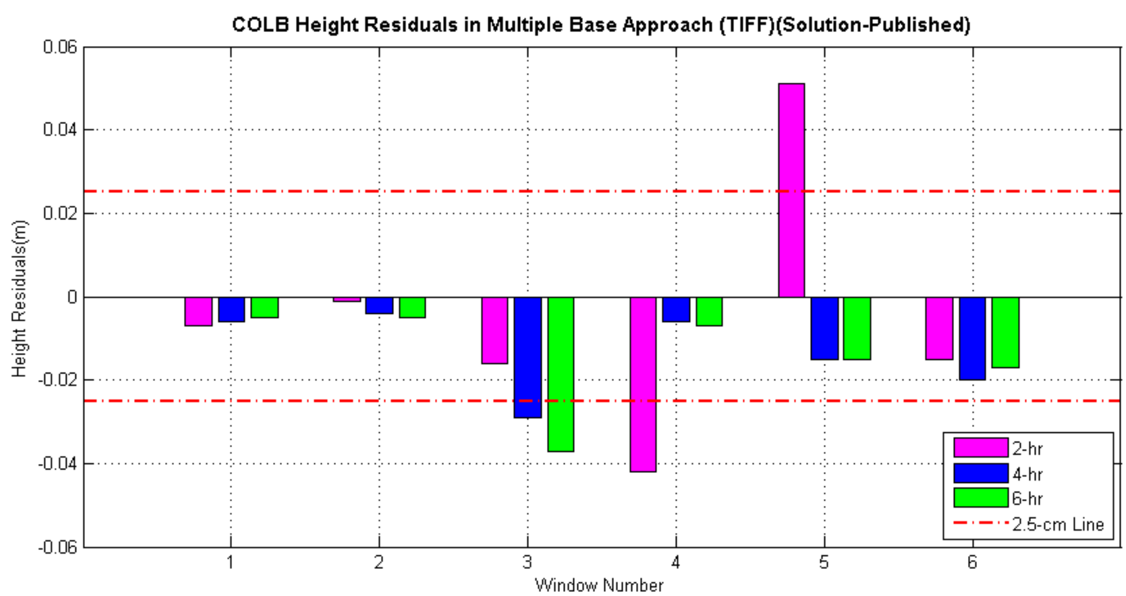

Figure 6-22 - The Height Residuals of COLB Station from the Multiple Base Approach with TIFF

In Figure 6-21, over fifty percent of the height residuals were less than 2.5 cm, therefore it can be stated that majority of the solutions in the multiple base approach with TIFF agrees with the published ellipsoidal height of COLB station. However, the height residuals of 4-hour and 6-hour GPS spans in the time window 3, the 2-hour GPS spans in the time windows 4 and 5 are higher, as compared to other solutions.

Further the Mean and Standard Deviation of the height Residuals were computed and are shown in Table 6-8. From the table, the time window 3 displays the highest mean. In addition, the standard deviations of time windows 3, 4 and 5 are higher, as compared to other time windows.

Table 6-8 - The Mean and Standard Deviation of the Heights Residuals of COLB Station from the Multiple Base Approach with TIFF

The Mean and Standard Deviation of the Heights Residuals					
Window Number	GPS Data Spans			**Mean**	**Standard Deviation**
	2 hour	4 hour	6 hour		
1	-0.007	-0.006	-0.005	**-0.006**	**0.001**
2	-0.001	-0.004	-0.005	**-0.003**	**0.002**
3	-0.016	-0.029	-0.037	**-0.027**	**0.011**
4	-0.042	-0.006	-0.007	**-0.018**	**0.021**
5	0.051	-0.015	-0.015	**0.007**	**0.038**
6	-0.015	-0.020	-0.017	**-0.017**	**0.003**

From this experiment, it can be concluded that the multiple base approach solutions provided some significant improvements over the double base approach in terms of the accuracy and consistency of the zenith wet corrections, but not in the height residuals.

6.2 Summary of finding

This section attempted to investigate the required baseline length to de-correlate the tropospheric corrections at individual stations, as well as to determine the optimal network design. In order to perform these experiments, three (3) different networks were formed: the single, the double, and the multiple base station approaches. The comparison of these 3 approaches concluded that the multiple base approach (combination of CORS and IGS stations) is the optimal network, which improved the estimation of the tropospheric corrections, the quality of the processing results, and the positioning accuracy, especially in the height component. This configuration would reduce the possible errors associated with the base station, provide reliable tropospheric corrections and improve the accuracy of the ellipsoidal heights. These test cases also illustrated that a longer session provides higher accuracy and reliable ellipsoidal heights. Based on the results in this study, at least a two-hour data span should be used to determine the ellipsoidal heights accurately in OPUS-Projects. Additional a second independent observation should be used to increase the confidence in the processing results. In order to maximize independence of the observations, the second observation should be obtained on a different day and at a different time of day.

The recommendations from this section were implemented to reprocess the International Great Lakes Datum (IGLD) of 1985 Height Modernization projects data (2010, 2005, and 1997) to test on an existing dataset, the specifications and procedures to achieve a 2-5 cm of height accuracy.

7 Study Area and Methodology for Reprocessing and re-adjusting of the IGLD 2010, 2005 and 1997 Height Modernization surveys

7.1 The Great Lakes Region

The Great Lakes are a collection of freshwater lakes located in northeastern North America, on the Canada–United States border, which connect to the Atlantic Ocean through the Saint Lawrence Seaway and the Great Lakes Waterway. Consisting of Lakes Superior, Michigan, Huron, Erie, and Ontario, they form the largest group of freshwater lakes on Earth, containing 21% of the world's surface fresh water (GLIN 2013). The Great Lakes watershed includes part or all of eight U.S. states (Minnesota, Wisconsin, Illinois, Indiana, Michigan, Ohio, Pennsylvania and New York) and the Canadian province of Ontario (Figure 7-1). Today, more than 33 million people inhabit this drainage basin: more than one-tenth of the population of the United States and one-quarter of the population of Canada. These lakes contain about 23,000 km^3 (5,500 cu. mi.) of water, covering a total area of 244,000 km^2 (94,000 sq. mi.).

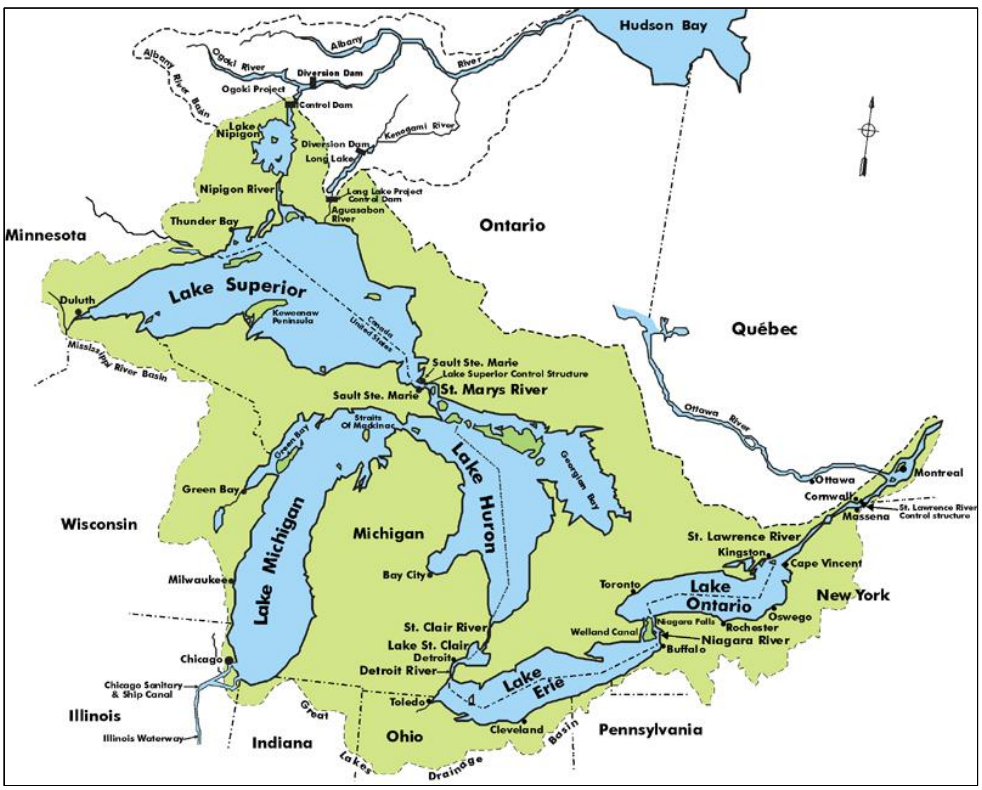

Figure 7-1 – Map of the Great Lakes basin watershed (GLIN 2013)

The channels that connect the Great Lakes are an important part of the system. The St. Marys River is the northernmost of these, a 60-mile waterway flowing from Lake Superior down to Lake Huron. The St. Clair and Detroit rivers, and Lake St. Clair between them, form an 89-mile long channel connecting Lake Huron with Lake Erie. The 35-mile Niagara River links lakes Erie and Ontario, and sends approximately 50,000 to 100,000 cubic feet of water per second over Niagara Falls; the manmade Welland Canal also links the two lakes, providing a detour around the falls. From Lake Ontario, the water from the Great Lakes flows through the St. Lawrence River all the way to the Atlantic Ocean, about 1,000 miles away. Figure 7-2 shows a profile of the Great Lake systems giving a representation of the channels connecting the lakes, the typical water surface elevations and comparative lake depths.

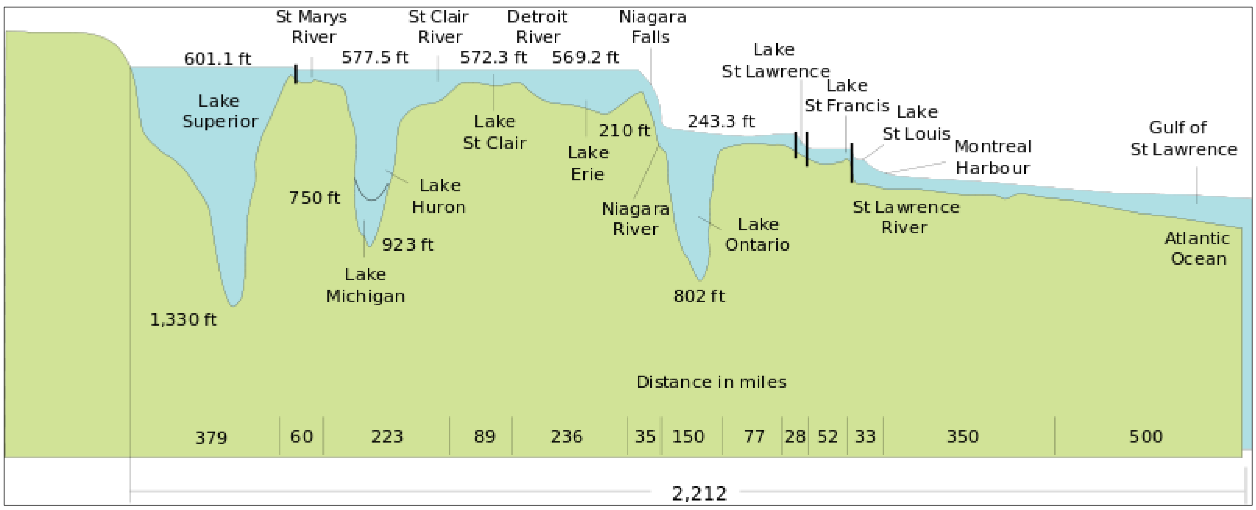

Figure 7-2 – System Profile of the Great Lakes (Wilby 2011)

These lakes are large enough to influence the regional climate, cooling summers and tempering winters, as well as increasing amounts of rain and snow in the region. Table 7-1 presents general facts and statistics of the physical features of the Great Lakes that may give an idea of the significance of this lake system.

Table 7-1 - Physical features of the Great Lakes (USEPA 2013)

Feature	Units	Lake Superior	Lake Michigan	Lake Huron	Lake Erie	Lake Ontario	Total
Average Depth (measured at low water)	**feet**	483	279	195	62	283	
	meters	147	85	59	19	86	
Maximum Depth (measured at low water)	**feet**	1,332	925	750	210	802	
	meters	406	282	229	64	244	
Volume (measured at low water)	**cubic miles**	2,900	1,180	850	116	393	**5,439**
	cubic km	12,100	4,920	3,540	484	1,640	**22,684**
Water Area	**Sq. miles**	31,700	22,300	23,000	9,910	7,340	**94,250**
	Sq. km	82,100	57,800	59,600	25,700	18,960	**244,160**
Major Settlement		Duluth, MN Marquette, MI Sault Ste. Marie, MI Sault Ste. Marie, ON Superior, WI Thunder Bay, ON	Chicago, IL Gary, IN Green Bay, WI Sheboygan, WI Milwaukee, WI Kenosha, WI Racine, WI Muskegon, MI Traverse City, MI	Alpena, MI Bay City, MI Owen Sound, ON Port Huron, MI Sarnia, ON	Buffalo, NY Cleveland, OH Erie, PA Toledo, OH	Hamilton, ON Kingston, ON Mississauga, ON Oshawa, ON Rochester, NY Toronto, ON	

7.1.1 OPUS-Projects Processing Settings and Data Upload

Data for the IGLD Height Modernization Projects 1997, 2005 and 2010 were collected from NGS archives. The dataset retrieved are indicated in the Table 7-2below;

Table 7-2 – Data acquired from NGS archives

Project Yr.	**Project #**	**No. of Stations**	**Data Type**					
			Log Sheets	**RINEX**	**GFiles**	**AFiles**	**BFiles**	**Reports and Doc.**
1997	GPS1212	72	✓	✓	×	×	×	×
2005	GPS2379	117	✓	✓	✓	✓	✓	✓
2010	GPS2824	154	✓	✓	✓	✓	✓	✓

✓ - data supplied; × - data missing

Note that the Number of stations includes in it total the number of benchmarks and the number of CORS used in the survey

Table 7-3 presents the quality indicator and processing settings used in OPUS-Projects.

Table 7-3 - Quality Indicators and Processing Settings used in GPS Data Processing

The Quality Indicators and Data Processing Settings					
Data & Solution Quality Thresholds			Data Processing Settings		
Precise Ephemeris	Best Available		Output Ref Frame	IGS08	
Minimum Observations Used	80 (%)		Output Geoid Model	GEOID12A	
Minimum Ambiguities Fixed	80 (%)		GNSS	GPS-Only	
Maximum Solution RMS	0.025 (m)		Troposphere Model	Piecewise Linear	
Maximum Height Uncertainty	0.020 (m)		Troposphere Interval	1800 (s)	
Maximum Latitude Uncertainty	0.020 (m)		Elevation Cutoff	15 (degree)	
Maximum Longitude Uncertainty	0.020 (m)		Constraint Weights	Normal	
			Network Design	USER; TRI	

8 Results and Analysis - Reprocessing and re-adjustment of the IGLD 2010, 2005 and 1997 Height Modernization surveys

Based on the results from the previous section, the multiple base approach was adopted for the reprocessing of the IGLD 1997, 2005 and 2010 Height Modernization surveys. This approach will translate as a USER session network design in OPUS-Project. The USER network design option as named allows the user to create a network design. The data was also processed using the triangle network design (TRI) which is OPUS-Projects predefined network strategy. These results were compared testing the overall robustness of OPUS Projects.

This USER configuration comprised of four (4) reference station, where one station is located near the unknown stations, and the remaining three (in some cases 4) stations located distant from the core network. These 4 stations were selected from the CORS and IGS networks. For the processing of these surveys the configuration was made up of, 1 CORS stations (HUB) and 3 IGS stations. The COR station was selected based on the location of the surveyed location and session. Additionally, the IGS stations were selected from the IGS network: ALGO, and NRC1 from Ontario, Canada, CAGS from Quebec, Canada, MDO1 from Texas, and GODE, from Maryland in the United States of America. These distant stations being selected from the IGS network were tightly constrained,

The triangle Network Design (Figure 8-1) selects baselines using the Delaunay triangulation algorithm. This algorithm selects lines connecting points such that no point falls inside the circumcircle of any triangle, i.e. the circle connecting the three vertices of the triangle. Other possible lines connecting points are ignored. Delaunay triangulation maximizes the minimum angle of all the angles of the triangles defined thereby avoiding “skinny triangles” as much as possible. This design may also permit the possibility of a station being several successive stations removed from a constrained station. Planning the location of constrained referenced stations within the overall network design is very important. In this configuration that all marks and CORS are automatically selected hubs (Armstrong, 2013). This network configuration also used the same CORS and IGS station as the USER configuration.

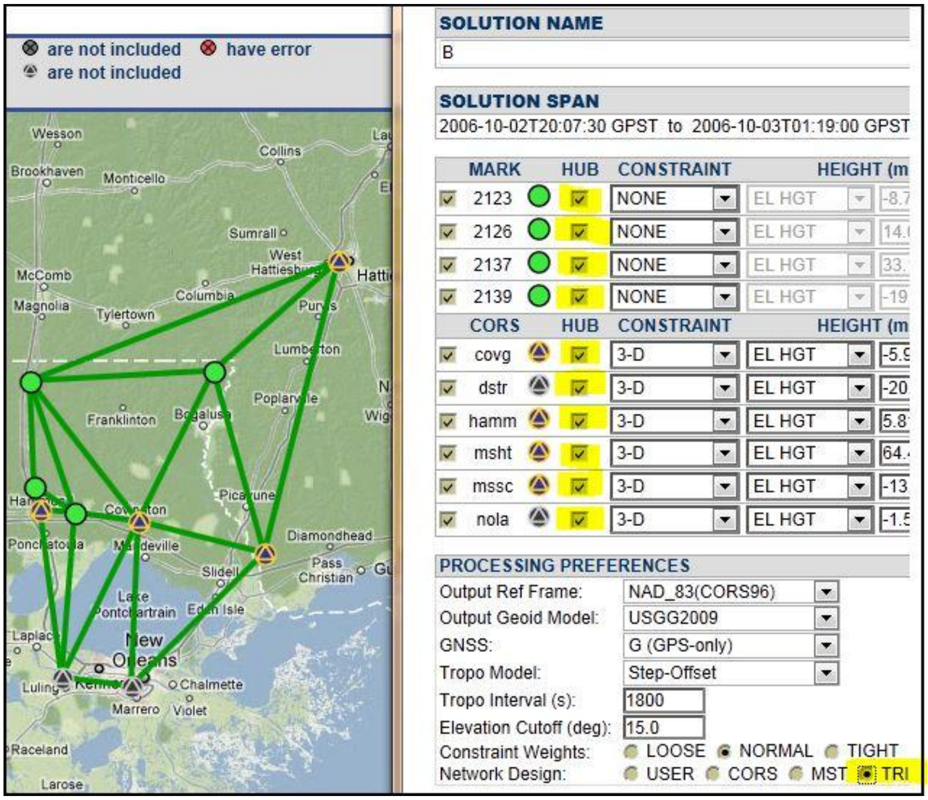

Figure 8-1 - Triangle Network Configuration (TRI) (Armstrong, 2013)

The TRI network design was selected for comparison as it also allows for multiple references to be included; however the major difference is the configuration of the network. The multiple base approached studied in the previous section is what is considered as an ‘OPEN LINKED’ network while the TRI configuration considered a “CLOSED LOOP” network.

Once all the GPS session were processed successfully using the selected network designs, meaning that the results fell within the preset tolerances, an adjustment was performed using OPUS-Project Network Adjustment suite. A network adjustment was only executed using the “best” GPS session solutions. Consequently, any session solution that fell outside of the tolerance were individually inspected and the stations within that session that were flagged were eliminated from the session. However there were situation that required a station to be eliminated from the project, due to poor satellite observation resulting in a very low presentation of observation, a large percentage of float solution versus fixed solution and the inability to verify antenna details (height and type). Even though there are preset tolerances, the user has the ability, to still accept flagged stations that are not very far off the tolerances

The results presented in this section shows the comparison of NGS' processing and adjustment software/algorithm in terms of an evaluation of the computed horizontal and vertical coordinates. The comparison would be illustrated from the results generated for the 2010 IGLD datasets.
Also a subsequent comparison would be done with the results determined by the Canadian partners of NGS on the IGLD project.

8.1.1 Comparison of OPUS-Projects Network Design (USER vs TRI)

The mean and the standard deviations for the comparison of the USER and TRI network configuration are seen in Table 8-1.

Table 8-1 - Comparison of OPUS Project USER to OPUS Project TRI

OPUS-Projects (USER) minus OPUS-Projects (TRI) results (m)				
	Delta Horz		Delta EHT	Delta OHT
	Delta X	Delta Y		
Min	-0.012	-0.005	-0.026	-0.026
Max	0.006	0.023	0.009	0.009
Mean	0.003	0.006	0.008	0.008
Std dev	0.000	0.005	-0.005	-0.005

8.1.2 Comparison of OPUS-Projects with ADJUST (Constraint Adjustment)

One of the outputs of OPUS projects are the compiled Bluebook format (Bfile) and GPS vector (Gfile) files. These outputs are the initial input files into NGS adjustment program ADJUST (reviewed in Section 4.3.2). The Bfile and Gfile in addition to the adjustment contrainted (Afile) were used to execute an independent network work adjustment. These results were compared to those generated by OPUS-Projects. The mean and the standard deviations for the comparison of the USER and TRI network configuration are seen in Table 8-2.

Table 8-2 – Comparison of OPUS Project to ADJUST

OPUS-Projects minus Final ADJUST results (m)			
OPUS-Projects constraints weight			
	Delta Horz	**Delta EHT**	**Delta OHT**
Min	0.000	-0.056	-0.061
Max	0.002	0.048	0.089
Mean	0.000	0.021	0.030
Std dev		-0.013	0.000

8.1.3 Comparison of OPUS-Projects and ADJUST to NGS Published Coordinates

This involved taking the difference between the published and the computed coordinate values. It should be noted that this will not include the Canadian Benchmarks since the NGS database does not include this points.

- Residual = Published Value - Computed Value

Figure 8-2 and Table 8- 3 presents the computed Residuals for the coordinates generated using the OPUS-Projects (USER; TRI) and ADJUST respectively.

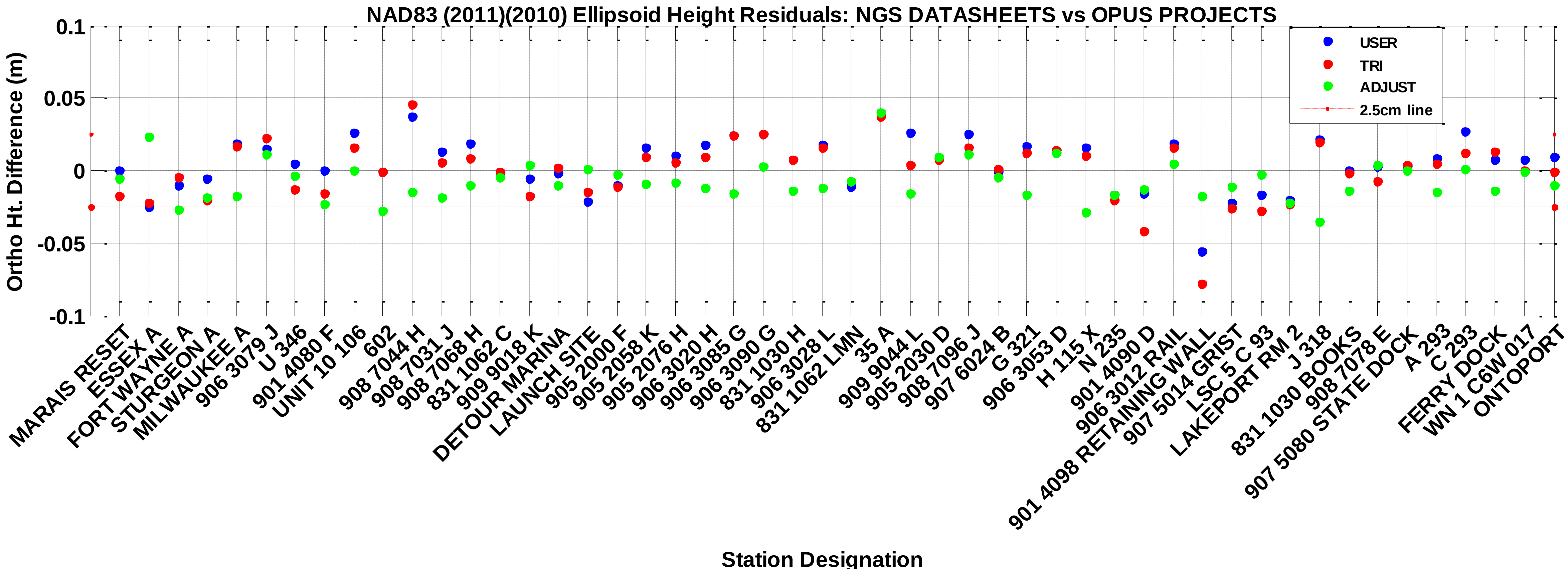

Figure 8-2 – Comparison of OPUS Project and ADJUST to NGS Published Coordinate (Ellipsoid Height)

Table 8-3 – Ellipsoidal Ht. Residual: NGS Published Ellipsoidal Ht. minus USER; TRI; and ADJUSUT

PID	Designation	St	ΔE OP USER (m)	ΔE OP TRI (m)	ΔE ADJUST (m)
AA2869	MARAIS RESET	MN	0	-0.018	-0.006
AA8053	ESSEX A	MI	-0.025	-0.022	0.023
AA8055	FORT WAYNE A	MI	-0.01	-0.005	-0.027
AA8057	STURGEON A	WI	-0.006	-0.02	-0.019
AA8061	MILWAUKEE A	WI	0.019	0.017	-0.018
AB6927	906 3079 J	OH	0.015	0.022	0.011
AC5969	U 346	MI	0.005	-0.013	-0.004
AC9129	901 4080 F	MI	0	-0.016	-0.023
AE8008	UNIT 10 106	MI	0.026	0.016	0
AE8289	602	MN	-0.001	-0.001	-0.028
AE9231	908 7044 H	IL	0.037	0.046	-0.015
AH5303	908 7031 J	MI	0.013	0.006	-0.019
AH5304	908 7068 H	WI	0.019	0.008	-0.01
AH7265	831 1062 C	NY	-0.002	-0.001	-0.005
AH7272	909 9018 K	MI	-0.006	-0.018	0.004
AH9228	DETOUR MARINA	MI	-0.002	0.002	-0.01
AH9229	LAUNCH SITE	MI	-0.021	-0.015	0.001
AH9230	905 2000 F	NY	-0.01	-0.011	-0.003
AH9232	905 2058 K	NY	0.016	0.009	-0.009
AH9233	905 2076 H	NY	0.01	0.006	-0.008
AH9234	906 3020 H	NY	0.018	0.009	-0.012
AH9237	906 3085 G	OH	0.024	0.024	-0.016
AH9238	906 3090 G	MI	0.025	0.025	0.003
DE7800	831 1030 H	NY	0.007	0.007	-0.014
DE7802	906 3028 L	NY	0.018	0.016	-0.012
DE7816	831 1062 LMN	NY	-0.011	-0.007	-0.007
DI7590	35 A	MI	0.04	0.037	0.04
DJ5175	909 9044 L	MI	0.026	0.004	-0.016
DJ5176	905 2030 D	NY	0.008	0.007	0.009
DJ5177	908 7096 J	MI	0.025	0.016	0.011
DJ5178	907 6024 B	MI	-0.001	0.001	-0.005
MB1563	G 321	OH	0.017	0.012	-0.017
MB1622	906 3053 D	OH	0.014	0.014	0.012
NE0516	H 115 X	MI	0.016	0.01	-0.029
NE0898	N 235	MI	-0.017	-0.02	-0.017
NE0955	901 4090 D	MI	-0.016	-0.042	-0.013
OG0217	906 3012 RAIL	NY	0.019	0.016	0.005
OJ0009	901 4098 RETAINING	MI	-0.056	-0.078	-0.018

	WALL				
OJ0219	907 5014 GRIST	MI	-0.022	-0.026	-0.011
OJ0517	LSC 5 C 93	MI	-0.017	-0.028	-0.003
OJ0599	LAKEPORT RM 2	MI	-0.02	-0.023	-0.022
OL0303	J 318	MI	0.021	0.02	-0.035
PH1012	831 1030 BOOKS	NY	0	-0.002	-0.014
PN0840	908 7078 E	WI	0.003	-0.007	0.004
QK0258	907 5080 STATE DOCK	MI	0.003	0.004	0
RJ0586	A 293	MI	0.008	0.005	-0.015
RJ0613	C 293	MI	0.027	0.012	0.001
RJ0617	FERRY DOCK	MI	0.007	0.013	-0.014
RJ1381	WN 1 C6W 017	MI	0.007	0	-0.001
RL1662	ONTOPORT	MI	0.009	-0.001	-0.01
			ΔE OP USER (m)	**ΔE OP TRI (m)**	**ΔE ADJUST (m)**
		Min	**-0.056**	**-0.078**	**-0.035**
		Max	**0.040**	**0.046**	**0.040**
		St.Dev	**0.018**	**0.021**	**0.014**
		Mean	**0.005**	**0.000**	**-0.008**

The difference observed from the comparison between OPUS Projects and ADJUST may be attributed to operation methods of the software packages. For example OPUS Projects does not adjust both ellipsoid and orthometric heights, it always uses the relationship $\boldsymbol{h = H + N}$, whereas ADJUST scales horizontal and vertical errors separately. Further OPUS-Projects adjusted observables are double differences while ADJUST adjusted observables are GPS vector components.

8.2 Summary of findings

Based on this dataset the comparison of OPUS-Projects USER and TRI network design, the USER network configuration showed slight improvement over the TRI, however not largely significant, indicating that the predefined network options are capable of generating a suitable results. The comparison of OPUS Projects final networks adjustment to ADJUST final network did not show significant variations, however the difference observed from the comparison between OPUS Projects and ADJUST may be attributed to operation methods of these software packages.

8.3 Vertical Velocities Computation – (comparison between epochs)

The reprocessed and readjusted IGLD surveys were compared between epoch, by computing the vertical coordinate difference (epoch 2 – epoch1). These differences were in turn used to compute the relative velocities (vertical coordinate difference / time difference). The relative velocities assist in identifying uplifts and subsidence within the Great Lakes region. Figures 8-3 to 8-5 shows the spatial location of the benchmarks the associated relative velocity. Full results of this velocity calcualtions can be seen in Appendix B

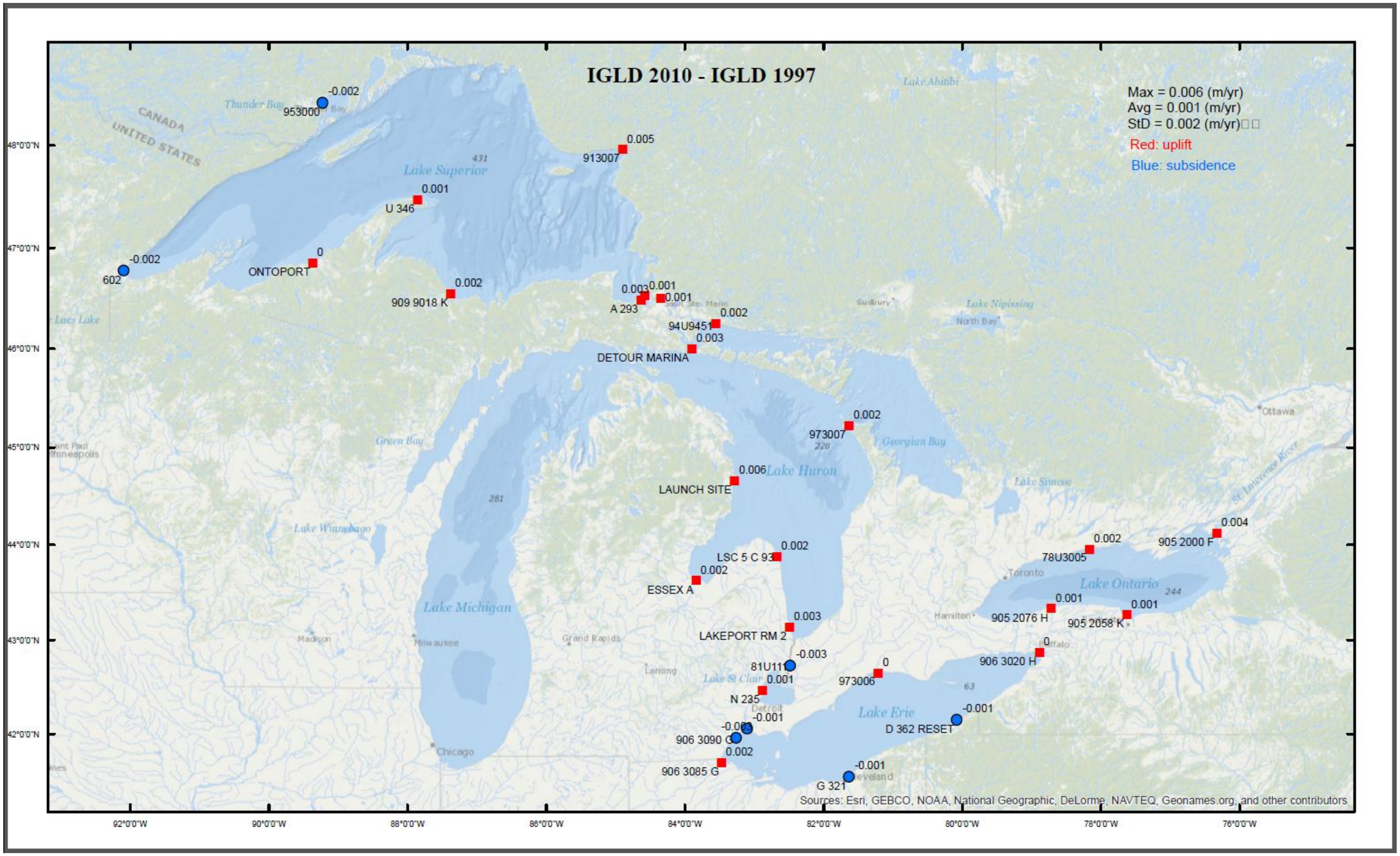

Figure 8-3 - IGLD 2010-1997

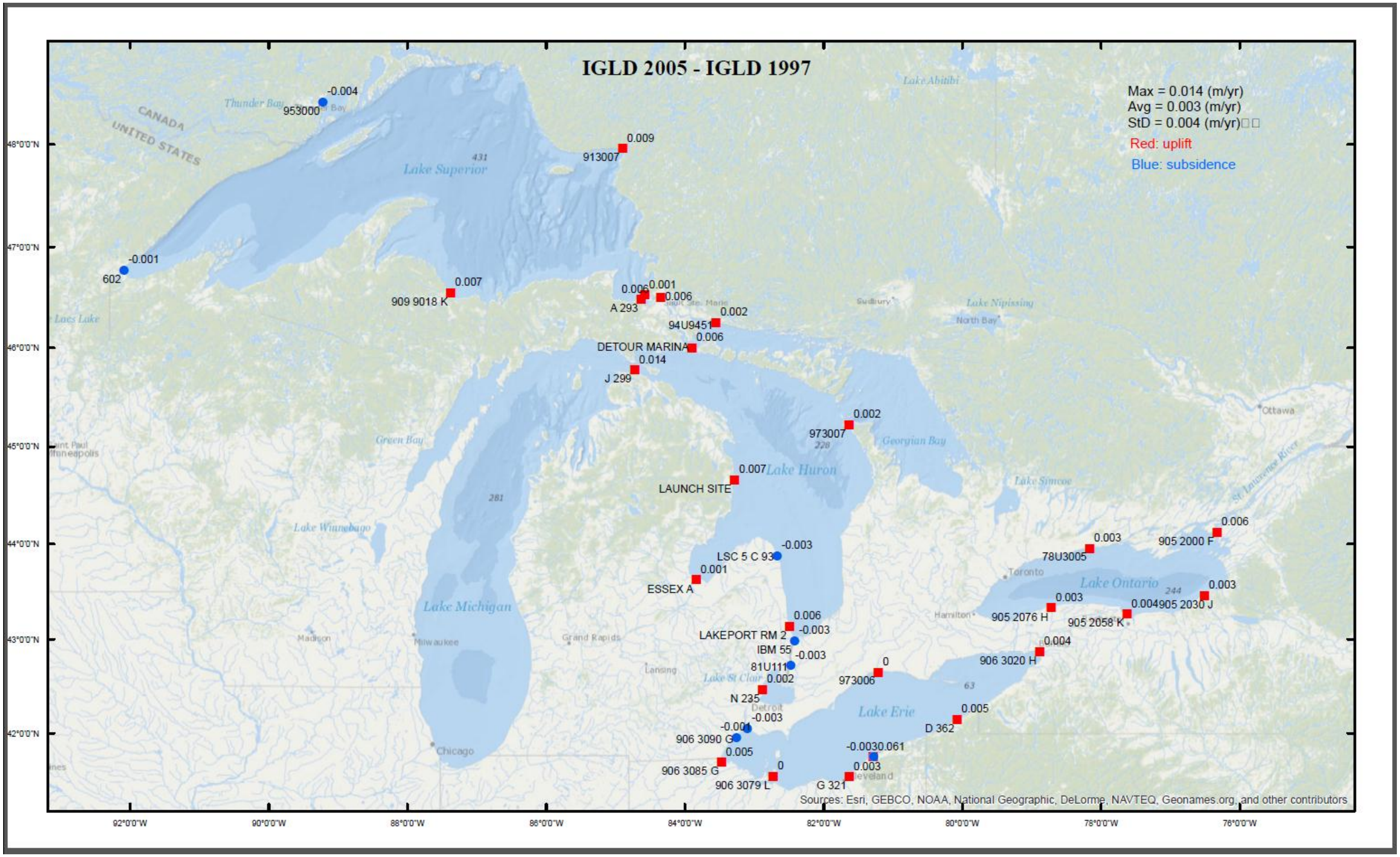

Figure 8-4 - IGLD 2005-1997

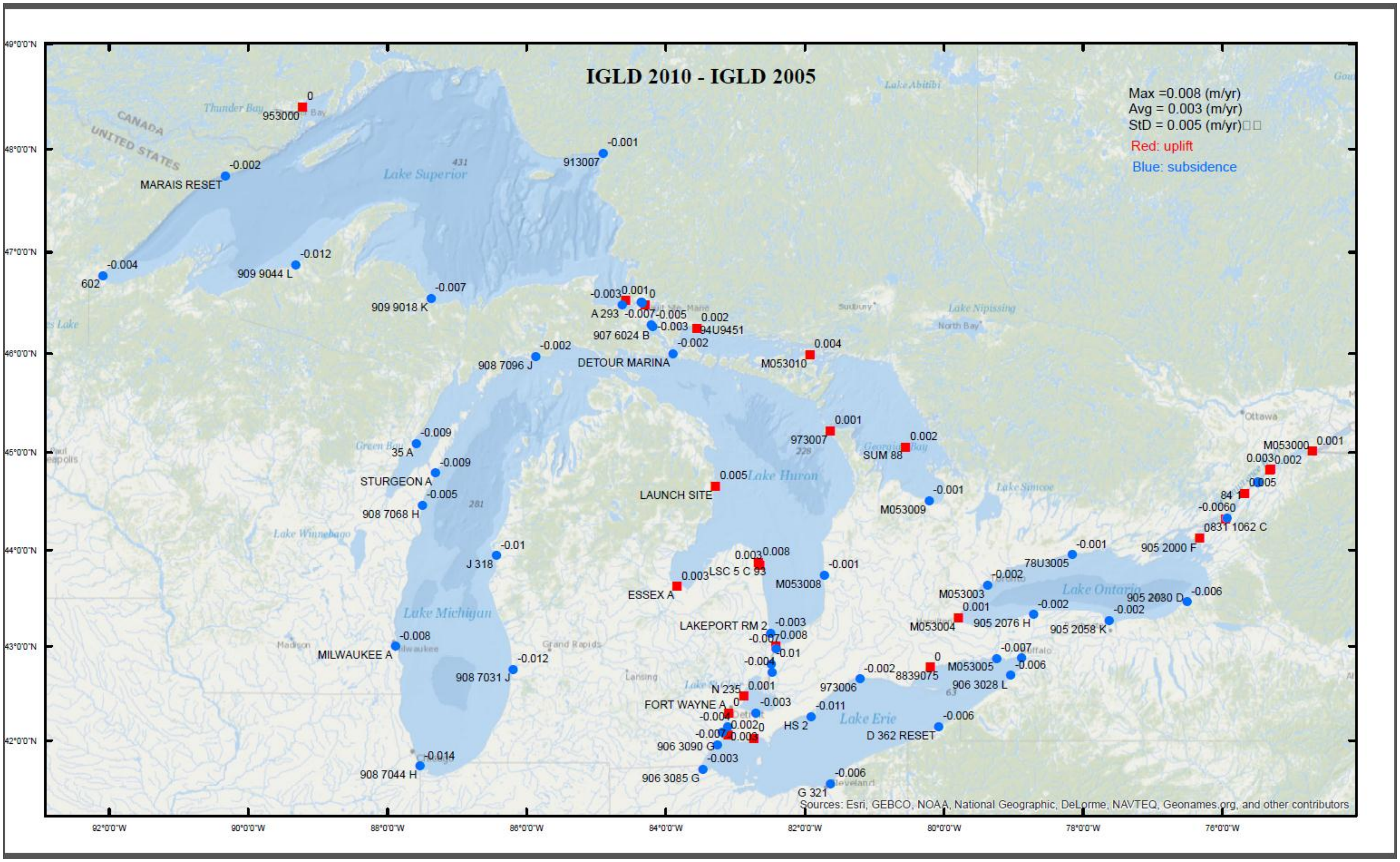

Figure 8-5 - IGLD 2010 - 2005

8.3.1 Comparison of the computed Velocties with Canadian Active Control System (CACS) and the United States CORS Vertical Velocity Field

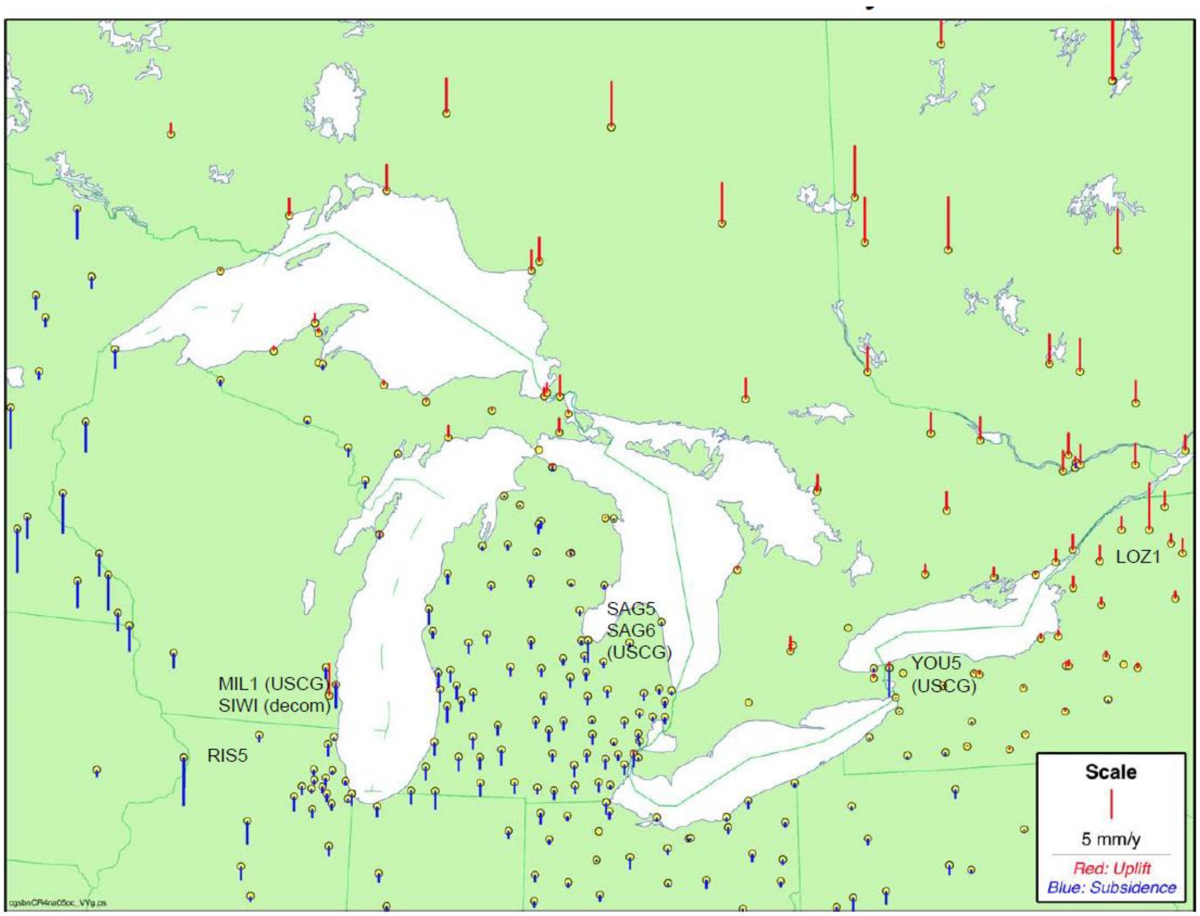

Figure 8-6 - CACS/CORS Vertical Velocity Field (Craymer et al., 2012)

Based on the (CACS) / CORS Vertical Velocity Field seen in Figure 8-6, the computed IGLD 2005 – 1997 and the 2010-1997 velocities seems to be in good agreement with exception for a few points. However the computed IGLD 2010 – 2005 not to be in total agreement as the velocities of benchmarks with the United States region exhibit very large negative values.

The reprocessing of the International Great Lakes Datum Height Modernization survey of 1997, 2005 and 2010 using OPUS-Projects using a consistent reference frame (IGS 08) allowed for the observation of any changes over time. The comparison of the velocities computed with the CACS and CORS vertical velocity network closely agreed for the time periods 2010-1997 and

2005-1997, however period 2010-2005 showed very little comparison. Further investigations are required into latter for a future conclusion to be drawn.

9 Conclusion and Recommendation

The primary goal of this research was to contribute to the improvement of height estimation using GPS that supports the goals of the National Height Modernization project led by NGS. This was attained by investigating the required baseline length to de-correlate the tropospheric corrections at individual stations, as well as to determine the optimal network design. In order to perform these experiments, three different networks were formed: the single, the double, and the multiple base station approaches.

The single base station approach shows that the tropospheric corrections follow a smoother trend for baselines longer than approximately 250-300 km. However, the estimated corrections even with long baselines (>250 km) might differ, even though they follow a smooth and similar trends. The solutions from the single base approach show that different base stations might result in some significant biases in the estimation of the ellipsoidal heights, if the GPS data span is shorter than 2 hours. In addition, the single base station approach confirms that the usage of long baselines reduces the quality of processing results, especially for short GPS data spans.

In the double base station approach, an additional CORS station is included in the network. One of two base stations is selected as close as possible to the unknown stations, and the other one is selected from a distant location to improve the tropospheric correction estimation. The double base station approach provides better tropospheric corrections, as compared to the single base solution. These corrections following a smoother trend illustrate a better agreement with the meteorological profiles and the Ground-Based GPS-IPW zenith delays. However, the double base approach does not result in any significant improvements in terms of the estimated ellipsoidal heights.

Furthermore, if one distant station in the network provides more accurate zenith corrections and the zenith total delay, then including more distant stations from among CORS and IGS networks could only improve the results. Moreover, the distant stations can be selected from the IGS network instead of CORS, which is considered one of the most accurate ground-based GNSS networks. That is why a set of three IGS stations was included in the experiments presented to introduce the multiple base approach. This solution is compared to the single and double base approaches.

The comparisons of all three proposed network configurations showed that the multiple base approach provides the best zenith corrections. In addition, the multiple base approach agrees with the Ground-Based GPS-IPW zenith delays better than the single and double base approaches. Moreover, the multiple base approach improves the accuracy of the estimated ellipsoidal heights, as compared to other approaches, especially for the short GPS data spans.

These three set of experiments concluded that the multiple base approach is the optimal network, which improved the estimation of the tropospheric corrections, the quality of the processing results, and the positioning accuracy, especially in the height component.

Additional experiments were performed to validate the double and multiple base approaches by testing with various GPS data spans of a specific station. These additional experiments attempted to determine the changes in the tropospheric corrections, and the ellipsoidal heights with respect to different times of day and GPS data spans. The results of this test further validating that the multiple base approach solutions provide some significant improvements over the double base approach in terms of the zenith wet corrections.

The overall conclusions and recommendations can be drawn based on the test case results presented in Section 6. The following recommendations can be noted for the users to obtain accurate and reliable ellipsoidal height, and to reduce the negative effects of the tropospheric delay in GPS data processing by using OPUS-Projects.

- **Duration of the Session**

  In general, a longer session provides higher accuracy and reliable ellipsoidal heights. Based on the results in this study, at least two-hour data spans should be used to determine the ellipsoidal heights accurately in OPUS-Projects.

  The additional experiments show that a second independent observation should be used to increase the confidence in the processing results. In order to maximize independence of the observations, the second observation should be obtained on a different day and at a different time of day.

- **Processing the GPS data**

Based on the results in this study, the user should include multiple base stations from CORS and IGS networks at various baseline lengths. The operation would reduce the possible errors associated with the base station, provide reliable tropospheric corrections and improve the accuracy of the ellipsoidal heights. Based on the results in this study, the network configurations of the multiple base approach is recommended, called "Multiple Base Station Approach".

The reprocessing of the International Great Lakes Datum Height Modernization survey of 1997, 2005 and 2010 using OPUS-Projects using a consistent reference frame (IGS 08) allowed for the observation of any changes over time. The comparison of the velocities computed with the CACS and CORS vertical velocity network closely agreed for the time periods 2010-1997 and 2005-1997, however period 2010-2005 showed very little comparison. Further investigations are required into latter for a future conclusion to be drawn.

10 Overview of additional investigation into improving height estimations with GPS

This section provides an overview of additionally investigations done to improve the accuracy and reliability of height determination. Full details and results of this test are record in the parallel study conducted titled “Impact of Lake Subsidence on Benchmark Reliability” (SJN: 134692). The overall goal of this parallel research was also to contribute to the improvement of height estimation using GPS that supports the goals of the National Height Modernization project led by NGS.

The was accomplished by focusing on two principal components: the investigation of the magnitude of environmental multipath on the resulting accuracy and reliability of GPS derived heights and analyzing the benefit of antenna specific calibration methods for field use versus using mean calibration parameters per antenna type.

The first component was carried out through the design of different case study scenarios that would analyze the effects of multipath in different environments and weather conditions. The scenarios designed for this testing were:

1. The effects of high voltage power lines overhead
2. Multipath reflection from a snow covered field
3. Multipath reflection caused by snow accumulation on GPS antennas
4. Severe multipath reflection in a roof top environment with and without different extremes of winter weather
5. The effects of a bird sitting on an antenna
6. Height variations caused by not accounting for the addition or removal of a radome in the antenna calibration parameters
7. Height variations caused by changing the antenna model used over a point

From the first scenario it is seen that high voltage power lines overhead will affect the computed GPS height of a point. This was seen most clearly by comparing the range of heights in a two standard deviation range around the mean to how the antennas performed under the power lines and how they performed under other conditions. Here, it was seen that the range of heights may change between two to ten centimeters, which makes a critical difference when high accuracy heights are needed. The results also confirm that the interference from power lines will not cause a constant effect on the quality of a GPS measurement and that it will change with the satellite geometry. It is recommended that proximity to power lines be avoided whenever possible. However, if the area is open enough good observations may still be obtainable if the visible satellites have a low enough elevation angle. Thus, the effects of the power lines may be lessened through planning observation sessions if data collection near power lines is unavoidable.

The second scenario examined the repeatability of multipath in a snow covered field with two GPS antennas for different depths of snow. From this scenario it was learned that gradual changes in snow depth do not have a significant impact on the observed height. It was confirmed for both antennas that a change in snow depth up to an inch between successive days results in a similar pattern of multipath reflection and was noted to result in up to a five millimeter change in the height of a point. It was also observed that changes in the depth of snow up to three inches resulted in an eight millimeter change in the height of a point. It is therefore possible to get reliable GPS heights with multipath reflection from the snow, but only for small changes in the surrounding snow depth. It is also recommended that observations in a snow covered environment be taken with caution, as it is not known how the multipath reflection from the snow may alter the multipath reflection from the surrounding environment.

The data collected from the third scenario shows that the effect on GPS height caused by snow accumulation on antennas depends as much on the antenna as the depth of snow accumulating. In general, the smaller sized antennas performed better under the snow accumulation than the bigger antennas. Height variations were observed for these antennas that ranged from three to seven centimeters greater than what they normally would have been in an open field under normal weather. The results of this scenario also indicate that the relative heights of the antennas may still be reliable with the snow accumulation, but there may be an offset between the observed GPS height of a point and the published GPS height of a point. For antennas that will be out in snow conditions it is recommended that a radome be looked into to minimize the amount of snow able to accumulate on the antenna.

The fourth scenario was conducted in a high multipath rooftop environment, where reflections occurred from tall walls on three sides of the antenna. This scenario also considered data collected when a thick ice layer was built-up around the antennas, during a snow storm when heavy snow accumulation occurred, and with a skin of ice to simulate freezing rain. The results for the different winter weather conditions processed here showed surprisingly little variation, with the mean heights changing up to two centimeters. This is a significant amount when high accuracy heights are required and will affect CORS stations in these environments. It was also seen that different antenna types of antennas responded differently to the winter weather scenarios tested and that one responded the best to two of the scenarios, but no single antenna responded the best to all three of them. This suggests that the antennas to be used in an environment that receives a lot of winter weather should be evaluated for performance in the types of winter weather most commonly received and the ones that perform the most accurately in those conditions should be used for CORS stations. CORS stations also pose another trouble in that an individual CORS station may be experiencing a particular kind of winter weather that data being collected at another location and post-processed against the CORS data is not experiencing. This makes it particularly important to review the weather history for CORS stations in the winter prior to using them for data processing when high accuracy heights are required. This may also require the implementation of a weather monitoring system for all of the CORS stations.

The fifth scenario was split into two parts and consists of the analysis of a time period when a Robin was observed sitting on an antenna and when Cornish hens were used to simulate seagulls sitting on an antenna. In the case of a Robin sitting on the antenna, only a small deviation in heights in the millimeter level was noticed. Furthermore, if the Robin were only sitting on the antenna for a short time the effects will quickly average out of the solution. Its minor impact on the GPS height was aided by a hemispherical radome, which forced the Robin to sit precisely at the top and still allowed unobstructed observations from satellites at lower elevation angles.
Bigger sized birds, such as seagulls, cause a more pronounced height variation. This scenario was proposed because seagulls had been observed to sit on CORS antennas along the Lake Erie shoreline for long periods of time with an unknown effect on the GPS height. These results cannot be directly compared to other scenarios since the observations had to be processed with the less accurate pseudoranges, but the results show that the noise in the solution increases by a

significant amount when a Cornish hen is placed on an antenna. The standard deviation of heights doubled compared to when the antenna was open, which resulted in the standard deviation changing from 0.5 or 0.6 meters to 1 to 1.3 meters. This poses a particularly troublesome uncertainty when post-processing GPS observations with CORS data along the Lake Erie shoreline, as there is no way to know if a seagull was sitting on an antenna during the during the time of data collection being processed. The best available option for keeping seagulls from sitting on CORS antennas is to use a conical radome.

The sixth scenario presented above used a TRM59800 antenna with a SCIS radome. Data was collected using different combinations of the antenna with and without the radome as well as different combinations of the relative calibration parameters for the antenna with and without the radome. These tests were done to see how neglecting a radome and the PCVs it causes affect the computed height of a point. The results of the different combinations showed that the heights deviated by up to four millimeters and the standard deviation of the heights deviated by up to two millimeters. Similarly, the range of elevations in a two standard deviation interval of the mean changes by about seven millimeters from the day with the most extreme heights observed under each of the test configurations. This suggests that while it must be accounted for to obtain the most accurate heights possible, neglecting a radome will not necessarily result in a huge error in height. More troublesome is the possibility of ultraviolet radiation from the sun wearing the radome thinner in some areas than others that will eventually result in signals from satellites at certain elevations and directions encountering less delay from the radome than they should, resulting in an inaccurate position determination for those satellites.

The seventh scenario focused on the height deviations of a point caused by changing the antenna model over that point. This was tested for GPS antennas setup at different heights from the ground and it was found that the different antennas would receive a similar amount of noise and multipath reflection from the surrounding environment, but that the heights would change by five to twenty millimeters depending on the antenna models used and the heights of those antennas off the ground. Using different antenna types needs to be considered in two separate cases: for a CORS station and when doing a repeat survey. Even if the changing the height of an antenna at a CORS station results in a five millimeter height change, it will carry over to projects using the CORS data. For instance, the antenna on a CORS station being used may be changed between phases of a multiphase project. In this case, care would have to be taken with GPS heights, as the heights of GPS observations made between phases may need to be accounted for depending on the required accuracy of GPS heights. This may also have a noticeable impact on the GPS heights of points, such as those used to realize the International Great Lakes Datum, which are resurveyed at certain intervals to update the datum and track subsidence and uplift in the Great Lakes region.

Additionally, a case study was designed to see how changing the network configuration of the selected CORS would change the height of an observation in an OPUS solution. Testing was done using the data from all of the scenarios above and half of the processed observations tested to change significantly for nine different CORS network configurations. Furthermore, the amount of multipath or signal interference in the environment where an observation was collected had an influence on how the observation would process under the different network configurations, but it was not a strong enough factor to determine how all observations in a particular environment would process under the different network configurations.

In addition to the environmental multipath analysis scenarios, two scenarios were developed to test the merits of different antenna calibration techniques. The first of these focused doing antenna specific calibrations in an anechoic chamber and the second focused on doing in-situ antenna calibration, or antenna specific calibrations in the environment where data the collection was occurring.
The relative calibration parameters obtained from the anechoic chamber seemed to compare reasonably well with the relative calibration parameters obtained through field surveying methods by NGS. However, the data processed with the anechoic chamber calibration parameters was not as accurate as the same data processed with NGS's calibration parameters. This seems to be most likely caused by two reasons. First, there appears to bias in calibration methods. NGS performs a calibration that fits the data to a higher order polynomial and the calibration in the anechoic chamber obtained the calibration parameters in a linear fashion by scalar multiplication with a ration. The second reason has more to do with the environment the calibrations occurred in. An anechoic chamber is an ideal environment with multipath absorbing foam over every surface. NGS's calibrations were done in an outdoor facility where the effects of the antenna mount and some far-field multipath affect the PCVs of the antenna. The

environment NGS uses resembles the environment were data was collected more so than the anechoic chamber does and even contains a trace of the errors caused by multipath in such an environment. Since the anechoic chamber relative calibration parameters are obtained in the absence of multipath, the presence of multipath in a real world environment is more likely to alter the measured PCVs, resulting in a less accurate solution and promoting the need for an in-situ antenna calibration. It is therefore recommended that the accuracy of anechoic chamber evaluations be evaluated before using to collect high accuracy height observations.

The final scenario was designed to evaluate the merits of in-situ GPS antenna calibration. The relative antenna calibration parameters obtained from each of the reference antennas shows that there is little change in the in-situ calibration parameters from day to day. The use of the in-situ calibration parameters over NGS's relative calibration only resulted in a small improvement for the parameters obtained from one of the antennas and the parameters obtained from the other two antennas resulted in a slight decrease in performance. This may in fact be caused by one of several reasons. First, the environment might not have had enough multipath interference to alter the test antenna PCV in a way that would make in-situ calibrations essential to recover the antenna calibration parameters. Secondly, the reference antenna may not have been sufficiently isolated from the environment of the test antenna. Thirdly, there is the slight chance that the in-situ calibrations may have an antenna bias, where antennas of the same manufacturer perform better than mixing antennas from different manufacturers.

It is recommended that more research be spent into investigating the merits of in-situ calibrations. How the choice of reference antenna affects the in-situ calibration parameters of the test antenna needs to be investigated in further detail. Additionally, the optimum placement of the reference antenna with respect to the test antenna needs to be found to isolate the reference antenna from the environment of the test antenna while still maintaining a small enough baseline so that each antenna receives similar atmospheric distortions and has a similar satellite visibility.

11 Implementation Plan

Given the results of this study involving the imposition of GPS errors on determining accurate heights ODOT would be well advised to:

- Collect at least two-hour GPS data spans to determine the ellipsoidal heights accurately in OPUS-Projects. Also a second independent observation data set should be used to increase the confidence in the processing results order to maximize independence of the observations, the second observation should be obtained on a different day and at a different time of day.
- Utilize multiple base stations from CORS and IGS networks at various baseline lengths during data processing. This operation would reduce the possible errors associated with the base station, provide reliable tropospheric corrections and improve the accuracy of the ellipsoidal heights.
- Utilize the metrological data for the CORS and IGS station selected for the baseline processing. As the adverse weather condition can ultimately affect the estimation of tropospheric corrections.
- Utilizing the kinematic solution of any static data session observed to carry out further analysis of the variation of GPS height estimation.

References

Armstrong, M. L. OPUS-Projects User Instruction and Technical Guide. OPUS-Projects Training Course. The National Geodetic Survey. July 1, 2013.

Beutler, G, Baueršíma I, Gurtner W, Rothacher M, Schildknecht T, and Geiger A (1988): Atmospheric refraction and other important biases in GPS carrier phase observations. University of New South Wales, School of Surveying, Monograph 12.

Brunner, F.K., Welsch, W.M., 1993. Effect of the troposphere on GPS measurements. GPS World, 42–51.

Craymer, M., Henton, J., Lapelle, E., and Piraszewski, M. 2012. Canadian GPS Networks in the Great Lakes Region Status Report. Natural Resources Canada. 92nd Meeting of the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrological Data, Burlington, May 8-9, 2012.

Davis, J. L., Herring, T. A., Shapiro, I. I., Rogers, A. E., & Elgered, G. (1985). Geodesy by Radio Interferometry: Effects of Atmospheric Modeling Errors on Estimates of Baseline Length. Radio Science, Vol. 20, 1593-1607.

Great Lakes Commissio (GLC), 2010. Resolution: Maintaining Accuracy of the International Great Lakes Datum (IGLD). Adopted at the 2010 Semiannual Meeting of the Great Lakes Commission, Washington, D.C., Feb. 23, 2010.

Hofman-Wellenhof, B., Lichtenegger, H., Collins, J., 2001. GPS Theory and Practice, 5th ed., Springer, New York

Leick, A. GPS Satellite Surveying Third Edition. Hoboken, New Jersey: John Wiley & Sons, Inc., 2004.

Mader, G. L., Milbert, D. G., Morrison, M. L., Weston, N. D. The On-line Positioning User Service. Professional Surveyor Magazine. May (2003). August 18, 2013. http://www.ngs.noaa.gov/CORS/Articles/Toolkit2.pdf

Martin, D. OPUS Rapid Static. The American Surveyor. April (2007). August 18, 2013. http://www.ngs.noaa.gov/CORS/Articles/MartinOPUSRS-TAS.pdf

Mendes, V. D. (1999). Modelling the Neutral-Atmosphere Propagation Delay in Radiometric Space Techniques. Ph.D. Dissertation, Department of Geodesy and Geomatics Engineering, University of New Brunswick, New Brunswick, Canada

National Geodetic Survey (NGS). 2012. NOAA/NGS ANALYSIS STRATEGY SUMMARY. Version 2. (accessed November 2012) .http://igs.org/igscb/center/analysis/noaa.acn

The National Geodetic Survey (NGS). 2013. OPUS: Online Positioning User Service. (accessed August 2013). http://www.ngs.noaa.gov/OPUS/about.jsp

Great Lakes Information Network (GLIN). 2013. Introduction the Great Lakes (accessed September 2013) http://www.great-lakes.net/teach/geog/intro/intro_2.html

Roman, D., & Weston, N. (2011, May 18-22). OPUS-Database Supplemental Data for Better Datum Conversion Models. Marrakech, Morocco.

Rothacher, M.,2001. Estimation of station heights with GPS. International Association of Geodesy Symposia, vol. 124, Springer-Verlag, Drewes H, Dodson A, Fortes LPS, Sanchez L and Sandoval P (Eds.), Vertical Reference Systems Symposium, Cartagena, Colombia, Feb. 20-23, pp. 81-90.

Wilby, Robert L. 2011. Adaptation: Wells of wisdom. *Nature Climate Change* 1 (302). Nature Publishing Group. (accessed September 2013) http://www.nature.com/nclimate/journal/v1/n6/full/nclimate1203.html

Wooden, W.H., 1985. Navstar Global Positioning System. Proceedings of the first International Symposium on Precise Positioning with Global Positioning System, Rockville, Maryland, April 15-19, vol. 1, pp 23-32.

United States Environmental Protection Agency (USEPA). 2013. Great Lakes: Facts and Statisitics. (accessed September 2013) http://www.epa.gov/greatlakes/lakestats.html

Veilleux, Vicki. Height Modernization. January 3, 2013. National Geodetic Survey. March 20, 2013. http://www.ngs.noaa.gov/heightmod/About.shtml

Zilkoski, D. B., 1991. North American Vertical Datum and International Great Lakes Datum: They are One and the Same, National Geodetic Survey, Silver Spring, Maryland, USA.

APPENDIX

Appendix A: OPUS-Projects Recommended Default Processing Parameters

This appendix will describe the default parameters available in OPUS-Projects and provide recommended default parameters. These parameters will be used as the default in all data processing done in OPUS-Projects. Four categories of parameters will be discussed: Data & Solution Quality Thresholds, Data Processing Defaults, Session Definition, and Mark Co-location Definition. The discussion of each of these categories will begin with a screenshot of the default parameters when a new project is created and then proceed to discuss particular parameters in more detail and provide recommended default parameters to use in data processing.

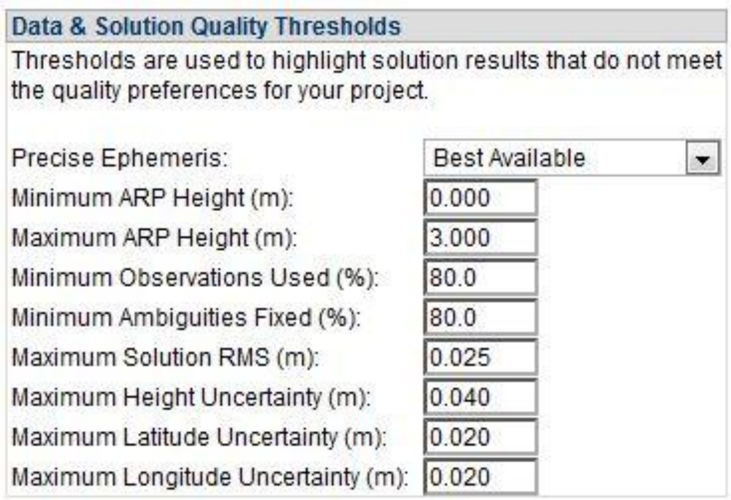

Figure A.12-1: Default data and solution quality thresholds in OPUS-Projects

The data and solution quality thresholds define how processing results are displayed on the project's web page. This applies to session solutions, network solutions, and any data uploaded to OPUS-Projects. Data meeting all of the thresholds is displayed as a green, open circle, whereas data failing to meet at least one of the thresholds is displayed as an orange barred circle. The default data and solution quality thresholds are defined in Figure A12-1 above. These include a selection of the type of ephemeris to use, a range within which to constrain a computed GPS height, the minimum number of observations to be used in a solution, the minimum number of integer ambiguities to be fixed in a solution, the maximum tolerated RMS of coordinates calculated in the solution, and the maximum uncertainty in latitude, longitude, and height computed in the solution.

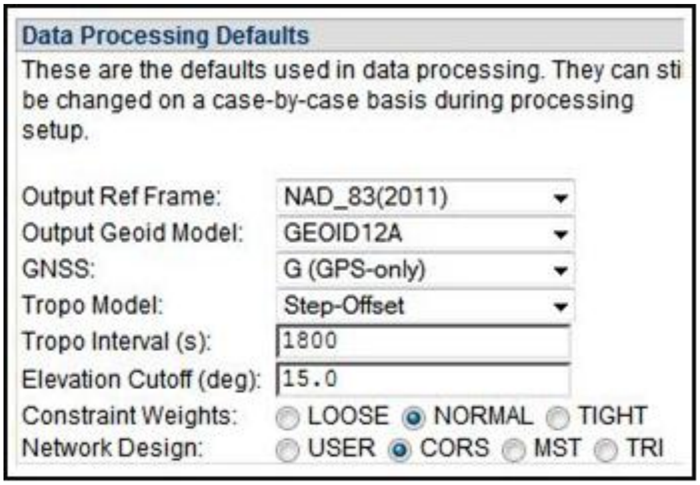

Figure A.12-2: Default data processing parameters in OPUS-Projects

The data processing defaults, shown in Figure A12-1 above, define the defaults offered on the processing controls. It is recommended that these be set to a value and left alone for consistency of results within a project. By default, the output reference frame will be "Let OPUS Choose", which will use the most current realization of NAD83. Other usable reference frames include current and past realizations of the NAD83, WGS84, ITRF, and IGS reference frames. The output geoid model will also default to "Let OPUS Choose," which will select the latest geoid model. In this case, the GEOID12A model will be selected, but the user has the option of selecting other geoid models from the dropdown list. The troposphere model and troposphere intervals used should be customized together. A piecewise linear model, created by fitting line segments from the tropospheric corrections of different time intervals should have a default time interval of 7200 seconds. A step-offset tropospheric model only an offset is fitted to the data in each time segment as opposed to the offset and slope used by the piecewise linear model. A piecewise linear offset is recommended as the normal strategy a step-offset may work better on more challenging datasets (Armstrong, 2013). The troposphere interval for a step-offset model should be set to 1800 seconds. The elevation cutoff masks defaults to fifteen degrees. This mask can be changed to a lower cutoff here to apply to all solutions and it can be changed when setting up an individual solution to apply only in that solution. The choice of constraints will affect the accuracy of the adjustment. A loose constraint provides a one meter accuracy, a normal constraint provides a one meter accuracy, and a tight constraint provides a one-tenth of a millimeter accuracy. As with the elevation angle, the value entered here will be the default for all solutions and it can be customized for individual solutions. The network design determines the default network design strategy to apply when setting up a session or network solution. Regardless of the strategy selected here, the user has the ability to modify it to meet their accuracy/design requirements and will most likely have to do so.

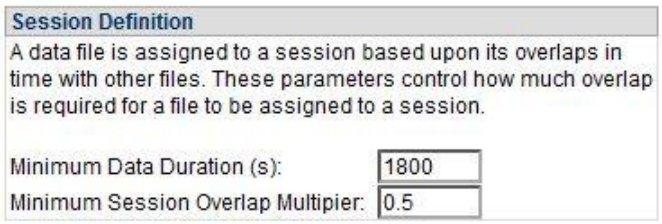

Figure A.12-3: Default session definition parameters in OPUS-Projects

The session definition preferences, shown in Figure A 12-3 above, define how data files are grouped into sessions. It is recommended that these settings be left as they are without changing. The minimum data duration sets the minimum data file duration for use in OPUS-Projects in seconds. Currently, the minimum file duration for upload to OPUS-Projects is two hours. By default, the minimum data duration is set to a lesser amount to ensure that the entire file is used in processing (Armstrong, 2013). The minimum session overlap multiplier is used to determine the minimum overlap in time between the files for them to be grouped into the same session. Unlike the other settings discussed so far, these settings can only be changed before session processing has begun.

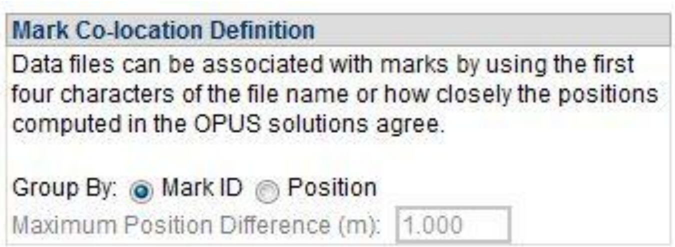

Figure A.12-4: Default mark co-location parameters in OPUS-Projects

The default mark co-location parameters, shown in Figure A12-4 above, are used to define how data files are associated with marks. This can be set to Mark ID, in which every unique marker identifier will be treated as a new mark or to position, in which case the user can specify the maximum difference between marks to consider them to be unique marks. The default for the position setting is one meter.

All but three of the default settings will be used for data processing in OPUS-Projects. The troposphere model will be changed to piecewise linear and the constraint weight will be changed to tight. However, the interval in which to compute the troposphere corrections will remain at the default 1800 seconds. Additionally, the network design option will be changed to USER, so it will accept a customized network from the user. The only other setting that will be changed is the elevation angle, which will occur as needed in data processing to improve the quality of the solution. Any settings changed from the default settings listed in the figures above will be documented along with the data processing.

Appendix A: OPUS-Projects Recommended Default Processing Parameters – Computed Velocity

Please note that all units are in meter unless otherwise stated.

Table B 12-1 – Coordinate Comparison and Vertical Velocity values for IGLD 2010-1997

				1997 Coordinates				. 2010 Coordinates							
PID	**Designation**	**St.**	zone	Northing	Easting	Ortho. Ht.	Ellipsoid Ht.	Northing	Easting	Ortho Ht.	Ellipsoid Ht.	Δ Ortho Ht.	Δ Ellip Ht.	velocity Ortho Ht.	Velocity Ellip. Ht.
AA8053	ESSEX A	MI	UTM 17	4834526.383	271027.879	178.315	143.7	4834526.376	271027.885	178.341	143.726	0.026	0.026	0.002	0.002
AC5969	U 346	MI	UTM 16	5258213.229	435210.076	189.829	154.492	5258213.235	435210.069	189.839	154.502	0.01	0.01	0.001	0.001
AE8008	UNIT 10 106	MI	UTM 16	5153480.771	702951.176	185.637	149.003	5153480.772	702951.171	185.652	149.018	0.015	0.015	0.001	0.001
AE8289	602	MN	UTM 15	5180532.452	569189.408	184.378	156.113	5180532.439	569189.399	184.351	156.086	-0.027	-0.027	-0.002	-0.002
AH7272	909 9018 K	MI	UTM 16	5154848.777	470970.197	187.911	153.091	5154848.783	470970.197	187.937	153.117	0.026	0.026	0.002	0.002
AH9228	DETOUR MARINA	MI	UTM 17	5098021.446	275403.757	177.925	141.114	5098021.457	275403.744	177.965	141.154	0.04	0.04	0.003	0.003
AH9229	LAUNCH SITE	MI	UTM 17	4947876.825	318790.308	177.561	141.68	4947876.821	318790.3	177.64	141.759	0.079	0.079	0.006	0.006
AH9230	905 2000 F	NY	UTM 18	4886488.572	393671.959	91.649	57.449	4886488.577	393671.96	91.698	57.498	0.049	0.049	0.004	0.004
AH9232	905 2058 K	NY	UTM 18	4794074.737	286726.771	75.931	40.013	4794074.731	286726.775	75.949	40.031	0.018	0.018	0.001	0.001
AH9233	905 2076 H	NY	UTM 17	4800479.228	684878.236	87.67	51.531	4800479.232	684878.24	87.681	51.542	0.011	0.011	0.001	0.001
AH9234	906 3020 H	NY	UTM 17	4749321.408	672342.608	176.453	141.299	4749321.419	672342.609	176.458	141.304	0.005	0.005	0.000	0.000
AH9237	906 3085 G	OH	UTM 17	4618644.381	294274.477	175.705	140.3	4618644.378	294274.471	175.729	140.324	0.024	0.024	0.002	0.002
AH9238	906 3090 G	MI	UTM 17	4647702.654	312624.359	176.502	141.266	4647702.652	312624.357	176.46	141.224	-0.042	-0.042	-0.003	-0.003
AH9241	78U3005	ON	UTM 17	4870927.117	727513.219	76.817	40.612	4870927.128	727513.224	76.841	40.636	0.024	0.024	0.002	0.002
AH9244	913007	ON	UTM 16	5314159.005	656568.845	193.724	156.685	5314159.014	656568.841	193.795	156.756	0.071	0.071	0.005	0.005
AH9247	94U9451	ON	UTM 17	5125443.468	303228.273	179.145	142.097	5125443.479	303228.264	179.171	142.123	0.026	0.026	0.002	0.002
AH9248	953000	ON	UTM 16	5363869.858	335528.523	186.467	150.314	5363869.854	335528.512	186.439	150.286	-0.028	-0.028	-0.002	-0.002
AH9249	973006	ON	UTM 17	4722928.758	482506.483	176.006	140.35	4722928.754	482506.49	176	140.344	-0.006	-0.006	0.000	0.000
AH9250	973007	ON	UTM17	5008044.368	450107	209.761	172.73	5008044.373	450106.995	209.781	172.75	0.02	0.02	0.002	0.002
MB1563	G 321	OH	UTM 17	4598897.075	447104.446	177.827	143.43	4598897.088	447104.438	177.817	143.42	-0.01	-0.01	-0.001	-0.001
ND0194	D 362	PA	UTM 17	4667190.627	576137.286	175.514	140.56	4667190.631	576137.29	175.503	140.549	-0.011	-0.011	-0.001	-0.001
NE0898	N 235	MI	UTM 17	4704086.025	345269.799	177.274	142.632	4704086.026	345269.804	177.293	142.651	0.019	0.019	0.001	0.001

OJ0517	LSC 5 C 93	MI	UTM 17	4859590.009	365461.521	178.922	143.769	4859590.007	365461.524	178.944	143.791	0.022	0.022	0.002	0.002
OJ0599	LAKEPORT RM 2	MI	UTM 17	4777492.809	378424.285	180.644	145.847	4777492.8	378424.287	180.681	145.884	0.037	0.037	0.003	0.003
RJ0586	A 293	MI	UTM 16	5150546.375	681725.165	187.752	151.282	5150546.38	681725.153	187.786	151.316	0.034	0.034	0.003	0.003
RL1662	ONTOPORT	MI	UTM 16	5191219.413	319426.254	194.333	162.984	5191219.418	319426.258	194.33	162.981	-0.003	-0.003	0.000	0.000
TY2525	70U672	ON	UTM 17	4658702.634	325966.646	175.97	140.937	4658702.643	325966.666	175.954	140.921	-0.016	-0.016	-0.001	-0.001
TY5484	81U111	ON	UTM 17	4731831.993	379077.218	177.056	142.058	4731831.992	379077.22	177.014	142.016	-0.042	-0.042	-0.003	-0.003
TY5827	GROS 1	ON	UTM 16	5155525.933	685413.796	184.517	148.019	5155525.93	685413.786	184.529	148.031	0.012	0.012	0.001	0.001

Table B 12-2 - Coordinate Comparison and Vertical Velocity values for IGLD 2005-1997

				1997 Coordinates				. 2005 Coordinates							
PID	Designation	St	zone	Northing	Easting	Ortho. Ht.	Ellipsoid Ht.	Northing	Easting	Ortho Ht.	Ellipsoid Ht.	Δ Ortho Ht.	Δ Ellip Ht.	velocity Ortho Ht.	Velocity Ellip. Ht.
AA8053	ESSEX A	MI	UTM 17	4834526.383	271027.879	178.315	143.700	4834526.366	271027.882	178.324	143.709	0.009	0.009	0.001	0.001
AE8008	UNIT 10 106	MI	UTM 16	5153480.771	702951.176	185.637	149.003	5153480.774	702951.178	185.685	149.051	0.048	0.048	0.006	0.006
AE8289	602	MN	UTM 15	5180532.452	569189.408	184.378	156.113	5180532.440	569189.409	184.373	156.108	-0.005	-0.005	-0.001	-0.001
AH7272	909 9018 K	MI	UTM 16	5154848.777	470970.197	187.911	153.091	5154848.787	470970.197	187.971	153.151	0.060	0.060	0.008	0.008
AH9228	DETOUR MARINA	MI	UTM 17	5098021.446	275403.757	177.925	141.114	5098021.447	275403.746	177.977	141.166	0.052	0.052	0.006	0.006
AH9229	LAUNCH SITE	MI	UTM 17	4947876.825	318790.308	177.561	141.680	4947876.816	318790.294	177.615	141.734	0.054	0.054	0.007	0.007
AH9230	905 2000 F	NY	UTM 18	4886488.572	393671.959	91.649	57.449	4886488.570	393671.962	91.696	57.496	0.047	0.047	0.006	0.006
AH9231	905 2030 J	NY	UTM 18	4813711.432	377796.875	76.721	41.924	4813711.436	377796.883	76.745	41.948	0.024	0.024	0.003	0.003
AH9232	905 2058 K	NY	UTM 18	4794074.737	286726.771	75.931	40.013	4794074.728	286726.774	75.961	40.043	0.030	0.030	0.004	0.004
AH9233	905 2076 H	NY	UTM 17	4800479.228	684878.236	87.670	51.531	4800479.225	684878.240	87.692	51.553	0.022	0.022	0.003	0.003
AH9234	906 3020 H	NY	UTM 17	4749321.408	672342.608	176.453	141.299	4749321.408	672342.609	176.482	141.328	0.029	0.029	0.004	0.004
AH9235	906 3053 F	OH	UTM 17	4622207.934	476179.783	177.208	142.741	4622207.939	476179.786	177.186	142.719	-0.022	-0.022	-0.003	-0.003
AH9236	906 3079 L	OH	UTM 17	4600539.474	355586.241	176.078	140.587	4600539.478	355586.243	176.075	140.584	-0.003	-0.003	0.000	0.000
AH9237	906 3085 G	OH	UTM 17	4618644.381	294274.477	175.705	140.300	4618644.368	294274.477	175.746	140.341	0.041	0.041	0.005	0.005
AH9238	906 3090 G	MI	UTM 17	4647702.654	312624.359	176.502	141.266	4647702.647	312624.358	176.494	141.258	-0.008	-0.008	-0.001	-0.001
AH9241	78U3005	ON	UTM 17	4870927.117	727513.219	76.817	40.612	4870927.119	727513.224	76.844	40.639	0.027	0.027	0.003	0.003

AH9244	913007	ON	UTM 16	5314159.005	656568.845	193.724	156.685	5314159.010	656568.840	193.798	156.759	0.074	0.074	0.009	0.009
AH9247	94U9451	ON	UTM 17	5125443.468	303228.273	179.145	142.097	5125443.463	303228.266	179.162	142.114	0.017	0.017	0.002	0.002
AH9248	953000	ON	UTM 16	5363869.858	335528.523	186.467	150.314	5363869.858	335528.518	186.437	150.284	-0.030	-0.030	-0.004	-0.004
AH9249	973006	ON	UTM 17	4722928.758	482506.483	176.006	140.350	4722928.752	482506.492	176.008	140.352	0.002	0.002	0.000	0.000
AH9250	973007	ON	UTM17	5008044.368	450107.000	209.761	172.730	5008044.367	450106.996	209.775	172.744	0.014	0.014	0.002	0.002
MB1563	G 321	OH	UTM 17	4598897.075	447104.446	177.827	143.430	4598897.085	447104.434	177.847	143.450	0.020	0.020	0.003	0.002
ND0194	D 362	PA	UTM 17	4667190.627	576137.286	175.514	140.560	4667190.634	576137.296	175.556	140.602	0.042	0.042	0.005	0.005
NE0898	N 235	MI	UTM 17	4704086.025	345269.799	177.274	142.632	4704086.026	345269.806	177.286	142.644	0.012	0.012	0.002	0.002
NE0963	IBM 55	ON	UTM 17	4760751.369	384142.539	178.605	143.692	4760751.369	384142.536	178.582	143.669	-0.023	-0.023	-0.003	-0.003
OJ0517	LSC 5 C 93	MI	UTM 17	4859590.009	365461.521	178.922	143.769	4859590.006	365461.523	178.902	143.749	-0.020	-0.020	-0.003	-0.003
OJ0599	LAKEPORT RM 2	MI	UTM 17	4777492.809	378424.285	180.644	145.847	4777492.806	378424.291	180.696	145.899	0.052	0.052	0.006	0.006
QK0428	J 299	MI	UTM 16	5071909.580	676733.732	179.574	144.160	5071909.639	676733.745	179.685	144.271	0.111	0.111	0.014	0.014
RJ0586	A 293	MI	UTM 16	5150546.375	681725.165	187.752	151.282	5150546.385	681725.162	187.802	151.332	0.050	0.050	0.006	0.006
TY2525	70U672	ON	UTM 17	4658702.634	325966.646	175.970	140.937	4658702.634	325966.651	175.944	140.911	-0.026	-0.026	-0.003	-0.003
TY5484	81U111	ON	UTM 17	4731831.993	379077.218	177.056	142.058	4731831.989	379077.220	177.036	142.038	-0.020	-0.020	-0.003	-0.002
TY5827	GROS 1	ON	UTM 16	5155525.933	685413.796	184.517	148.019	5155525.930	685413.791	184.525	148.027	0.008	0.008	0.001	0.001

Table 12-3 - Coordinate Comparison and Vertical Velocity values for IGLD 2010-2005

PID	Designation	St	ZONE	2005 Coordinates				. 2010 Coordinates				Δ Ortho Ht.	Δ Ellip Ht.	velocity Ortho Ht.	Velocity Ellip. Ht.
				Northing	Easting	Northing	Easting	Northing	Easting	Northing	Easting				
AA2869	MARAIS RESET	MN	UTM 15	5291417	699795.1	186.971	156.079	5291417	699795.1	186.96	156.068	-0.011	-0.011	-0.002	-0.002
AA8053	ESSEX A	MI	UTM 17	4834526	271027.9	178.324	143.709	4834526	271027.9	178.341	143.726	0.017	0.017	0.003	0.003
AA8055	FORT WAYNE A	MI	UTM 17	4684911	327356.9	176.854	142.3	4684911	327356.9	176.856	142.302	0.002	0.002	0.000	0.000
AA8057	STURGEON A	WI	UTM 16	4960251	475169.5	181.697	144.93	4960251	475169.4	181.65	144.883	-0.047	-0.047	-0.009	-0.009
AA8061	MILWAUKEE A	WI	UTM 16	4761508	427538.4	180.298	145.167	4761508	427538.4	180.259	145.128	-0.039	-0.039	-0.008	-0.008
AC9129	901 4080 F	MI	UTM 17	4741449	378512	182.228	147.232	4741449	378512	182.18	147.184	-0.048	-0.048	-0.010	-0.010
AE8008	UNIT 10 106	MI	UTM 16	5153481	702951.2	185.685	149.051	5153481	702951.2	185.652	149.018	-0.033	-0.033	-0.007	-0.007
AE8289	602	MN	UTM 15	5180532	569189.4	184.373	156.108	5180532	569189.4	184.351	156.086	-0.022	-0.022	-0.004	-0.004
AE9231	908 7044 H	IL	UTM 16	4619921	455219.5	178.352	144.849	4619921	455219.6	178.281	144.778	-0.071	-0.071	-0.014	-0.014
AH5303	908 7031 J	MI	UTM 16	4734637	565856.5	183.234	149.751	4734637	565856.5	183.174	149.691	-0.060	-0.060	-0.012	-0.012
AH5304	908 7068 H	WI	UTM 16	4923503	460033.2	177.591	141.284	4923503	460033.2	177.568	141.261	-0.023	-0.023	-0.005	-0.005
AH7265	831 1062 C	NY	UTM 18	4909199	425488.7	79.75	46.405	4909199	425488.7	79.72	46.375	-0.030	-0.030	-0.006	-0.006
AH7272	909 9018 K	MI	UTM 16	5154849	470970.2	187.971	153.151	5154849	470970.2	187.937	153.117	-0.034	-0.034	-0.007	-0.007
AH9228	DETOUR MARINA	MI	UTM 17	5098021	275403.7	177.977	141.166	5098021	275403.7	177.965	141.154	-0.012	-0.012	-0.002	-0.002
AH9229	LAUNCH SITE	MI	UTM 17	4947877	318790.3	177.615	141.734	4947877	318790.3	177.64	141.759	0.025	0.025	0.005	0.005
AH9230	905 2000 F	NY	UTM 18	4886489	393672	91.696	57.496	4886489	393672	91.698	57.498	0.002	0.002	0.000	0.000
AH9232	905 2058 K	NY	UTM 18	4794075	286726.8	75.961	40.043	4794075	286726.8	75.949	40.031	-0.012	-0.012	-0.002	-0.002
AH9233	905 2076 H	NY	UTM 17	4800479	684878.2	87.692	51.553	4800479	684878.2	87.681	51.542	-0.011	-0.011	-0.002	-0.002
AH9234	906 3020 H	NY	UTM 17	4749321	672342.6	176.482	141.328	4749321	672342.6	176.458	141.304	-0.024	-0.024	-0.005	-0.005
AH9237	906 3085 G	OH	UTM 17	4618644	294274.5	175.746	140.341	4618644	294274.5	175.729	140.324	-0.017	-0.017	-0.003	-0.003
AH9238	906 3090 G	MI	UTM 17	4647703	312624.4	176.494	141.258	4647703	312624.4	176.46	141.224	-0.034	-0.034	-0.007	-0.007
AH9241	78U3005	ON	UTM 17	4870927	727513.2	76.844	40.639	4870927	727513.2	76.841	40.636	-0.003	-0.003	-0.001	-0.001
AH9243	84 1	ON	UTM 18	4937272	445884.7	75.881	43.184	4937272	445884.7	75.908	43.211	0.027	0.027	0.005	0.005
AH9244	913007	ON	UTM 16	5314159	656568.8	193.798	156.759	5314159	656568.8	193.795	156.756	-0.003	-0.003	-0.001	-0.001
AH9247	94U9451	ON	UTM 17	5125443	303228.3	179.162	142.114	5125443	303228.3	179.171	142.123	0.009	0.009	0.002	0.002
AH9248	953000	ON	UTM 16	5363870	335528.5	186.437	150.284	5363870	335528.5	186.439	150.286	0.002	0.002	0.000	0.000
AH9249	973006	ON	UTM 17	4722929	482506.5	176.008	140.352	4722929	482506.5	176	140.344	-0.008	-0.008	-0.002	-0.002
AH9250	973007	ON	UTM 17	5008044	450107	209.775	172.744	5008044	450107	209.781	172.75	0.006	0.006	0.001	0.001
DE7800	831 1030 H	NY	UTM 18	4949853	460811.4	75.51	43.283	4949853	460811.4	75.502	43.275	-0.008	-0.008	-0.002	-0.002
DE7802	906 3028 L	NY	UTM 17	4728468	659975.2	177.068	142.112	4728468	659975.2	177.038	142.082	-0.030	-0.030	-0.006	-0.006
DE7816	831 1062 LMN	NY	UTM 18	4908185	423683.5	83.271	49.871	4908185	423683.5	83.27	49.87	-0.001	-0.001	0.000	0.000
DI7590	35 A	MI	UTM 16	4993773	453575.4	178.365	141.384	4993773	453575.5	178.319	141.338	-0.046	-0.046	-0.009	-0.009
DJ5175	909 9044 L	MI	UTM 16	5193840	322999.5	184.7	153.239	5193840	322999.5	184.64	153.179	-0.060	-0.060	-0.012	-0.012
DJ5176	905 2030 D	NY	UTM 18	4813656	377673.6	76.653	41.854	4813656	377673.6	76.622	41.823	-0.031	-0.031	-0.006	-0.006

DJ5177	908 7096 J	MI	UTM 16	5091606	587350.5	181.274	146.213	5091606	587350.4	181.263	146.202	-0.011	-0.011	-0.002	-0.002
DJ5178	907 6024 B	MI	UTM 16	5127293	716460.4	177.994	141.485	5127293	716460.4	177.977	141.468	-0.017	-0.017	-0.003	-0.003
DJ5179	8839075	ON	UTM 17	4736915	565339.6	175.754	139.96	4736915	565339.6	175.754	139.96	0.000	0.000	0.000	0.000
DJ5180	M053000	ON	UTM 18	4984603	522713.2	48.077	17.441	4984603	522713.2	48.084	17.448	0.007	0.007	0.001	0.001
DJ5181	M053001	ON	UTM 18	4964870	475502.5	76.014	44.226	4964870	475502.5	76.029	44.241	0.015	0.015	0.003	0.003
DJ5182	M053002	ON	UTM 18	4963261	474649.3	76.609	44.804	4963261	474649.3	76.617	44.812	0.008	0.008	0.002	0.002
DJ5183	M053003	ON	UTM 17	4833060	630898.5	76.224	39.672	4833060	630898.5	76.216	39.664	-0.008	-0.008	-0.002	-0.002
DJ5184	M053004		UTM 17	4794788	597859.4	76.395	40.096	4794788	597859.5	76.398	40.099	0.003	0.003	0.001	0.001
DJ5185	M053005	ON	UTM 17	4748529	642942	175.915	140.44	4748529	642942	175.879	140.404	-0.036	-0.036	-0.007	-0.007
DJ5186	M053006	ON	UTM 17	4654270	356422.1	175.317	140.129	4654270	356422	175.317	140.129	0.000	0.000	0.000	0.000
DJ5187	M053007	ON	UTM 17	4684031	358920	178.169	143.344	4684031	358920	178.155	143.33	-0.014	-0.014	-0.003	-0.003
DJ5188	M053008	ON	UTM 17	4843620	441711.8	182.096	146.61	4843620	441711.8	182.091	146.605	-0.005	-0.005	-0.001	-0.001
DJ5189	M053009	ON	UTM 17	4928776	562020	178.894	142.925	4928776	562020	178.887	142.918	-0.007	-0.007	-0.001	-0.001
DJ5190	M053010	ON	UTM 17	5092880	427990.8	178.891	141.902	5092880	427990.8	178.911	141.922	0.020	0.020	0.004	0.004
DJ5191	M053011	ON	UTM 16	5154452	702999.3	184.681	148.043	5154452	702999.3	184.675	148.037	-0.006	-0.006	-0.001	-0.001
DJ5192	SUM 88	ON	UTM 17	4989703	535112.7	47.261	16.897	4989703	535112.7	47.269	16.905	0.008	0.008	0.002	0.002
MB1563	G 321	OH	UTM 17	4598897	447104.4	177.847	143.45	4598897	447104.4	177.817	143.42	-0.030	-0.030	-0.006	-0.006
ND0163	D 362	PA	UTM 17	4667191	576137.3	175.556	140.602	4667191	576137.3	175.503	140.549	-0.053	-0.053	-0.011	-0.011
ND0171	HS 2	ON	UTM 17	4679060	424563.7	175.442	140.438	4679060	424563.7	175.412	140.408	-0.030	-0.030	-0.006	-0.006
NE0516	H 115 X	MI	UTM 17	4662646	318829.3	177.295	142.384	4662646	318829.3	177.279	142.368	-0.016	-0.016	-0.003	-0.003
NE0898	N 235	MI	UTM 17	4704086	345269.8	177.286	142.644	4704086	345269.8	177.293	142.651	0.007	0.007	0.001	0.001
NE0955	901 4090 D	MI	UTM 17	4758941	384326.8	177.9	142.978	4758941	384326.8	177.864	142.942	-0.036	-0.036	-0.007	-0.007
OJ0009	901 4098 RETAINING WALL	MI	UTM 17	4762486	384070.5	179.615	144.708	4762486	384070.5	179.654	144.747	0.039	0.039	0.008	0.008
OJ0219	907 5014 GRIST	MI	UTM 17	4855918	367394	180.302	145.143	4855918	367394	180.317	145.158	0.015	0.015	0.003	0.003
OJ0517	LSC 5 C 93	MI	UTM 17	4859590	365461.5	178.902	143.749	4859590	365461.5	178.944	143.791	0.042	0.042	0.008	0.008
OJ0599	LAKEPORT RM 2	MI	UTM 17	4777493	378424.3	180.696	145.899	4777493	378424.3	180.681	145.884	-0.015	-0.015	-0.003	-0.003
OL0303	J 318	MI	UTM 16	4866185	544815.6	178.023	142.632	4866185	544815.6	177.971	142.58	-0.052	-0.052	-0.010	-0.010
PH1012	831 1030 BOOKS	NY	UTM 18	4949682	460897.8	80.467	48.244	4949682	460897.8	80.435	48.212	-0.032	-0.032	-0.006	-0.006
RJ0586	A 293	MI	UTM 16	5150546	681725.2	187.802	151.332	5150546	681725.2	187.786	151.316	-0.016	-0.016	-0.003	-0.003
RJ0613	C 293	MI	UTM 16	5153122	703883.3	184.296	147.651	5153122	703883.3	184.261	147.616	-0.035	-0.035	-0.007	-0.007
RJ0617	FERRY DOCK	MI	UTM 16	5151546	707117	178.184	141.511	5151546	707117	178.185	141.512	0.001	0.001	0.000	0.000
RJ1381	WN 1 C6W 017	MI	UTM 16	5129403	714779.4	177.461	140.951	5129403	714779.4	177.434	140.924	-0.027	-0.027	-0.005	-0.005
TY2525	70U672	ON	UTM 17	4658703	325966.7	175.944	140.911	4658703	325966.7	175.954	140.921	0.010	0.010	0.002	0.002
TY2540	71U117	ON	UTM 17	4667956	325322.3	175.812	140.985	4667956	325322.3	175.794	140.967	-0.018	-0.018	-0.004	-0.004
TY5484	81U111	ON	UTM 17	4731832	379077.2	177.036	142.038	4731832	379077.2	177.014	142.016	-0.022	-0.022	-0.004	-0.004
TY5827	GROS 1	ON	UTM 16	5155526	685413.8	184.525	148.027	5155526	685413.8	184.529	148.031	0.004	0.004	0.001	0.001