Height Modernization Program in the United States: Implementing a Vertical Datum Referenced to a Gravimetric Geoid Model

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Key words: GNSS, orthometric height, elevation, vertical datum, gravimetric geoid model

SUMMARY

Around the world, government agencies responsible for positioning and mapping are looking at new technologies to improve the way they carry out their missions. While many surveyors continue to use traditional line-of-sight surveying techniques, the improvements in accuracy and cost savings realized using Global Navigation Satellite Systems (GNSS) has led a growing number in the surveying community to embrace these new techniques. However the ability to measure very accurate heights using GNSS continues to be a challenge. While traditional leveling yields relative height differences within a few millimeters over regional distances, the very nature of GNSS makes it inherently difficult to achieve this level of accuracy. Finding ways to convert GNSS heights into meaningful elevations adds to the challenge.

In the United States, NOAA's National Geodetic Survey (NGS) is charged with defining, maintaining, and providing access to the National Spatial Reference System (NSRS), the country's official national reference frame for geospatial data. The North American Vertical Datum of 1988 (NAVD 88) is the current national vertical datum for the conterminous United States (CONUS) and Alaska, and it is primarily realized through a leveling network that, despite its high level of relative accuracy, is expensive to update, difficult to maintain, and vulnerable to systematic error (in particular, a cross-country one meter tilt). In order to address the deficiencies of the NAVD 88, NGS has been engaged in a National Height Modernization Program, enabling better access to accurate heights through the use of GNSS combined with traditional surveying techniques, remote sensing, and gravity data. While the Program has been successful, this approach remains dependent on passive control for definition and access, and it has become increasingly evident this kind of network is difficult and costly to maintain.

A new approach to defining the vertical datum, first codified as official policy in the NGS Ten-year Plan, includes building a high-accuracy gravitational geoid model derived from the gravity data collected through a project called Gravity for the Re-definition of the American Vertical Datum (GRAV-D). Height information referenced to this kind of datum will be accurate, reliable, current, and consistent. In addition, access to this new vertical datum will be easier, faster, and more cost effective. However, a datum defined in an entirely different way, accessed through a network of active control stations, will be adopted by the surveying community only after they are provided with the infrastructure, models, tools, and procedures to implement it.

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1. BACKGROUND

The National Geodetic Survey (NGS) is the agency in the United States responsible for defining, maintaining, and providing access to the National Spatial Reference System (NSRS), the national reference frame for geospatial positioning. NGS is part of the National Oceanic and Atmospheric Administration (NOAA), a scientific agency within the U.S. Department of Commerce, and its roots go back over 200 years to the establishment of the Survey of the Coast by President Thomas Jefferson on February 10, 1807. While the Mission of NGS has remained essentially the same since the creation of the Survey of the Coast, advances in technology have dramatically altered the way in which NGS accomplishes that mission.

In the United States, federal mapping activities are shared by several U.S. government agencies, distinguished by their responsibilities for such things as floodplain mapping (Federal Emergency Management Agency), management of water resources (U.S. Geological Survey), and engineering projects (U.S. Army Corps of Engineers) . These and other federal civil agencies are directed to use the official datums defined by NGS, but local government and private industry also often find it advantageous to tie their work to the NSRS. Since the 1940s, cooperative surveys done in partnership with federal and local government agencies became more common. These projects together with NGS surveys were incorporated into the NSRS, enhancing and strengthening the national network.

2. NORTH AMERICAN DATUM OF 1988 AND HEIGHT MODERNIZATION

The earliest geodetic quality leveling (established by NGS' predecessor, the U.S. Coast and Geodetic Survey (USC&GS)) was performed in the 1850's, and in 1887, the first United States trans-continental geodetic leveling survey was begun, starting in Maryland and following the 39th parallel (Zilkoski, 2001). In 1900 a full adjustment of all the leveling data was completed, creating a national vertical datum. Adjustments incorporating new survey data followed in 1903, 1907, and 1912 (Berry, 1976). The next General Adjustment of all the geodetic leveling produced the Sea Level Datum of 1929 (later renamed to the National Geodetic Vertical Datum of 1929 (NGVD 29). The last comprehensive adjustment of the network was done in 1988, producing the current national vertical datum, the North American Vertical Datum of 1988 (NAVD 88). Each adjustment was performed to improve on the accuracy of the network. The greatest change was from NGVD 29 to NAVD 88. Additional data (350,000 km of leveling) and changes in approach for the network adjustment (e.g.

constrained to 26 tide gauges in 1929 vs. minimally constrained in 1988) all contributed to removing distortion, minimizing cross-continental error accumulation, and strengthening the network. (However a cross-nation one meter tilt, likely brought about by a mix of minimal constraints and 2nd order leveling effects, would be introduced and not successfully diagnosed until the satellite era had brought both GPS and GRACE to bear). NGS had large field parties to do much of the work, but cooperative survey projects by federal and state agencies with the capacity and interest to do geodetic surveys were encouraged to send their data to NGS, where it was adjusted with NGS projects, incorporated into the NSRS, and published for the nation to use for geodetic control.

As good as NAVD 88 was on a national scale, when it was released in 1991, there were still many parts of the United States where it was less than sufficient. California in particular had issues because of the crustal motion they are subject to, being at the juncture of the Pacific and North American tectonic plates. While there was plenty of historic leveling data throughout California, in many cases it could not be reconciled to a single epoch, and so could not be used in the adjustment. Other parts of the country subjected to subsidence or post-glacial isostatic adjustment experienced problems caused by combining observations over time, or like California, having observations removed from the adjustment entirely. Knowing that it would be cost prohibitive to continue to rely on leveling in these dynamic areas, the surveying community petitioned the federal government to direct funding to NGS to support an investigation into the use of GNSS compared to other technologies for measuring heights (NGS, 1998).

2.1 Using GNSS for Height Determination

GNSS (primarily GPS through 2010 and referred to as GPS for remainder of this section) was showing great promise as a tool for performing geodetic surveys. Line of sight was no longer a requirement, which meant large areas could be surveyed more quickly, and with a much smaller work force. It was soon determined that GPS could measure very accurate horizontal positions. Geodetic surveys using GPS commonly met or exceeded first order standards according to the *Geometric Geodetic Accuracy Standards and Specificiations for Using GPS Relative Positioning Techniques* published by the U.S. Federal Geodetic Control Committee (FGCC, 1989). However, measuring accurate heights proved to be a more complex problem because the nature of GPS made it difficult to get accuracy from the vertical components of the observations. In addition, the height that was measured was referenced to the ellipsoid, which as yet did not have a well-defined relationship to the geoid, or the NAVD 88.

Using the funding awarded by Congress, NGS conducted pilot survey projects. Numerous field and adjustment procedures were tested, together with the impact of control spacing and distribution on adjustment results. The results were compiled into two sets of guidelines for surveying with GPS. Using *NOAA Technical Memorandum NOS NGS-58: Guidelines for Establishing GPS-Derived Ellipsoid Heights* surveyors could expect to see ellipsoid heights to two centimeter relative accuracy between co-observed stations, and five centimeter absolute, or network, accuracy, within acceptable levels of probability. The second set of guidelines, *NOAA Technical Memorandum NOS NGS-59: Guidelines for Establishing GPS-Derived Orthometric Heights*, built on the procedures outlined in NGS-58, but specified control requirements and assumed an accurate geoid model. However the methods in NGS-59 still rely on passive marks to control NAVD 88 heights. While NGS was producing geoid models with acceptable accuracy to apply NGS 59, the model was not yet good enough (1 cm accuracy) to stand on its own without passive control, as the sole defining surface of the vertical datum.

2.2 Building an Accurate Geoid Height Model

Over the past 15 years, NGS has produced national geoid models in pairs – a purely gravitational geoid model, and one called a "hybrid" model. The hybrid model is developed by modifying the gravitational model to more accurately represent the relationship of the NAVD 88 Helmert orthometric heights to NAD 83 ellipsoid heights at sets of common passive control marks. The hybrid models have increased in accuracy from a little over a meter in the 1980s to 2.6 cm in 2009 (two sigma, based on a national average – accuracies may be significantly better or worse in some parts of the country) (Roman, 2009).

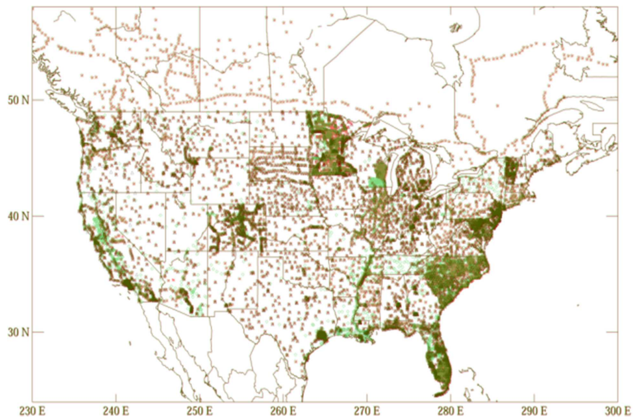

Figure 1. Stations with precise ellipsoid and orthometric heights

One of the factors that contributes to improvements in accuracy of the geoid models is the quality and quantity of the data used, including the gravity data and, for the hybrid model, the "GNSS on bench mark" data. The focus in the early years of Height Modernization was on collecting data from high accuracy GNSS surveys where marks had accurate NAVD 88 Helmert orthometric heights from leveling. Partnerships with local government agencies and universities across the country were a critical factor in making this possible. Agencies across the country completed GNSS and leveling surveys, and submitted the data to NGS. Even before the completion of GEOID06, the 2006 hybrid geoid model, it was obvious the disparity in the distribution of data from state to state was impacting the reliability of the model (Figure 1). Some states were getting significant funding support for these surveys and others were getting little or none. NGS knew it would not be able to create a consistent national model with this approach.

2.3 NOAA's National Height Modernization Program: The Early Years

The ultimate goal of Height Modernization has been to enable access to accurate NAVD 88 heights through the use of GNSS technology rather than expensive and time consuming leveling. Over the course of ten years, 18 states received varying levels of federal funding to implement Height Modernization. Other states found funding support within the state, but many had none. NGS managed the program through leadership and coordination of survey and outreach activities, research and development, and providing guidelines, models, and tools.

Much was accomplished during the first ten years of the Height Modernization Program. NGS partnered with states to train the surveying community in the skills to perform GNSS and geodetic leveling surveys and submit the data to NGS. Some state agencies or universities created “Spatial Reference Centers,” that served as liaisons between NGS and the local surveying community to provide support for education, surveys, and data distribution at the local level. Many states expanded their network of Continuously Operating Reference Stations (CORS) to support high accuracy GNSS surveys. Survey projects sent to NGS that met stringent requirements were added to the NGS database, published as geodetic control and distributed to the public. This data strengthened the network, and contributed to improving the models like GEOID06.

But these activities also highlighted problems with this early model for the Program. As Height Modernization surveys were completed, NGS and the user community realized that the condition of the vertical control passive network was poor. In many places it had been 30 years or more since leveling had been done, and many of the marks thought to be in the NSRS were disturbed or destroyed completely. There were some regions of the country where crustal motion, the processes that prompted the need for Height Modernization in the first place, made the published heights obsolete. New leveling surveys had to be done to accompany the GNSS. While it would continue to have a role in accessing the datum and measuring changes in heights, it was increasingly apparent that indefinitely maintaining the passive network as a means of defining the vertical datum was unrealistic. Add to this the previously mentioned concerns over the uneven distribution of data, and it was obviously time to assess the approach and see if these issues could be better addressed.

2.4 NGS’ Ten-year Plan – a New Direction for Height Modernization

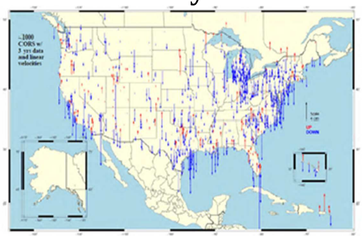

Figure 2. Vertical Shifts, NAD83 (CORS 96A Epoch 2010 – CORS 96 Epoch 2010

In 2008, NGS Leadership was evaluating its Mission goals in order to develop a long range strategy. NGS needed a strategic plan that would ensure that it could define and deliver the NSRS, while maintaining the reference frame in a dynamic world. NGS developed a Ten-year Plan, formulating a strategy for more efficiently and effectively delivering the NSRS to its users. Two components of the Plan were to modernize the geometric (“horizontal”) and geopotential (“vertical”) datums.

The ground work for modernizing the geometric and geopotential datums is already underway. In 2011, NGS completed a Multi-year CORS simultaneous solution (MYCS), with the intent to provide updated consistent coordinates together with accurate computed velocities (modeled velocities at sites with less than two and a half years of data) (Figure 2). The results of this solution were made available in September, 2011, in the NSRS-consistent frame of NAD 83(2011/MA11/PA11) epoch 2010.00 and in the global frame IGS08 epoch 2005.00. These results will be officially adopted early in 2012 with the release of the National Adjustment of 2011 (NA2011), when the passive control GNSS marks in the NSRS are adjusted to the MYCS.

NAD 83 will remain the official geometric datum for the U.S. in the near term, but will be replaced with a newly defined datum when the geopotential (vertical) datum is ready approximately ten years from now. The ellipsoid height component of the geometric datum will be a key part of defining the geopotential datum. The gravitational geoid model will provide the conversion from ellipsoid height to orthometric height. A key component of the work that will be done to improve this gravitational model is a comprehensive airborne gravity survey of the entire United States and its territories.

2.5 Gravity for the Re-definition of the American Vertical Datum (GRAV-D)
As emphasis on the importance of an accurate geoid model increased, accuracy of all the data that the models incorporate was evaluated. The efforts to collect GNSS on bench marks have been discussed, but the gravity data that forms the basis of the gravimetric geoid model, which after all is the foundation on which the hybrid model is built, was also evaluated. As with other kinds of data, NGS felt it could improve upon the quality of the data holdings, which had been collected over the span of several decades and from several sources. Similar to the bench mark data, gravity observations were not evenly distributed across the country, and there were voids in data all along the coast. NGS decided a comprehensive aerogravity survey would be the most effective and efficient way to collect such a large amount of data. Satellite gravity missions, GRACE (Gravity Recovery and Climate Experiment) and GOCE (Gravity Field and Steady-State Ocean Circulation Explorer), were underway, and the aerogravity data would provide the connection between the short wave-length provided with absolute gravity, and the long wave-length data from the satellites.

The GRAV-D project is well underway, and includes several components. The one-time aero-gravity survey is the most substantial phase of this effort. It alone is expected to take ten years, and its completion is dependent on funding support and partnerships. Started in 2008 with test flights to establish field procedures, the survey is now 16% complete. If current levels of funding are sustained, the aerogravity survey will be complete in 2022.

Other phases of the project include collecting additional terrestrial gravity data to better analyze the geoid in dynamic regions or areas exhibiting gravity anomalies, and a maintenance plan, where we would periodically update the geoid using in situ measurements and geodynamic modeling. In addition, research survey projects are planned to independently test the results we are getting from GRAV-D. The first of these “geoid slope validation surveys” (GSVS) involved collecting leveling, GNSS, terrestrial and airborne gravity, Lidar, and deflection of the vertical observations along a 300 km line in Texas (Figure 3).

Figure 3. Deflection of the Vertical camera and GPS collected for geoid slopevalidation survey

Preliminary results indicate GRAV-D will contribute results that will yield the 1cm geoid model NGS has targeted.

3. THE NATIONAL HEIGHT MODERNIZATION PLAN

The challenge that faces Height Modernization is how to support the need to access NAVD 88 today, and prepare the user community for the transition to a new kind of vertical datum. Certainly in regions of a stable crust, the systematic errors in the vertical datum don't cause significant relative error, and so updating the datum may not seem as necessary as in other regions of the country. However, as the keepers of country-wide consistent geodetic control, NGS cannot patchwork-fix the datum, and the update must be made across the country. The National Height Modernization Program will focus on the transition, not only helping surveyors measure NAVD 88 heights, but also informing the users about the advantages the new datum will bring. This effort will draw on many NGS resources, and strategic planning will help ensure this work is completed efficiently.

3.1 NGS Will Evaluate User Capability to Access the Vertical Component of the NSRS

Depending on the level of population growth, how much time has lapsed since a mark has been recovered and surveyed, and how stable the region is, many of the bench marks from the NAVD 88 adjustment have been lost or disturbed, or simply have moved, making their published heights obsolete. Some parts of the country have lost up to 60% of their control. In addition the need for accurate heights may vary among communities. For example, determining heights in the mountains can be difficult because leveling can be labor intensive and the geoid is complicated to model, but the accuracy requirements are not as stringent as they might be in a flat low-lying coastal region where the slightest change or error in elevation can have disastrous effect. A working group of experts in gravity, geoid modeling, vertical networks, and tidal/geodetic datum relationships will begin a systematic review of the network to determine what weaknesses may be impacting the ability to measure NAVD 88 heights. NGS Advisors, NGS employees who live and work in many states across the country, together with the many partners engaged in Height Modernization and other programs, will contribute their insight about local and regional issues.

NGS will also evaluate existing models and tools to determine if they are effective in delivering accurate NAVD 88 heights, given the nature of local issues. The Online Positioning User Service (OPUS), an online service that uses CORS to provide point positions from GNSS data submitted by users, uses the latest hybrid geoid model to derive NAVD 88 heights. Depending on the accuracy of the geoid model, OPUS may provide a height that is more up to date than the control available in a region.

Guidelines and standards used currently will be evaluated to see if they are obsolete and need to be replaced, or if they can simply be revised. The NGS-58 guidelines are now fifteen years old. NGS will review them to see how they could be combined and simplified because of improvements in GNSS and the infrastructure. New guidelines will be developed to explain changes in procedures to access the new datum.

3.2 NGS Will Strategically Address Gaps in NSRS

Once these gaps in infrastructure or weaknesses in the capacity of users to measure accurate heights have been identified, NGS will develop a strategy to determine what if any action should be taken. If access to NAVD 88 is difficult, there may be recommendations for surveys to update or establish control. Perhaps velocity or transformation models would be sufficient to update data.

Gaps in certain parts of the country identified as having more critical consequences will be prioritized for actions to be taken. NGS may not be able to address these gaps themselves, but may be able to recommend to the local community what actions would help the effort. In determining the proper strategy NGS will consider both the impact of infrastructure gaps on the ability to access NAVD 88 in the near term, and to transition to the new datum.

3.3 NGS Will Maintain Access to the Vertical Component of the NSRS

As the infrastructure is evaluated, and strategies for addressing gaps or problems are determined, NGS will need to consider whether these strategies will hold up for the years until it is time to implement the new datum. Actions to maintain or monitor the changes in coordinate values will also have to be considered. It may be possible to develop velocity models that can be used to update observations or coordinates. A transformation tool will be needed to enable users to update their own data, but if the values used to build that tool are out of date, the transformation will be useless.

New approaches for providing control data will be investigated. For control data in the NSRS that NGS feels is unreliable, published accuracy of a value could be downgraded, actual coordinate values could be suppressed, or messages could be posted so the user understands the risks in using the data. Metadata that provides additional information on how values were computed and the history of marks can help NGS and outside users research inconsistencies in control data.

NGS will work with federal agencies and users with specific applications to plan pilot projects that will help them develop new guidelines. The new datum will, for some, mean a shift in how they access the NSRS. Users of real time GNSS and remote sensing applications will need to understand how the transition to the new datum will impact their operations, and update their procedures accordingly.

3.4 NGS Will Build Technical Capacity for Users to Adopt Improvements to NSRS

The new datum will only be valuable if it is broadly adopted and fully replaces NAVD 88. It is human nature to resist change, and unless there are particular issues impacting the accuracy and availability of NAVD 88, users will continue using the reference frame they know. Ultimately, most people really use height differences, not absolute heights, so if they are unable to get those height differences at a desirable level of accuracy, or it is costly or difficult to do so, surveyors will look for a better way.

Communication and education have long been an important part of NGS' service to its user community. Through the Height Modernization Program, NGS will keep the surveying community and other users informed of decisions and status of various programs and projects, through publication of technical papers and reports in scientific journals, professional publications, and outreach materials. A section of the NGS web site dedicated to the Height Modernization Program has recently been updated to provide more comprehensive and timely information. The site includes links to key programs like GRAV-D, the Geoid model pages, the NGS Tool Kit, and research projects.

Figure 4. NGS Training Center, Corbin, Virginia

A training facility owned and operated by NGS supports workshops in field procedures and data processing, as well as informational presentations on basic geodesy and surveying (Figure 4). Many of these are available online through webinars, and are frequently taped and available for users who cannot attend the live webinar. These activities supplement the workshops and presentations NGS gives at conferences around the country.

NOAA held a Federal Geospatial Summit for users in other U.S. federal government mapping agencies to tell them about our plans to update the NSRS with these new datums, to hear their concerns and issues, and to discuss the impact this change will have on their agencies' products and services. The event was extremely successful, and paved the way for continued collaboration and coordination with those agencies as NGS moves forward. Two months following the 2012 FIG Working Week in Rome, NOAA will hold a second Summit, this time reaching out to the surveying community and the users of Geographic Information Systems (GIS). NGS plans to hold these events regularly to ensure everyone with an interest in geospatial positioning through GNSS is informed of the progress of our efforts to improve the NSRS, and that NGS is informed of the impact on those users.

4. CONCLUSION

Around the world GNSS has changed the way positioning is done. The NSRS will continue to be accessed through the passive control network, but increasingly the surveying community is accessing the NSRS through GNSS differential positioning relative to the CORS network. The NGS Ten-year Plan is underway, with improvements to the geometric datum (MYCS and NA2011) bringing us closer to the goal of aligning the datum with the ITRF. GRAV-D is 16% completed and at current funding levels is to be done in 2022. Maintaining the NSRS, one of the components of the NGS mission, will be accomplished by tracking temporal changes in the reference frame through daily monitoring of CORS and geoid monitoring activities . Redefining the vertical component of the NSRS, the geopotential datum, through CORS and a gravitational model is a natural step in the evolution of the reference frame. However, the user community needs to continue using NAVD 88 in the intervening years, and then will need support to adopt and embrace the new datum. To meet these needs the National Height

Modernization Program Plan must also change its approach to enabling access to accurate elevations, and will be a crucial player in paving the way for surveying in the United States.

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BIOGRAPHICAL NOTES

Ms. Shields is a Geodesist in the Geodetic Services Division of the National Geodetic Survey (NGS). She received a bachelor's degree in Mathematics from the University of Massachusetts/Boston in 1976. Ms. Shields has been with NGS since 1980, and has experienced major involvement in the geodetic adjustments for the North American Datum of 1983, and integration of new Global Positioning System (GPS) projects into the National Spatial Reference System (NSRS). This included assisting in the development of the constrained adjustment guidelines, primary responsibility for the High Accuracy Reference Networks adjustments, and the state-wide readjustment of several states. She has extensive experience in GPS and Geoid Height analysis, and has successfully used this experience to develop and conduct workshops around the country on incorporation of data into the NSRS. Renee is currently Project Manager for the National Height Modernization Program, an effort that has 17 states as regular participants and additional activities in a number of other states. She coordinates and manages the Program, through outreach activities, education, and development of policies and guidelines, with the goal of establishing nationwide implementation of Height Modernization.

Ms. Christine Gallagher is a Program and Management Analyst with NOAA's National Geodetic Survey (NGS). Christine joined NGS in August 2009 as a Presidential Management Fellow and completed two developmental assignment related to sea level rise impacts in coastal areas at the National Park Service and at the Environmental Protection Agency. Currently, Christine supports the Height Modernization Program and leads the Ecosystems and Climate Operations team at NGS. Christine holds two bachelor degrees from the University of Pittsburgh: a B.S. in Materials Science & Engineering as well as a B.A. in English Literature. At the University of Maryland, she earned a Masters in Engineering and Public Policy and specialized in environmental policy.

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