Geodesy, Geoids, and Vertical Datums:
A Perspective from the U.S. National Geodetic Survey

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SUMMARY

NOAA's National Geodetic Survey is responsible for maintaining the U.S. National Spatial Reference System, which includes positions in both ellipsoidal and geopotential or orthometric frameworks. As part of this, geoid height models developed by NGS exist in one arc-minute (2 km) grids and provide ready transformation between ellipsoidal and orthometric datums. In the United States, NAD 83 serves as the ellipsoidal datum suitable for use with GPS surveys while NAVD 88 is the orthometric datum suitable for use in leveling surveys (for the Conterminous U.S.A. and Alaska). Thus NGS provides the means for transforming coordinates easily and accurately derived through GPS into orthometric heights more suitable to applications involving waterflow (e.g., flood plain determination). Recently released models include the USGG2009 and GEOID09 models for all regions of the United States and its territories. These models are being uploaded and employed in GPS software as well as used in post-processing routines such as NGS's Online Positioning User Service (OPUS). USGG2009 is built upon the EGM2008 model, which is, in turn, based on GRACE gravity satellite mission data. USGG2009 also incorporates millions of surface gravity observations over the entire region of North America and the oceans around it. GEOID09 was developed starting from USGG2009 and combining it with nearly 20,000 points where GPS-derived NAD 83 ellipsoidal heights are known on NAVD 88 leveled bench marks (GPSBM's). These GPSBM's act as control points for determining a conversion surface between the geopotential datum determined by USGG2009 and that of NAVD 88. The fit of the control data to the GEOID09 model is precise to about 1.5 cm RMSE – about half the magnitude of the previous model, GEOID03. While these models represent the best effort possible using current techniques and data, NGS is moving into the future with the Gravity for the Redefinition of the American Vertical Datum (GRAV-D) project. GRAV-D has several components designed to reduce known errors in the millions of surface gravity data through controlled airborne surveys. Aerogravity will be combined with the terrestrial data and GRACE models to determine the best gravity field. Subsequent theoretical improvements under GRAV-D will be implemented with a goal of achieving a geoid height model of cm-level accuracy. This model will then serve as a future vertical datum replacing NAVD 88.

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1. INTRODUCTION

The National Geodetic Survey (NGS) is a program office within the National Ocean Service of the National Oceanic and Atmospheric Administration. NGS is responsible for defining, maintaining, and providing public access to the National Spatial Reference System (NSRS)**,** a consistent national coordinate system that provides the foundation for mapping and charting; transportation, communication, and land records systems; and numerous scientific and engineering applications. NSRS provides an extremely accurate geographic framework throughout the United States and its possessions. Components of the NSRS include:

1. Geodetic positional coordinates (latitude, longitude, and ellipsoid and orthometric heights) in the official U.S. datums, currently, the North American Datum of 1983 (NAD 83) and the North American Vertical Datum of 1988 (NAVD 88)
2. Geopotential
3. Acceleration of gravity
4. Deflection of the vertical
5. Models, tools, and guidelines
6. The official national shoreline
7. Global Navigation Satellite System (GNSS) orbits
8. Orientation, scale, and offset information relating NAD 83 to international terrestrial reference systems
9. All necessary information to describe how these values change over time

However, the components of the NSRS are not static. New realizations are constantly being developed to better describe the Earth as a reference frame and to describe the change of these elements over time. This paper provides context for the existing datums, discusses existing geoid height models, and focuses on efforts to improve data and theory for these models.

2. BACKGROUND

NAD 83 was implemented over 20 years ago and NAVD 88 is nearly as old. Both datums have aged and no longer represent the best that NGS can generate and support. NGS (2008) developed a Ten Year Plan that lays out a plan for new ellipsoidal and orthometric datums. The stated goal requires cm-level of accuracy, which requires the development of software and algorithms based on more rigorous theory. The focus here will be on geodesy and geoids.

2.1 Terminology

Before discussing geodesy and geoids, it is best to clarify terms. Most readers should already be familiar with orthometric and ellipsoidal heights. Orthometric heights are more desirable, because they better relate to "down" in the geophysical sense. These heights refer to a vertical datum that is usually taken to be a best fit to mean sea level, either in a global sense or simply adopted from a local tide gage. Such a surface of equal potential of gravity (geopotential) best serves for describing height changes, because water will flow and self-level to the lowest geopotential surface. While a geoid better relates heights to the ocean surface, determining a network of orthometric heights above it is time-consuming and expensive.

Ellipsoidal heights are very easily obtained in the GNSS age, but they are of less utility. An ellipsoid model is a mathematical construct based on only the grossest physical characteristics of the Earth (mass, flattening, spin rate, and equatorial radius). While this describes the major features of the Earth to better than 99%, horizontal and vertical mass variations (continents, oceans, etc.) are neglected that create geoid undulations of up to 100 meters.

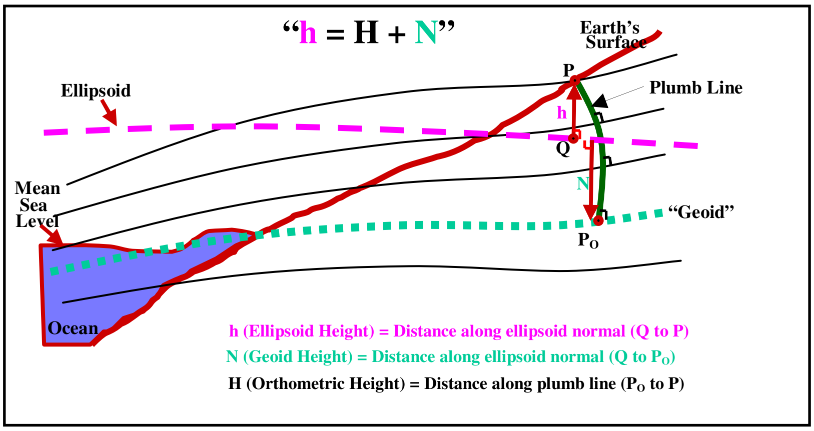

Figure 1 Relationship between ellipsoid, geoid and orthometric heights.

The difference between an ellipsoid surface and the geoid is the geoid undulation or geoid height (Figure 1). However, the determination of the geoid surface is problematic. The true geoid is not directly observable and estimating it may vary as current knowledge improves. Hence, there may be many models of the geoid surface and, consequently, many geoid height models. Likewise, there are many different models of the ellipsoidal datum. So, geoid heights should only be used to transform between the specific ellipsoidal and geoid datums for which they are designed. They cannot be mixed and matched. Understanding these relationships is important, because geoid height models are the way to the future for determining heights.

2.2 The Future Vertical Datum

NGS has determined that the optimal choice for a new vertical datum will be to generate a gravimetric geoid height model that will work in conjunction with a chosen ellipsoidal model. However, the simple relationship expressed in Figure 1 doesn't take into account systematic or random errors in the GPS, leveling, or the gravimetric geoid. Removing the geoid height and orthometric height from the ellipsoid height will leave a residual (Eq. 3). If the residual value were zero (i.e., no errors existed), then the equation shown in Figure 1 results.

h = H + N + residual (Eq. 1)   H = h – N + residual (Eq. 2)   residual = h – N – H (Eq. 3)

Using Equation 2, an orthometric height may be created by removing a geoid height (interpolated from a model) from an ellipsoidal height (from GPS) with some likely residual error. This retains the efficiency of GPS but obtains the more desirable orthometric height at any location where GPS works and avoids the higher costs of leveling.

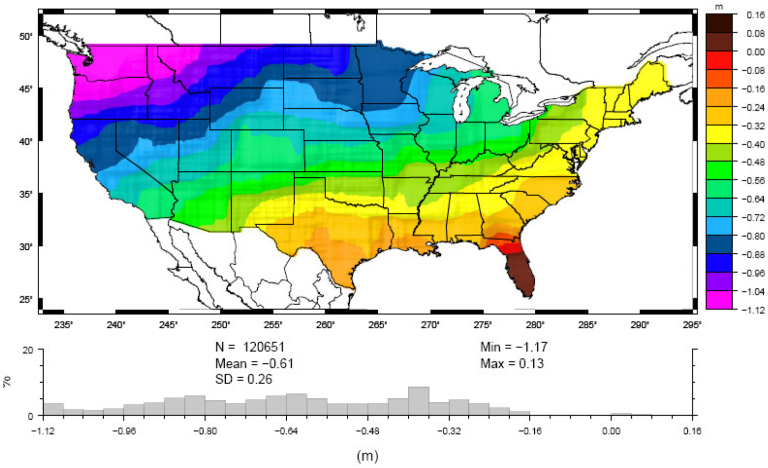

Figure 2 GRACE geoid heights (N) and NAVD 88 heights (H) were removed from GPS-derived ellipsoid heights (h) to form residuals (Eq. 3). A 500 km low pass filter was applied. Note the meter level trend.

While in principal this seems easy, implementing it will be difficult. There is always a great reluctance to change. Why change away from the existing vertical datum and adopt a new one? Simply put, the known errors in NAVD 88 far exceed the accuracy of GNSS observed heights – by a couple orders of magnitude. Figure 2 shows the large scale systematic errors associated with NAVD 88. The GRACE satellite mission (Tapley et al 2005) developed a GGM that is deemed cm-level accurate when describing features at 100's of km in scale.

Hence, a geoid height model determined only from GRACE was combined with cm-level accurate GPS-derived ellipsoid heights to determine orthometric heights. These are removed from NAVD 88 leveled heights to create residuals (Equation 3). A 500 km low-pass filter is applied to emphasize only those features at a scale to which GRACE is sensitive. The remaining signal shows the long wavelength disagreement between the GRACE geoid and the zero elevation reference surface of NAVD 88 - a meter level trend across the country. It is also likely that there are smaller scale errors in NAVD 88, which will likely be better highlighted by the forthcoming GOCE (Rummel et al 2009) mission. A gravity field developed from the combined GRACE and GOCE missions should resolve geoid features at about the 200 km scale. All of these errors in NAVD 88 are simply buildup of the error in the original observations. On top of this are the localized errors caused by crustal motion, which are not shown on Figure 2 but which can be meter-level in the worst locations.

The big take away is that NAVD 88 has known systematic errors within the North America region and needs to be replaced. Using a combined GRACE/GOCE field for a reference will ensure that any future vertical datum is consistent with those developed by other nations in other regions. The intent is to develop a North American geoid height model to serve as a common, regional vertical datum. The models will be recapped first ending with the latest.

2.3 Historical Geoid Height Models

NGS has been developing geoid height models for nearly 20 years. GEOID90 (Milbert 1991) and GEOID93 were the first models and represented the first attempts at providing a geoid height model. These models were termed *gravimetric* geoid height models, because they were based on gravity and terrain data only, without attempting to be a conversion between the official datums of the U.S.A. (NAD 83 and NAVD 88). Both gravity and geopotential fields are functions of the Earth's masses. Hence observations of gravity (relatively easy to make) can be transformed into a geopotential surface (which is not easy to measure) using well studied functions.

The development of geoid height models is paralleled by the development of NAD 83 and NAVD 88. The initial NAD 83 datum was accessed only as horizontal coordinates on passive marks in 1986. As GPS became more prominent in the mid-90's, NGS developed campaigns to collect dense GPS information for High Accuracy Reference Networks (HARN's) in each state. A more concerted effort was made during these campaigns to occupy leveled bench marks in order to better coordinate heights between these NAD 83 and NAVD 88.

Consequently, GEOID96 (Smith and Milbert 1999) represented the first *hybrid* geoid at NGS. G96SSS was developed as a gravimetric geoid following the techniques of the earlier models. This was then modified to fit the control data where GPS-derived NAD 83 ellipsoid heights were known on leveled NAVD 88 bench marks (GPSBM's). The initial network of points was somewhat limited (6169) and not equitably distributed. However, the intent was to use the gravimetric geoid to describe the smaller scale features of the geoid while forcing the fit through the GPSBM's to ensure that the resulting geoid height model would convert between NAD 83 and NAVD 88. This was determined by forming residuals using Equation 3 implemented at the GPSBM's with G96SSS. A conversion from the ITRF94 reference frame into NAD 83 was required to make G96SSS coincidental with the framework for the GPSBM's (NAD 83). The correlated signal in the residuals formed at the GPSBM locations was modeled using Gaussian functions in Least Squares Collocation (LSC):

$$C = C_0 e^{-\left(d^2/L^2\right)} \quad \text{(Eq. 4)}$$

where: C_0 = function variance (m^2) d = distance between points (km) L = correlation length

Note that the G96SSS and GEOID96 models are in different reference frames. G96SSS was developed in ITRF94 since it gave the most geocentric reference frame for determining positions. GEOID96 was in NAD 83, because NAD 83 was and is the official United States datum. Almost since its adoption, however, the geocenter of NAD 83 has been seen to be off from the "true" geocenter by about two meters. This cannot simply be neglected. The GPSBM distribution directly impacted the quality of the GEOID96 model. These data were more likely to have been collected in coastal states and more likely in the eastern states than the western states. This followed the development of the HARN's in states around the country. The residuals formed by Equation 3 derive from errors in all three values. Uncertainties in GPS typically are more random, but the HARN adjustments resulted in state by state systematic effects. Certainly, there were systematic errors in the development of G96SSS. Finally, there were the systematic errors in NAVD 88 that ranged in scale from the original level loop to features that spanned the country. The goal of the LSC was not to fix these errors – only model them. GEOID96 was designed to replicate the NAVD 88 datum exactly as if a surveyor had leveled in between two of the control points - complete with systematic effects.

GEOID99 (Smith and Roman 2001) and GEOID03 (Roman et al 2004) followed in much the same vein. They were necessary updates because the heights at the GPSBM's were adjusted as newer realizations of the NAD 83 reference frame were developed and as more data points were added (more GPS on existing leveled bench marks). To take advantage of this increased density of points, a more sophisticated algorithm (multi-matrix LSC or MMLSC) was created to model the correlated signal but the overall technique remained the same. It was about this time that the initial GRACE gravity field products were becoming available. Early tests showed much the same trend that is seen in Figure 2. If anything, the current geoid height models have made it clearer that the systematic tilt derives from NAVD 88.

3. CURRENT GEOID MODELS FOR THE U.S.A.

While this discussion will focus on development of the models for the CONUS region, models were developed using similar procedures for Alaska, Guam, the Commonwealth of the Northern Marianas Islands, American Samoa, Puerto Rico and the U.S. Virgin Islands.

3.1 USGG2009

The United States Gravimetric Geoid of 2009 (USGG2009) represents a significant improvement and departure from the previous models given above. The significant improvement comes in large part from reliance on a vastly improved reference model. Whereas the significant departure comes from how NGS uses that model

3.1.1 EGM08 Versus EGM96

A global gravity model (GGM) was used for a reference field in a remove-compute-restore technique and accounted for the gravity field outside of the NGS modeling regions. Removing reference GGM values from observed gravity formed residual values that were more easily manipulated and produced proportionally smaller errors. However, the quality of the reference GGM directly impacts the quality of the gravimetric geoid derived from it. USGG2003 was built using EGM96 (Lemoine et al 1998), while USGG2009 was built using EGM2008 (Pavlis et al 2008). The differences between EGM96 and EGM2008 are quite significant.

One major reason for this was inclusion of GRACE gravity field data in EGM2008. GRACE collected information over the poles and provides the first truly global gravity field map. The long wavelength (large scale) components of EGM96 were developed by synthesizing orbital tracking from numerous satellite missions. EGM2008 was developed from surface gravity data binned at 5’ and 15’ spacing (10 km and 30 km data spacing, respectively). More of these bins reflected actual data than in EGM96, where significant portions were geophysically interpreted from terrain data. Ellipsoidal harmonics were used for EGM2008, while EGM96 used spherical harmonics. Since the reference surface is an ellipsoid, EGM2008 follows a more rigorous approach. A more globally consistent DEM was utilized for EGM2008 based mainly on 3” (90 m) Shuttle Radar Topography Mission (SRTM) data, which was employed in Residual Terrain Modeling (RTM) (Forsberg 1984) to better account for the shortest wavelengths (smallest features) of the Earth’s gravity field. The net effect is that EGM2008 incorporated more data, implemented better algorithms to treat that data, and resulted in a more accurate model that resolved the Earth’s geopotential field to smaller scales. EGM96 is complete to degree and order 360 (resolving features of about 100 km), while EGM2008 is complete to degree and order 2160 (resolving features to about 10 km for most regions).

There are limitations to EGM2008, mainly due to omission and commission errors. Omission errors result from the 5’ resolution of EGM2008. Signal shorter than this is omitted and cannot be resolved when relying on EGM2008 alone. Studies (Wang 2010, Jekeli 2010) have shown that a model should have 1’ resolution to achieve sub-cm level of accuracy, the stipulated goal of the NGS Ten Year Plan and desired for the new vertical datum. Commission errors must also be overcome. NGS has much of the same surface gravity data that went into the development of EGM2008 for the North America region. It is known that there are significant systematic effects in those gravity data that contribute to dm-level errors in the geoid. In the absence of other independent gravity information, nothing can be done to resolve any systematic effects due to the quality of the existing data.

3.1.2 Harmonics, Terrain and the Kernel

NGS opted to use EGM2008 but not in its entirety. After several tests, a truncated kernel was adopted. Previous NGS models relied upon EGM96 for a reference model. An unmodified kernel was used, because of known dm-level errors in EGM96 for the United States (Smith and Milbert 1997). Hence, NGS placed more belief in the accuracy of its surface gravity data.

Reference gravity values from EGM96 were subtracted from observed data. These residual gravity contained long wavelength differences with EGM96, which were passed through the unmodified Stokes kernel and transformed from residual gravity into a residual geoid height. A final geoid model was determined by adding the residual geoid model to that generated from EGM96. The effect then was to correct the long wavelength errors inherent in EGM96.

Since EGM2008 is built on the GRACE gravity field, this is no longer the case. Now a modified kernel is adopted to reject the long wavelength part of the surface gravity, which forces the gravity field to fit GRACE data at long wavelengths and deriving the smaller scale features from the surface gravity data. The question is then, where should the cut be made?

After repeated experiments, the full 2160 model was selected with a modified the kernel at degree 120. Residuals from point gravity data and the full EGM2008 model were filtered to remove signal longer than about 300 km in scale. Residual values greater than 6 Mgal were dropped. This removed hundreds of thousands of points in the northern Rockies that were too disagreeable, but kept most of the signal from the remaining points. However, this entailed using EGM2008 to quality check the same data from which it was made, which is circuitous.

NGS procedures previously used Faye anomalies to approximate Helmert anomalies, Terrain Corrections (TC) to account for the impact of the terrain, and the geoid as a reference. Since EGM2008 was built using a 5’ RTM and harmonic continuation to the ellipsoid, this was no longer possible. Methods using RTM and TC cannot be mixed because they solve the problem of accounting for the terrain in mutually exclusive manners. Use of EGM2008 meant that NGS must adopt a new approach.

Following such an approach then, the RTM effects between 3” (the resolution of the underlying SRTM DEM) and 5’ (the resolution of EGM2008) should be taken into account, too. Accounting for this omitted signal greatly reduced the number of rejected points (down to 1400) but also degraded the overall solution. While future work will likely resolve this, USGG2009 was developed using only the inherent 5’ RTM effects in EGM2008.

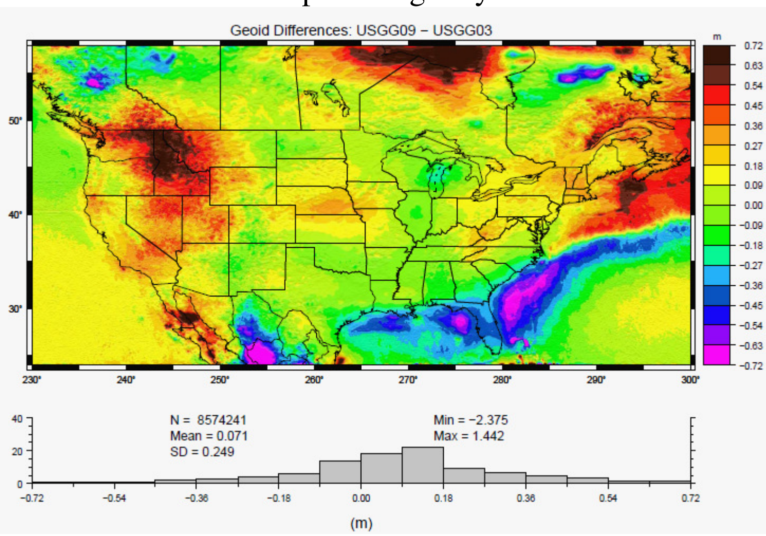

Figure 3 Geoid height differences between USSGG2009 and USGG2003.

While only the differences between USGG2003 and USGG2009 for CONUS are shown in Figure 3, USGG2009 models were made for the other regions given above using similar techniques to ensure that models exist for citizens in all U.S. states and territories. While both models are in ITRF00, significant differences are seen. Some is due to the shift from EGM96 to EGM2008, some from points dropped in the northern Rocky Mountains, and some due to using DNSC08 (Andersen et al 2008) altimetric anomalies offshore.

3.2 GEOID09

The hybrid modeling follows the same path as previous hybrid models, though with a greater degree of GPSBM fitting than ever before. Additionally, the amount and quality of available GPSBM has changed as well.

3.2.1 GPSBM2009 Control Data

Aside from the underlying gravimetric geoid, the GPSBM data control the development of the hybrid model. These control data are determined from the existing coincidental ellipsoid and orthometric heights in the NGS database at the time the model is developed. As the database changes, the existing hybrid model becomes more out of date.

The GPSBM2009 data were drawn from the NGS database in the summer of 2009. The bulk of this was used to develop the CONUS grid, which was the most complex. There are 18,398 points spread across the lower 48 states plus the District of Columbia. An additional 579 points are spread across mainly southern Canada. These are also a part of the NAVD 88, though not actively maintained because Canada did not adopt NAVD 88. Finally, there are an additional 1471 points that were rejected either as being unreliable or inconsistent with its neighbors based on qualitative and quantitative comparisons.

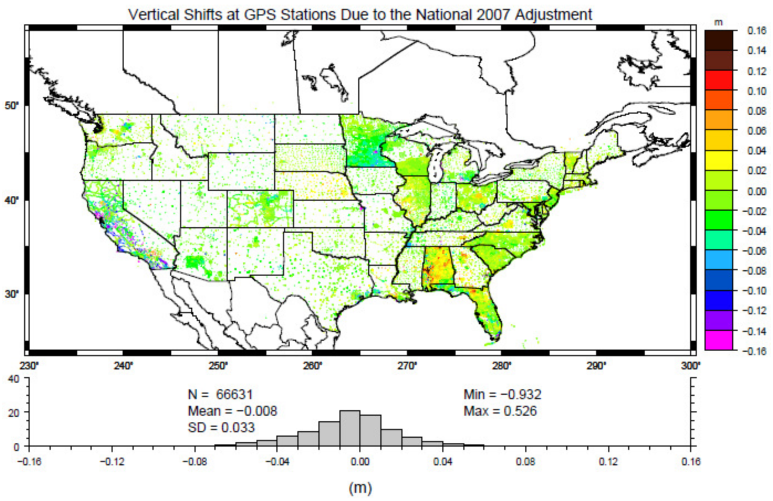

Figure 4 Ellipsoidal height changes that resulted from the National Readjustment of 2007.

3.2.2 National Readjustment of 2007

Pursell and Potterfield (2008) documented the results of the National Readjustment of 2007 (NRA2007), which caused significant changes to many ellipsoidal heights in the NGS database (Figure 4). Because of the relationship expressed in Equation 3, changes to only one of the heights directly impacts the residuals that are formed and, therefore, the overall model. The resulting changes in ellipsoid heights have produced dm-level biases in some states (California) as well near meter level changes at some specific points. Such large scale changes in ellipsoid heights directly impact the residuals formed to develop the hybrid geoid.

3.2.3 Multi-Matrix Least Squares Collocation

As covered briefly above, MMLSC (Roman et al 2004) is employed to model the systematic effects in residuals formed at the GPSBM's. Since the residuals form from systematic and random errors in all three sources (GPS, leveling, and gravimetric geoid), the scale of these features may vary significantly. Additionally, the spatial density of the GPSBM's is heterogeneous. For example, Minnesota has over 4000 GPSBM, nearly a quarter of the total for the country. Within that state, points approach 2 km spatial resolution. In western states, GPSBM spacing can be 100 km. Hence, features are present at many scales based on the spatial resolution and quality of the existing GPSBM's.

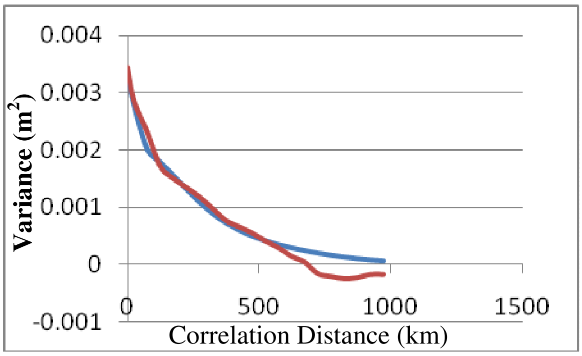

Figure 5 Variance of correlated signal (Y-axis) versus correlation distance in km (X-axis). Empirical data in red. MMLSC derived in blue.

Table 1 Characteristics of the six stacked Gaussian functions (Eq. 4) used in MMLSC. The sum of these (blue line in Figure 5) creates a math function designed to best fit the irregular signal seen in the empirical data (red line in Figure 5).

#	Correlation Length (km)	Standard Deviation (cm)
1	600	2.9
2	260	3.5
3	120	0.1
4	90	1.4
5	60	1.6
6	30	3.2

The residual values are correlated with each other based on distance. The correlations are binned by distance and an empirical data set is built to show the fall off with distance (Figure 5, red line). Multiple Gaussian functions (Eq. 4) are added to best model (blue line) the empirical data. Each must be positive definite, and the sum of the positive definite matrices results in a single positive definite matrix, which is invertible (i.e., there is a solution).

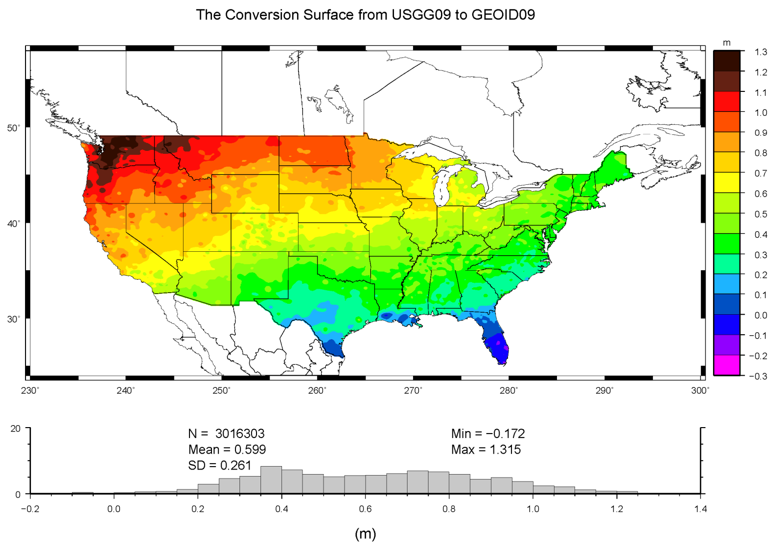

Figure 6 Conversion surface created from GPSBM2009 control data. Converts USGG2009 into GEOID09 (i.e., from the best known gravimetric geoid surface to NAVD 88). Note the inverse similarity to Figure 2.

3.2.4 Conversion Surface

After determining the mathematical functions that best fit the residual values at the GPSBM's, these same functions are then used to predict on a regular 5' grid to capture all the signal is the residual values at the GPSBM's. The 5' data were then regridded to 1' to match the USGG2009 grid interval. The bias and trend were restored and the difference between ITRF00 and NAD 83 taken into account. The sum of these is then the conversion surface necessary for changing USGG2009 into GEOID09. The CONUS grid is shown in Figure 6. Due to the sense of the sign used when forming the residuals, the conversion surface negatively correlates with the systematic error trend seen in Figure 2. Most of the error accounted for by the conversion surface was due to the trend in NAVD 88. Note that the datums for the various outlying regions were adopted, so GEOID09 will fit NAD 83 and the locally official vertical datum (e.g. GUVD04 for Guam, etc). For CONUS, GEOID09 fits the GPSBM2009 control points is 1.5 cm RMSE or 3.0 cm at the 95% confidence level.

4. GRAVITY FOR THE REDEFINITION OF THE AMERICAN VERTICAL DATUM

The errors in NAVD 88 seen in Figure 2 demonstrate the compelling need for an improved vertical datum in the United States. Re-leveling the country would cost billions of dollars and would likely result in similar systematic errors found in NAVD 88. Additionally, the weaknesses of relying on exclusively on passive marks would remain. Previous studies highlighted a basic relationship between ellipsoidal, orthometric and geoid heights: if two are known, the third can be determined. Hence, NGS decided to adopt a gravimetric geoid as the basis for a future vertical datum. Given the cm-level accuracy seen in GPS-derived ellipsoidal heights, a similar quality geoid height model is required. Propagating the errors of both GPS and the geoid height model will provide an estimate of the accuracy for the derived orthometric heights. GPS and a geoid height model would yield an accurate orthometric height anywhere desired for a starting point for a level survey. Geodetic leveling from that start point would then be used to complete local surveys, thereby tying local surveys to the national vertical datum. Certainly then the error budget for such a geoid product is very small. Error sources must be eliminated or reduced where possible. Two areas present the greatest possibility: theory and data.

The Gravity for the Redefinition of the American Vertical Datum (GRAV-D) project was implemented for a number of reasons. An earlier study (Roman 2007) showed dm-level artifacts in NAVD 88 in southern Louisiana. This study prompted an analysis of existing NGS gravity data to better understand errors created in resulting gravimetric geoid height models.

4.1 Improved Data Quality

Additional data are required to assess the quality of the existing gravity data. A systematic collection of airborne gravity data would easily cross the shoreline and provide a single source for comparison to existing terrestrial and shipborne gravity data. Surveys are planned with sufficient crossover ties for internal accuracy checks. The scope of each region is generally 400 km x 500 km permitting comparison with GRACE and eventually a combined GOCE/GRACE model. The aerogravity would be constrained to the satellite model and should result in a regional gravity field that can resolve features to 20 km resolution. The combined aerogravity and satellite model would then be used to help detect and eliminate systematic errors in the existing surface data – a significantly more rigorous and independent approach than using EGM2008 for such a task. Finally, the effects of the terrain and density variations would be modeled to provide the shortest wavelengths of the gravity field.

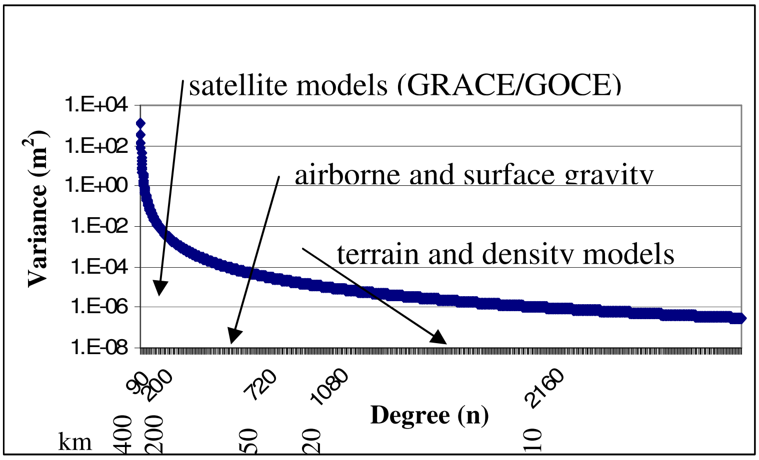

Figure 7 Curve shows power (variance) of the geoid versus degree harmonic (which corresponds to the scale of features in km). Expected contributions from various sources including satellites (deg. 2-200), terrain and density models (deg. 1080-10800), and airborne and surface gravity (deg. 90-1080).

Ultimately, a gravity field will be developed that is seamless in spectral character and which stretches across the entire North American landmass. It would be dominated by different sources at various scales as shown in Figure 7. To complete this then, long term monitoring of changes in the Earth's gravity field would be made. GRACE provides some of this now but will eventually cease. The desire is to maintain a long term record of the most significantly changing aspects of the gravity field. However, this improved gravity field must be accompanied by similar quality improvements to theory.

4.2 Improved Geodetic Theory and Implementation

Several different theoretical approaches were explored in the development of USGG2009. Assuming perfect data and implementation of rigorous theory, they should all be equally valid. Though significant progress has been made on elements of several different approaches, use of EGM2008 as a reference model necessitated following similar development for USGG2009. When a combined GRACE/GOCE reference model becomes available, this should be less of a constraint. Most theoretical approaches should then yield similar results.

NGS is constantly in dialog with its counterparts for governments in the hemisphere and, in conjunction with the International Association of Geodesy, seeks to develop a geoid height model for all of North America. Each nation is looking to adopt such a model for a vertical datum. The aim for this group is to adopt a common model, acceptable by all, that meets the accuracy needs for a GNSS-accessed vertical datum. Each country has adopted slightly different approaches. Hence, a broader effort will be made to study and implement various theoretical approaches with a goal of determining the optimal approach.

5. EXTERNAL METRICS FOR CALIBRATION AND VALIDATION

Determination of this optimal approach will also require external metrics. Several such data sets are being assembled. Local mean sea level variations are caused by temperature, pressure and salinity variations as well as atmospheric and ocean bottom effects. A mean dynamic ocean topography (MDOT) model describes these variations and can be combined with a geoid height model to make comparisons to the actual ocean surface at tide gages:

Geoid Height (global MSL) = Local MSL (ocean surface) - MDOT (Eq. 5)

NOAA has engaged in a robust campaign to collect GPS on tide gages to directly observe local MSL in an ellipsoidal reference frame. This will help to constrain and evaluate the geoid height (and MDOT) model at the shoreline. Additionally, some lidar flights over the near shore have also been obtained that can extend a similar analysis perpendicular to the shore.

Additional comparison data comes from the initial products of the GPSBM's, where GPS and leveling are treated separately but similarly. Adjustment projects involve smaller regions where systematic errors do not accumulate significantly. A single point is fixed for a height adjustment (ellipsoidal or orthometric) resulting in a set of relative heights that are internally consistent but not constrained to a datum. These minimally constrained heights best represent real changes sans the datum errors associated with NAD 83 and NAVD 88. Differences at coincidental points (i.e., a GPSBM) provide relative geoid heights that should better reflect local gravity features. Additional validation data is available from astrogeodetic observations and geoid height models from other investigators.

6. CONCLUSIONS AND OUTLOOK

NGS is charged with defining, maintaining and providing access to the National Spatial Reference System. The existing datums in the NSRS are NAD 83 (ellipsoidal) and NAVD 88 (vertical). They are outdated by modern standards, have known meter level systematic effects, and are not suitable in the GNSS era with expectations of cm-level accuracy.

NGS's most recent gravimetric geoid height model is USGG2009, while the most recent hybrid geoid height model is GEOID09. Both follow similar techniques used in earlier models. USGG2009 is based on an updated reference model, EGM2008, and shows significant improvements over USGG2003 – its immediate predecessor. GEOID09 has seen similar improvements and has a precision of 3.0 cm (95% confidence level) relative to the official U.S.A. datums. Both models represent the culmination of the existing theory and data.

The Gravity for the Redefinition for the American Vertical Datum (GRAV-D) project will overcome deficiencies in existing gravity data, develop a seamless and accurate gravity field, and use this improved gravity in more rigorous theory to achieve a cm-level accurate geoid height model. This model will serve as a future vertical datum in combination with a future ellipsoidal 4-D reference frame. Technical details on how to develop geopotential numbers from such a model must be worked out, so as to develop other types of heights (e.g., dynamic heights) or for comparisons in South America where the height system will be based on geopotential numbers. Ideally, a single model will be implemented for all North American countries to adopt as they wish, which will provide a common, accurate vertical datum.

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BIOGRAPHICAL NOTES

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