Beyond GEOID12: Implementing a New Vertical Datum for North America

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SUMMARY

The National Geodetic Survey (NGS) is responsible for maintaining both the horizontal and vertical datums within the U.S. National Spatial Reference System (NSRS), which are the North American Datum of 1983 (NAD 83) and the North American Vertical Datum of 1988 (NAVD 88), respectively. NGS periodically produces hybrid geoid height models that transform between these datums to facilitate GPS/leveling in surveying as well as other engineering and scientific activities. The GEOID12 model represents the latest effort in this series. However, both NAD 83 and NAVD 88 have significant systematic problems, which the current hybrid geoid height models faithfully replicate. While the datums remain internally consistent (i.e., precise) they are inconsistent with other reference systems at the meter level (i.e., not accurate). Comparisons at tide gauges and with global satellite gravity field models demonstrated a meter level cross-continent trend in NAVD 88 likely due to accumulated leveling errors in the adjustment that created it. Likewise NAD 83 is known to have a 2.2 meter offset from IGS 2008. The Gravity for the Redefinition of the American Vertical Datum (GRAV-D) project was started to realize a new vertical datum that is both accurate and precise. The aim of the project is to produce a gravimetric geoid height model that is accurate to cm-level and can be combined with an improved geometric reference frame to produce similarly improved physical heights, removing entirely the need to have “hybrid” geoid models which absorb systematic datum errors. Several factors are critical to ensuring this works. In anticipation of its adoption in 2022 at the completion of GRAV-D, an optimum geopotential surface (geoid) was recently selected based on comparisons with tidal bench marks around Canada and the United States and some portions of the Caribbean. A geopotential value of 62,636,856.00 m^2/s^2 best fit available data. This value is the same as that adopted by the International Astronomical Union (IAU) & the International Earth Rotation and Reference Systems Service (IERS) and is one of many that have been offered as the best representative of global mean sea level (MSL). Comparisons all around the North American continent with tide gauges, satellite altimeter measurements of the ocean surface, and models of ocean height variability all support adoption of this number as the best estimate of MSL for North America and future vertical reference systems defined for the United States and Canada. Canada will be adopting this value and a geoid height model based on it as their official vertical datum in 2013 while the United States will follow suit in 2022. The United States continues to collect aerogravity to remove systematic errors in the terrestrial gravity data holdings to ensure that a cm-level of accuracy is achieved. This is on track and should be accomplished as planned in 2022 with a new vertical datum realized by a gravimetric geoid height model and GNSS observations.

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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 maintaining both the geometric and geopotential datums within the U.S. National Spatial Reference System (NSRS). The focus of this paper is on the ongoing development of geoid height models as a mechanism for accessing the geopotential datum through use of GNSS technology. Geoid heights are essentially heights above the ellipsoid to the geoid (the geopotential surface that approximates MSL). Many such models exist both at global and regional scales, and they are constantly being refined.

The two most recent regional models for the United States are USGG2012 (the U.S. Gravimetric Geoid of 2012) and GEOID12 (which is the latest in a long series of “hybrid” geoid models). USGG2012 is in IGS2008 (epoch 2005.0) to be consistent with the coordinate system used for the satellite orbits, CORS sites, and OPUS solutions. USGG2012 is the best estimate of global MSL based on comparisons with satellite altimetry & tide gauges but with a focus on North America. Derived geoid heights are applied to IGS2008 coordinates to obtain geopotential heights that most accurately reflect heights and changes in height. GEOID12 is in NAD 83 (2011) epoch 2010.0, which is the official geometric datum of the NSRS in which the passive control (bench marks) are published as a result of the National Adjustment of 2011 (NA2011) Project. GEOID12 heights provide the separation between NAD 83 and NAVD 88, the official vertical datum of the NSRS.While NAD 83 and NAVD 88 remain the official components of the NSRS for now, they are slated for replacement in 2022. NAD 83 has a known 2.2 m geocenter offset from most recent ITRF models (Snay 2003) and NAVD 88 has a 1-2 meter offset from satellite-determined EGM's (Wang et al. 2012). Hence, a geometric datum will be adopted in 2022 that will likely be derived from the then most current realization of the International Terrestrial Reference System. Also, a geopotential datum will be adopted that will contain a geoid height model tied into that same geometric datum. This paper will focus on the steps that are being implemented to adopt such a geoid model.

NGS is an active member of the IAG's Sub-Commission 2.3.c: the North American Geoid. The intent of IAG SC 2.3.c is to develop a regional geoid height model suitable to all countries in the region or at least to establish a common set of data for development of models that are consistent to an acceptable tolerance level (cm-level). NGS has collaborated with cadastral agencies in Canada, Mexico (the current chair), most countries throughout Central America, several countries in the Caribbean region, and the Geocentric Reference System for the Americas (SIRGAS) committee in planning such a model. NGS’ efforts, in particular, are focused on the development of a harmonic model that describes all aspects of the gravity field to include geopotential numbers. With geopotential numbers, any type of height may generated and be consistent with the local gravity field values.

To ensure such consistency, several layers of collaboration and data collection are required. NGS is engaged with ESA and other scientific agencies involved in the Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) and Gravity Recovery And Climate Experiment (GRACE) satellite gravity models as well as in GGOS to ensure that the North American Vertical Reference System (a working name for the 2022 geopotential datum) will be consistent with the eventual World Height System. Additionally, comparisons are made at tide gauges throughout North America to ensure consistent ties to MSL values observed regionally and not just in a global least squares sense. A comprehensive aerogravity campaign was instituted by NGS to ensure consistency and accuracy and to link the global satellite gravity models to the millions of terrestrial data points. Finally, all of these overlapping data sets must be melded to provide a consistent, accurate, seamless, gravity field model suitable for cm-level height determination in conjunction with GNSS. This paper will first address the development of USGG2012 and selection of the geoid surface based on tide gauge comparisons. It then covers the development of GEOID12, and finally addresses the outlook for future work and impacts on other programs.

2. UNITED STATES GRAVIMETRIC GEOID 2012 (USGG2012)

NGS has produced a series of gravimetric geoid height models for about 20 years (Wang et al. 2012, Roman et al. 2004, Smith and Milbert 1999). The process for developing these has become more refined using increasingly accurate long wavelength models from satellite gravity missions such as GRACE (Tapley et al. 2004) and more GOCE (Drinkwater et al. 2006). These models were blended into NGA's EGM2008 model (Pavlis et al. 2008) to produce a consistent reference model for calculating gravimetric geoids in the Conterminous United States (CONUS), Alaska, Hawaii, Puerto Rico & the U.S. Virgin Islands (PRVI), American Samoa, Guam, and the Commonwealth of the Northern Marianas Islands (CNMI).

Terrestrial and shipborne gravity are available for all of these regions and DTU10 altimetric anomalies (Cheng and Andersen 2011) were used to supplement data in littoral regions surrounding the landmasses. No aerogravity was used pending ongoing testing and evaluation. Future models will likely include such data. These included gravity data and the reference model were combined using a modified kernel that removed long wavelength disagreements between the terrestrial data and the satellite data in order to force a fit to the long wavelengths provided from GRACE and GOCE. The shorter wavelengths of the terrain were also taken into account. EGM2008 accounts for the effects of the terrain through about five arcminute (5') or about 10 km scale. SRTM 3” (90 m) data are available globally and a Residual Terrain Model (RTM) between 3” and 5’ accounted for much of the high frequency variability seen in the residual gravity signal. This removed short wavelength variability that appeared to be noise, smoothed the residual signal, and resulted in much greater accuracy in the final model.

The techniques employed to perform these steps largely follow the blueprint laid out in Wang et al. (2012) for the development of USGG2012. While no significant advances were made in technique, one aspect of USGG2012 is worthy of further mention. The geopotential surface selected as the geoid (datum surface or W_0) for this model was chosen as 62,636,856.00 m^2/s^2. This value defines which equipotential surface will serve as the geoid and thus the datum from which heights are measured. Geopotential numbers are defined as the change in geopotential value from the chosen W_0. The geoid serves as the zero surface from which heights are determined to be above and even below. Choosing this value now has taken on added significance in view of the ongoing collaboration between the United States and Canada to determine a common surface for defining heights. Canada needed to determine a value this year for their gravimetric geoid, which will serve as their official vertical datum next year. The United States will follow suit in 2022, after significant data problems are addressed via the Gravity for the Redefinition of the American Vertical Datum (GRAV-D) project (GRAV-D Science Team 2011). Until that time, hybrid models such as GEOID12 (Section 4) will continue to serve as the primary mechanism for determining orthometric heights from GNSS.

3. DETERMINING THE DATUM SURFACE FOR A NORTH AMERICAN GEOID

USGG2012 is required to make GEOID12 and provided amplifying information between control points used in GEOID12. USGG2012 also provided a check on progress towards a common geoid model with the Canadians to ensure the greater likelihood of a unified North American Vertical Datum as was envisioned for NAVD 88. Tide stations around Alaska, Canada, CONUS, and PRVI were all evaluated to estimate the most optimal geopotential value for selection of the geoid surface for a future vertical datum (Figure 1).

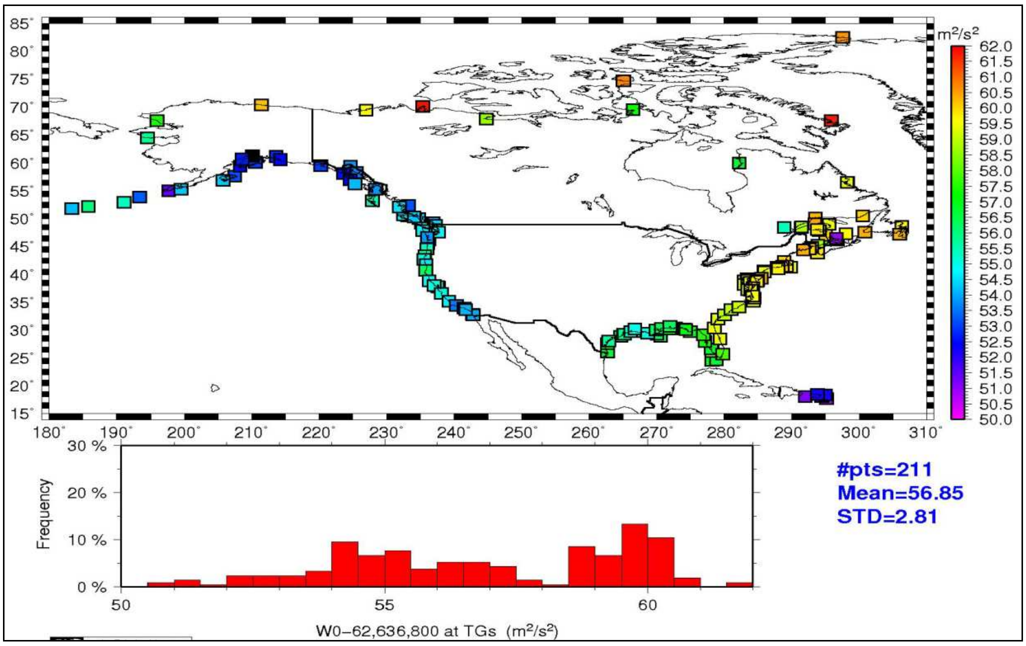

Figure 1 Geopotential values determined for tide gauges around Alaska, Canada, CONUS, and PRVI. The effects of SST can be seen especially along the Atlantic Coast. A constant value of 62,636,800 was removed from all numbers. Based on this comparison, the average W_0 should be 62,636,856.85 m^2/s^2.

GNSS observations at these tide stations placed the local Mean Sea Level (MSL) value into a geometric reference system. However, quite a bit of variability remained in the original observations due to the effects of Sea Surface Topography (SST) or Mean Ocean Dynamic Topography. Ocean currents, such as the Gulf Stream of the Labrador Current, not only provide a constant deviation of mean sea level from an equipotential surface, they also move warmer (less dense) and colder (more dense) waters along the shoreline. The combined effect of these produces upwards of a meter trend along the Atlantic shoreline. Additionally, an approximate 50 cm difference exists in the ocean heights (relative to the geoid) between the Atlantic and Pacific Oceans. SST models by oceanographers (Foreman et al. 2008, Thompson and Demirov 2006) are shown in Figure 2 and greatly reduce the difficulty of determining the value of the optimal geopotential surface from MSL observations.

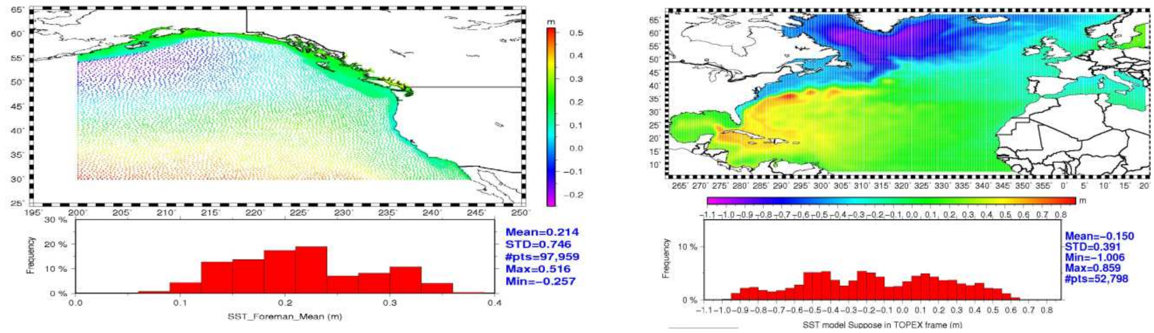

Figure 2 SST Models for the Pacific (Foreman et al. 2004) and Atlantic (Thompson-Demiorov 2006). SST models account for ocean surface variations away from a global norm (local vs. global MSL).

Figure 3 shows the revised geopotential values at tide gauges with the SST taken into account. The value of 62,636,856.00 m^2/s^2 best fits the North American region and provides the best estimate of MSL to serve as a datum. Coincidentally, this value was originally published by Burša et al. (2007) from an analysis of global data and was adopted by the IAU and IERS. It, therefore, provides a value vetted for global models but matched to regional tide gauges.

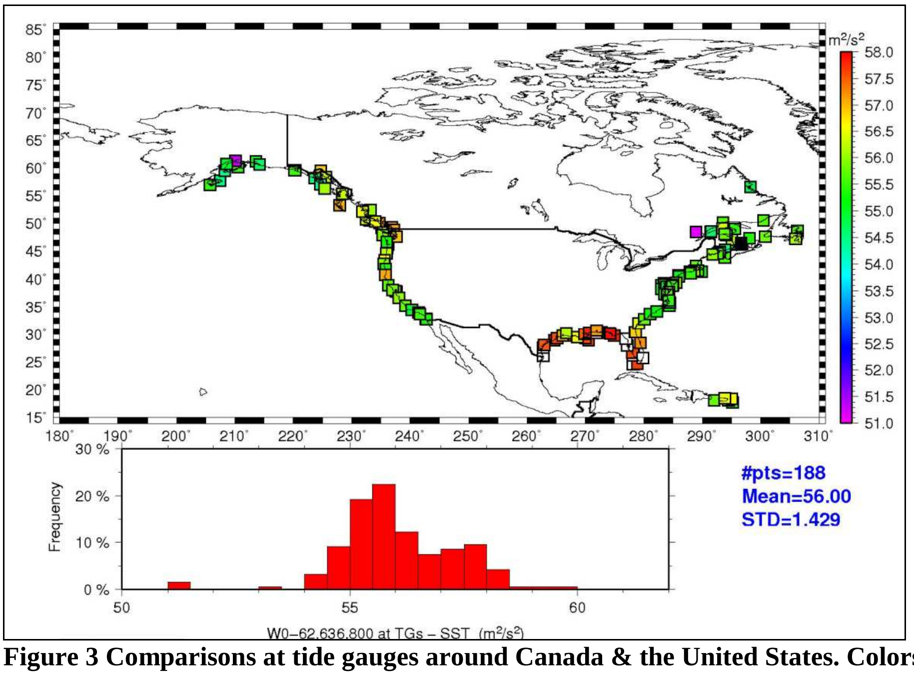

Figure 3 Comparisons at tide gauges around Canada & the United States. Colors scale the geoptential values (W_0) of local MSL at the tide gauges taking into account Sea Surface Topography. A whole value of 62,636,800 was removed from the scale. The best value then for appoximating MSL is 62,636,856.00 m^2/s^2.

Since the SST models didn't span the Arctic and other outlying (and largely unoccupied) regions, the scope of the stations was somewhat reduced from Figure 1 to Figure 3. The likely effect of adding those stations back in would be to increase the mean value. However, the value needed is intended for all of North America. While GNSS observations on tide gauges in Mexico and regions of Central America and the Caribbean are not readily available, the expected values there would lower the mean value. Hence, regions that have been excluded should offset and produce a value consistent with that selected. For those reasons then, the value of 62,636,856.00 m^2/s^2 was officially adopted by Canada and the United States for gravimetric geoid models in 2012 and the immediate future (with its adoption in 2022 remaining open to re-evaluation).

4. GEOID12

The GEOID12 model represents the latest in a series of models designed to transform between NAD 83 and NAVD 88. Updates are necessary as the intent of these models is to ensure that they best match the coordinates on those datums for bench mark control stations maintained by NGS. Any changes or updates to the values in the database require that new models be produced. Such models represent a blend of the underlying gravimetric geoid through the control points defined at the bench marks, where both ellipsoidal and orthometric heights are required information. The resulting model is a blend or hybrid that reflects the systematic differences between NAD 83 and NAVD 88 realized through the bench marks and using the information in the gravimetric geoid model to provide detail between the control points.

Hence, the nature and distribution of the control points is critical. The GPS-derived ellipsoidal heights on leveled Bench Marks available in 2012 (GPSBM2012) represent the intersection of nearly 500,000 bench marks in NAVD 88 with the nearly 70,000 bench marks with NAD 83 coordinates. The intersection is only around 23,000 points, which is not surprising when one considers that most NAVD 88 bench marks were installed in locations very unwelcoming to tripods and GNSS surveying in general (against walls, poles, posts and in bridge culverts). With the advent of GPS and further GNSS technologies, a more concerted effort has been made to occupy more leveled bench marks, as possible.

Additionally, the distribution of the points remains non-uniform with about half of the points in GPSBM2012 being located in only five of the 48 states in CONUS. Western states, in particular, are very poorly represented and often have significant subsidence problems at the few available points due to groundwater & oil extraction and mining activities.

As in 2009, the GPSBM2012 were vetted by a larger group of NGS employees with surveying experience and knowledge of potential problem marks not obvious from examination of the database. NGS maintains a Regional/State Adviser program to ensure that there is a link between NGS HQ actions, models, and planning and what is desired or implemented at the various state agencies responsible for geodetic applications (e.g., state Department of Transportation).

5. USE OF ONLINE USER POSITION SERVICE DATABASE (OPUS-DB)

For this reason, over 700 supplemental control points available from the OPUS-DB (Weston et al. 2007) were examined to provide increased density. This collection of archived GNSS observations is input by surveyors. A smaller subset of these points was made on existing leveled bench marks previously not occupied by GNSS (OPUSDBBM12). This amplifying information fills in between the existing GPSBM2012 control to further refine hybrid geoid models such as GEOID12 (Roman and Weston 2011). Figure 4 shows their distribution and highlights the fact that only some states have participated in this effort. Given that this can be a targeted effort, use of OPUS-DB is expected to grow in future models and bridge gaps that are currently interpolated producing systematic errors thought to be in the dm range. These new data provided significant improvements in Texas but were less helpful in other states.

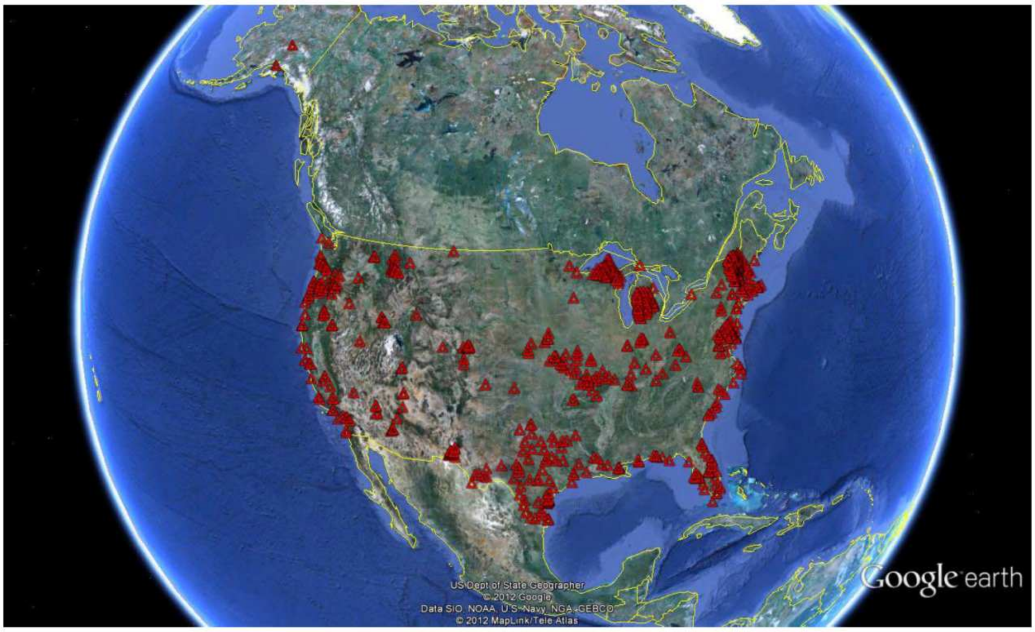

Figure 4. Locations of 709 points stored in the OPUS-DB and where no geometric coordinates exist in the NGS database. These GNSS observations on leveled bench marks (OPUSDBBM12) supplement GPSBM2012. Texas is an example of where this supplemental information created dm-level changes.

These control points (GPSBM2012 plus OPUSDBBM12) were used to develop a conversion surface that reflects the changes needed to transform the USGG2012 grid into GEOID12. Multiple matrices were inverted through Least Squares Collocation to develop this surface. Additional information was available both in Canada and Mexico where leveled bench mark heights above NAVD 88 also exist, although they were not formally adopted by those countries. Similar models were developed for all U.S. regions with CONUS and Alaska being on the NAVD 88 datum and outlying territories being on their own respective tidal datums.

6. OUTLOOK

For the next decade, NGS will continue to produce both gravimetric and hybrid geoid models as they have in the past. Steady improvements are expected in the development of gravimetric geoids with the goal being to achieve cm-level accuracy in an absolute sense. A common geopotential value has already been selected jointly with the Canadians. Available terrestrial data have begun to be analyzed and adjusted to be consistent with satellite models of the Earth's gravity field. Aerogravity, gravity collected from an airborne platform and sensor in flight, serve to bridge the gap between the satellite-based global models and the terrestrial data. In turn, rigorous theory is being implemented to take this improved gravity data to meld it into a geoid height model suitable for use as a vertical datum. The Gravity for the Redefinition of the American Vertical Datum (GRAV-D) Project is intended as the means of accomplishing all of this. The current status of aerogravity flights is given in Figure 5.

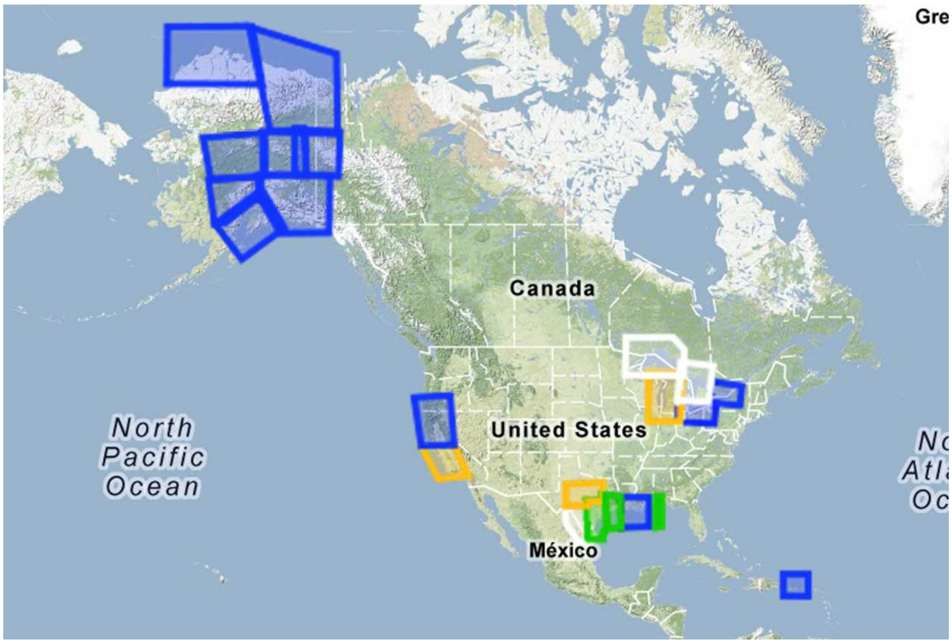

Figure 5 Extent of aerogravity collections as of Spring 2012. Map Key: Green: Available data and metadata; Blue: Data being processed, metadata may be available; Orange: Data collection underway; and White: Planned for data collection.

To insure data integrity, aerogravity is flown in a consistent manner following rigorous standards. Base station ties are made with an A-10 absolute gravimeter, concurrent with the aerogravity survey, and not made to older gravity points that may have changed. In turn, the aerogravity and satellite models are merged to produce an improved reference model to detect and mitigate any systematic errors in the terrestrial data due to either geophysical changes (e.g., subsidence) or bad base station ties (e.g., a survey bias).

Gravimetric geoid models are being developed that include this information and will be posted on the GRAV-D page (http://www.geodesy.noaa.gov/GRAV-D/) as experimental models to highlight the expected vertical datum values in 2022. As these models become more refined, they may be adopted as future USGG20xx models, though that is subject to further testing against external metrics such as tide gauges. In 2022, however, USGG2022 will effectively become GEOID22.

There will continue to be follow-on hybrid geoid models such as GEOID12 through 2022. At that time, no further hybrid models will be posted as official products. However, a conversion surface will continue to be generated (as was required to make GEOID12 from USGG2012). This surface will effectively transform between the new datum surface and NAVD 88 for as long as is required; much as VERTCON provides a transformation between NGVD 29 and NAVD 88. Note though that bench marks will no longer be vigorously maintained and that the network of passive marks will eventual become obsolete (or "secondary access" to the vertical datum, meaning that the reliability of passive marks will be entirely dependent on the user community's desire and effort to re-survey points of interest to them). At that point, future gravimetric geoid models and GNSS surveying will serve as the primary means of accessing the NSRS.

7. SUMMARY

NGS is charged with defining, maintaining and providing access to the National Spatial Reference System. The existing datums in the NSRS are NAD 83 (geometric) and NAVD 88 (geopotential). GEOID12 is based on a larger pool of control data (GPSBM2012) than previous models and was supplemented by OPUSDBBM12 observations on leveled bench marks. It serves as the official model because it transforms between the official datums.

The underlying gravimetric geoid model, USGG2012 was built first and used to underpin the GEOID12 model. It was determined from satellite data and terrestrial observations with no aerogravity included. This model was defined as the best current representation of the geopotential surface (W_0) with the value of 62,636,856.00 m^2/s^2. This surface was selected as the best fit through tide gauges through Canada and the United States when the effects of Sea Surface Topography were taken into account. It, therefore, provides the best estimate of MSL in all of North America – a suitable datum for determining heights. It also is the value adopted by many others as an estimate of global MSL. This surface was adopted by Canada and will be used to define their CGG2013 model, which will become their official vertical datum definition next year. The United States will follow suit with a similar adoption of a gravimetric geoid height model as the means for determining heights presumably about 2022.

Between now and then, the GRAV-D project will collect aerogravity to bridge the gap between global gravity field models from satellite missions and terrestrial data, and then use that data to develop a geoid height model that is determined to be cm-level accurate from comparisons to other external metrics such as tide gauges. When that model is complete and in place for all U.S. states and territories, it will be implemented with a target date of 2022.

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BIOGRAPHICAL NOTES

Daniel R. Roman, Ph.D., has been a Research Geodesist with the National Geodetic Survey since 1999. He is the team lead for Geoid Modeling and Research as well as the Principal Investigator for the Gravity for Redefinition of the American Vertical Datum (GRAV-D) Project. He developed GEOID99, GEOID03, GEOID06, GEOID09, and associated models.

Neil D. Weston, Ph.D. is the Chief of Spatial Reference System Division at the National Geodetic Survey and a principle behind the development of OPUS. He has also been involved in the development of OPUS-DB and OPUS Projects.

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