GEOID18: Last U.S. Hybrid Geoid Prior to NAPGD2022

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SUMMARY

The United States National Spatial Reference System will be updated in 2022 to be four terrestrial reference frames directly tied to the International Terrestrial Reference Frame and the North American-Pacific Geopotential Datum of 2022 (NAPGD2022) that will be based in those TRF's. Until then, the existing US NSRS will continue to be realized by the North American Datum of 1983 (NAD 83) and the North American Vertical Datum of 1988 (NAVD 88). These datums are maintained separately and realized separately. To connect them, so called "hybrid" geoid models are developed from an underlying gravimetric geoid and the GPS-derived ellipsoid heights on the spirit-levelled bench marks (GPSBM). Least Squares Collocation is used to warp the surface of a gravity-based geoid model to fit through over 30,000 GPSBM's. These gravity geoid provides continuity between the GPSBM to develop a consistent transformation between NAD 83 and NAVD 88 to facilitate work by surveyors around the country. Numerous recent collections were made as a part of a concerted effort to fill in gapped regions and provide a better spatial distribution for this model.

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1. INTRODUCTION

The National Geodetic Survey (NGS) is a program office in the Unites States Department of Commerce's National Oceanic and Atmospheric Administration. The NGS and its predecessor agencies have been responsible for providing geodetic control for over 212 years to the U.S. to enable accurate and precise positioning and measurement.

The U.S. National Spatial Reference System (NSRS) is currently accessed from both a geometric datum, the North American Datum of 1983 (NAD 83) (Schwarz 1989), and a vertical datum, the North American Vertical Datum of 1988 (NAVD 88) (Zilkoski et al. 1992). The most recent national adjustment of all geometric control on bench marks realization in the NAD 83 reference frame occurred in 2011. NAD 83 (2011) thus represents the most up-to date geometric coordinates for positioning in the United States. NAVD 88 was put in use in 1991. While leveling between new bench marks has been accomplished since then, these leveling data were constrained to fit the existing NAVD 88 network. This effectively means that NAVD 88 is static except for the special region of southern Louisiana, where subsidence related changes have been adopted on an episodic basis.

Geoid height models that transform between NAD 83 and NAVD 88 are highly desirable, because they permit the use of relatively inexpensive GNSS-technology to obtain more practical orthometric heights. This accomplished using a fundamental linear relationship that relates orthometric (H), ellipsoidal (h) and geoid (N) heights:

$$H = h - N \qquad \text{Equation 1}$$

The ellipsoidal height is determined using GNSS observations, while the geoid height can be interpolated from a grid or by using a model of harmonic coefficients. To develop these models though, control data are necessary.

Control data come from GNSS (GPS) observations made on leveled bench marks (GPS on BM). There are over 800,000 leveled bench marks that were a part of the NAVD 88 adjustment. At least 500,000 of these are in the conterminous Unites States (the lower 48). Many reach through Canada into Alaska and also reach into Mexico. There are also about 80,000 bench marks where GNSS data have been observed. However, the intersection of these two groups is much smaller. In addition, these data are not equitably distributed. Only a few states have very active programs, and so a bulk of the points might be available in limited region. Because the control points by themselves are inadequate to describe the datum surface everywhere, gravimetric geoid height models are used to fill in the gaps. The control data

(GPS on BM's) are used to warp the surface of the gravimetric geoid to fit through the NAVD 88 and NAD 83 surfaces at the bench marks. Hence, the term "hybrid geoid" is used to describe such models to distinguish them from geoid models based only on gravity field data (gravimetric geoid height models).

Hybrid geoid height models have been developed for nearly 20 years at NGS including GEOID96 (Smith and Milbert 1999), GEOID99 (Smith and Roman 2001), GEOID03 (Roman et al. 2005), and GEOID09 (Roman et al. 2009). The latest models in this series were in 2012. GEOID12 was initially put forth to coincide with the release of the NAD 83 (2011) adjustment. However, some of the data primarily in the Louisiana subsidence area but also in other areas around the U.S produced errors from 10-40 centimeters. This was partially due to inclusion of faulty leveling heights near the edges of the subsidence region that should not have been included in the final model development. There were also several control marks from regions with spurs where little data was available to make a comparison of relative quality. At the time, it was felt that inclusion of data was more desirable than exclusion. However, these significant errors required the development of the GEOID12A model to fix the regions with faulty data (see Figure 1).

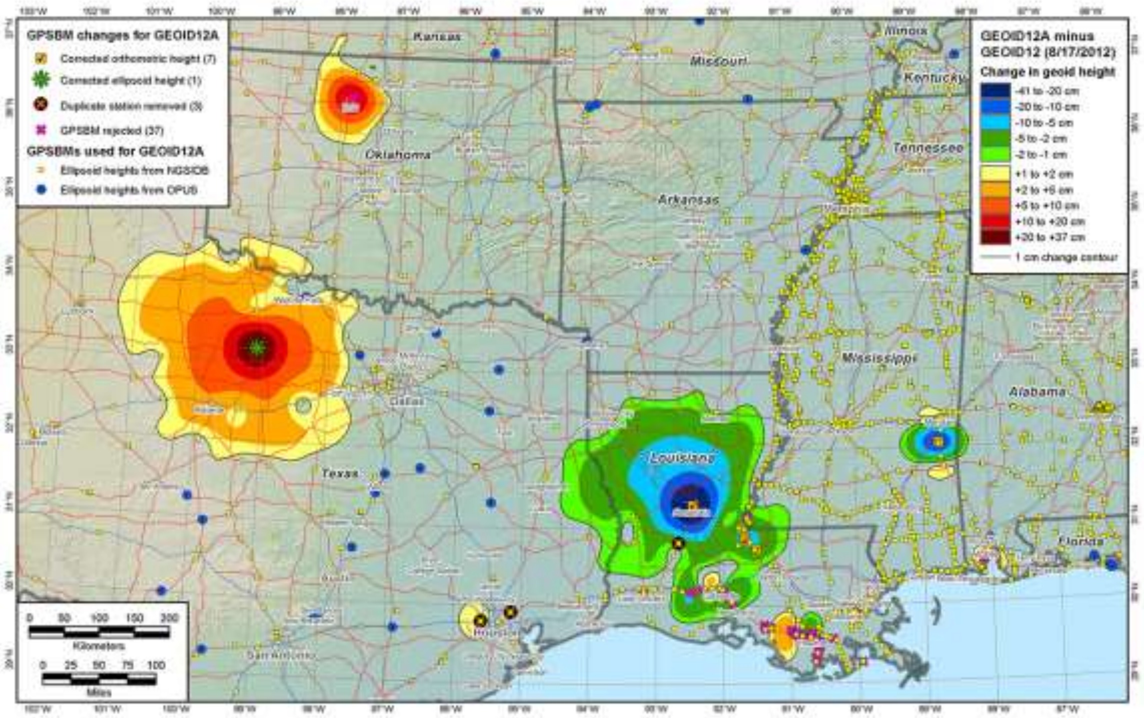

Figure 1 Differences between GEOID12A and GEOID12. Highlighted are the suspect control data (GPS on BM) that were removed.

Later still, it was determined that data in Puerto Rico had been incorrectly attributed to the Puerto Rico Vertical Datum of 2002 (PRVD 02) instead of the actual ties to local tidal (LT) datum (i.e., the nearest tide gauge). The difference between PRVD 02 and LT ranged up to 20 centimeters and was primarily in the southwestern portion of the island. As a result, GEOID12B was required to remedy this situation (see Figure 2). The only differences between GEOID12A and GEOID12B are in this region of Puerto Rico.

Given the criticality of the quality and distribution of GPS on BM data to development of hybrid geoid models, it was deemed necessary to focus on improving and densifying these control data for a future hybrid model (e.g., GEOID18) and the eventual datum conversion surface once the new vertical datum is implemented in 2022 as given in Blueprint Part 2 (NGS 2017). The next section in this paper discusses some of the initial analysis of the existing GPS on BM data, the next covers the GPS on BM Campaign to vet and densify the control data and the last covers the development of GEOID18, which includes CONUS and Puerto Rico and U.S. Virgin Islands.

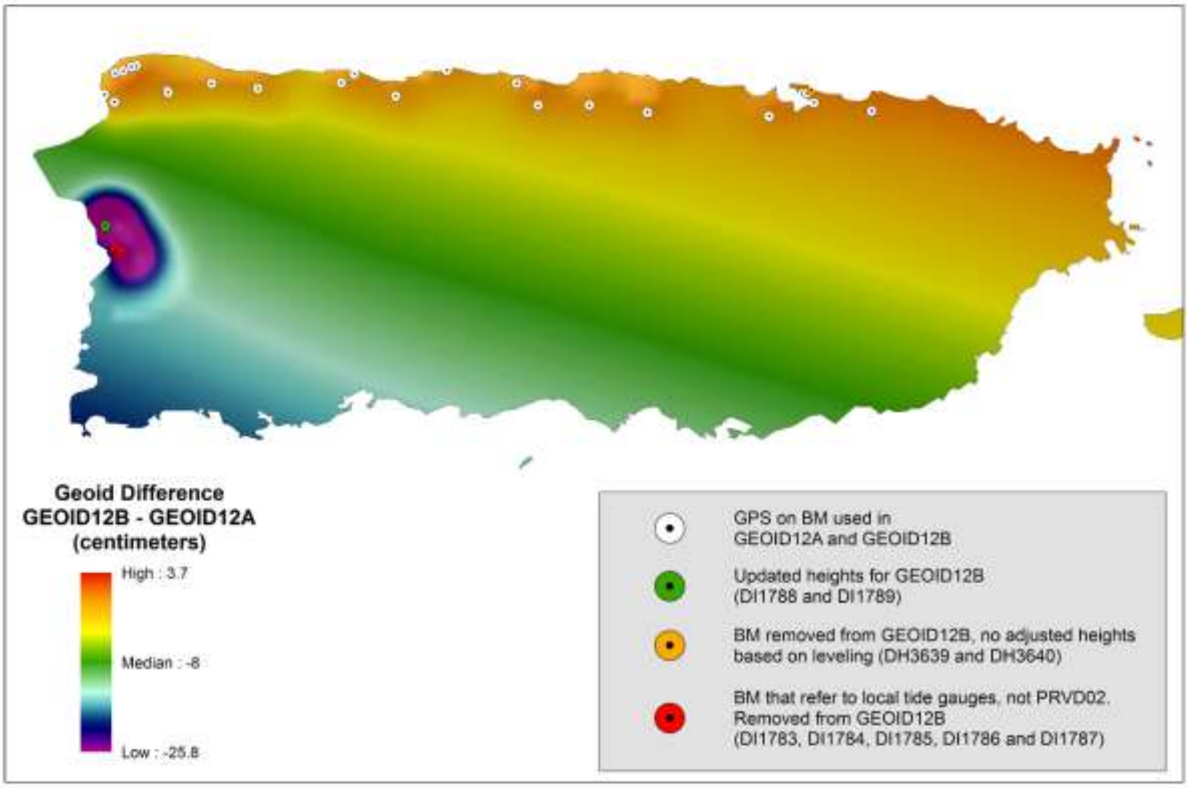

Figure 2 Differences between GEOID12B and GEOID12A. The only difference is in Puerto Rico due to control data (GPS on BM) that were incorrectly ascribed to PRVD 02 and were actually tied to LT.

2. NATIONWIDE GNSS ORTHOMETRIC HEIGHT PROJECT

The initial analysis after 2012 was designed to try to locate control data (GPS on BM) where some aspect of the data was suspect. To explain this, some background is provided here on how a hybrid geoid height model is developed. This will then make clear how the process may be adapted to look for suspect data. To develop a hybrid geoid a residual is first formed from the GPS-derived ellipsoid height (h), the leveling derived orthometric height (H) and the geoid height (N) from a gravimetric geoid model:

$$\text{Residual} = h - H - N \qquad \text{Equation 2}$$

In a perfect world, the residuals would all be near zero. However, there may be significant residuals caused by datum defects, such as the established meter-level tilt in the NAVD 88 datum (Roman 2017), local problems in the network, local gravity field problems, etc. The residual values are formed as individual points, but least squares collocation is used to find the correlated signal between the points (Smith and Roman 2001). This correlated signal is modeled and then added as a corrector surface to the gravimetric geoid height model to make it into a hybrid geoid height model.

The analysis performed by Nagendra Paudel (NGS Observations and Analysis Division) and Dave Zilkoski (NAVD 88 project administrator) focused on forming residuals using an experimental gravimetric geoid height, xGEOID14, and the existing hybrid geoid height model, GEOID12B. From their internal report:

Basic Steps performed for evaluating the GPS on Bench Mark file

- Plot Geoid Model Values minus GPS/Leveling derived values
  - Geoid12B minus computed geoid height using NAD 83 (2011) and NAVD 88
  - xGeoid14B minus computed geoid height using NAD 83 (2011) and NAVD 88
  - xGeoid15B minus computed geoid height using NAD 83 (2011) and NAVD 88
- Check neighbors for large relative differences in residuals (outliers)
  - Differences greater than 3 cm for stations less than 20 km
  - Differences greater than 5 cm for stations less than 50 km
- Investigate all outliers
  - Accuracy of ellipsoid height and network design (a lot of redundancy or minimum connection to network, date of survey)
  - NAVD 88 network design – date of leveling, number and size of loops in the region, original NAVD 88 data or new data incorporated into NAVD 88
  - In mountainous regions, check gravity used in NAVD 88 adjustment and areas void of gravity observations

This analysis looked at the significant outliers in the leveling data that might be caused by heights not actually tied to NAVD 88, large distribution corrections indicative of a significant outliers, the age of various level lines, level loop misclosures, old versus new at crossovers between level lines, etc. An analysis was also performed on the GPS-derived ellipsoid heights that were a part of the National Adjustment of 2011 (NA2011) that contributed coordinates for NAD 83 (2011). The benefit of such an adjustment is that the NA2011 analysis helped to highlight potential outliers and provided error assessments. The strength and quality of the network was also examined to ensure that the results were not overly optimistic, a known problem when performing a least squares adjustment. Finally, the gravimetric geoid height model was also examined to determine if insufficient or poor quality gravity data may have impacted the local quality of the geoid height model.

With this information, it was possible to identify priority control data (GPS on BM) that were suspect and needed to be revisited. Additionally, it was possible through a gap analysis to assess to regions where leveled bench marks should be occupied by GNSS (GPS) to add new data. This analysis completed in May 2016 and enabled the start of the GPS on BM Campaign.

3. GPS ON BENCH MARK CAMPAIGN

3.1. Collection

With the above assessment completed, a concerted program for data collection was begun in 2017. It should be noted that the NGS leveraged the willingness of U.S. surveyors to collect the priority data in the suspect regions identified in the previous section. Data were collected in four hour occupations (and desirably were revisited a second time), and the data submitted to OPUS Share for assimilation into the control data being analyzed.

3.1.1. Support from U.S. Surveyors

Figure 3 highlights the rate of collections steady through 2017 but ramping up through October 2018. The final data pull was made in December 2018 for determining the data for GEOID18. A little under half of the priority points were collected (2496 of 5866).

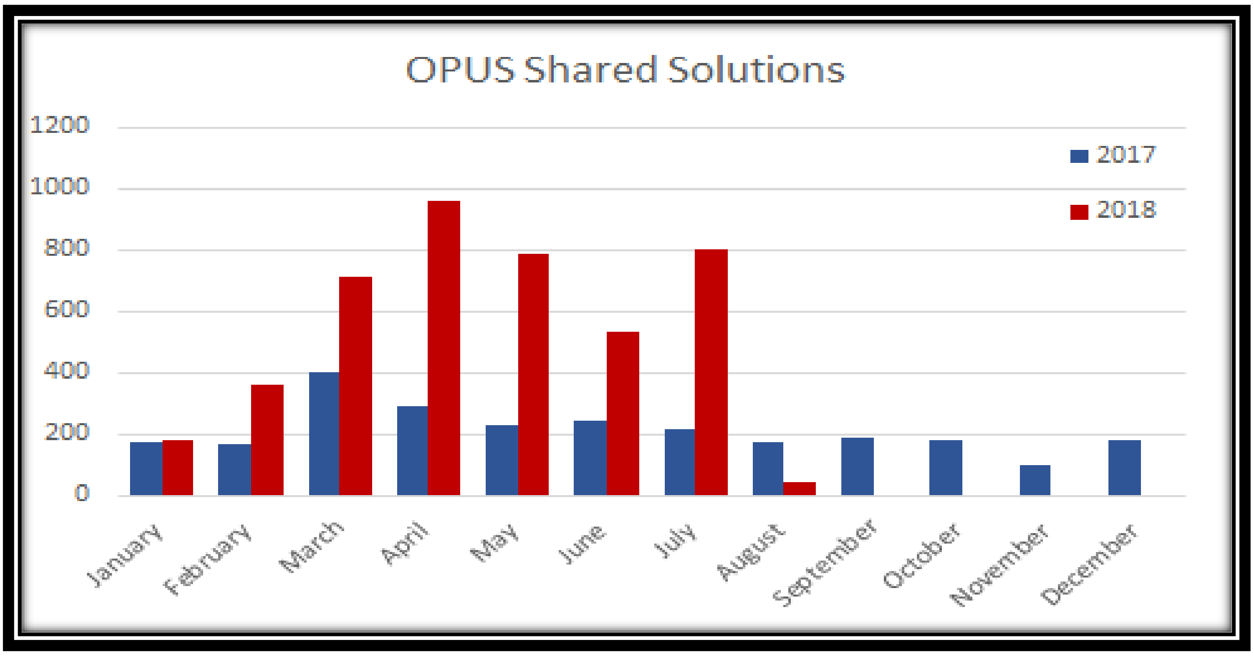

Figure 3 OPUS Shared solution submissions from 2017 through October 2018. The final data pull was made in December 2018 for making GEOID18. These submissions represnt the new observations on suspect control points or first observations on marks previously unsurveyed by GNSS.

3.1.2. Example Region of Collections

The GPS on BM Campaign website (https://geodesy.noaa.gov/GPSonBM/) showed the updated status for the prioriity marks. A surveyor would log on to the site and determine if any bench marks near the area they worked in might be required. They could pull down the relevant bench mark datasheet and proceed to collect data. Figure 4 shows the tool that a surveyor would see in an example area of eastern Iowa.

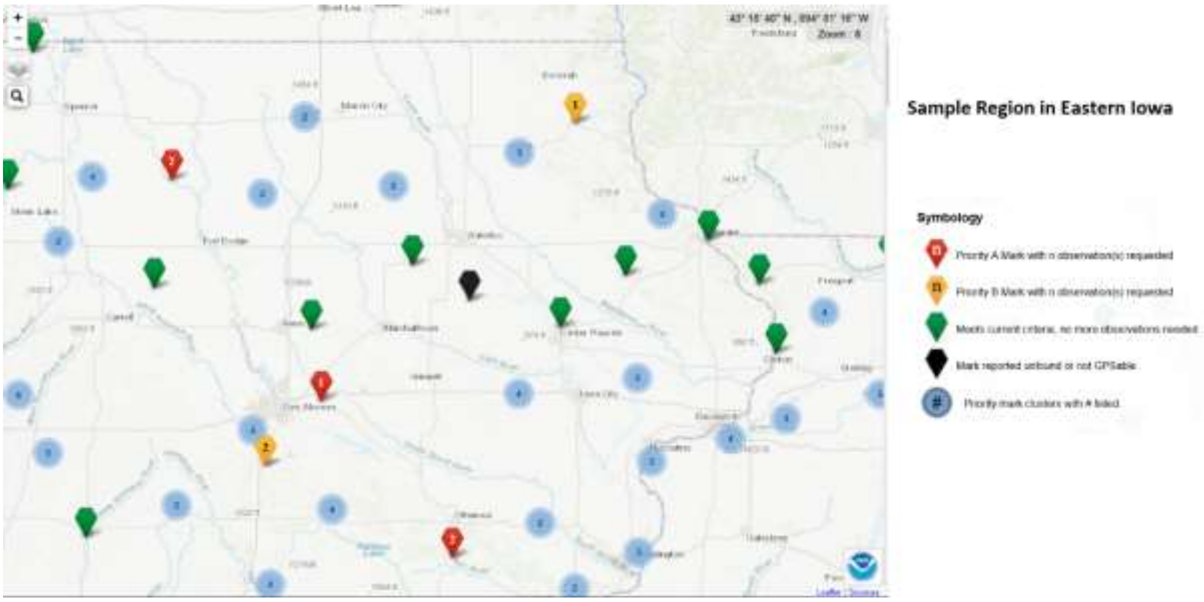

Figure 4 Sample plot showing regions to be targeted for collection. Green indicates marks collected, red is for those still uregently required, yellow is for those less required, and black is for an unrecoverable mark. The numbers indicate clusters of marks the preceeding.

3.2. Analysis

3.2.1. Goals of Analysis

There were over 35,000 GPSonBM's available to use. Many outliers were already flagged for removal. NGS' Regional Advisors, state geodetic coordinators, and other geodetic collaborators were asked to **flag marks that need to be changed from their current status** in the model. There were FOUR main flags to choose from:

1. Add PID's - Flag marks that are **not being used, but should be** used
2. Remove PID's - Flag marks **that are being used that should not be** used.
3. Use OPUS instead - Flag marks where **OPUS Share values should be used instead of and old/bad IDB ellipsoid height**
4. Add single OPUS - in rare cases when needed to fill data gaps

The result of this effort was to directly engage the local surveyors in the assessment of the data used in developing GEOID18. Many times, the local surveyors were more aware of the condition and quality of a mark that might make it a better or poorer choice for inclusion. This was critical in regions where many marks might be available and selection of the correct one for use was imperative.

3.2.2. Example

One example where this effort succeeded in deconflicting data on a bench mark (PID DH0371) is shown in Figure 5. Two observations already existed in OPUS Share. However, they differed by about 17 cm (262.909 m in 2017 vs. 262.737 m in 2011). The latter value was used in making GEOID12B (as it was the only one available then). But which to use in making GEOID18? By targeting this bench mark, a third collection determined a value close to the 2017 value (less than a centimeter). Hence, the corrected value was used and 17 cm difference evolved between the GEOID12B and GEOID18 (Beta) value for that area. Many other regions were similarly improved.

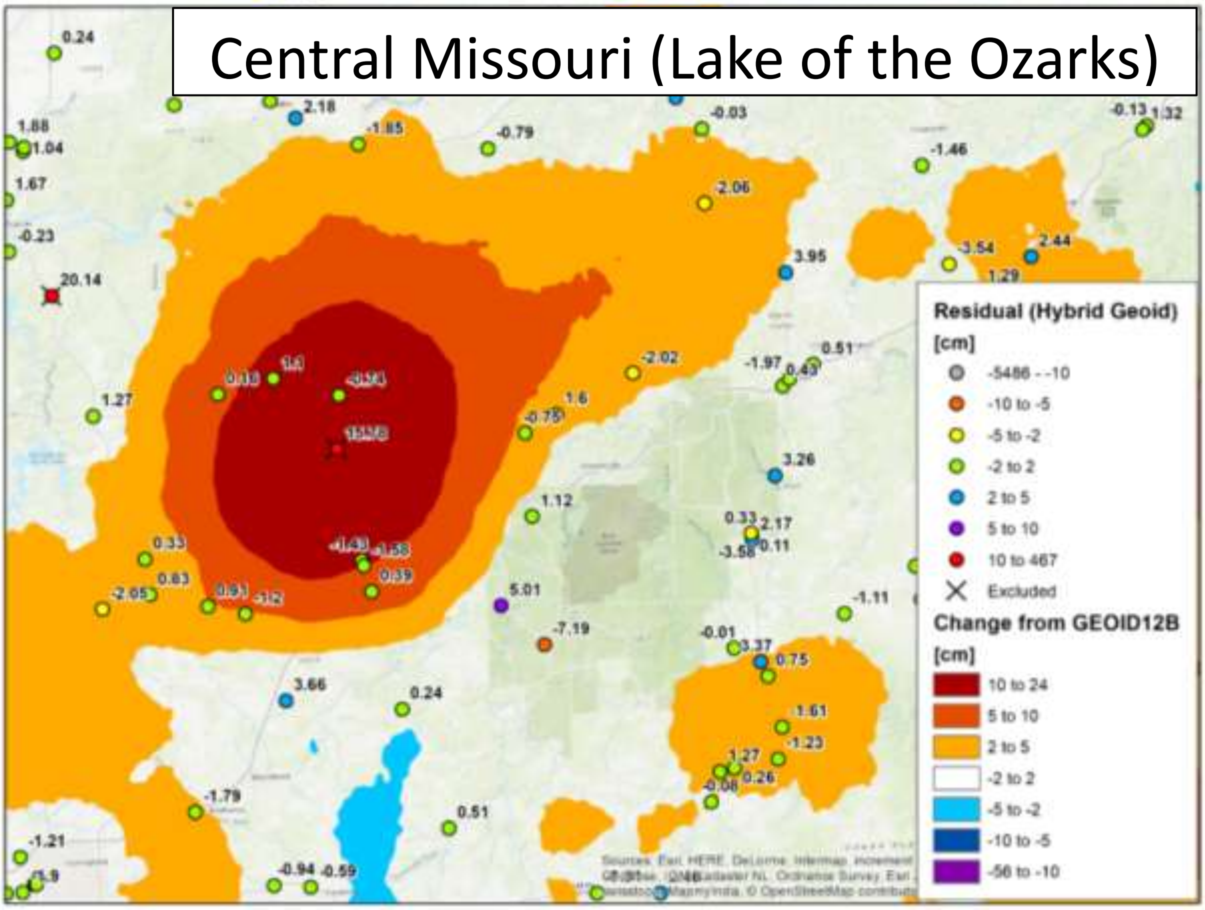

Figure 5 Example point where suspect control data (PID HD0371) was revisited. OPUS solution from 2011(ellipsoidal height = 232.737 m) disagreed with later OPUS solution from 2016 (ellipsoid height = 262.909 m). A third observation in 2018 as a part of the GPS on BM campaign (ellipsoid height = 262.915 m) was acceptably close to the second and confirmed that value.

What was key to this approach was enabling the use of OPUS Share to upload the observations and avoid the tedious (but accurate) process of submitting the data using Bluebook procedures normally mandated by the NGS.

4. GEOID18 (BETA)

Finally, a data set was available for use. The distribution was improved (Figure 6) where new data were added into regions that previously were gapped (green dots) or previously rejected data were corrected and incorporated (blue dots).

Figure 6 Control data (GPS on BM) used in making GEOID18 (Beta).

The tabular distribution of these data is given in Table 1. There were over 35,000 marks available but about 5% were rejected. Mostly, these data are drawn from the NGSIDB (i.e., are official values). However, over 2,000 were added from UPUS Share where two observations supported consistency (see the Example given in previous section). Additionally, some points were selectively added where only a single OPUS Share solution was available. While this is not desirable, having a gap in coverage was even less desirable.

Table 1 Control data (GPS on BM) assessed for making GEOID18 (Beta). Data were used from the NGSIDB and OPUS Share (grouped as either single observations or two or more). Changes in numbers since GEOID12B as well as the new data observed as a part of the GPS on BM Campaign. The data in the final column are shown in Figure 6.

GPS on BM	Available	Flagged as bad fit	Used in Model	Number since GEOID12B	Used since GEOID12B
NGS IDB:	30,128	1,987 (6.6%)	28,141	6,610	6,324
OPUS Share: 2+ Obs.	3,313	288 (8.7%)	3,025	3,009	2,748
OPUS Share: 1 Obs.	2,349	-	211	2,141	186
Canada	579	14	565	0	0
Mexico	247	41	206	0	0
Total:	**36,616**	**2,330**	**32,148**	**11,760**	**9,258**

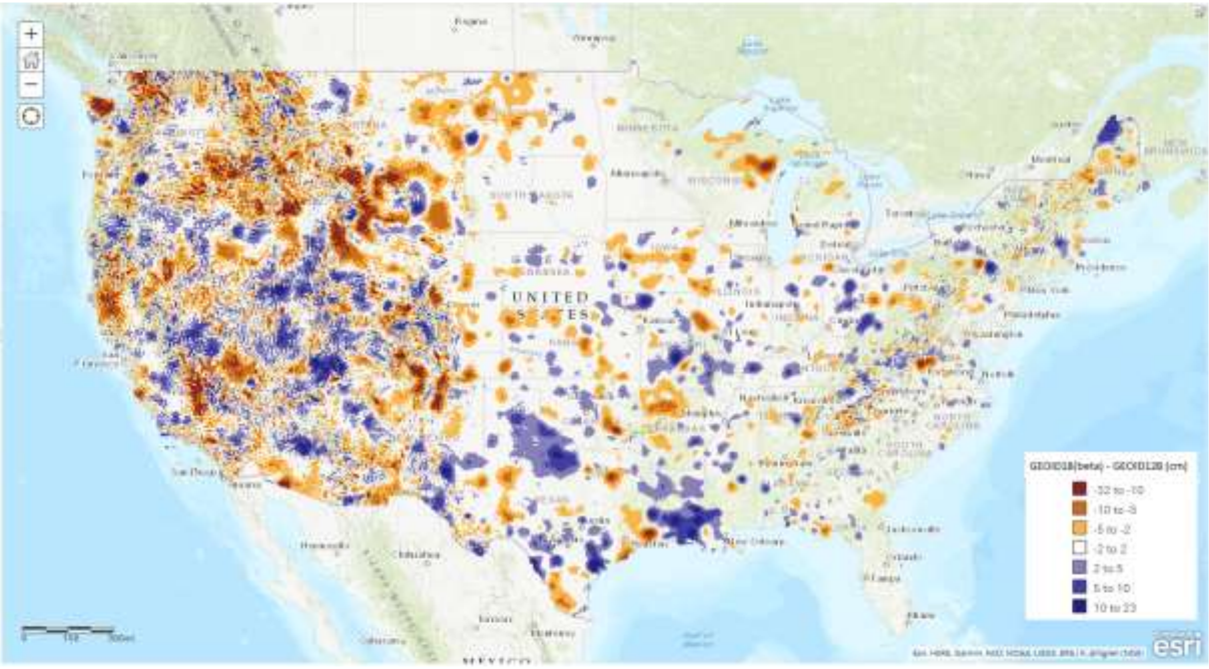

Figure 7 Differences between GEOID18 (Beta) and GEOID12B. New and updated control data (GPS on BM) can be seen in the globular differences. The effect of change in the in the underlying gravimetric geoid height models (xGEOID18 vs. USGG2012) are seen primarily in the mountainous areas (Rockies and Applachian Mountains).

Least squares collocation was used to generate a grid of the correlated signals between the residual values according to equation 2. The resulting grid was removed from GEOID12B and the resulting differences are highlighted in Figure 7. The globular differences highlight the expected change in the geoid height models largely driven by the change in the GPS on BM values. In the mountainous regions of the Rockies (western U.S.) and Appalachia (eastern U.S.), sharper features can be seen that reflect the change in the underlying gravimetric geoid height models. GEOID12B was built using the USGG2012 model, while GEOID18 was built using the xGEOID18 model. Note that geoid models beginning in an ‘x’ are all a series of gravimetric geoid models. So xGEODI18 is a gravimetric geoid height model built from the latest data and techniques, while GEOID18 is a hybrid geoid to be used in transforming from NAD 83 (2011) to NAVD 88.

5. SUMMARY AND OUTLOOK

As a result of the lessons learned in developing GEOID12B, a more thorough analysis was performed on the underlying control data (GPS-derived ellipsoid heights on leveled bench marks). This analysis determined where some of the GPS on BM data were suspect and where there were outright gaps in coverage. A concerted collection campaign was begun, where U.S Surveyors volunteered their time and effort to collect and upload their observations on these priority marks. In turn these data were used to develop a refined and improved hybrid geoid height model, GEOID18, that will serve as the final such model until the eventual release of the North American Geopotential Datum of 2022 (NAPDG 2022) that will replace it ash the defining vertical datum within the U.S. National Spatial Reference System.

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BIOGRAPHICAL NOTES

Daniel Roman graduated from the Ohio State University with a Master of Science in Geodetic Science and Surveying in 1993 and a Ph.D. in Geological Sciences (emphasis in geophysics/gravity & magnetism) in 1999. He then joined the National Geodetic Survey as a Research Geodesist, where he led geoid modeling efforts for over a decade and then served as Chief of Spatial Reference System Division for three years. He is now the Chief Geodesist for NGS and involved in developing and implementing the new National Spatial Reference System for 2022 and international collaboration.

Kevin Ahlgren graduated from the Ohio State University with a Ph.D. in Geodetic Science and Surveying in 2015. He is currently the technical lead for GEOID18 and the NGS Project Manager for the Geoid Monitoring Service project. He also is involved in numerous geoid related projects at NGS and is an active member of FIG Commission 5.

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