Geoid Modeling at NOAA's National Geodetic Survey as 2022 Approaches

Kevin M. AHLGREN, Simon A. HOLMES, Xiaopeng LI, Yan Ming WANG, Monica A. YOUNGMAN, United States

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SUMMARY

The National Oceanic and Atmospheric Administration's (NOAA) National Geodetic Survey (NGS) is currently undertaking a massive modernization of the United States' National Spatial Reference System (NSRS) in the form of new horizontal and vertical datums. This paper will focus on the geoid modeling efforts to support this new vertical datum.

This geoid model is defined to be a time dependent, spherical harmonic based model using gravity data from satellites, surface observations, and newly acquired airborne gravity data from the Gravity for the Redefinition of the American Vertical Datum (GRAV-D) project. In order to prepare for the new datums slated for 2022, the NGS produces an experimental geoid model annually.

A number of investigations have been undertaken to assess the quality of the geoid models that NGS is producing. Most important of these is a series of Geoid Slope Validation Surveys (GSVS). These linear field surveys collect ground truth data to compare with various models. In initial results, the geoid model accuracy was found to be 1 cm over wavelengths from 0.4 – 325 km. (Smith et al., 2013). In the second validation survey over more a more gravimetrically challenging area, the predicted geoid accuracy was between 1 – 3 cm (Wang, et al., in press). A final validation survey is currently being planned over mountainous terrain with field work to begin in May 2017.

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1. INTRODUCTION

The National Geodetic Survey (NGS) within the National Oceanic and Atmospheric Administration (NOAA) is in the midst of redefining and redeveloping the horizontal and vertical datums in the United States as part of the National Spatial Reference System (NSRS). These new datums are slated to be completed by 2022. In the following paper, the geoid modeling efforts at NGS will be highlighted in support of a new vertical geopotential datum, the North American-Pacific Geopotential Datum of 2022 (NAPGD2022).

The most significant component of the NAPGD2022 will be a time-dependent geoid model, GEOID2022. This geoid model will cover approximately 1/4 of the Earth from 0^o - 90^o N and 170^o - 350^o E. Additionally, it will cover the U.S. territories of American Samoa, Guam, and the Commonwealth of the Northern Mariana Islands. This model will support the primary method for a user to access the NSRS using a GNSS observed ellipsoid height (h) and a modelled geoid height (N) to determine one's orthometric height (H):

$$H = h - N \tag{1}$$

This is a considerable change from previous vertical datums, which were predominantly accessed through spirit leveling. As a result, the NGS typically produced both a hybrid and gravimetric geoid model to support the NSRS. The hybrid model was consistent with the biased vertical datum and had high relative accuracy. The gravimetric model had a high global accuracy but wasn't necessarily consistent with the long-wavelength biases in the vertical datum. A summary of the NGS historical geoid models will be presented in Section 2.

As the NGS prepares for the new datums, the geoid modeling methodology and research is continually evolving. The primary product of this extensive work is an experimental geoid model series that is released on an annual basis. These models utilize satellite, airborne, and terrestrial gravity datasets, but the primary new information is in the form of airborne gravity collected by the NGS as part of the Gravity for the Redefinition of the American Vertical Datum (GRAV-D) project. The current state of geoid modeling at NGS will be presented in Section 3.

In Section 4, the results of a number of investigations, validations, and surveys that have been undertaken over the past few years to assess the level of accuracy and quality that the geoid model is able to achieve will be presented. NGS has undertaken a series of three geoid validation surveys where high accuracy field observations are collected using numerous geodetic observing techniques. The results of these validations show the persistent improvement taking place but also the areas where further improvement is needed. In Section 5, the geoid efforts will be extrapolated into the future in anticipation of 2022 and afterwards.

2. HISTORICAL GEOID MODELS

Due to the popularity in using GPS/GNSS for vertical coordinate determination, the NGS has been producing geoid models for use in North America since the early 1990's in various varieties (Smith and Milbert, 1999; Roman, et al., 2004; Wang, et al., 2012). Numerous model iterations have been constructed for the conterminous United States (CONUS), Alaska, Hawaii, Puerto Rico, the U.S. Virgin Islands, Guam and the Commonwealth of the Northern Mariana Islands, and American Samoa (see Table 1).

	Geoid Models	CONUS	Alaska	Hawaii	Puerto Rico/ U.S. Virgin Islands	Guam / Northern Mariana Islands	American Samoa
Gravimetric Models	USGG2012	X	X	X	X	X	X
	USGG2009	X	X	X	X	X	X
	USGG2003	X	X				
	GEOID93	X		X	X		
	GEOID90	X			X		
Hybrid Models	GEOID12B	X	X		X	X	X
	GEOID09	X	X		X	X	X
	GEOID03	X					
	GEOID99	X					
	GEOID96	X					

Table 1: Selected NGS Geoid Models (see https://www.ngs.noaa.gov/GEOID/ for a complete list of NGS geoid models)

The NGS geoid models have typically been one of two varieties: a gravimetric geoid or a 'hybrid' geoid. The gravimetric geoid models utilize information about the gravitational field of the Earth by incorporating terrestrial, shiptrack, airborne, and satellite gravity observations; however, these models are not mutually consistent with the official U.S. vertical datum, the North American Vertical Datum 1988 (NAVD88). Alternatively, the various hybrid geoid models are consistent with NAVD88 and utilize an underlying gravimetric model, orthometric heights from spirit leveling, and geometric (ellipsoid) heights obtained with GPS/GNSS. At official benchmarks that have both an orthometric and a geometric height, the hybrid models are 'warped' to be consistent with these two heights. In areas completely void of official benchmarks or in between benchmarks, the underlying gravimetric model determines the geoid undulation. A prime example of this is for the state of Hawaii, which does not utilize an official vertical datum. The hybrid geoid here simply reproduces the gravimetric model.

3. EXPERIMENTAL GEOID MODEL SERIES (XGEOID)

3.1 Fundamentals

The Experimental Geoid Model Series (xGEOID) are a series of gravimetric geoid models that are produced by NGS on an annual basis using the most relevant gravity data available. The xGEOID models have been produced since 2014 and are meant to exhibit continual improvement in terms of quality and accuracy in anticipation of using knowledge and experience gained for the initial static GEOID2022 geoid model. The xGEOID models cover an area from 5°-85° N and 170°-350° E, use 1' x 1' spacings, and are determined through classical remove-compute-restore techniques (Wang et al., 2012). These models are based on a geopotential surface with W_0 = 62,636,856.00 m^2/s^2 representing the mean geopotential surface based on hundreds of tide gauges in the U.S. and Canada (Roman and Weston, 2012).

The geoid undulation (N) can be found from Stokes' integral (2) where a number of different techniques can be utilized to calculate the various elements (Heiskanen and Moritz, 1967).

$$N = N_{Ref} + \frac{R}{4\pi\gamma} \iint_{\sigma} \Delta g * S(\psi)\, d\sigma \tag{2}$$

where: N_{Ref} is computed from a reference model, R is the mean Earth radius, γ is the normal gravity on a reference ellipsoid, σ is a spherical cap of integration, and $S(\psi)$ is Stokes' function with central angle (ψ) between the evaluation point and the integration point. In the most recent xGEOID models, the gravity anomaly is determined from (3) (Wang et al., 2012):

$$\Delta g = \Delta g_{FA} - \Delta g_{Ref} - \Delta g_{RTM} \tag{3}$$

where all quantities are determined on the Earth's surface and Δg_{FA} is the surface free-air anomaly, Δg_{Ref} is the free-air anomaly synthesised from EGM2008, and Δg_{RTM} is the gravity anomaly associated with a residual terrain model (RTM) (Forsberg, 1984).

Ultimately, the various xGEOID models come in the form of a set of spherical harmonic coefficients to degree 2190. The annual xGEOID model actually consists of two separate models: an A model and a B model. The xGEOIDA and xGEOIDB models are identical except that the xGEOIDB models contain airborne gravity data from the GRAV-D project while the xGEOIDA models do not. This allows for a comparison to be readily available between the two models to provide an assessment of the contribution in the geoid models directly attributed to the GRAV-D airborne gravity data.

3.2 Data

3.2.1 Elevation Data

The supporting digital elevation model (DEM) dataset performs a number of critical tasks in the geoid model construction including calculating anomalies, modeling the ultra-high frequency components of the gravity field, residual terrain effect, etc. For the xGEOID models, the NGS utilizes a 3" combined DEM dataset that fills in gaps, cleans up errors, and provides consistency (Li, et al., 2008). This data is a combination of data from a number of sources including 3" SRTM data below 64° (Farr, et al., 2007) and the United States Geological Survey's National Elevation Dataset (NED) (Gesch, et al., 2009) above 64°.

3.2.2 Surface Gravity Data

The NGS has an extensive database of approximately 2.5 million gravity measurements throughout North America. However, this data has various levels of accuracy as it has been conglomerated from thousands of sources over the past 70 years with much of the underlying information related to the observations, adjustments, and corrections having been lost (Saleh, et al., 2013). Approximately 1 million gravity measurements are from shipborne surveys, which have notoriously large biases and tilts along the tracks (Wessel and Watts, 1988). Over the oceans, this data is augmented with altimetry derived gravity anomalies from DTU10 (Andersen, 2010).

The vast majority of the surface gravity data is of high accuracy; however, individual surveys are prone to large biases compared to surrounding surveys, inaccurate gravity/positional values, and incomplete or lost metadata. A number of methods are used to determine these observations, fix them, and/or remove the points, but that is a difficult endeavor to achieve with any level of certainty. Some of the methods that are used to clean this dataset involve using K-nearest neighbors, internal and external survey crossover errors, and various reference model residuals to determine gravity errors at all wavelengths. However, it is clear that bad data can only be massaged so much in the hopes of producing a 1-cm geoid model; consequently, highly accurate gravity data was needed leading to the launch of the GRAV-D project to collect it.

3.2.3 Gravity for the Redefinition of the American Vertical Datum (GRAV-D)

GRAV-D was started by the NGS in 2007 to collect high-accuracy airborne gravity over the entire U.S. and its territories. Its primary goal is to support the construction of a 1-cm accurate geoid model. GRAV-D surveys are typically flown at an altitude of approximately 6000 m with 10 km line spacing. This configuration provides a minimum resolution of 20 km (GRAV-D Team, 2013).

As of January 2017, GRAV-D has completed 58% of the total targeted area, which is 15.6 million square kilometers covering the U.S. and its territories. Surveying will be complete in 2022 for the roll out of the new vertical datums. Figure 1 shows the current status of the project with publically released surveys, surveys currently being processed, and surveys that have been partially completed. Released data, which includes gravity data, metadata, and user manuals describing the collection and processing, can be found on the NGS website: (https://www.ngs.noaa.gov/GRAV-D/data_products.shtml).

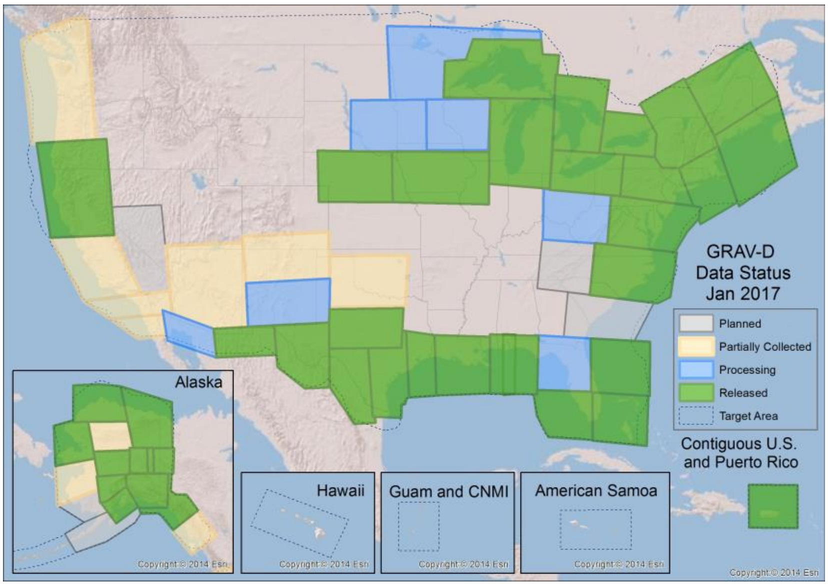

Figure 1: GRAV-D Project Status

3.2.4 Satellite Gravity/Reference Data

A reference model is used to accurately reflect the long wavelength components of the gravity field. This reference model is based on EGM2008 (Pavlis, et al., 2012) and a satellite gravity model. In the most recent xGEOID16 models, the GOCO05S (Mayer-Gurr, et al., 2015) satellite gravity model based on data from the GOCE satellite mission was selected. Various satellite models have been used in previous models and will continue to evolve in the future.

3.3 Construction Methodology

The blending of these various short, medium, and long wavelength datasets is one significant area of ongoing research at the NGS. In the most recent xGEOID16 models, the xGEOID16A reference model is constructed by combining EGM2008 and GOCO05S over a very local geographic area followed by a spectral combination (Wang, et al., in press). Additionally, the xGEOID16B reference model spectrally incorporates the GRAV-D airborne data, which acts as a replacement of EGM2008 where GRAV-D data is present. Fortuitously, the reference model will replicate EGM2008 where GRAV-D is absent, globally. The high resolution (1' x 1') NGS surface gravity and RTM information are then incorporated in a remove-restore fashion (see Section 2). The actual combination of the various gravimetric datasets relies on appropriately determining spectral weights for each of the datasets at corresponding degrees. An example of the spectral weighting scheme that has been used in previous models is shown in Figure 2 from Wang, et al., in press.

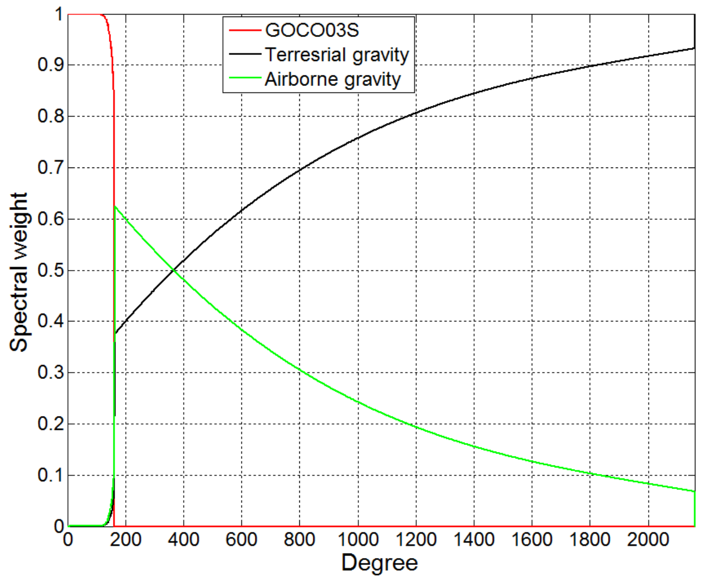

Figure 2: Spectral Weighting Example by degree (used in xGEOD15)

3.4 Geoid Slope Validation Surveys (GSVS)

Due to the difficulty in assessing the quality of a geoid model, three Geoid Slope Validation Surveys were designed to take place in areas with smooth, moderate, and rugged gravity fields, respectively. Instead of evaluating 'absolute' geoid heights, these validation surveys concentrate on the 'internal' differential accuracy between geoid heights or the geoid slope. The first of these surveys, GSVS11, took place in southern Texas and confirmed that 1-cm geoid accuracy was achievable in ideal gravimetric conditions (Smith, et al., 2013). The second survey, GSVS14, took place over central Iowa where there is limited topographic variation but strong gravity variation due to a failed geologic rifting event known as the Mid-Continental Rift. GSVS14 produced geoid accuracies between 1 – 3 cm (Wang, et al., in press). The third survey will be completed in the summer of 2017 across central Colorado. This traverse across the Rocky Mountains will provide insight into the geoid model's accuracy in the worst-case scenario.

The GSVS data collection and methodology is of the highest accuracy achievable. A number of different surveying techniques are utilized to assess the geoid model quality through external and independent observations including GNSS static and RTN positioning, First-Order Class II spirit leveling, absolute and relative gravimetry, and astronomic observations to determine deflections of the vertical. The data from these surveys is publicly available on the NGS website for other forms of geodetic validation and research.

Since these surveys evaluate the differential accuracy, the NGS compares observed slopes from the terrestrial surveys to modeled slopes from the gravimetric and satellite models between any two points, i and j, as shown in (4) (for completeness see Smith, et al., 2013):

$$\Delta N = N_i - N_j = \Delta h - \Delta H = (h_i - H_i) - \left(h_j - H_j\right) \quad (4)$$

The entire set of two point combinations is then sorted into similar distances for analysis, which reflects the geoid slope accuracy over different wavelengths or distances. Since error estimates can be determined for the ellipsoid heights and orthometric heights, the geoid-only accuracy can be isolated and analyzed.

4. RESULTS

4.1 GRAV-D Airborne Gravity

The inclusion of GRAV-D airborne gravity in the xGEOIDB models is key to assess contributions to the NGS geoid models. Figure 3 - Figure ***5*** show the contribution in the geoid surface due to GRAV-D in the current xGEOID16 models. The areas that experience the most change are typically those where the terrestrial gravity is not present or is in error. This is extremely evident over Lake Michigan in Figure 3 where several ship-track surveys were found to have large biases that disagreed with the airborne data (Li, et al., 2016). Over Alaska (Figure 4), there are very limited amounts of surface gravity measurements due to a variety of factors. The GRAV-D data clearly carries a significant amount of influence here and is reflected in decimeter level changes in the geoid surface over large portions of Alaska. Another area where the airborne data significantly changes the geoid model is in littoral areas where there is a gap between the shipborne and ground data. Figure 5 along the Gulf of Mexico clearly shows this contribution from the GRAV-D data.

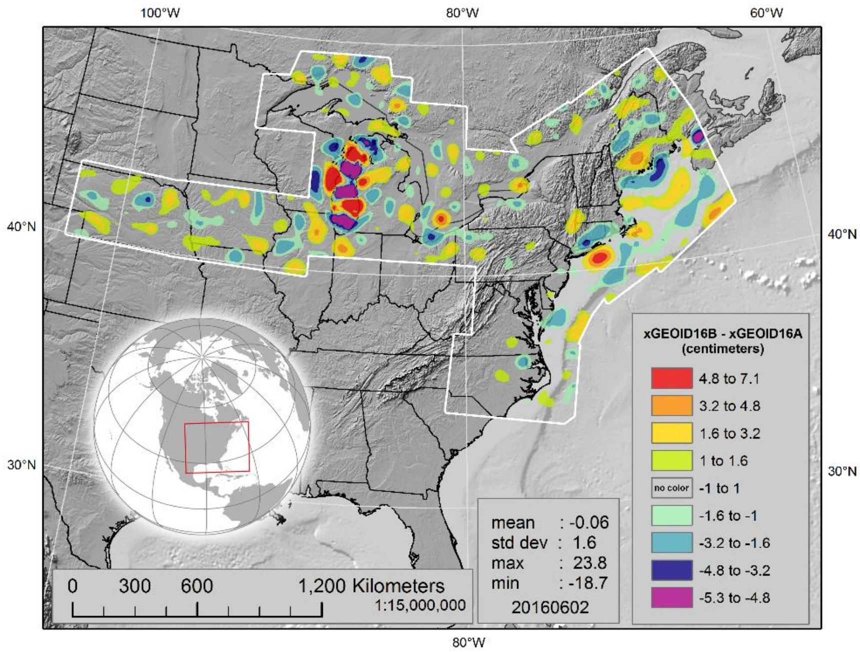

Figure 3: GRAV-D Contribution over Northeast CONUS. The contribution from GRAV-D airborne gravity data inclusion as represented by comparing the xGEOID16B and xGEOID16A model difference. Boxed areas are where GRAV-D information was available for the comparison. Additional maps and figures available on the NGS GEOID website: https://beta.ngs.noaa.gov/GEOID/xGEOID16/xGEOID16_technical_details.shtml#ref

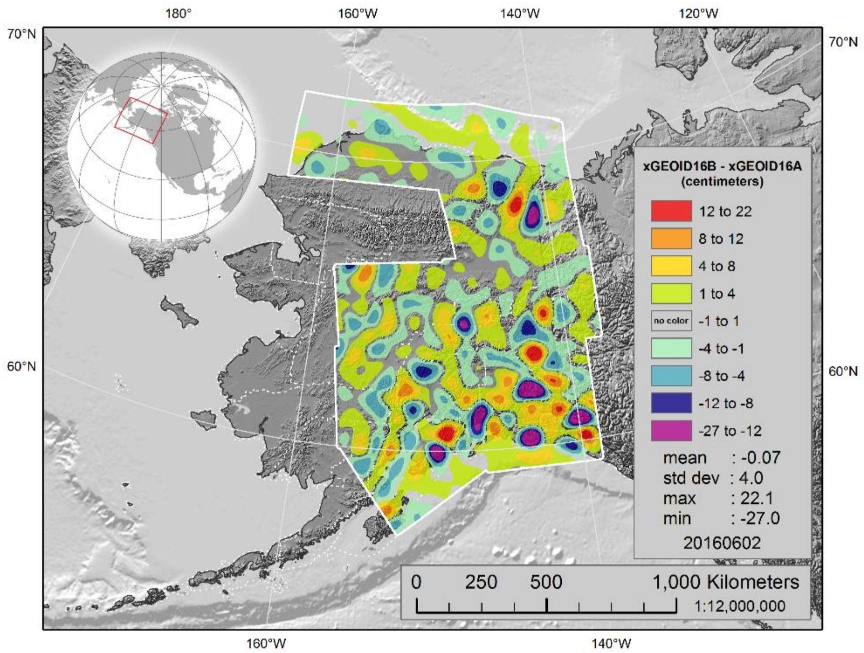

Figure 4: GRAV-D Contribution over Alaska. The majority of Alaska is completely void of surface gravity observations causing differences between the xGEOID16B and xGEOID16A model to reach 20+ cm.

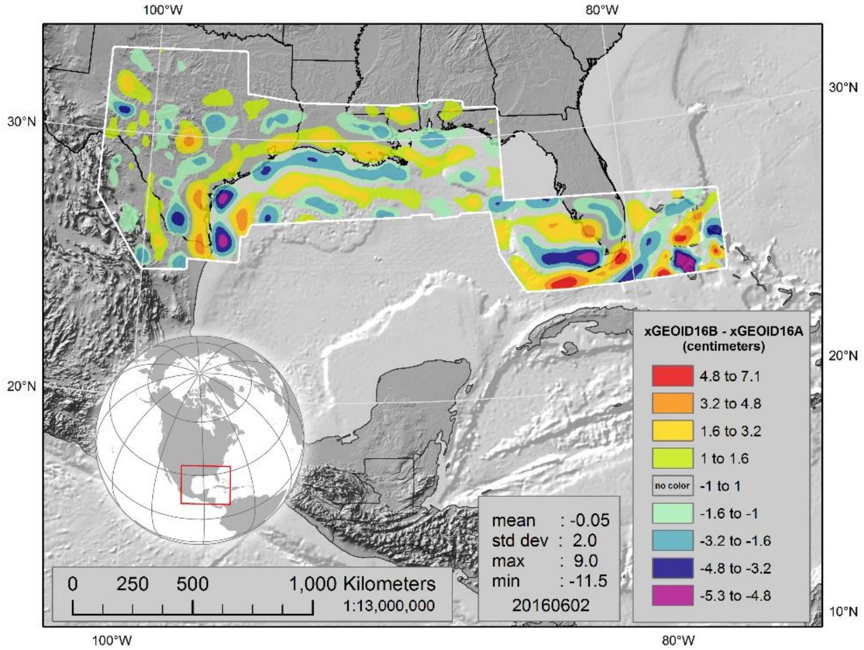

Figure 5: GRAV-D Contribution over the Gulf Coast

4.2 GSVS11

The first geoid slope validation survey to assess the accuracy of geoid modeling at the NGS took place over a low and flat region in Texas. A total of 218 points were observed along a 325 km traverse (see Figure 6).

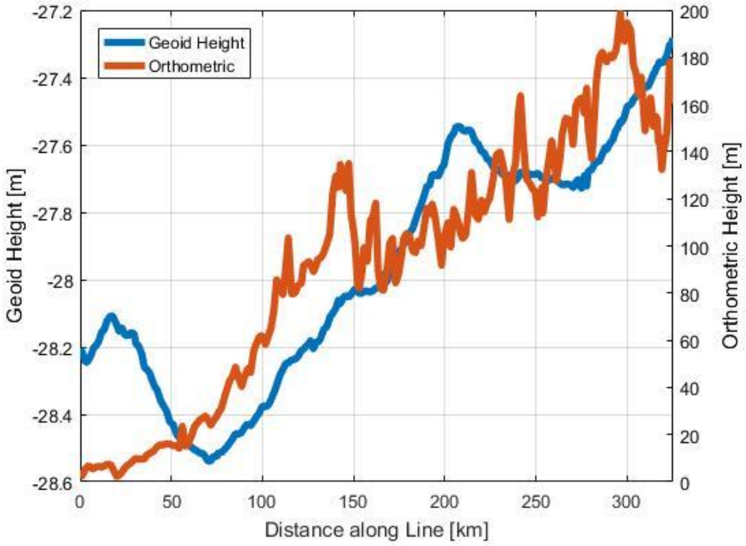

Figure 6: GSVS11 Profile from South-North

One of the key results of this validation was the improvement in the NGS geoid models over all wavelengths by including GRAV-D airborne gravity data (Smith, et al., 2013). The inclusion of the airborne data lowered the differential geoid-only error from ~3 cm to ~1 cm as shown in Figure 7 (Figure 14 from ibid). The xEGM-GA and the xUSGG2011 are the two models that include the GRAV-D data and experience drastic improvements compared with the other models.

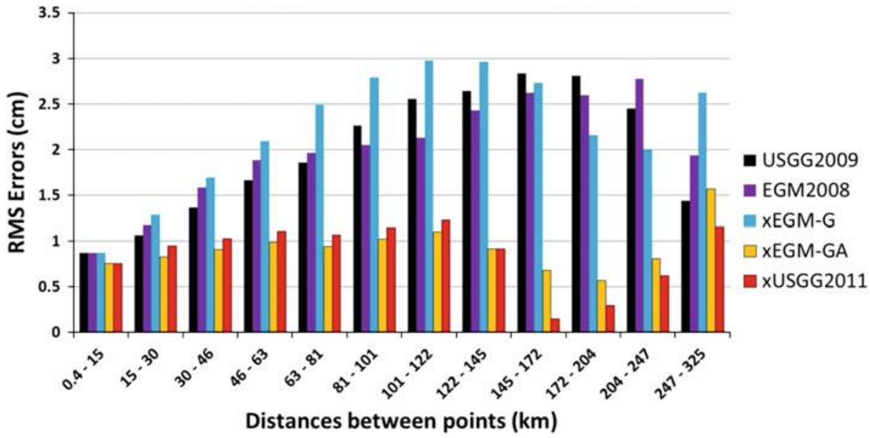

Figure 7: GSVS11 Geoid-Only Predicted Errors (from Smith, et al., 2013)

Additionally, another investigation looked into the various spectral weighting combinations of the gravimetric data and found that the gravimetric geoid agreement with GPS/L data was lowered from ±1.1 cm to ±0.8 cm (standard deviation) by including GRAV-D airborne data (Jiang and Wang, 2016).

4.3 GSVS14

The results from the GSVS14 survey did not duplicate the extremely high level of accuracy as the earlier GSVS11 survey. This is not completely unexpected as the gravity signal and geoid over this region is considerably more variable due to local geological effects (see Figure 8). A total of 204 points were observed over a 306 km line.

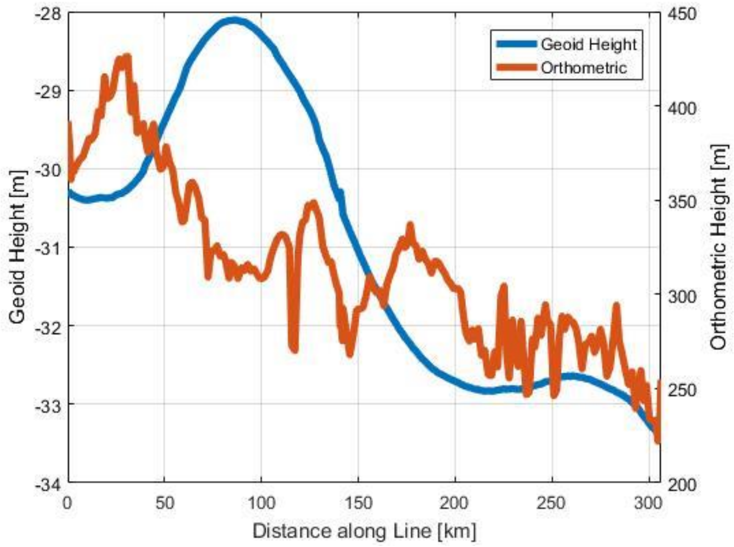

Figure 8: GSVS14 Profile from West-East

Using a similar comparison as performed in GSVS11 over all inter-station distances, the geoid-only accuracy shows only a minimal improvement by including GRAV-D data as shown in Figure 9 (from Wang et al., in press). Except for the EGM2008 model, the other models have accuracies at the 1-3 cm level over all wavelengths, which is still a considerable achievement but not completely at the desired 1-cm level.

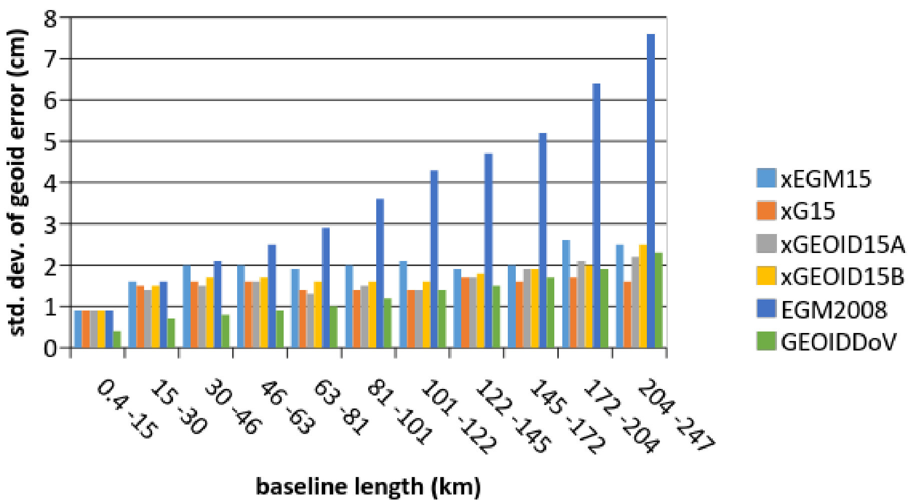

Figure 9: GSVS14 Geoid-Only Predicted Errors (from Wang, et al., in press).

The various geoid models that were evaluated along the GSVS14 line are shown in Figure 10 with respect to the ground truth data from GPS/Leveling. Their general shape is very similar to one another with a noticeable slope in the western ~50 km. Since this slope is present in both the NGS models and external models (like EGM2008), it would seem that the likely cause is one of the common input datasets – the surface gravity data or the terrain data. Further investigation into the cause of this slope is ongoing in order to fix and avoid any future problems.

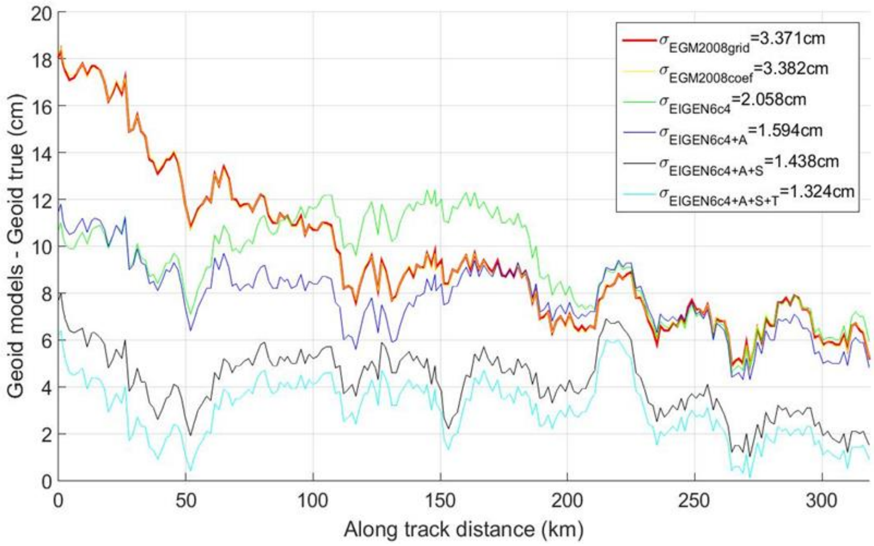

Figure 10: Geoid Model Comparisons along GSVS14 from West-East (from Li, 2016)

If this western 50 km portion of the validation line is removed from the model comparison, the geoid accuracy has a noticeable improvement. Figure 11 illustrates the geoid-only predicted errors for all possible inter-station distances without including stations from the western 50 km. In this case, the predicted errors are typically below 2 cm. Additionally, the xEGM15 and xG15 models, which include GRAV-D data, have errors that are approximately 1 cm over all baseline distances. These two models use slightly different spectral weighting schemes than the other models along with the GOCO03s satellite model. The xGEOID15B model also exhibits a noticeable improvement from xGEOID15A showing the GRAV-D only contribution as these two models are identical apart from airborne data. The xGEOID15B model has predicted errors at approximately 1.5 cm over all distances.

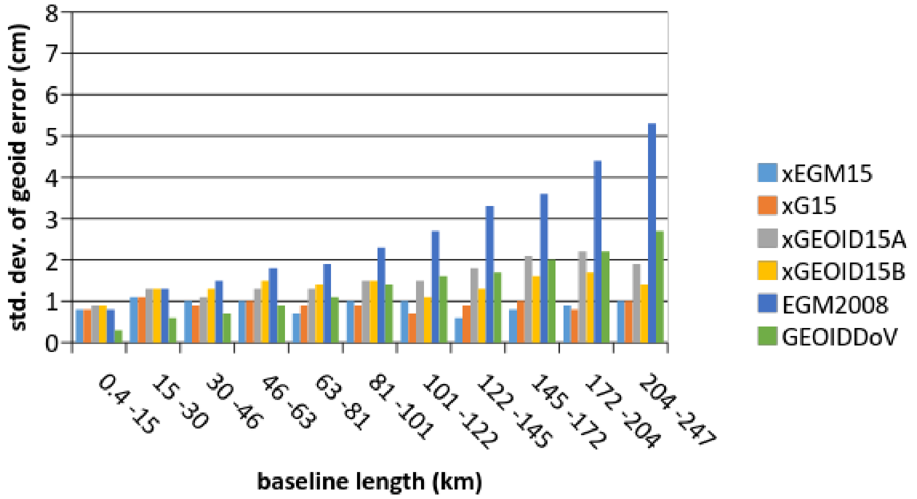

Figure 11: GSVS14 Geoid-Only Predicted Errors without the western 50 km of the survey (from Wang, et al., in press).

5. FUTURE OUTLOOK

Prior to 2022, a variety of significant work and validation in improving the quality, accuracy, and resolution of the NGS geoid models will take place. Most of these efforts will take place continually until 2022 but some major single events also will occur. In the immediate future, the third GSVS traverse in the Rocky Mountains of Colorado will take place. This survey will be similar in methodology to the previous GSVS lines but will provide model validation in some of the most challenging areas within the U.S. and its territories for geoid modeling due to the rugged terrain.

Additionally, airborne gravity flights will continue to cover the non-surveyed areas of the United States. These surveys provide much of the new information that is ingested into the gravimetric geoid models. The xGEOID series will continue to develop a geoid model on an annual basis with the latest iteration scheduled to be completed and released to the public around 1 July 2017. The quality of these geoid models is of the highest priority, and a number of potential improvements will be investigated including further refinement in the terrestrial gravity data editing, error estimation, spectral weighting scheme, combination methodology, etc.

The NGS geoid models will also benefit from a number of international geoid model improvements. An updated global geopotential model (GGM) from NGA is expected around 2020, which will likely contain a number of improvements and enhance the reference field that goes into the NGS geoid model. Additionally, the various satellite gravity models are continuing to be refined and improved as GOCE data is further analyzed and additional data from GRACE is obtained. The GRACE Follow-On mission is planned for launch in early 2018, which will provide continuity for the GRACE derived reference models.

As the NAPGD2022 geopotential datum will not correspond to the current NAVD88 vertical datum, some type of product will need to be created in order to provide a method of obtaining NAVD88 elevations. This might be in the form of a final hybrid geoid model (similar in structure to GEOID12B) or through a transformation surface that links NAPGD2022 with NAVD88 at a defined time epoch.

Looking beyond 2022, the NGS is developing details on the second goal of the GRAV-D project, which relates to a time-dependent geoid model. The actual product from this portion of the project will not be completed prior to 2022, however, a Geoid Monitoring Service (GeMS) and its function are being investigated and developed over the next few years so that a roadmap for time-dependent geoid models is in place beyond 2022.

6. SUMMARY

In anticipation of a new geopotential, spherical harmonic based vertical datum titled NAPGD2022, the National Geodetic Survey has been continually testing, researching, and improving its regional geoid models. An experimental geoid series is released on an annual basis consisting of two slightly different models. The major difference in the two models is in the incorporation of newly acquired airborne gravity from the GRAV-D project. This project is a huge undertaking by the NGS to fly and measure gravity across the entire United States and its territories. The incorporation of the airborne data into the geoid models has provided a number of benefits. Primarily, the accuracy of the geoid model does improve. Additionally, the airborne data is able to remedy geographic areas void of surface gravity observations or where the surface data is in error. While the airborne project is almost 60% complete, the geoid models still have further fine-tuning that can be achieved to improve their overall quality and accuracy.

Results from two completed Geoid Slope Validation Surveys have shown that over flat terrain close to sea-level a geoid accuracy at approximately 1 cm over all wavelengths is achievable. However, the second validation survey, which took place in an area with a larger gravimetric signal, produced estimated geoid accuracies at the 1 – 3 cm level. A third validation survey in mountainous terrain will take place from May – September 2017 providing further evidence of the practically achievable geoid accuracy.

Prior to the launch of the official GEOID2022 model and NAPGD2022 vertical datum, a number of experimental geoid model will be released and evaluated. Improvements to the reference model from satellite models, a future EGM model, and other sources of new data will continue to improve the NGS regional models, but there are also a number of areas for improvement within the NGS models. The surface gravity errors, airborne gravity processing, spectral weighting scheme, etc. can all be further refined to achieve a 1 - 2 cm accurate geoid for all of the U.S. and its territories.

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BIOGRAPHICAL INFORMATION

The authors make up the National Geodetic Survey's Geoid Team, which is responsible for regional geoid modeling and analysis.

CONTACTS

Dr. Kevin M. Ahlgren
NOAA's National Geodetic Survey
1315 East-West Highway
Silver Spring, MD
UNITED STATES
Tel. +1 240 533 9894
Fax +1 301 713 4327
Email: kevin.ahlgren@noaa.gov
Web site: https://www.ngs.noaa.gov/GEOID/