Towards a More Consistent Geoid Model for North America

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Key words: geoid, reference frames, geopotential datum, gravity, DEM

Vertical Reference Frames

SUMMARY

In support of a new vertical datum in 2022, the National Oceanic and Atmospheric Administration's (NOAA) National Geodetic Survey (NGS) is continually improving, updating, acquiring, and sharing our datasets used in geoid modeling applications. One of the foundations of the North American-Pacific Geopotential Vertical Datum 2022 (NAPGD2022) is a static geoid model (GEOID2022). This geoid model will be produced through a collaborative effort between colleagues across North America including the Canadian Geodetic Survey (CGS), Mexico's Instituto Nacional de Estadística y Geografía (INEGI), and NGS. Towards this effort, a number of common datasets are required in order to produce such a model including terrestrial gravity data, shiptrack gravity data, altimetric gravity data, digital elevation models, etc. Additionally, various data sharing and collaborations between NGS and the National Geospatial-Intelligence Agency (NGA) have recently been initiated in support of both the NGA's Earth Gravitational Model 2020 (EGM2020) and NAPGD2022. NGS has received extensive surface gravity data from NGA, and NGS will provide NGA with processed GRAV-D airborne gravity data.

The goal of these international collaborations and data sharing is a more consistent geoid model across North America. Improvements in NGS' experimental geoid models (xGEOID) are already evident as a result of these collaborations. The xGEOID17 model relied on the previously mentioned surface gravity dataset from NGA and shows considerable improvement in a number of areas from previous xGEOID models. This paper will highlight the collaborative efforts that have been initiated with the goal of producing a more consistent and accurate geoid model for North America.

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1. INTRODUCTION

The National Oceanic and Atmospheric Administration's (NOAA) National Geodetic Survey (NGS) is in the process of modernizing the United States' National Spatial Reference System (NSRS) to better 'meet our nation's economic, social, and environmental needs'. One component of this modernization, which will be highlighted in the paper, is the North American-Pacific Geopotential Datum of 2022 (NAPGD2022). This datum will define and include the various quantities related to the Earth's geopotential. While orthometric heights are the most popular product, it is currently possible to include a number of additional quantities that are derived and related to the Earth's geopotential field within NAPGD2022. In this way, NGS provides consistency between the various geopotential quantities.

This paper will highlight two collaborative initiatives undertaken by NGS with different partner agencies and countries both within the United States and across North America. The first portion of this paper describes efforts to provide a solid foundational reference model for NAPGD2022 and highlights data sharing between NGS and NGA to support the EGM2020 reference model. The second component of this paper looks at how best to provide a consistent geopotential datum for all of North America. This necessitates the cooperation and collaboration of NGS along with other partners in North America including the Canadian Geodetic Survey (CGS) and Mexico's Instituto Nacional de Estadística y Geografía (INEGI).

2. BACKGROUND

The NSRS modernization includes both geometric and geopotential components with NAPGD2022 representing the geopotential datum. One of the major components of NAPGD2022 will be to define the vertical reference surface for orthometric heights. This will be accessed through a user's ellipsoid height obtained through GNSS and a gravimetric geoid model (GEOID2022). This will replace NGS' current vertical datum, North American Vertical Datum 88 (NAVD 88). NAPGD2022 is much more than just a vertical height datum though. Additional quantities will also be defined as part of NAPGD2022 like geopotential numbers, deflections of the vertical, surface gravity, a digital elevation model, and a spherical harmonic model of the Earth's gravitational potential (see NGS, 2017 for additional details about NAPGD2022).

NAPGD2022 is a regional model that will cover the geographic areas shown in Figure 1– Figure 3. The geopotential quantities relevant to this paper, which includes the geoid model and the DEM, will have spatial resolutions of 1 arc-minute and 3 arc-seconds at a minimum, respectively.

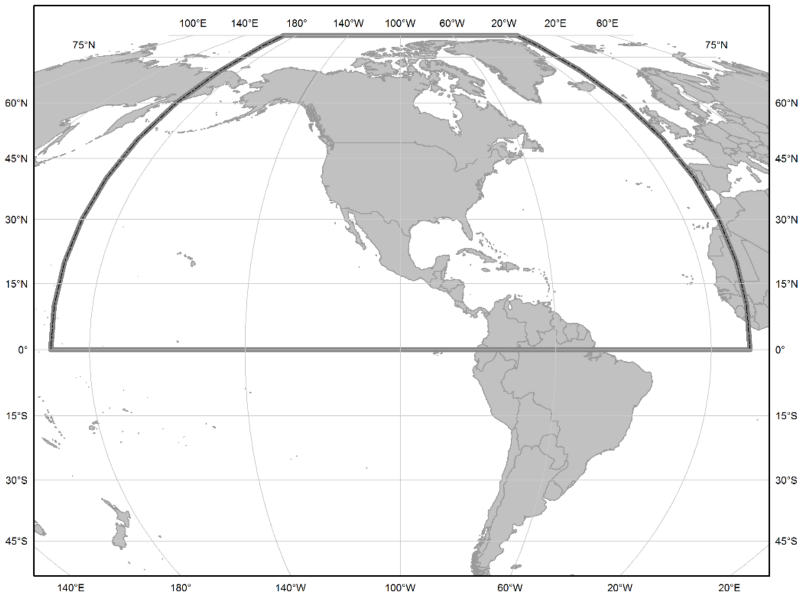

Figure 1: NAPGD2022 Coverage

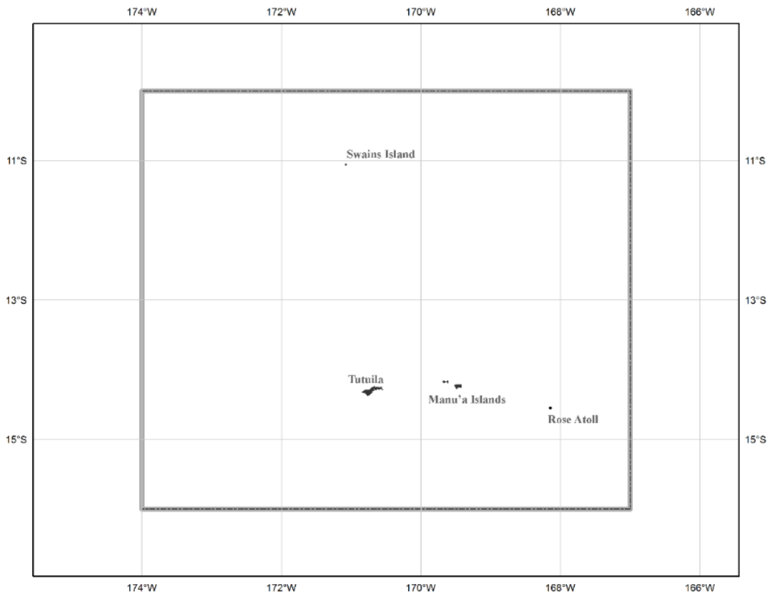

Figure 2: NAPGD2022 Coverage over American Samoa

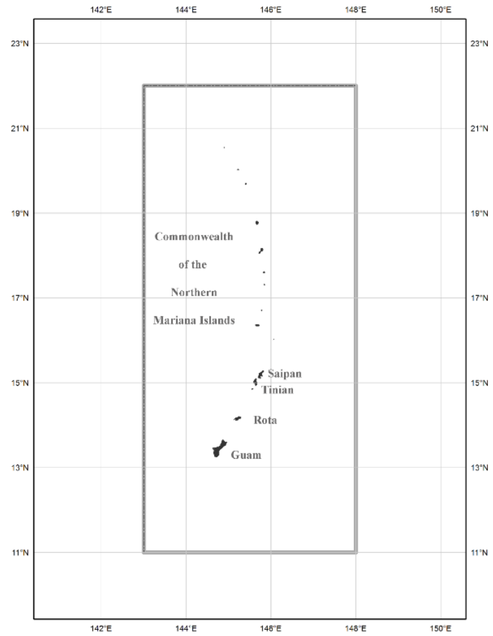

Figure 3: NAPGD2022 Coverage over Commonweath of the Northern Mariana Islands and Guam

3. DATA SHARING BETWEEN NGS AND NGA

3.1 NGA Surface Gravity Data

NGA produces one of the geodetic community's premier global geopotential models in EGM2008 (Pavlis, et al. 2010). Their models are typically the measuring stick against which others compare their global, regional, and local models. EGM2008 and the upcoming EGM2020 have both been state-of-the art models for use in geoid modeling and other applications. While both of these models (EGM2008 and EGM2020) have been to degree and order 2159 implying a spatial resolution of 5', a significant amount of omission error is still present that local and regional geoid modeling must fill. The signal from 5' to 3" (and possibly further) is of particular interest to NGS for inclusion in NAPGD2022. Thus, the reference model and the high frequency content used to augment the reference model must be as consistent as possible. In order to achieve this, NGS has requested and received surface gravity data from NGA where permissible. In some geographic areas, there is not significant amounts of new NGA data compared with NGS' original holdings. However, other areas greatly benefit by adding the NGA data. Figure 4 illustrates those geographic areas in CONUS where individual surface gravity data are present in only one dataset (and not the other), either the NGA dataset or in the NGS dataset. There is another 1.2 million points present in both of the datasets. These duplicated points often have minor corrections or edits that have been made to either the elevation or gravity value. Figure 5 shows the difference in the (gridded) free-air anomaly when the NGA and NGS gravity datasets are compared at duplicated points (i.e. with the same latitude and longitude coordinates).

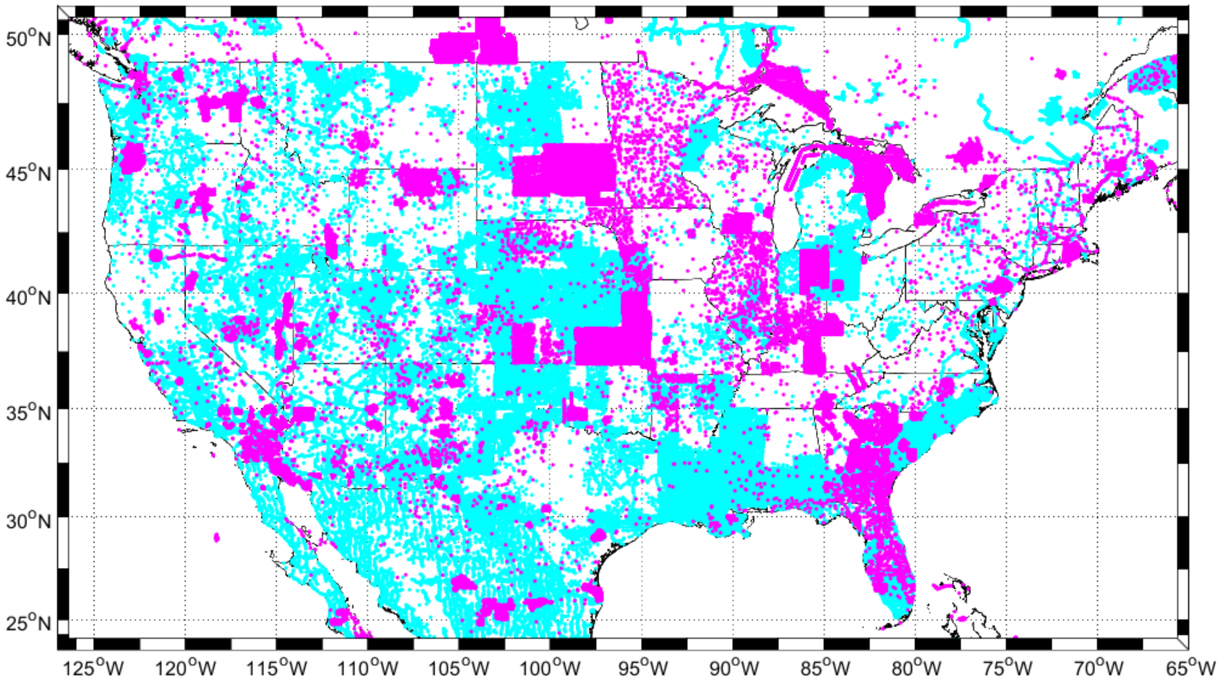

Figure 4: CONUS with Unique Gravity Data from NGA (magenta) and NGS (cyan)

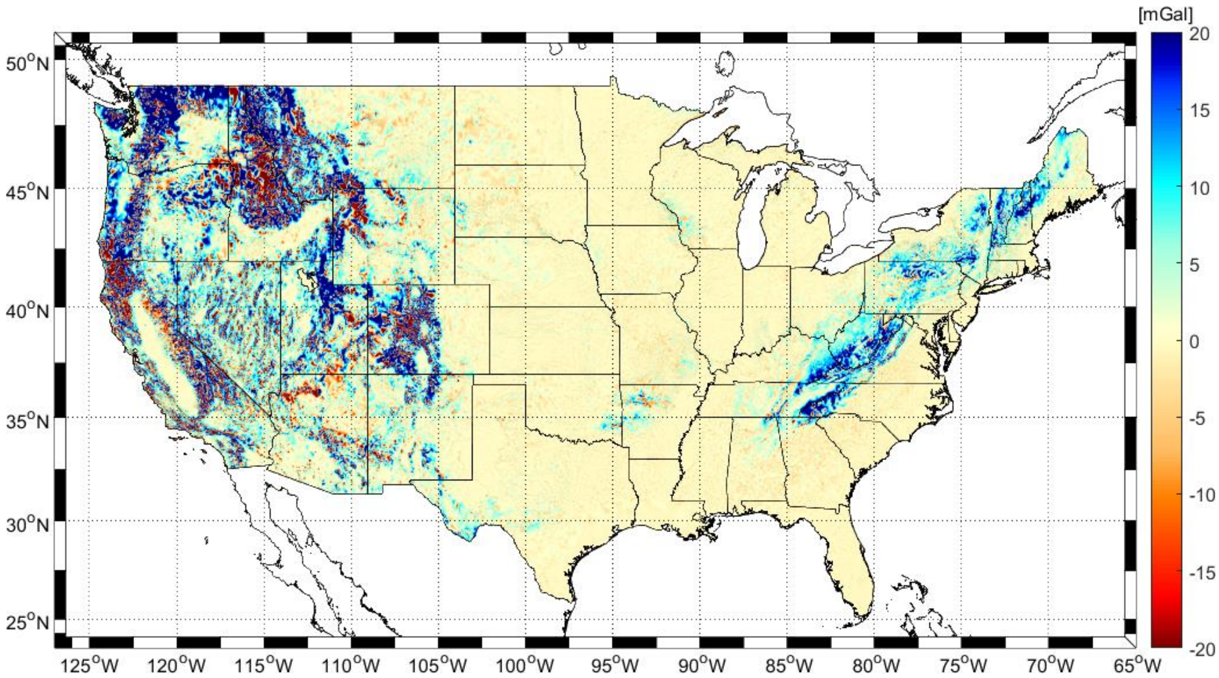

Figure 5: Free-Air Anomaly Difference between NGA data and NGS data at Duplicated Points

3.2 NGS GRAV-D Data

One of the major new datasets that is being incorporated in EGM2020 is airborne gravity collected by NGS' Gravity for the Redefinition of the American Vertical Datum (GRAV-D) project (GRAV-D Team, 2013). The major data collection portion of GRAV-D will not be completely finished in time for NGA's EGM2020 model release in December 2019. Thus, NGA and NGS have agreed to an annual cycle of data sharing, model development, and validation involving available GRAV-D data. Starting in 2018, NGS will provide all collected, processed, and 'cleaned' GRAV-D data to NGA for inclusion into its annual reference model. These data are slightly different than the publically available data as they have been debiased on a block by block and line by line basis. NGA is developing a few preliminary reference models (PGM) prior to and in anticipation of EGM2020. NGS will then validate and evaluate NGA's reference models over the U.S. and its territories. After the EGM2020 release, this cycle will continue on a regular basis (most likely annually) until the completion of the first of two campaigns of GRAV-D data collection in 2022.

Additionally, this cooperation between NGS and NGA will benefit the greater geodetic community. After a few annual cycles, the methods in which the NGS GRAV-D data is cleaned and debiased will be thoroughly vetted and incorporated into EGM2020 and subsequent reference models. After this validation, the debiased GRAV-D data will included in our publically available data products for the geodetic community to use.

4. COMMON DATASET PROJECT BETWEEN CGS, INEGI, AND NGS

4.1 Background & Schedule

CGS, INEGI and NGS have historically produced vertical reference surfaces in collaboration with one another but more or less independently. For example, NAVD 88 was developed with NGS and CGS in the early 1990's, but never officially adopted for use in Canada. More recently, Canada adopted the Canadian Geodetic Vertical Datum of 2013 (CGVD2013) as its geoid-based vertical datum. The various regional geoid models don't exist in a vacuum though – and need to be consistent across common borders and international waters. Two problems exist though when trying to compare two or more regional geoid models: 1) different input datasets and 2) different computational methods. With the goal of a regionally consistent geoid model in mind, NGS has set a goal to identify a common gravity dataset and digital elevation model which is available to the USA, Canada, and Mexico (and other partners) for geoid computation purposes. The intent is to use this dataset (or its updates) to compute geoid models using different methodologies. In this way, ONLY the computational methodologies will cause geoid differences.

NGS has a goal to finalize the common datasets by the end of 2019. Newly collected data will continue to be incorporated after this deadline, but we anticipate this is only a minor task as new surveys are rare and impact only small geographic areas. Currently, surface gravity and

DEM datasets have been compiled and finished, shiptrack gravity will be completed in 2018, minor updates and tweaks will be made to the datasets throughout 2019, and official adoption will occur shortly thereafter.

4.2 Definitional Datasets

A number of preliminary decisions were made at the onset of this project: whom is responsible for what datasets and where, choice of an existing (i.e. off-the-shelf) altimetric gravity dataset to use over the deep ocean, and which global geopotential model and metadata to use as the satellite gravity contribution. Currently, DTU15 altimetry data (Andersen et al. 2016) and GOCO05S (n_{max} = 280) (Mayer-Guerr, et al. 2015) have been chosen for the deep ocean coverage and global geopotential model, respectively. These initial decisions will likely be updated as new information is released prior to 2022.

Additionally, we are basing all models on an agreed upon W_0 value of 62,636,856.00 m^2/s^2. This value was agreed to in an MOU between the United States and Canada and represents coastal mean sea-level from tide gauges in the U.S. and Canada. This value is identical to the Bursa et al. 1998 W_0 value, which is often described as the IERS value. Furthermore, all models are in a 'Tide-Free' system to be compatible with GNSS determined coordinates. For additional defining and derived parameters, see NGS, 2017.

4.3 Surface Gravity

The determination of a common surface gravity dataset is likely to be the most labor intensive part of this project for two reasons. First, the size and complexity of the datasets is quite formidable. Secondly, over the past few decades, CGS, INEGI, and NGS have regularly shared gravity datasets amongst one another and with NGA (and its predecessors). This has resulted in a dataset that has been cleaned and corrected by one group, uncorrected by another group, and shared back with the original group. The tangle goes on and on, and is not easily unwound.

Each agency provided surface gravity data in its jurisdiction or geographic vicinity. INEGI provided data from Mexico and other regions in Central and South America. CGS provided data across Canada and the Great Lakes. NGS provided data across CONUS, Alaska, Hawaii, Puerto Rico/U.S. Virgin Islands, and other regions throughout the Caribbean.

4.4 Digital Elevation Models (DEM)

NGS is not the primary source of elevation data for the United States and its territories. Thus, it is not NGS' mission to actually produce a DEM to the highest spatial resolutions and accuracies allowable today. For example, a 5 m resolution DEM will not significantly benefit our geoid models currently. NGS is more a user of a DEM product to meet our mission. With that said, we are planning on publically releasing what ultimately is used in support of our vertical datum and geoid modeling needs. The current version of the DEM has 3" spatial resolution, defined over land areas, covering latitude ranges from 0 – 90 degrees and longitude ranges from 170 – 350 degrees with additional grids over CNMI/Guam and American Samoa (see Figure 1 – Figure 3). The DEM has a number of different data sources and requires minor corrections, despiking, and void filling, which will be described in this section.

4.4.1 DEM Data Sources

The DEM utilized for a number of tasks in our geoid modeling relies on a number of different data sources. The largest geographic region is based on the Shuttle Radar Terrain Model (SRTM) v4.1 (Jarvis, et al. 2008). The SRTMv4.1 data is used everywhere over land south of 60^o latitude. In Canadian regions above 60^o, we are using the Canadian Digital Elevation Dataset (CDED). In Alaska or Russian areas north of 60^o, we are currently using a combined dataset from Li et al. 2008. Over Greenland, the Greenland Ice Mapping Project (GIMP) (Howat, et al. 2014) elevation data is used. In Iceland, we are utilizing data from Landmælingar Íslands (The National Land Survey of Iceland).

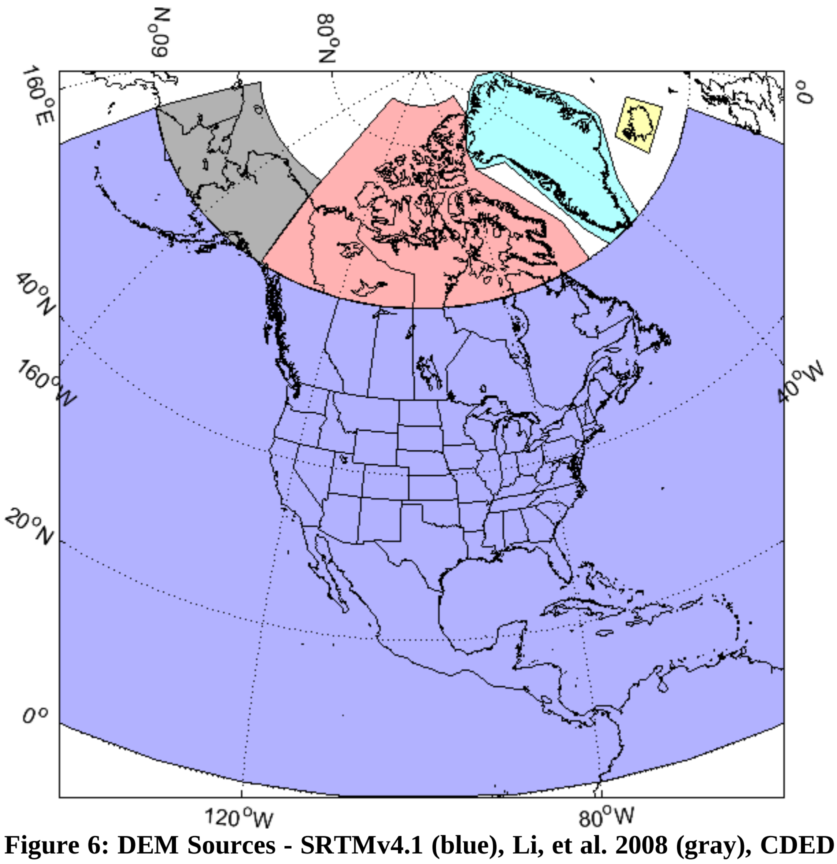

Figure 6: DEM Sources - SRTMv4.1 (blue), Li, et al. 2008 (gray), CDED (red), GIMP (cyan), and Iceland National Survey (yellow)

4.4.2 DEM Despiking and Void Filling

A despiking procedure and a void filling procedure were both implemented in order to fix a handful of small problems in the DEM datasets. Currently, these off-the-shelf DEMs do not have many problems, but a few geographic locations were fixed. The despiking process was done across the whole dataset to detect where a given cell had a significant difference from its neighboring cells. Only a few hundred cells (out of millions) had to be corrected. Many of these areas were in the Andes Mountains in South America, but a few areas in CONUS still needed some remedy. The procedure for filling incorrect values required identifying the geographic locations with a despiking procedure, extraction of a 2 km radius surrounding all the incorrect cells, removal of the incorrect cell values, and a biharmonic spline interpolation to fill the incorrect cells. An example of this procedure is shown in Figure 7 for a location that has extremely erroneous cells of -351 m surrounded by 2500+ m cells.

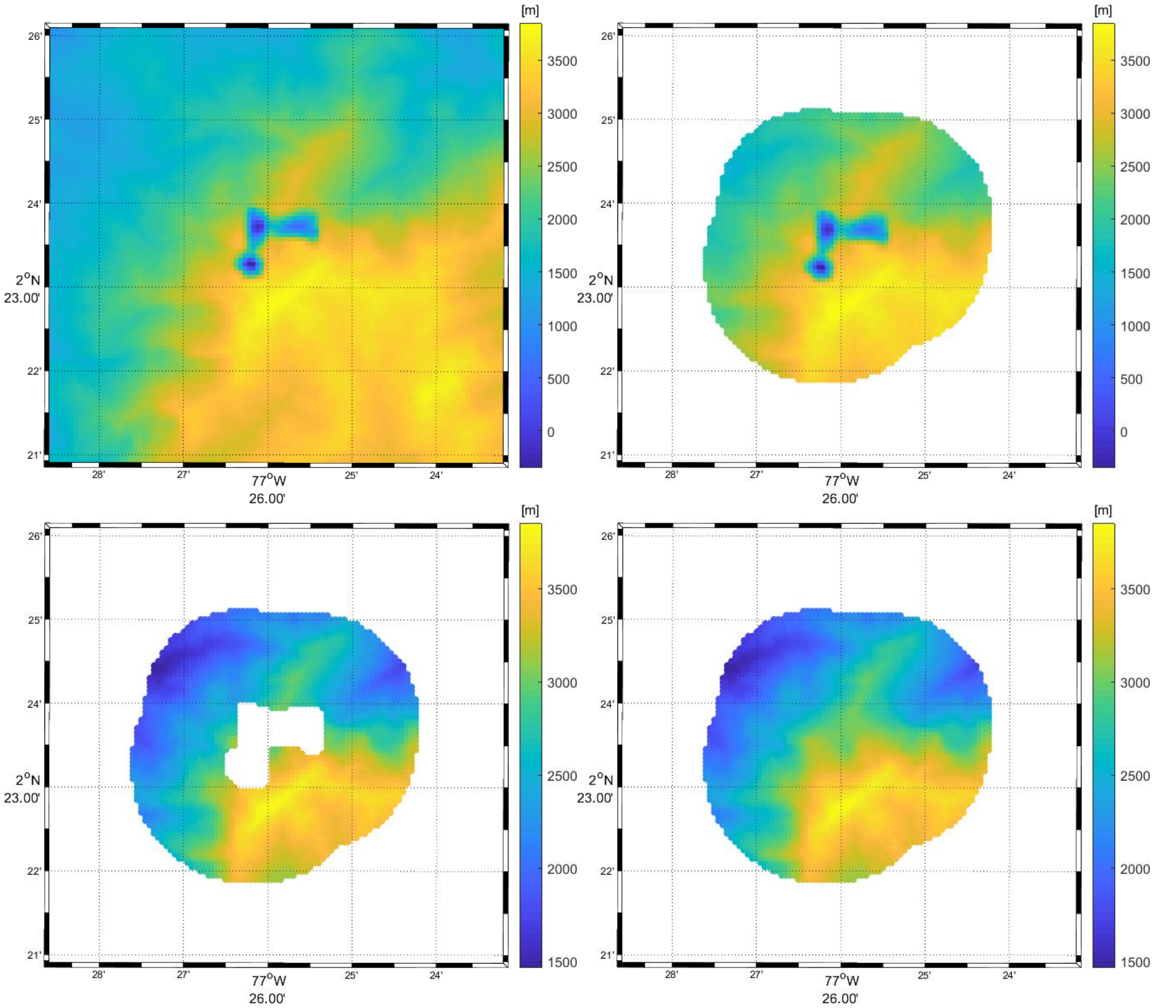

Figure 7: Void Filling Procedure: Original DEM (top left), 2 km buffer (top right), Extraction of cells to fill (lower left), Biharmonic Spline Interpolation (lower right)

5. SHIPTRACK GRAVITY DATA

NGS has access to a large database of shiptrack gravity data through NOAA's National Center for Environmental Information (NCEI) in addition to datasets obtained from NGA; however, NGS has typically not used either of these datasets in our geoid modeling in the past. Three main reasons for this decision are that: 1) better results are obtained without the data; 2) bias and noise in the data degrade the overall quality and confidence in the data; and 3) altimetric derived data is of very high quality over the deep ocean. The shiptrack data does has the potential to improve NGS geoid models in a couple of situations. First, the shiptrack data has the potential to contribute short wavelengths near the shoreline. GRAV-D can capture the medium wavelengths, but the shiptrack data contains content at the shorter wavelengths (20 km and under). Second, the shiptrack data can enhance areas with shallow water where the altimetric data are not as accurate. This is especially relevant throughout the Caribbean. Additionally, areas in the Atlantic Ocean off the eastern coast of North America are impacted by the North Atlantic Jet Stream, which causes the altimetric data to be less accurate providing an opportunity for the shiptrack data to improve the geoid models. For the potential to improve the geoid models in these areas, our goal is to estimate and correct any biases present in the data and utilize the data in targeted locations. It is planned that this data will be finalized and shared by end of 2018.

6. RESULTS

6.1 Geoid Improvement due to NGA Surface Gravity Data

The additional NGA surface gravity data has been used to augment our existing gravity database and was used to construct our most recent experimental gravimetric geoid (xGEOID17). xGEOID17 is the latest iteration in NGS' annual xGEOID model series, where each model consists of two separate models: an A model and a B model. The A and B models are identical except that airborne gravity data from the GRAV-D project are used to construct the B reference model and xGEOIDB models while the A reference model and xGEOIDA models do not contain GRAV-D data.

The xGEOID17 models are based on completely new reference models, independent from EGM2008, utilizing the latest NGA surface gravity data, DEM data, altimetry data, satellite gravity data, and GRAV-D data (for REF17B and xGEOID17B). All of the 2017 xGEOID reference models and geoid models have incorporated the new NGA surface gravity data, but have not incorporated the common datasets (surface gravity, DEM, shiptrack, etc.) between CGS, INEGI, and NGS.

Using NGS' Geoid Slope Validation Surveys (GSVS) over Texas (GSVS11) (Smith, et al. 2013) and Iowa (GSVS14) (Wang, et al. 2017) to validate the recent xGEOID models, a minor but noticeable improvement is present with models created using the NGA surface gravity data. On the GSVS11 residual profile (Figure 8), the models are driven more by the inclusion of

GRAV-D data than by the NGA surface gravity data as evidenced by the two B models moving in lockstep while the two A models do the same with one another (see 150 km and 275 km locations in Figure 8). However, on the GSVS14 profile (Figure 9), the xGEOID16 models are in lockstep while the xGEOID17 models are together. Most importantly, both xGEOID17 models exhibit a 2-3 mm improvement with the GPS-leveling data compared with the xGEOID16 models (Table 2). This is evidence that the NGA gravity data does improve our NGS geoid models in the GSVS14 area. Over the GSVS11 line, the improvement is only 1 mm in the xGEOIDB models from 2016 to 2017 but still an improvement.

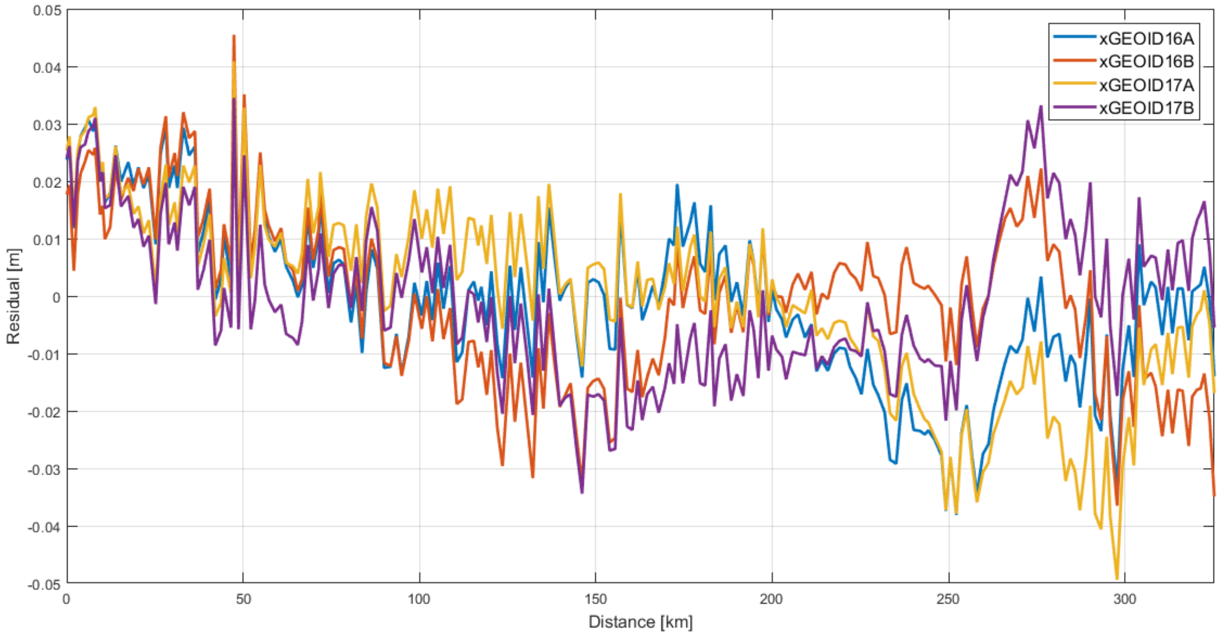

Figure 8: GSVS11 Residual (h – H – N)

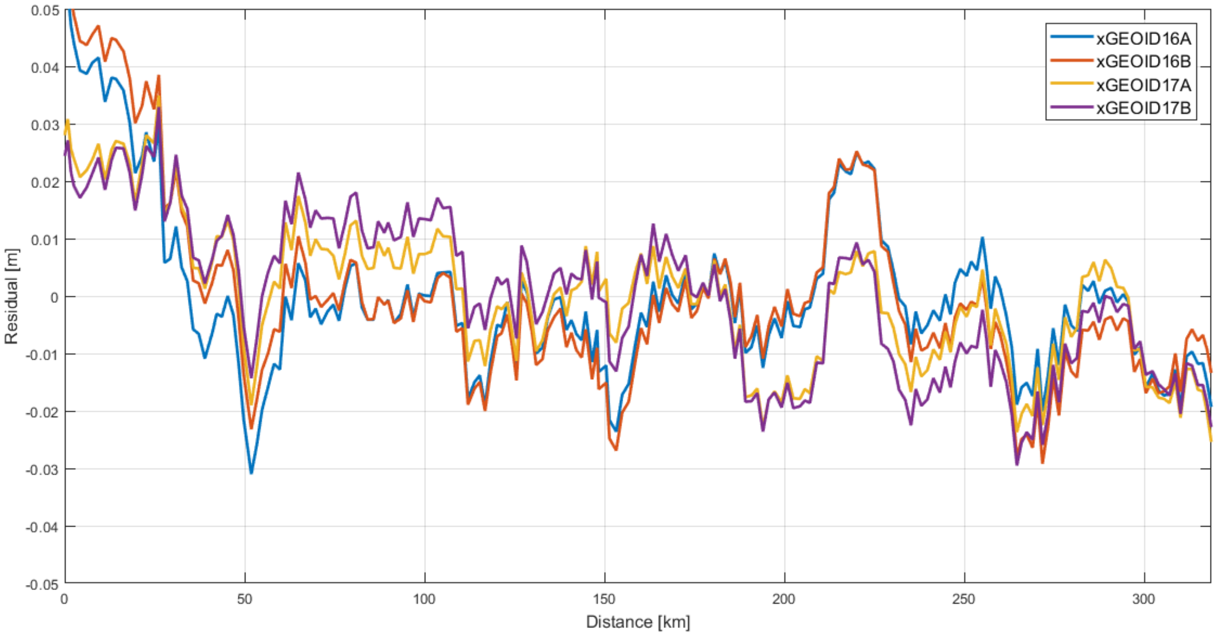

Figure 9: GSVS14 Residual (h - H - N)

Table 1: GSVS11 Residual Statistics (Bias Removed) [meters]

	Minimum	Maximum	RMS
xGEOID16A	-0.0381	0.0428	0.015
xGEOID16B	-0.0365	0.0455	0.015
xGEOID17A	-0.0494	0.0409	0.017
xGEOID17B	-0.0344	0.0345	0.014

Table 2: GSVS14 Residual Statistics (Bias Removed) [meters]

	Minimum	Maximum	RMS
xGEOID16A	-0.031	0.053	0.015
xGEOID16B	-0.029	0.058	0.017
xGEOID17A	-0.025	0.035	0.013
xGEOID17B	-0.030	0.033	0.014

7. CONCLUSIONS AND INVITATION

NGS has undertaken two major initiatives to improve its geoid model while simultaneously producing a more consistent geoid model for North America. Through these national and international collaborations, common and consistent datasets that are used as input datasets in our geoid modeling have been created and shared or will be in the near future. Improvements in NGS geoid models due in part to newly acquired NGA gravity data are already present in our xGEOID17 models at the 2-3 mm level as a result of this data sharing.

CGS, INEGI, and NGS have also begun an initiative to combine our various geoid input datasets resulting in additional geoid model improvement and consistency across North America. Surface gravity data, a DEM, and various preliminary datasets have all be identified and shared between the various geoid modeling groups currently. Additional shiptrack gravity data will be shared and combined by the end of 2018. While geoid modeling improvements haven't been realized yet as it is too early in the project, the goal of this work is to provide a more consistent and improved geoid model for all of North America.

For other agencies and countries with a desire to join and contribute to this regional geoid project, we enthusiastically welcome your participation. Our goal is to finalize the previously discussed common datasets by the end of 2019, and contributed data would need to be included by that time.

REFERENCES

Andersen, O. B., Stenseng, L., Piccioni, G., & Knudsen, P. (2016). The DTU15 MSS (Mean Sea Surface) and DTU15LAT (Lowest Astronomical Tide) reference surface. ESA Living Planet Symposium 2016, Prague, Czech Republic.

Burša M, Kouba J, Radeˇj K, True S, Vatrt V, Vojtíšková M (1998). Mean Earth's equipotential surface from TOPEX/Poseidon altimetry. Studia geoph et geod 42:456–466. doi:10.1023/A:1023356803773.

GRAV-D Team (2013). "GRAV-D General Airborne Gravity Data User Manual." Theresa Damiani and Monica Youngman, ed. Version 2. Accessed: 2/10/2017. Online at: http://www.ngs.noaa.gov/GRAV-D/data_products.shtml.

Howat, I. M., Negrete, A., & Smith, B. E. (2014). The Greenland Ice Mapping Project (GIMP) land classification and surface elevation data sets. The Cryosphere, 8(4), 1509-1518.

Li X., Roman D.R., Saleh J. and Wang Y.M. (2008): High Resolution DEM over Alaska and Its Application to Geoid Modeling. American Geophysical Union, Fall Meeting 2008, abstract #G51B-0617.

Mayer-Guerr, T. et al., (2015). The combined satellite gravity field model GOCO05s. Paper presented at the EGU General Assembly Conference Abstracts. Vienna, April 2015.

National Geodetic Survey, (2017). Blueprint for 2022, Part 2: Geopotential Coordinates, NOAA Technical Report NOS NGS 64. Available at: https://www.ngs.noaa.gov/PUBS_LIB/NOAA_TR_NOS_NGS_0064.pdf, downloaded 2018 02 01.

Pavlis, N. K., Holmes, S. A., Kenyon, S. C., & Factor, J. K. (2012). The development and evaluation of the Earth Gravitational Model 2008 (EGM2008). Journal of Geophysical Research: Solid Earth, 117(B4).

Smith, D. A., Holmes, S. A., Li, X., Guillaume, S., Wang, Y. M., Bürki, B., et al., (2013). Confirming regional 1 cm differential geoid accuracy from airborne gravimetry: the Geoid Slope Validation Survey of 2011. Journal of Geodesy, 87(10-12), 885-907.

Wang, Y.M., Becker, C., Mader, G., Martin, D., Li, X., Jiang, T., Breidenbach, S., Geoghegan, C., Winester, D., Guillaume, S., and Burki, B. (2017). The Geoid Slope Validation

Survey 2014 and GRAV-D airborne gravity enhanced geoid comparison results in Iowa. Journal of Geodesy, 91(10), 1261-1276.

BIOGRAPHICAL NOTES

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