Analysis of a Geopotential Datum at Tide Gauge Stations

Daniel ROMAN, U.S.A. and Xiaopeng LI, U.S.A.

Key words: Coastal Zone Management, GNSS/GPS, Reference Frames, Geoid, MSL, TBM, Vertical Datum

SUMMARY

The United States will be updating its National Spatial Reference System (NSRS) in 2022. Primary responsibility for maintaining and updating the NSRS resides with NOAA's National Geodetic Survey (NGS). NGS works with its counterpart agencies in Canada (NRCan), Mexico (INEGI) and other countries in North America and the Caribbean to ensure that this updated NSRS will be consistent with the principles of the United Nations Global Geospatial Reference Frame (UN GGRF). This update will include a realization of physical heights based on a geoid-based vertical datum using the geopotential value of 62,636,856.00 m^2/s^2. IERS and IAU both adopted this value, but IAG has selected a different value. However, it was determined as the best fitting value based on a comparison of an earlier geopotential model (USGG2012) at over 200 tide gauges throughout North America. This paper revisits that study based on newer and more comprehensive geopotential models to evaluate the selected datum. With INEGI and NRCan, NGS has developed a series of experimental gravimetric geoid models with the most recent being xGEOID19. These models incorporate all available satellite-gravity data as well as airborne gravity for the Gravity for Redefinition of the American Vertical Datum (GRAV-D) project. Hence, xGEOID19 provides a much better basis for analyzing the tide gauge data in view of the adopted geopotential value. The old analysis based on USGG2012 (NGS 2012) will be revisited and then updated based on comparison to xGEOID19. The primary difficulty relates to uncertainties in the available Mean Ocean Dynamic Topography (MODT) models that describe variations in MSL based on pressure, temperature and salinity variations. Hence, available MODT models will also be assessed.

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1. INTRODUCTION

Sea Level is in fact not level. The mean tide surface can vary from one spot along the shoreline to the next due to pressure, temperature and salinity variations of the ocean. This causes deviations away from a nominal global mean sea level value - sometimes higher, sometimes lower. These variations are termed the Mean Ocean Dynamic Topography. If the MODT is added to a global value approximating a vertical datum, the variations should match observations made at the tide gauges, such as the National Water Level Observation Network(NWLON) stations maintained by NOAA's CO-OPS. This study develops the geopotential values at the MSL as indicated at the tide gauges and then estimates the MODT along the shoreline with an eye to finding models that are suitable for use in between the tide gauges.

2. NSRS MODERNIZATION

The US will be updating the NSRS in 2022 as highlighted in three blueprint documents (NGS 2017a, NGS 2017b, NGS 2019) provided on our website (Figure 1). This includes definition of a geopotential datum for determining vertical positions (highlighted in red in Figure 1).

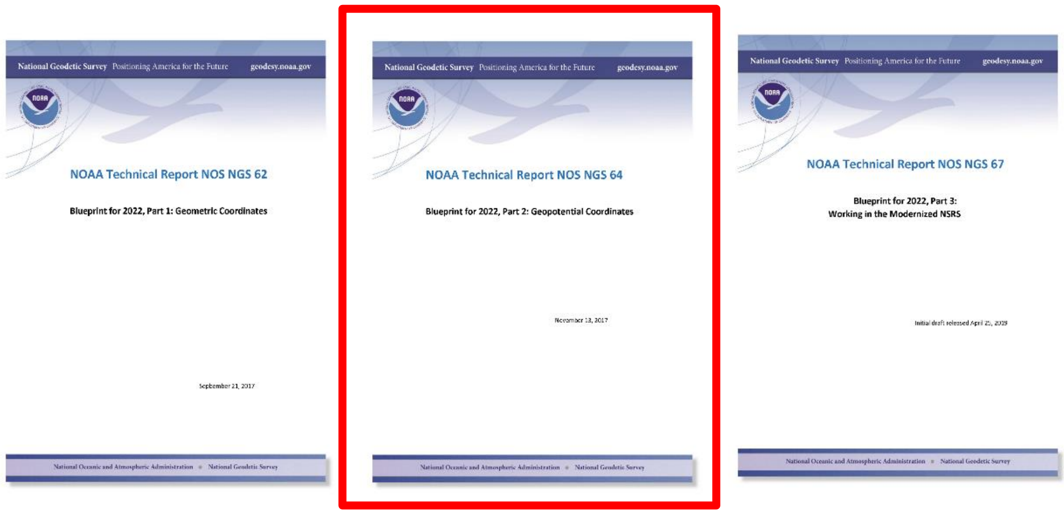
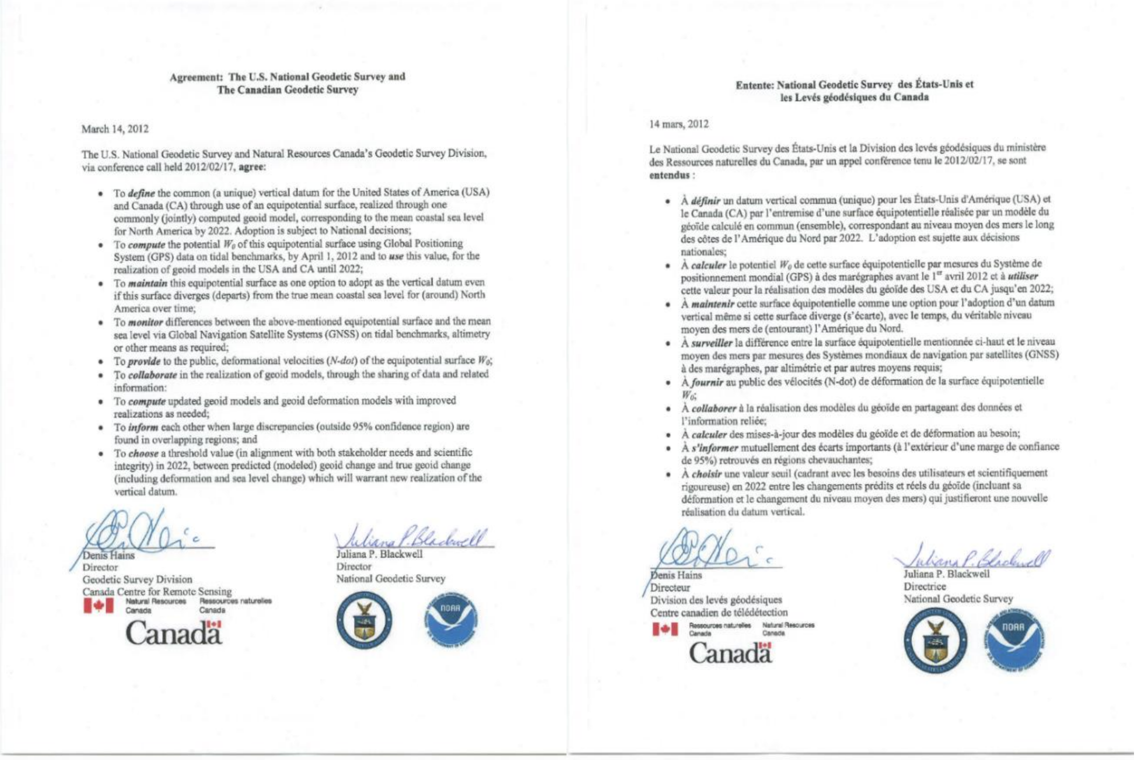


Figure 1. Three definitional Blueprints are available from NGS to explain the planned update to the U.S. National Spatial Reference System in 2022. NOS NGS 64 pertains to development of the geopotential or vertical datum.

To that end, it is necessary to first define the optimal value for this geopotential datum to replace the existing North American Vertical Datum of 1988 (Zilkoski et al. 1992). NAVD 88 was intended to serve as a common datum for all of North America. However, it was not adopted in Canada or Mexico. The U.S., Canada and Mexico have been working closely to establish a common geopotential datum for use in all regions. The value of 62,636,856.00

m^2/s^2 was adopted by the United States and Canada in 2012 (Figure 2). Mexico and other countries in Central America and the Caribbean also indicated a desire to adopt this datum. This will provide unified heights in the entire northern portion of the western hemisphere.



Agreement: The U.S. National Geodetic Survey and The Canadian Geodetic Survey

March 14, 2012

The U.S. National Geodetic Survey and Natural Resources Canada's Geodetic Survey Division, via conference call held 2012/02/17, **agree:**

- To ***define*** the common (a unique) vertical datum for the United States of America (USA) and Canada (CA) through use of an equipotential surface, realized through one commonly (jointly) computed geoid model, corresponding to the mean coastal sea level for North America by 2022. Adoption is subject to National decisions;
- To ***compute*** the potential W_0 of this equipotential surface using Global Positioning System (GPS) data on tidal benchmarks, by April 1, 2012 and to ***use*** this value, for the realization of geoid models in the USA and CA until 2022;
- To ***maintain*** this equipotential surface as one option to adopt as the vertical datum even if this surface diverges (departs) from the true mean coastal sea level for (around) North America over time;
- To ***monitor*** differences between the above-mentioned equipotential surface and the mean sea level via Global Navigation Satellite Systems (GNSS) on tidal benchmarks, altimetry or other means as required;
- To ***provide*** to the public, deformational velocities (*N-dot*) of the equipotential surface W_0;
- To ***collaborate*** in the realization of geoid models, through the sharing of data and related information:
- To ***compute*** updated geoid models and geoid deformation models with improved realizations as needed;
- To ***inform*** each other when large discrepancies (outside 95% confidence region) are found in overlapping regions; and
- To ***choose*** a threshold value (in alignment with both stakeholder needs and scientific integrity) in 2022, between predicted (modeled) geoid change and true geoid change (including deformation and sea level change) which will warrant new realization of the vertical datum.

Denis Hains
Director
Geodetic Survey Division
Canada Centre for Remote Sensing
Natural Resources Canada / Ressources naturelles Canada
Canada

Juliana P. Blackwell
Director
National Geodetic Survey

Entente: National Geodetic Survey des États-Unis et les Levés géodésiques du Canada

14 mars, 2012

Le National Geodetic Survey des États-Unis et la Division des levés géodésiques du ministère des Ressources naturelles du Canada, par un appel conférence tenu le 2012/02/17, se sont **entendus** :

- À ***définir*** un datum vertical commun (unique) pour les États-Unis d'Amérique (USA) et le Canada (CA) par l'entremise d'une surface équipotentielle réalisée par un modèle du géoïde calculé en commun (ensemble), correspondant au niveau moyen des mers le long des côtes de l'Amérique du Nord par 2022. L'adoption est sujette aux décisions nationales;
- À ***calculer*** le potentiel W_0 de cette surface équipotentielle par mesures du Système de positionnement mondial (GPS) à des marégraphes avant le 1er avril 2012 et à ***utiliser*** cette valeur pour la réalisation des modèles du géoïde des USA et du CA jusqu'en 2022;
- À ***maintenir*** cette surface équipotentielle comme une option pour l'adoption d'un datum vertical même si cette surface diverge (s'écarte), avec le temps, du véritable niveau moyen des mers de (entourant) l'Amérique du Nord.
- À ***surveiller*** la différence entre la surface équipotentielle mentionnée ci-haut et le niveau moyen des mers par mesures des Systèmes mondiaux de navigation par satellites (GNSS) à des marégraphes, par altimétrie et par autres moyens requis;
- À ***fournir*** au public des vélocités (N-dot) de déformation de la surface équipotentielle W_0;
- À ***collaborer*** à la réalisation des modèles du géoïde en partageant des données et l'information reliée;
- À ***calculer*** des mises-à-jour des modèles du géoïde et de déformation au besoin;
- À ***s'informer*** mutuellement des écarts importants (à l'extérieur d'une marge de confiance de 95%) retrouvés en régions chevauchantes;
- À ***choisir*** une valeur seuil (cadrant avec les besoins des utilisateurs et scientifiquement rigoureuse) en 2022 entre les changements prédits et réels du géoïde (incluant sa déformation et le changement du niveau moyen des mers) qui justifieront une nouvelle réalisation du datum vertical.

Denis Hains
Directeur
Division des levés géodésiques
Centre canadien de télédétection
Ressources naturelles Canada / Natural Resources Canada
Canada

Juliana P. Blackwell
Directrice
National Geodetic Survey

Figure 2. Signed agreement between the United States and Canada in 2012 to adopt the value of 62,636,856.00 m2/s2 as a common geopotential datum for both countries.

It should be noted that the adopted value is consistent with that used by IERS and IAU (Burša et al. 2007), but is not consistent with the value adopted by IAG (62,636, 853.4 m^2/s^2) per Resolution 1 of the IAG Resolutions at the XXVI IUGG General Assembly 2015 held in Prague. IAG is proceeding with the development of the International Height Reference System (IHRS) using their value. However, the bias between them can be determined and a transformation applied if necessary to switch heights from the planned North American-Pacific Geopotential Datum of 2022 (NAPGD2022) to any future IHRF model.

3. DETERMINATION OF AN OPTIMAL GEOPTENTIAL VALUE

This paper revisits prior work that was based on older and less accurate models. Hence, it is necessary to revisit that work and then provide an update to see if the selected geoptential value is still the most optimal value.

3.1 Available Tide Gauges

Roman and Weston (2012) previously presented the basis for determining the value adopted for NAPGD 2022. Comparisons were made at tide gauges where GPS-derived heights provided the coordinates of local mean sea level (LMSL) in ITRF2008 (Altimimi et al. 2010).

There are 211 tide gauges available in the U.S. and Canada as shown in Figure 3. All of these are on the National Tidal Datum Epoch of 1983-2001. The values shown are actual geopotential numbers calculated from the EGM2008 (Pavlis et al. 2012) model. Only the last four digits are shown – two on each side of the decimal. The mean value is then 62,636,856.85 m^2/s^2.

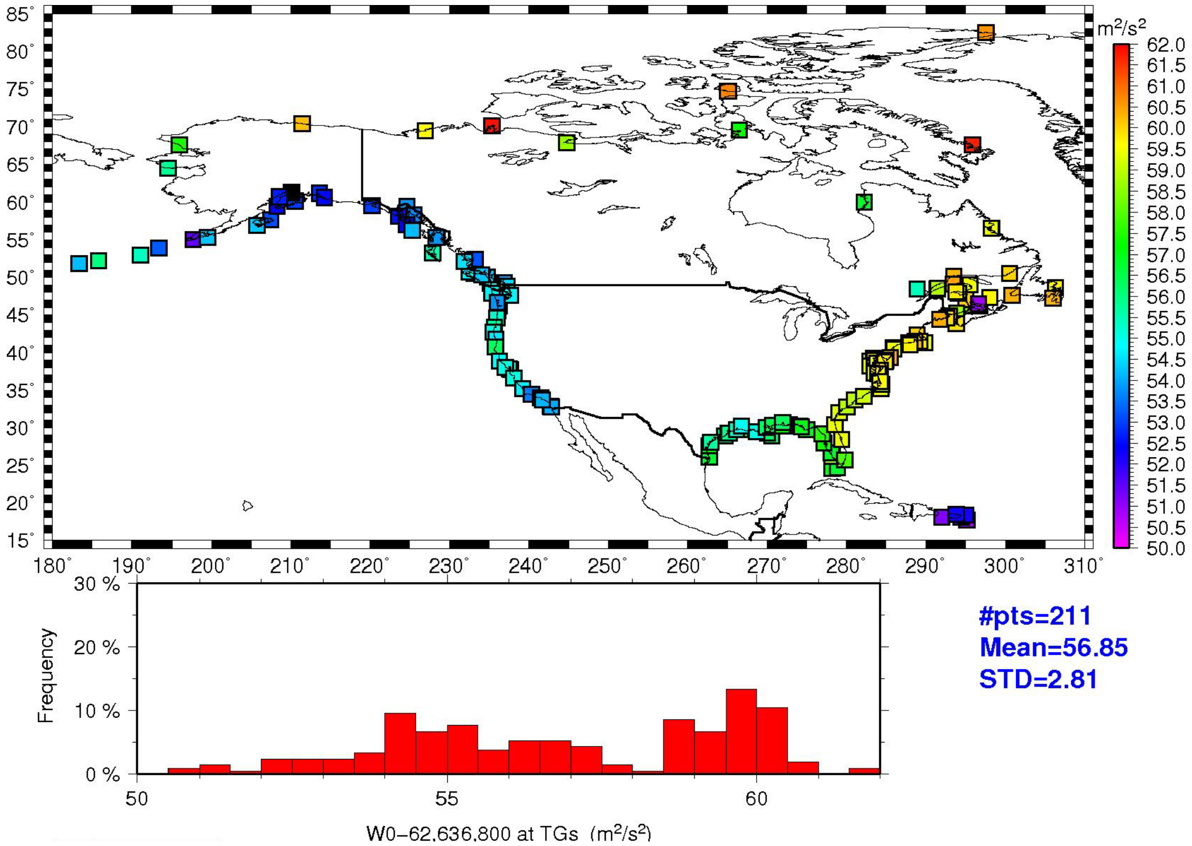
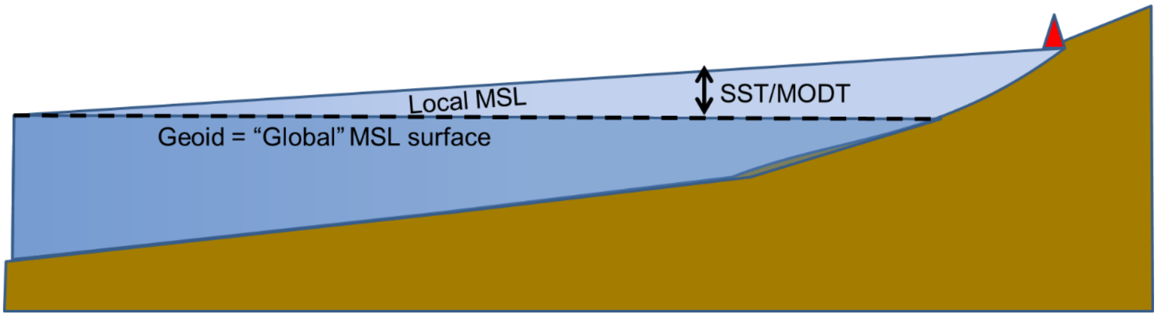


*Figure 3. Available tide gauges (211) with geometric coordinates of local MSL from GPS. Coordinates are used to determine geopotential values from EGM2008. Note trends along shorelines and outliers. Mean value is 62,636, 8**56.85** m^2/s^2.*

However, significant trends can be seen along the respective shorelines of the Gulf of Mexico and the Atlantic, Pacific & Arctic Oceans. Significant outliers from these trends can also be seen, particularly in the Arctic. Stations in the Arctic areas are not as well established and are more isolated. However, the density of the stations along the other shorelines and the apparent trends and biases indicate some systematic physical characteristics. In point of mean sea level is not level.

3.2 Mean Ocean Dynamic Topography (MODT)

Variations in pressure, temperature and salinity cause variations in local mean sea level. In point of fact, the MSL value at any given tide gauge may have a different geopotential value (i.e., sit at a different height in the gravity field) than others. Such variations are often drivers for the ocean currents such as the Gulf Stream or the Labrador Current. For the east coast of the U.S., this means nearly 1.5 meters of variation from Florida to Maine. So any nominal value for global MSL will vary quite a bit compared to LMSL observed at a tide gauge. This variation has been defined many ways including MODT but has also been termed Sea Surface Topography (SST) and Topography of the Sea Surface (TSS). MODT is prefered to deconflict with other physical oceanography terms. Figure 4 highlights this and defines a simple relationship between MODT, the geoid (assumed to be the global MSL value) and LMSL.



Figur 4. Pressure, temperature and salinity are not constant and produce variations in the ocean surface away from a nominal global MSL value, which is assumed to be the geoid surface. Geoid + MODT = LMSL (as observed at tide gauge).

To mitigate these MODT variations, models developed from physical oceanography are preferred. These models should be as independent as possible from other data sets used here. Much of the satellite altimeter profiles have been utilized in geoid modeling. Hence, MODT models developed primarily from such data are best avoided. Two such models (Foreman et al. 2004, Thompson-Demirov 2006) are shown in Figure 5.

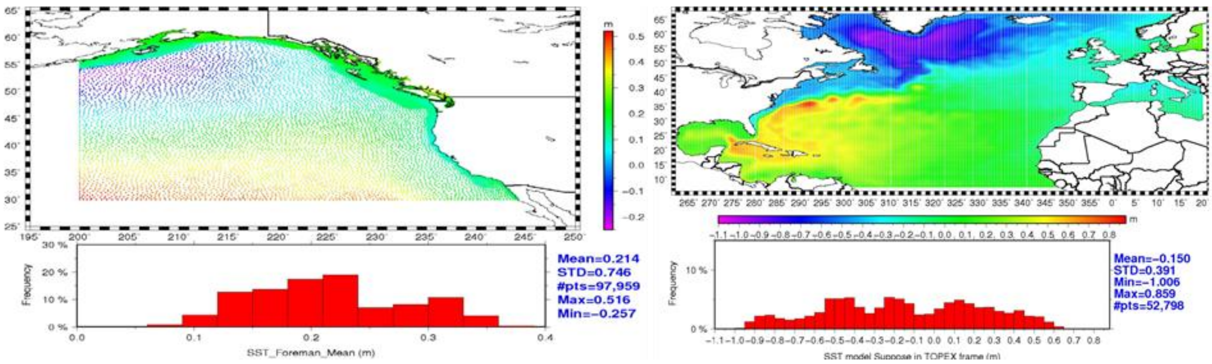


Figure 5. Two MODT models for the Gulf of Mexico and the Pacific and Atlantic Oceans: Foreman et al. 2004 (left), THompson-Deemirov 2006 (right).

3.3 Previous Work

In Roman and Weston (2012), MODT values were removed from the above models to develop estimates of the global MSL at each tide gauges (MSL/geoid = LMSL – MODT). Note, however, that the geographic extents of the MODT models is less than that of the available tide gauges. As such, only 188 of 211 tide gaues are available for further analysis.

Figure 6 highlights the geopotential values at the 188 remaining tide gauges. Note that the values along the Pacific and Atlantic Coasts are much flatter and more constant. The values along the Gulf of Mexico show more variability and an overall bias with respect to either the Pacific or Atlantic Coasts.

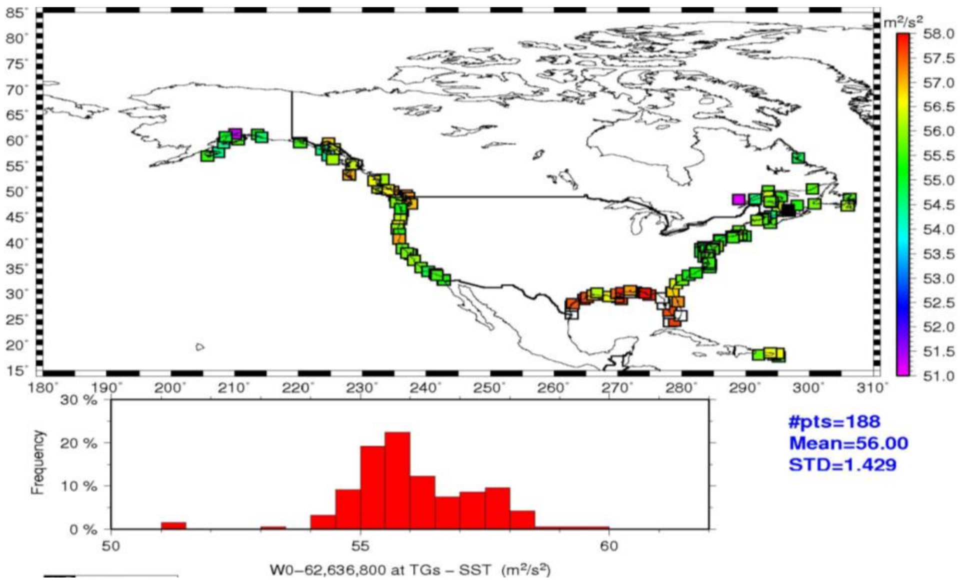


Figure 6. Geopotential values at tide gauges after removal of estimated MODT heights. Atlantic and Pacific coasts are fairly flat and consistent. The Gulf of Mexico shows more variability and bias compared to the other two. Note that the average value is 62,636,856.00 m^2/s^2

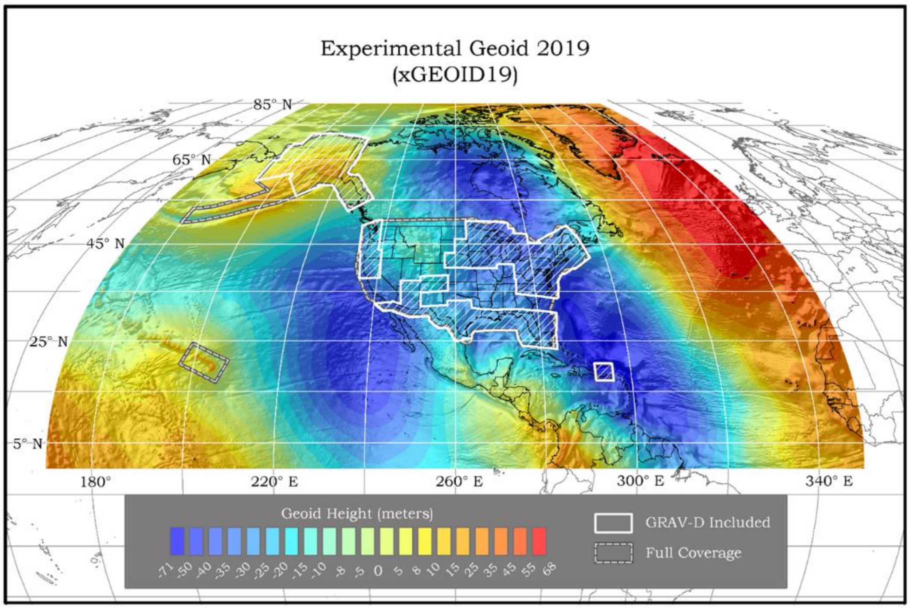


Figure 7. The xGEOID19 model for the North American-Pacific Geopotential region. White boxes highlight regions where aerogravty has been incorporated.

3.4 Updated Study

Since 2012, NGS has developed a series of experimental geoid models built on its vast amount of GRAV-D airborne (NGS 2010) data (Roman and Li 2014) and improved EGM's as well as satellite gravity models. The xGEOID19 model represents the latest such model (Figure 7). These models are at a one arcminute grid spacing and provide resolution at about 2 km. However, they are built using reference models that are bit sparser in coverage but that are global in coverage. The xGEODI16A_REF and xGEOID19B_REF models were used to create the xGEOID19A and xGEOID19B models. The "A" model has no aerogravity included, while the "B" model includes all available aerogravity from the GRAV-D Project in the Gravity Program (NGS 2010).

Both the reference field models started from EGM2008 and added significant additional satellite gravity data from GRACE (Mayer-Gürr et al. 2010) and GOCE (Gruber et al. 2011). As such, both represent an improvement over EGM2008 by mitigating errors of omission and commission.

3.4.1 Comparisons sing xGEOID16A_REF

The intent of the xGEOID16A_REF model was to provide a model following the best techniques and using all available data except the aerogravity data. Comparisons to equivalent "B" models then highlight the contribution of the aerogravity to a specific comparison. Note that there were no significant processing or data improvements since 2016. Hence, the 2016 "A" model is continued in use for assessments. Figure 8 shows the geoptential numbers at the same tide gauges given in Figure 6 using the MODT models given in Figure 5.

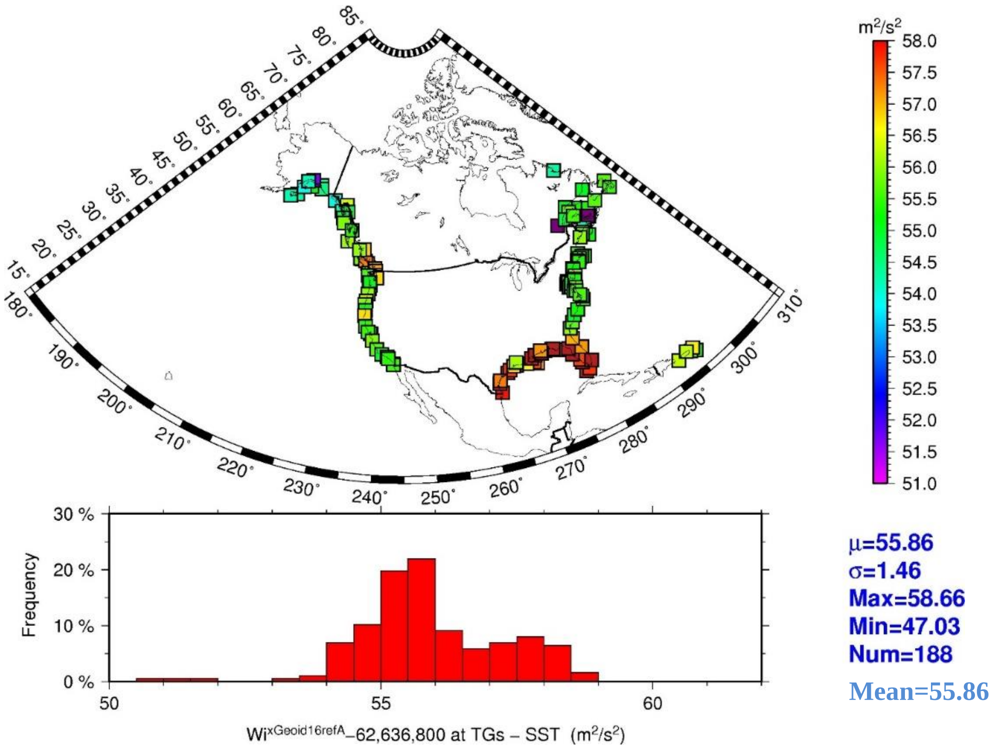


Figure 8. Geopotential numbers from the xGEOID16A_REF model at the same tide gauges and using the same MODT models as seen in Figure 6. Mean value is 62,636,855.86 m2/s2.

3.4.2 Comparisons using xGEOID19B_REF

As indicated above, the “B” models include the aerogravity available at the time they were completed. In this case, the xGEOID16A_REF model was adjusted to reflect available aerogravity in 2019. The xGEOID19B_REF model (Figure 9) is still only at five arcminute (10 km) resolution. Though there are a few changes in the stations over the Alaska pan handle area and the Gulf Coast area, the mean signal is the same here as is seen in Figure 8, as the GRAV-D data should not impact the degree zero values of the vertical datum.

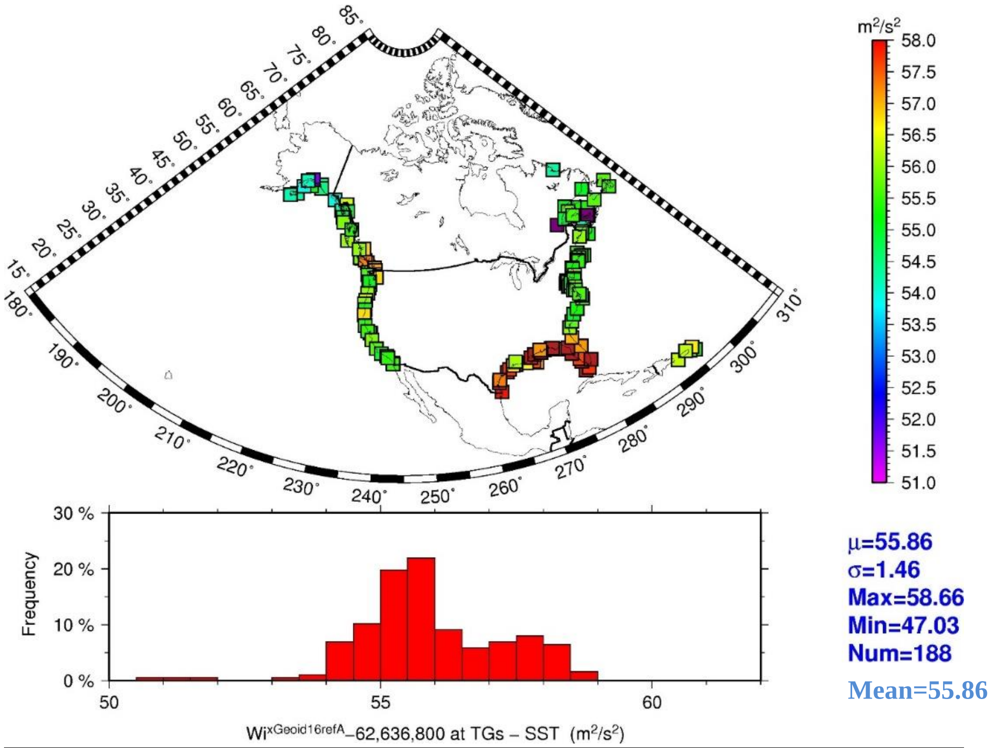


Figure 9. Geopotential numbers from the xGEOID19B_REF model at the same tide gauges and using the same MODT models as seen in Figure 6. Mean value is 62,636,855.86 m^2/s^2.This is the same value as in Figure 8.

3.4.3 Residual Geopotential Signals

The signal evaluated in sections 3.4.1 and 3.4.2 above are only through 10 km resolution, because the reference field models can only achieve that level of resolution. These models facilitated this analysis because they produce various aspects of the Earth’s geopotential field (geopotential numbers, gravity anomalies, geoid heights, etc.).

However, signal below 10 km is therefore omitted from the above comparison. No reference models yet exist at one arcminute resolution due to computation restrictions. The reference models are used to produce higher resolution grids of data. For example, the xGEOID19B_REF (5’) model was used to create the xGEOID19B geoid grid model (1’).

Hence, subtracting the two yields omitted signal between one and five arcminutes. This can be manipulated to generate a residual geopotential for assessing the impact of omitted signal.

Figure 10 highlights this signal. The mean value of the omitted signal is 0.08 m^2/s^2. Since this was formed by subtracting the 5’ signal from the 1’ signal, this residual signal should be added to the mean values seen in Figures 8 and 9.

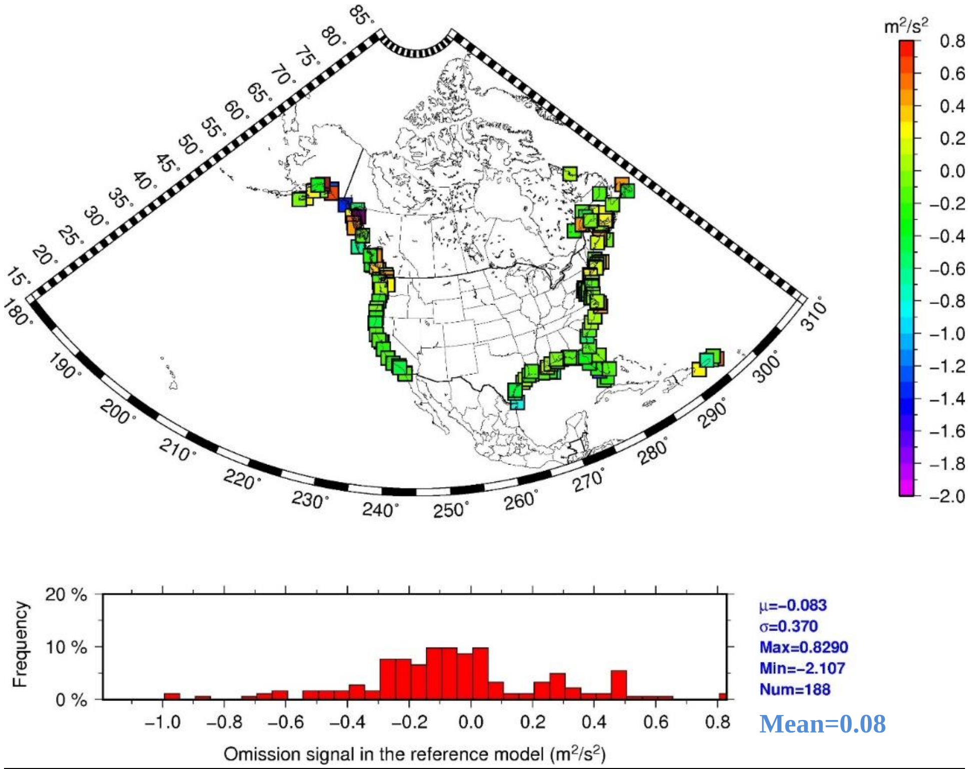


Figure 10. Residual geopotential values were used to assess the impact of omitted signal between one and five arcminutes. Hence, the below signal should be added to the above. The mean value here is 0.08 m^2/s^2.

4. SUMMARY

In 2012, the US National Geodetic Survey and the Canadian Geodetic Survey performed a joint evaluation to determine the optimal value for a geopotential (vertical) datum. Comparisons were made at 188 tide gauges where the geometric coordinates of the water surface was determined using GPS. The effects of MODT were removed at the tide gauges to better estimate true global MSL. Geopotential numbers were determined using the EGM2008 model at five arcminutes (10 km) resolution. The average value was 62,636,856.00 m^2/s^2. This value is consistent with that adopted by the IERS and IUGG. It was adopted by Canada and the U.S. and has since been accepted as a datum value by other coutrnies oin the Caribbean and Central America.

These same values were assessed again using updated reference models utlized in making the xGEOID19 model. One reference model included aerogravity and the other did not. Both yielded the same result within statistical certainty: 62,636,855.86 m^2/s^2. Both models omit signal below 10 km resolution. A residual geopotential value was determined for signal between 1' and 5' (2-10 km). That added back about 0.08 m^2/s^2. Hence, the net mean value for the more complete signal is 62,636,855.94 m^2/s^2. This value is very close to the currently adopted value of 62,636,856.00 m^2/s^2. The difference of 0.06 m^2/s^2 is equivalent to about 6 mm. Therefore, the currently adopted value will be retained.

Finally, it should be noted that both Figures 8 and 9 highlight an apparent bias in the Gulf of Mexico shoreline with respect to the Pacific and Atalantic Coasts. This may be indicative of a problem in the MODT model for the region.

5. FUTURE WORK

This work fixed the tide gauge observations and MODT models to evaluate the impact of changing the underlying geoid models. There was no appreciable impact by using an updated geopotential model. Therefore, next steps will assess other MODT models to see if the apparent Gulf of Mexico bias can be mitigated.

Eventually, the next NTDE (2002-2020) will be released and all the local MSL values at the tide gauges recalculated. The tide gauges themselves have been revisited with updated GPS campaigns using ITRF2014 (Altimimi et al. 2016), too. Incorporating these changes and then evaluating the impact on geopotential number determination are next steps.

The aim remains to evaluate and determine a final datum value for adoption in the North American-Pacific Geopotential Datum of 2022 (NAPGD 2022) as a part of the roll out of the updated US 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.

Xiaopeng Li worked as a contractor for NGS after obtaining his Ph.D. in Physical Geodesy in 2007. He is now employed as an employee in the Geosciences Research Division of NGS, where he works spherical/ellipsoidal harmonic modeling and regional geoid computation.

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CONTACTS

Dr. Daniel Roman
NOAA's National Geodetic Survey
1315 East-West Highway, SSMC3, N/NGS
Silver Spring MD 20910
U.S.A.
Tel. +1-240-533-9673
Email: dan.roman@noaa.gov
Web site: www.geodesy.noaa.gov