Determining an Optimal Geoid-based Vertical Datum

Daniel ROMAN (U.S.A.)

Key words: Geoid, MSL, TBM, Vertical Datum

SUMMARY

As a part of modernizing the U.S. National Spatial Reference System, the North American-Geopotential Datum of 2022 (NAPGD2022) will be implemented in Terrestrial Reference Frames derived most likely from the planned ITRF2020. NAPGD2022 will serve as a vertical datum in the U.S. and will be the final product developed from a series of experimental gravimetric geoid models (xGEOIDs). NAPGD2022 should be a best fit to global Mean Sea Level (MSL), which can vary locally by up to two meters in some cases. This is due primarily to pressure, temperature and salinity variations that drive oceanic currents. Picking a geopotential value to serve as a geoid model for a vertical reference frame must account for this mean ocean dynamic topography (MODT). By determining the geopotential values at tide gauges and offshore buoys, estimates of this observed MODT are compared to modeled MODT to devise the best connection between the geoid, MODT, and the local MSL surface. Several MODT models were evaluated using xGEOID20-derived geopotential numbers to determine the (1) best fit and (2) an optimal geopotential surface to serve as a geoid for North America. This process will ensure a better tie between bathymetry and terrestrial elevations, improved forecasting of the extents of storm surge onshore, and enhanced coastal resilience.

Determining an Optimal Geoid-based Vertical Datum

Daniel ROMAN (U.S.A.)

1. INTRODUCTION

Vertical datums are necessary to define physical heights, particularly with respect to sea level. They are defined traditionally through an adjustment of leveling, such as the North American Vertical Datum of 1988 (NAVD 88) in the U.S. (Zilkoski et al. 1992). See Figure 1.

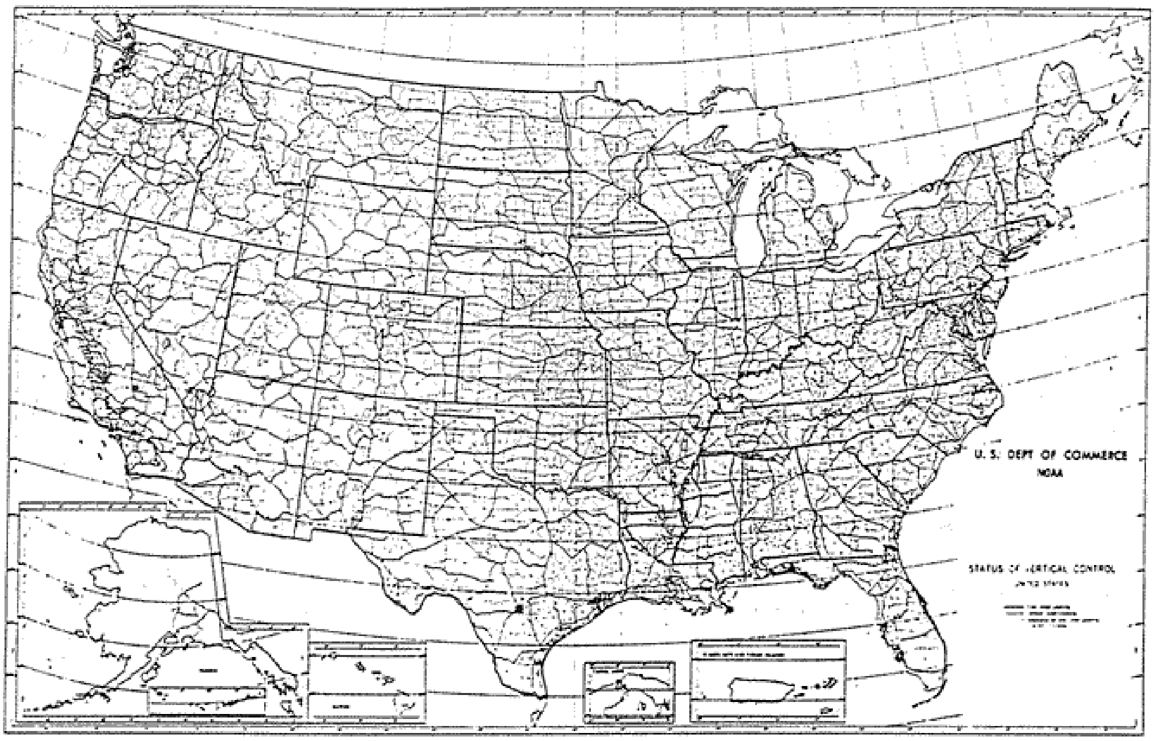

Figure 3. Vertical control used in 1988 adjustment.

Figure 1. Taken from Zilkoski et al. (1992) Figure 3. As a result of the adjustment, 505,000 bench marks were established.

NAVD 88 was an adjustment of geopotential numbers determined from the leveling and interpolated gravity. The adjustment was made using Helmert Blocking and tied to tide gauges from Father Point/Rimouski in Canada. All corrections were applied and data carefully collected and processed according to Bluebook procedures.

However, adjustment of such large amounts of data will result in errors. Figure 2 shows the tide gauge in Seattle, Washington. Note that the heights are given with respect to MLLW at that tide gauge. So local MSL is above 2 meters, but NVAD 88 is only above MLLW by 0.7 m. This means that the NAVD 88 datum is actually about 1.3 m below the actual sea surface.

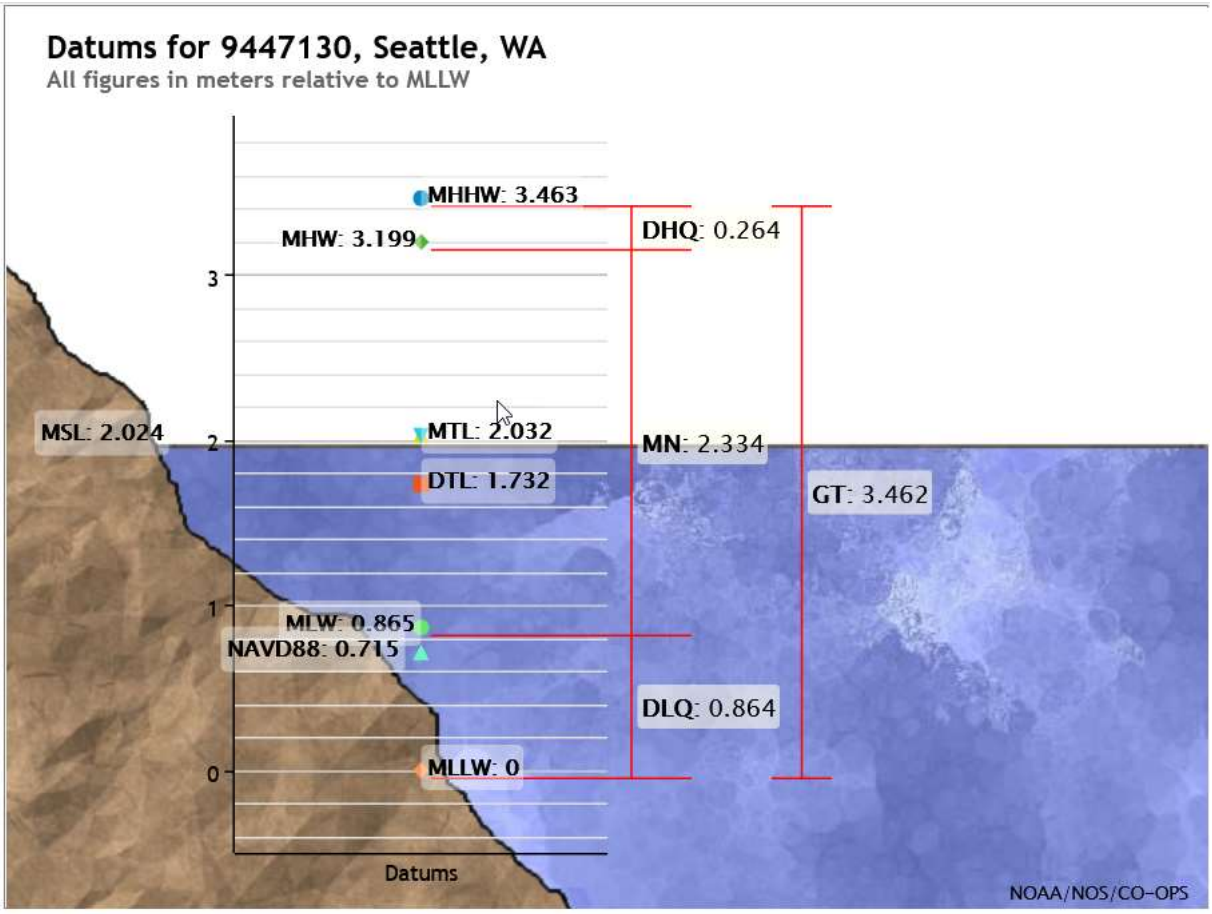

Figure 2. Tide gauge at Seattle, Washington showing various datums with respect to MLLW. Note that MSL is at +2.024 m,while NAVD 88 is a +0.715 m. This shows NAVD 88 to be 1.3 m below sea level.

Some of this may be due to variations in the topography of the sea surface, but that only accounts for 30-50 cm. Clearly then, a level datum is not sufficient for a continental scale vertical datum. Particularly when modern efforts are bent on melding different data together.

This paper follows two previous papers (Roman and Weston 2012, Roman and Li 2016) that described efforts to update the U.S. vertical datum. Roman (2018) described the vertical datum update as a part of a broader plan to update the U.S. National Spatial Reference System (NSRS) (Roman 2018). A broader international effort drives this need to adopt a common positioning framework for geometric and physical heights (e.g., heights above MSL). This paper focuses on how countries might optimize their efforts to update their respective NSRS to achieve a synergy of effort. Hence, this will eventually affect all surveying professionals, GIS programmers, and others who collect or maintain geospatial data.

Section 2 reviews international efforts to codify these international reference systems. Section 3 reviews the methodology described in Roman & Weston (2012) and Roman & Li (2016). Section 4 discusses practical considerations for determining an optimal geoid based vertical datum for a country. The final section summarizes the paper.

2. INTERNATIONAL CONTEXT

A United Nations General Assembly resolution (A/RES/69/266) formally established the need for a Global Geodetic Reference Frame (GGRF) in 2015. The management of geospatial information is the critical element in these national and international efforts. This means ensuring that all geospatial data are registered in common and accurate reference systems for both geometric coordinates and for physical heights tied to a vertical datum. All countries – not just the United States – will be pursuing updates to their respective NSRS. These updates will proceed using templates developed as a part of the Integrated Geospatial Information Framework (IGIF).

2.1 Global Geodetic Reference Frame (GGRF)

Per the UN –GGIM knowledge database:

> *"The Global Geodetic Reference Frame (GGRF) is a generic term describing the framework which allows users to precisely determine and express locations on the Earth, as well as to quantify changes of the Earth in space and time. Most areas of science and society at large depend on being able to determine positions at a high level of precision. At present the GGRF is realized through the International Terrestrial Reference Frame (ITRF), International Celestial Reference Frame (ICRF) and physical height systems."*

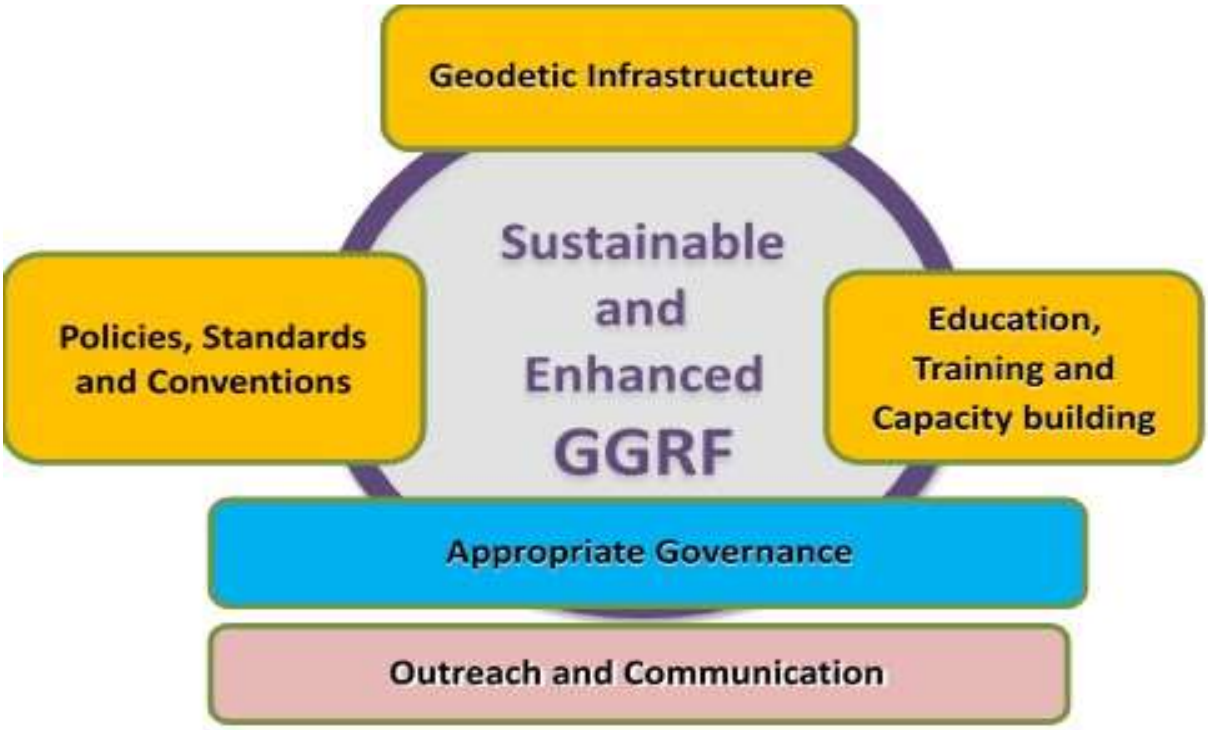

Figure 3. The five primary focus areass of the GGRF are shown above. The most central to UN efforts concerns governance.

Five main areas are laid out in Figure 3. Geodetic Infrastructure (GI) is the hardware that forms the basis for defining, maintaining and accessing a NSRS. CORS Networks are an example. Policies, Standards and Conventions (PSC) are how the GI is accessed. The procedures that must be followed; how the job is performed. In the U.S., this is traditionally the Bluebook standard. Now more broadly, ISO and OGC standards are to be followed. This includes ISO 19161-1:2020 – the ITRS (section 2.2). Education, Training and Capacity Building (ETCB) focuses on making sure that surveying professionals use the GI and the PSC correctly to get the optimal results.

Appropriate Governance is under the purview of the countries and, collectively, under the UN per the GGRF agreement. In the U.S, the Geospatial Data Act (GDA) codifies how geospatial data are to be collected, maintained and distributed by all US government agencies. It authorizes a central geospatial body for the entire US government – the Federal Geospatial Data Committee. This is probably the most critical element in the GGRF. Each country must have unity of effort to be successful. Hence, similar structures must be put in place – probably before all else. This will also come into play later when developing country plans (section 2.4).

Finally, outreach and communication is necessary not just for the UN to reach countries but also within each country to reach its citizens. This will ensure the broadest outreach to all professionals dealing with geospatial data. You can have the infrastructure, procedures, training, and laws in place, but you must make everyone aware that they need to use them.

2.2 International Terrestrial Reference System (ITRS)

As noted above, the GGRF will adopt the ITRS. There have been many realizations of frames in the ITRS. The most recent is ITRF2014 (Altamimi et al. 2016). However, the GGRF does not require all countries to adopt the same ITRF realization nor even the same epoch. All that is required is that they pick one. Rigorous mathematical transformations exist to shift from one realization to another, which thereby enables the international exchange of geospatial data – the whole intent of the GGRF and many of the UN SDG's. Practically then, a nation would adopt a specific realization of an ITRF model at a specific epoch (e.g., ITRF2014 at epoch 2010.0). Then a geopotential model might then utilize the geometric coordinates to determine physical heights above a geoid or quasi-geoid based vertical datum.

2.3 International Height Reference System (IHRS)

The IHRS is relatively recent compared to the ITRS. Ihde et al. (2017) discussed plans for unification of heights globally, which were updated more recently in Sanchez et al (2021). Just as ITRF realizations are made within the ITRS, there will be IHRF realizations made within the IHRS. The key concept here is that positions will first be realized in the ITRS and then expressed in the IHRS. This means that GNSS-accessed geodetic coordinates will determine your position in a realization of the ITRF. Using those ITRF coordinates, geopotential values will be determined from an equivalent IHRF model based above a datum of W_0 = 62,636,853.4 m^2 s^{-2}. This effectively gives your position in the Earth's gravity field, which is a physical height. In adopting such a model then, all countries might provide consistent physical heights across their national boundaries and over the oceans.

The IHRF will likely be based on some global geopotential model such as EGM2008 (Pavlis et al. 2012) or its successor the impending EGM2020. However, such GGM's lack sufficient resolution for all areas (best resolution is 5 arcminutes or about 11 km), and lack significant data in many areas (e.g., central South America). GGM's are usually augmented by airborne, shipborne, and terrestrial gravity observations to provide a more useful national datum. However, these are still based on the same datum (W_0) given above. Consideration may be given to looking at the offset to local tide gauges to establish a different geopotential value for a country. However, a transformation to the internationally accepted value should also be maintained.

Since most countries still rely on traditional leveling based datums such as NAVD 88, Sanchez et al. (2021) provided a mechanism for incorporating level datums into the IHRS. Principally through the geopotential number of the datum point. Recall that NAVD 88's datum was Father Point/Rimouski tide gauge in Canada. Hence, the geopotential value at that tide gauge can be determined. This would address how to incorporate the level network, but the inherent errors in the level network (e.g., the 1.3 m tilt in NAVD 88) would also translate into errors in the IHRF. This is not a mechanism for fixing bad data – only aligning it.

2.4 Integrated Geospatial Information Framework (IGIF)

The IGIF strengthens the geospatial information management both within a country and between countries in regional arrangements. It helps the countries develop a plan for all aspects of geospatial data. Within the IGIF, several specialized layers are being created. One such will be a geodetic layer designed to develop the essential geodetic elements given in the GGRF but expressed for each country's unique situation. Not all countries want or need VLBI antennas that must be maintained – not if they can gain the benefit of it through collaboration with others in the global community. This plan determines the requirements for a country's NSRS to underpin all geospatial data and tasks that involve such data.

3. METHODOLOGY REVIEW

Roman and Weston (2012) and Roman and Li (2016) highlight a potential approach for defining the optimal geopotential datum tied to the IHRS but accessed from the ITRS. In those papers, GNSS observations were made on 211 tide gauges scattered around the Atlantic, Gulf of Mexico, and Pacific Coasts. It is beyond the scope of this paper to discuss how geodetic coordinates are derived. The principal is that GNSS observations are made over a tidal bench mark, and then leveling transfers are made to the tide gauge to establish the geodetic coordinates of local MSL. These coordinates are then used in a geopotential model (e.g., EGM2008) to estimate the geopotential numbers at each tide gauge for local MSL (Figure 4).

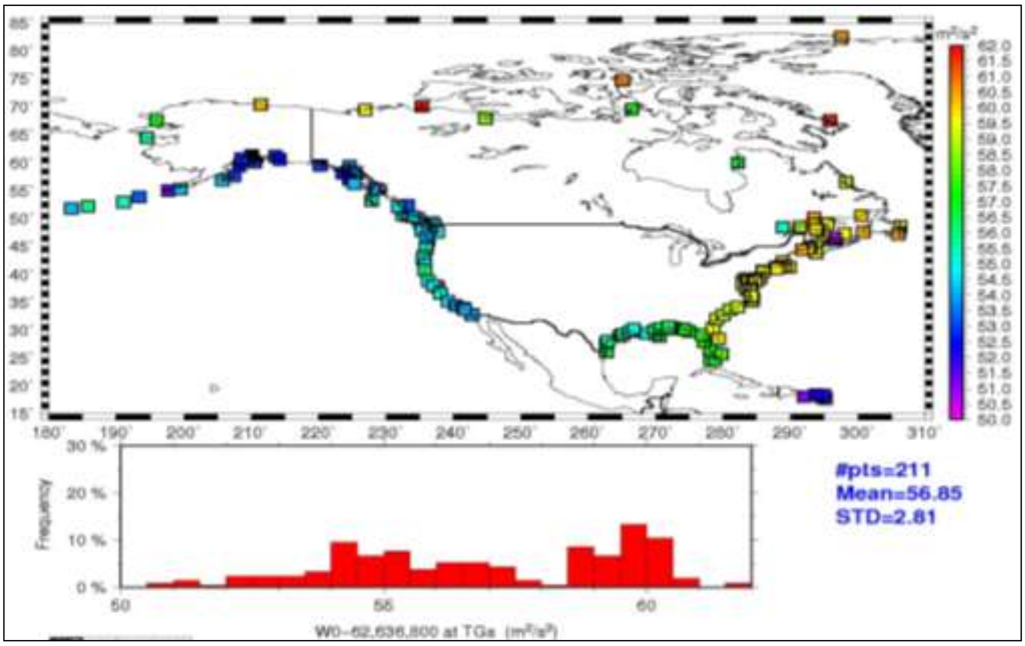

Figure 4 Geopotential values determined for tide gauges around Alaska, Canada, CONUS, and PRVI. The effects of TSS can be seen especially along the Atlantic Coast. A constant value of 62,636,800 was removed from all numbers. Based on this comparison, the average W_0 should be 62,636,856.85 m^2/s^2.

The effects of TSS can be seen along the Atlantic Coast. To convert the above to approximate dynamic heights, divide by 10 – rounding up from 9.8 m/s^2. This shows that realtive variations along the Atlantic Coast to be about 50 cm. The Pacific Coast and Gulf Coast are much more uniform.

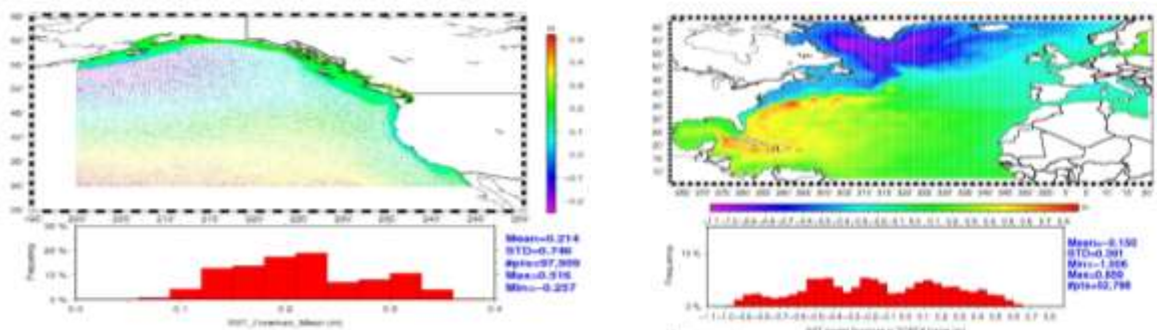

Figure 5 TSS Models for the Pacific (Foreman et al. 2008) and Atlantic (Thompson-Demiorov 2006). TSS models account for ocean surface variations away from a global norm (local vs. global MSL).

Two models (Foreman et al 2008, Thompson- and Demirove 2006), shown in Figure 5, were used to estimate and remove the effects of the TSS. In the image to the left in Figure 5, no significant variations are observed along the Pacific Coast. In the righthand image, multi-dm level variation can be seen along the Atlantic Coast. This reflects the warmer, less dense water of the Gulf Stream off of Florida that transitions to the colder, denser waters of the Labrador Current in the North. This TSS model reflects these lateral variations along the shoreline and are variations in Local MSL observed at tide gauges observed in Figure 4.

The desire is to remove these effects to determine the global MSL value. Hence the grids in Figure 5 are interpolated to the locations of the tide gauges to estimate TSS and remove it. Since the TSS grids do not overlap entirely in the space of the tide gauges, only 188 tide gauges are considered further. Figure 6 shows the variations at tide gauges after the TSS is removed. Note that there is greater consistency between the Pacific and Atlantic Coasts but that Gulf Coast shows a 30 cm relative bias. This possibly because the Thompson-Demnirov model was intended for the Atlantic and may have been less optimized for the Gulf Coast.

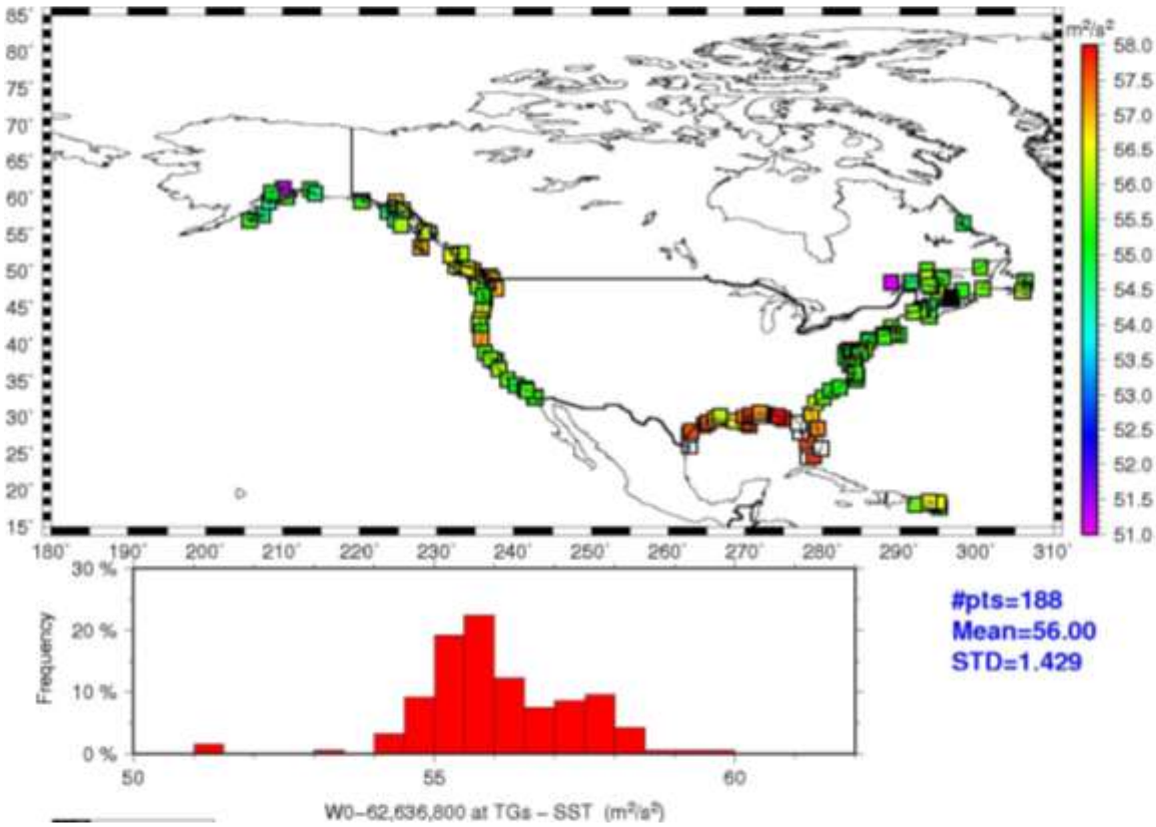

Figure 6. Geopotential numbers (Wi) were determined TBM/WLS along coastal regions of the U.S. and Canada except the Arctic using an enhanced EGM2008 model. To facilitate comparisons, 62,636,800.00 m2/s2 was removed. Add that to the mean above for an average geopotential surface of 62,636,856.00 m^2/s, which was adopted by the U.S. and Canada as the geoid datum surface.

4. DISCUSSION

The U.S. has significant advantages in terms of data collection and available models. However, the above case highlights a potential path for other countries seeking a vertical datum tied into the IHRS. Certainly having 200 tide gauges with a long time series is a great advantage. However, only a couple along the shoreline might be necessary providing that a suitable TSS model is available to provide detail along the shoreline between them.

The U.S. has coasts facing three ocean bodies and has a complicated ocean signal. This may be a similar circumstance for Central American Nations that border both the Caribbean and Paicifc. Significant TSS variations may occur between tide gauges on different coasts. There are global efforts at modeling TSS that may provide suitable models for use.

Finally, global gravity field models are being developed that have increasing resolution. EGM2008 and the eventual EGM2020 are 5 arcminute models – meaning a spatial resolution of 10 km half-wavelengths. A country might not have available gravity data or programming capability to generate a higher resolution geopotential model. However, advances are being made towards realizing global gravity models are 2.5 arcminutes (degree and order 5400).

Steps then that a country might take to invest in a vertical datum:

- Install and maintain a few select tide gauges to ensure a direct link to the ocean(s)
- Obtain or develop TSS models for lateral variations along the shoreline(s)
- Install suitable Geodetic Infrastructure to access the ITRS from GNSS observations
  - Observe GNSS on tidal bench marks around the tide gauges
  - Transfer the geodetic coordinates to the local MSL at the tide gauges
  - Remove the modeled TSS for the tide gauge
- Obtain or collect additional terrestrial or airborne gravity data
  - Augment a a reference global gravity model (e.g., EGM2020) from the IHRS
  - Use augmented GGM and geodetic coordinates to obtain geopotential values
  - Determine the optimal geopotential value for a vertical datum

Note also that for the U.S., the final selected value was 62,636,856.0 m^2/s^2. This varies by 0.6 m^2/s^2 or about 6 cm from the IHRS value. As long as the offset to the global value is known and an effective transformation is available, then the national vertical datum can be tied to the globally adopted value for the IHRS.

5. SUMMARY

There is a great deal of activity in modernizing how geospatial data are collected, processed and maintained globally. International agreements are in place to have everyone adopt the Global Geodetic Reference Frame to facilitate geospatial data transfer. The approach will be to realize coordinates in the International Terrestrial Reference Frame and then obtain physical heights from the International Height Reference Frame. Countries may adopt any realization of the ITRF but are restricted to a single geopotential value in the IHRF - W_0 = 62,636,853.4 m^2/s^2. If comparisons to local tide gauges demonstrate this is not optimum for national definitions of a vertical datum, then an alternate geopotential datum can be determined based on an approach that requires supplemental information.

GNSS-observations on multiple tide gauges will establish local Mean Sea Level and any variations due to Topography of the Sea Surface. A model of the TSS would be required to remove TSS effects at tide gauges to determine the geodetic coordinates of MSL. Use of a geopotential model enhanced by locally obtained gravity data would yield the geopotential number(s) at tide gauge(s). Assuming multiple tide gauges, then an average or some statsitcial analysis might be made to determine the optimal geopotential value to select as a geoid.

REFERENCES

Altamimi, Zuheir & Rebischung, Paul & Métivier, Laurent & Collilieux, Xavier. (2016). ITRF2014: A new release of the International Terrestrial Reference Frame modeling non-linear station motions: ITRF2014. Journal of Geophysical Research: Solid Earth. 121. https://doi.org /10.1002/2016JB013098.

GGRF: https://www.unggrf.org/

Foreman, MGG, WR Crawford, JY Cherniawsky, and J Galbraith (2004) Dynamic ocean topography for the northeast Pacific and its continental margins. GRL 35, 22. https://doi.org/10.1029/2008GL035152

IGIF: https://ggim.un.org/igif

Ihde, J., Sánchez, L., Barzaghi, R. *et al.* (2017) Definition and Proposed Realization of the International Height Reference System (IHRS). *Surv Geophys* 38, 549–570. https://doi.org/10.1007/s10712-017-9409-3

Pavlis, NK, SA Holmes, SC Kenyon, and JK Factor (2012), The development and evaluation of the Earth Gravitational Model 2008 (EGM2008), J. Geophys. Res.,117, B04406, doi:10.1029/2011JB008916.

Roman, DR (2018) United States NSRS 2022: Terrestrial Reference Frames, presented at FIG Congress 2018, Istanbul, Turkey 6-11 May, 2018.

Roman DR, and ND Weston (2012) Beyond GEOID12: Implementing a New Vertical Datum for North America, presented at the FIG Working Week 2012, Rome, Italy 6-10 May 2012.

Roman, DR, and X Li (2016) Physical Heights from GNSS-Derived Geometric Coordinates and a Geophysical Model**,** presented at FIG Working Week 2012, Rome, Italy 6-10 May 2012.

Sánchez, L., Ågren, J., Huang, J. *et al.* (2021) Strategy for the realisation of the International Height Reference System (IHRS). *J Geod* 95**,** 33 https://doi.org/10.1007/s00190-021-01481-0

Thompson, K. R., and E. Demirov (2006), Skewness of sea level variability of the world's oceans, *J. Geophys. Res.*, 111, C05005, doi:10.1029/2004JC002839

Zilkoski, DB, JH Richards, and GM Young (1992) Results of the General Adjustment of the North American Vertical Datum of 1988, American Congress on Surveying and Mapping *Surveying and Land Information Systems*, Vol. 52, No. 3, 1992, pp.133-149

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.

CONTACTS

Dr. Daniel Roman
NOAA’s National Geodetic Survey
SSMC3, N/NGS
1315 East-West Highway
Silver Spring MD
U.S.A
Tel. +1-240-533-9673
Fax + 1-301-713-4324
Email: dan.roman@noaa.gov
Web site: https://geodesy.noaa.gov/