Physical Heights from GNSS-Derived Geometric Coordinates and a Geophysical Model

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

Key words: GNSS/GPS, Positioning, Reference Frames, Geoid, Geopotential

SUMMARY

The U.S. will be implementing a new Geodetic Reference Datum of 2022 (GRD 22) to replace the North American Datum of 1983 (NAD 83) and the North American Vertical Datum of 1988 (NAVD 88). NAD 83 and NAVD 88 are mandated by legislation as the official definitions of the National Spatial Reference System (NSRS) for the United States. The National Geodetic Survey (NGS) has primary responsibility for maintaining the NSRS and will be implementing GRD 22 to provide improved access. It has long been a practice to use geometric coordinates and geoid height model to derive physical heights. This approach works within the accuracy of both the GNSS-derived geometric coordinates and the geopotential or geoid height model according to the simple linear relationship between ellipsoidal heights (h), orthometric heights (H) and geoid heights (N): $h = H + N$. Geoid Slope Validation Survey studies were completed in 2011 and 2014 to examine how well this approach could work. In particular, aerogravity from the Gravity for the Redefinition of the American Vertical Datum (GRAVD) Project were incorporated to resolve potential systematic errors in the terrestrial gravity data. The results of the published GSVS 11 study and the forthcoming GSVS 14 results all support achieving cm-level comparisons between rigorously collected GPS/leveling and gravimetric geoid heights used in conjunction with GNSS data processed using Online Positioning User Service (OPUS) tools. Similarly, geopotential values may be derived from underlying reference field models to determine dynamic heights for comparisons at water level stations along the shoreline of the oceans and Great Lakes for the U.S. and Canada. Comparisons with ocean Water Level Stations (WLS) were consistent at the dm-level, which is reasonable given the degree of uncertainty in the ocean topography that was removed. Comparisons at WLS on Lakes Superior and Erie achieved better results though still not at the desired mm-level envisioned for a replacement for the International Great Lakes Datum of 1985 (IGLD 85). The expectation is that this process or one similar to it will be adopted in 2022 for the U.S. as the means for accessing the NSRS.

Physical Heights from GNSS-Derived Geometric Coordinates and a Geophysical Model

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

1. INTRODUCTION

The National Geodetic Survey (NGS) is responsible for developing and maintaining access to the U.S. National Spatial Reference System (NSRS). This currently realized by the North American Datum of 1983 (NAD 83) (Schwarz and Wade 1990) and North American Vertical Datum of 1988 (NAVD 88) (Zilkoski et al. 1992). It has long been recognized that both NAD 83 and NAVD 88 are flawed as datums at the meter level nationally and inconsistent with other global and regional models (Smith et al. 2013a). To reduce the potential impact of this mismatch on GIS, surveying, engineering, and other communities, NGS will implement the Geodetic Reference Datum of 2022 (GRD 22) representing all geodetic components.

GNSS technology would be used to access the GRD 22, and online processing and models would develop geometric and geophysical heights as well as other aspects of the NSRS (e.g., gravity values). As envisioned in the current NGS Ten Year Plan (2013), 15 minutes of GNSS data would be needed to realize cm-level positioning. This requires sophisticated online processing that has modeled and accounted for many physical parameters that would otherwise dilute the precision of the coordinates. Likewise, an equally accurate geophysical model would be required to ensure that the total propagated error would remain below a centimeter – at least in the most ideal cases. Certainly, it will also be necessary to test these results against outside data of the highest quality to ensure the fidelity of the resulting datum. NGS has begun work on the third of three surveys designed to validate this approach. These Geoid Slope Validation Surveys (GSVS) have been conducted with an eye to testing profiles in varying terrain. Further testing has been made against shoreline data both for the oceans and on the Great Lakes. In the absence of disturbing forces, water will flow to a common geopotential surface. Hence, comparisons at Water Level Stations (WLS) in the vicinity of Tidal Bench Marks (TBM) will provide an important metric and tie to oceanographic datums.

Section 2 will provide a little more clarity on the current plans for GRD 22; discussing considerations for both the geometric and geophysical components. Section 3 will cover some of the broader results from recent GSVS results and the implications for GRD 22 in different conditions of ruggedness. Section 4 will cover the comparisons at both ocean and Great Lakes WLS. Section 5 will summarize and provide an outlook to future work.

2. GEODETIC REFERENCE DATUM OF 2022

GRD 22 will be realized through a combination of a geometric frame and a geopotential model. GRD 22 will replace both NAD 83 and NAVD 88 and serve as the principal means of accessing the NSRS within the U.S. The intended approach for use of GRD 22 is based on the simple linear relationship between heights. For orthometric heights this is as that the ellipsoid height (h) is equal to the orthometric height (H) added to the geoid height (N): h = H + N. For comparisons at WLS on the ocean, the sea surface topography (SST) must be removed from local MSL (LMSL) to derive a value equivalent to the geoid: N = LMSL – TSS.

Hence, models of SST are vital to determining the geoid at the shoreline and thereby ensuring agreement (Roman and Weston 2012). On large fresh water bodies such as the Great Lakes, SST is not perceived at an issue and has bene neglected for most purposes. Hydraulic correctors are applied to WLS stations but this is mainly intended to account for uncertainties in the development of IGLD 85 dynamic heights. The HC for Lake Superior range across nearly 15 cm, whereas those for Lakes Erie and Ontario are only a few cm. HC are less about the slope of the water surface than about the quality of the data.

2.1 Geometric Component

For both orthometric and dynamic heights, geometric coordinates will be determined first. It is expected that the most recent adoption of an IGS reference frame will be adopted as for the geometric component. ITRF2014 has been released on the web, and it is expected that a follow on IGS14 model will soon be released to model orbits and terrestrial positions. If no newer model has been released by 2022, then IGS14 will likely serve as the basis for GRD 22. While the geocenter of reference fame itself may be adopted, other aspects are still be debated. In particular, aspects related to velocities.

NAD 83 is a plate fixed model that removes velocities associated with the Stable North American Reference Frame (SNARF). To do this, Horizontal Time-Dependent Positioning (HTDP) software is used to remove velocities accounting for intraplate and geophysical motions (e.g., seismic shifts). HTDP is available for use through the NGS Tool Kit referenced in the weblinks at the end of this paper. For GRD 22, such a model may be employed though consideration is also being given to applying velocities for each plate. Alternatively, a simple Euler pole and plate rotation model may be applied or the velocities could be adopted from the IGS model. To best serve constituents, it is most likely that HTDP or a successor model would be adopted as this would perform the most rigorous accounting for velocities. A user could simply choose to adopt one of the simpler (and less rigorous) approaches outlined above as is currently permitted in HTDP.

The intent stated in the NGS Ten Year Plan is to access the NSRS through GRD 22 using only 15 minutes of GNSS data. This will require underpinning by detailed models and programming. The existing CORS Network (Snay and Soler 2000) may help to provide some assistance. The Online Positioning User Service (OPUS) Rapid Static (RS) solutions currently can generate solutions with less data, though not as low as 15 minutes. It relies on models generated from CORS site information to converge on a solution. Hence gaps in CORS coverage lead to poorer quality predictions or even no solution (Figure 1). Further resolution may be gained by use of Real Time Networks (RTN’s). While these are not going to be a part of the existing NGS network, guidelines and standards could be established so that RTN's could use a denser grid of stations to provide the requisite level of accuracy for minimum time on station. As should be clear from this discussion, not all aspects have been resolved on how best to achieve cm-level accuracy from only 15 minutes of data.

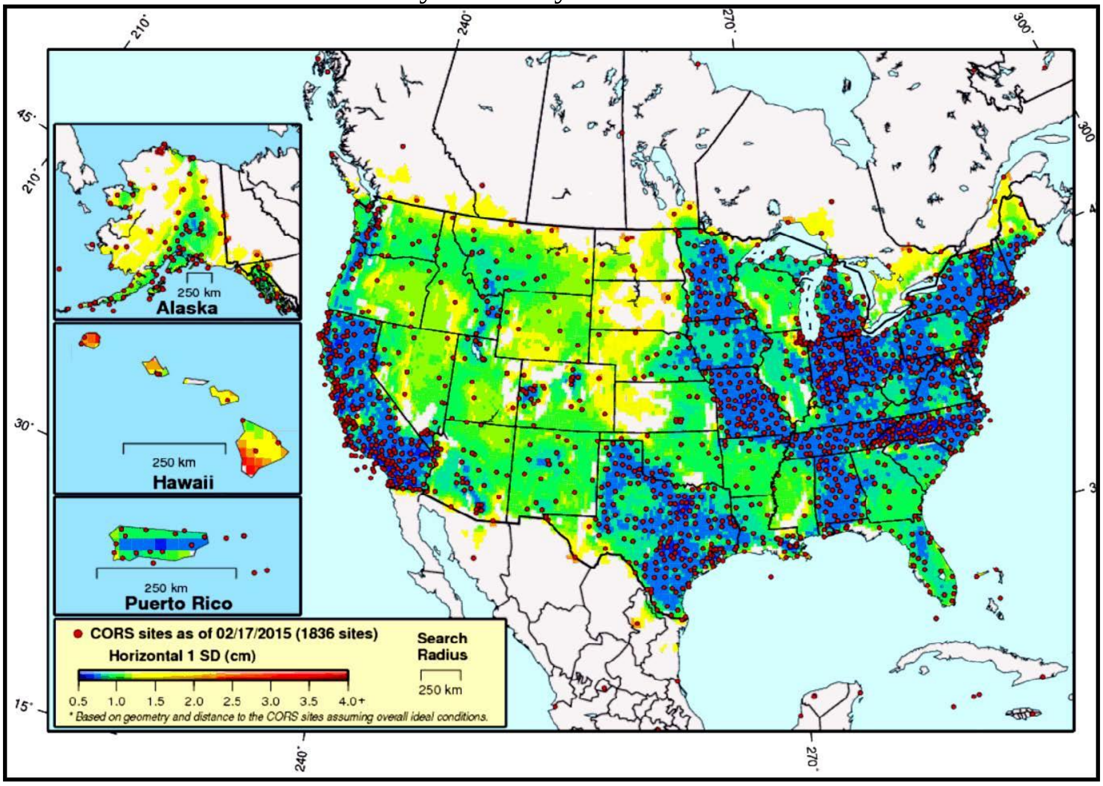

Figure 1 OPUS-RS error predictions based on distribution of CORS sites. Sparser distribution of CORS leads to poorer quality predictions.

2.2 Geophysical Component

The picture on the physical geodesy side is a little clearer. The Gravity for the Redefinition of the American Vertical Datum (GRAVD) Project (Smith 2007) has collected data for nearly a decade and is nearly 50% complete (Figure 2). Theses aerogravity profiles are required to produce an improved model over the U.S. mainland, Alaska, Hawaii, and territories such as American Samoa, Guam, and the Commonwealth of the Northern Mariana Islands (CNMI).

The intent of these aerogravity surveys is that they be blended with existing global gravity field models derived from satellite gravity field missions such as GRACE (Tapley et al. 2004) and GOCE (Pail et al. 2011).In turn, these data are currently combined with terrestrial data using a remove-compute-restore technique typical of previous NGS models (Wang et al. 2012). This is necessary because current reference field models, such as EGM2008 (Pavlis et al. 2012) are limited to five arcminute resolution. Previous NGS Analysis has shown that a minimum resolution of one arcminute signal is necessary to ensure that the omitted signal is less than a centimeter. Hence, it is necessary to enhance the reference field model to include the signal from one to five arcminutes to ensure the most optimum result. As computational power continues to increase, it is possible that a “reference” field model could achieve one arcminute resolution (e.g. Degree and Order 10,800).

As we are not there yet, experimental gravimetric geoid models are developed using the remove-compute restore technique while using a reference field model that includes the aerogravity signal. The latest such model is xGEOID15B and is available on the NGS Beta website (Figure 3). It is expected that there will be a new annual model released in June 2016.

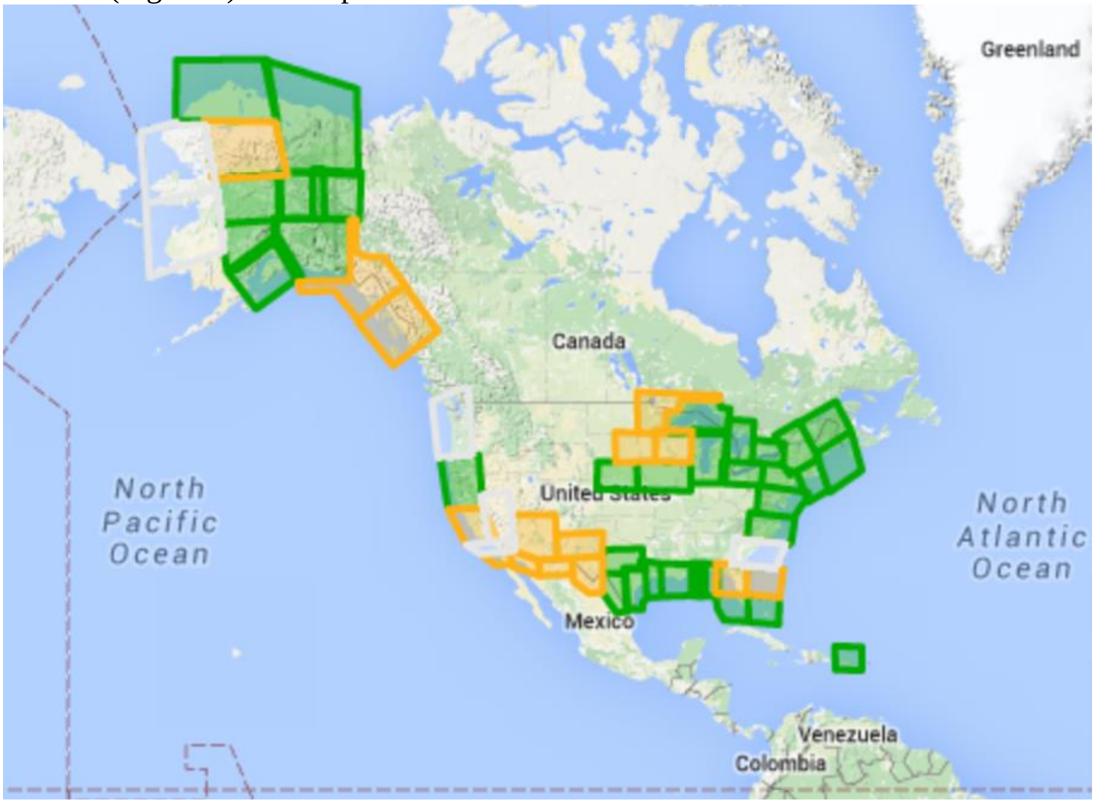

Figure 2 Extent of GRAVD coverage as of 13 February 2016. Nearly 50% complete. Green boxes are done and available. Yellow boxes are in progress. White are in planning. Not shown are hawaii, American Samoa, and Guam/CNMI.

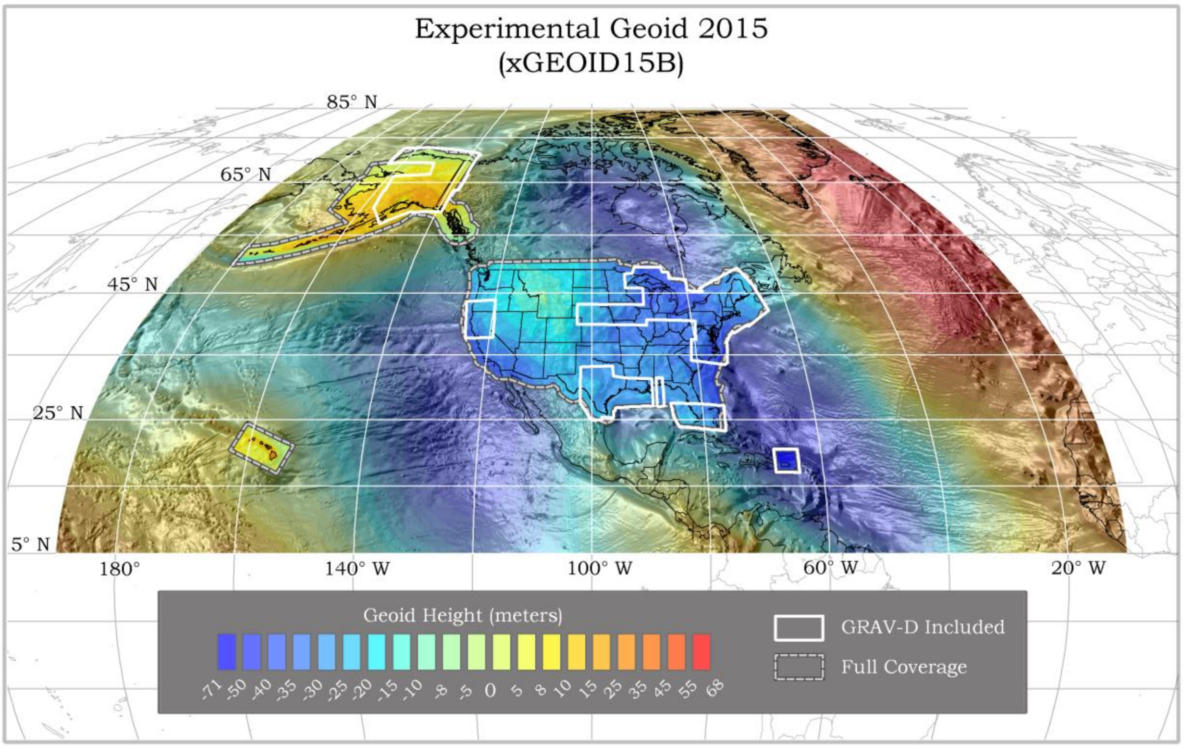

Figure 3 xGEOID15B with white boxes showing extent of processed aerogravity incorporated into the model.

3. GEOID SLOPE VALIDATION SURVEYS

While techniques are being refined to develop geometric positions and combine these with improved geoid height models, it is necessary to have a metric for validation/calibration. NGS conducted the Geoid Slope Validation Surveys (GSVS) for this purpose. Two such surveys have been completed and a third has begun mark setting with completion expected in 2017. These surveys collect GPS/leveling, relative/absolute gravity, and astrogeodetic Deflection of the Vertical measurements. Measurement of these different functionals of the gravity field permit a combined solution that provides the best means of analyzing geoid models.

3.1 GSVS 11

The first survey, GSVS 11, was conducted in Texas. The line stretched from Corpus Christi on the Gulf of Mexico inland to Austin. In general, it demonstrated that it is possible to achieve a cm-level accurate geoid model for vertical positions, especially using Online Positioning User Service (OPUS) tools such as OPUS Projects (OP) and OPUS-Rapid Static (OPUS-RS). OP was used to process GNSS observations along the line to obtain consistency at 0.4 cm between any of the 218 points along the 325 km long line. Leveling data closed at 1.3 cm for the entire length of the line. Comparison of the GPS/leveling data with a gravimetric geoid model calculated using the usual NGS remove-compute-restore technique (Smith et al. 2013b) were at the cm-level for any distance along the survey. While laudable for proving that it is possible to achieve the goal given in the NGS Ten Year Plan, it is also the simplest case. The terrain was very flat and the elevation of the profile was low and close to the geoid (MSL). As a result, errors were generally smaller since fewer assumptions about intervening masses were required. This study is complete and available for further details (Smith et al. 2013b).

3.2 GSVS 14

The second survey, GSVS 14, was conducted in central Iowa. A report on this is forthcoming later in 2016. There was moderate relief along this 320 km long line with a mean elevation of 350 m. More significantly, the mid-continental rift gravity field feature passed immediately underneath the center of the survey line. This feature has no expression on the surface and represents a fracture in the base of the continental crust that has been underplated by denser mantle material. This feature can be seen in global gravity field models but requires terrestrial and/or airborne gravity data to clarify it. This survey line then serves as an excellent test of the ability of a geoid model to capture such a feature.

Similar techniques were employed as were used in GSVS 11. GPS data were collected and processed using OPUS with an accuracy of 2 cm between any given pair of points out of the total of 204. Likewise, leveling data were processed using standard Bluebook procedures and the consistency between any bench mark is better than 1.25 cm. There 226 level bench marks observed to provide better ties into NAVD 88 to ensure that these data could be used to translate between datums. Preliminary comparisons show agreement with geoid models at between 1.3 to 1.7 cm for several models including xGEOID15B.

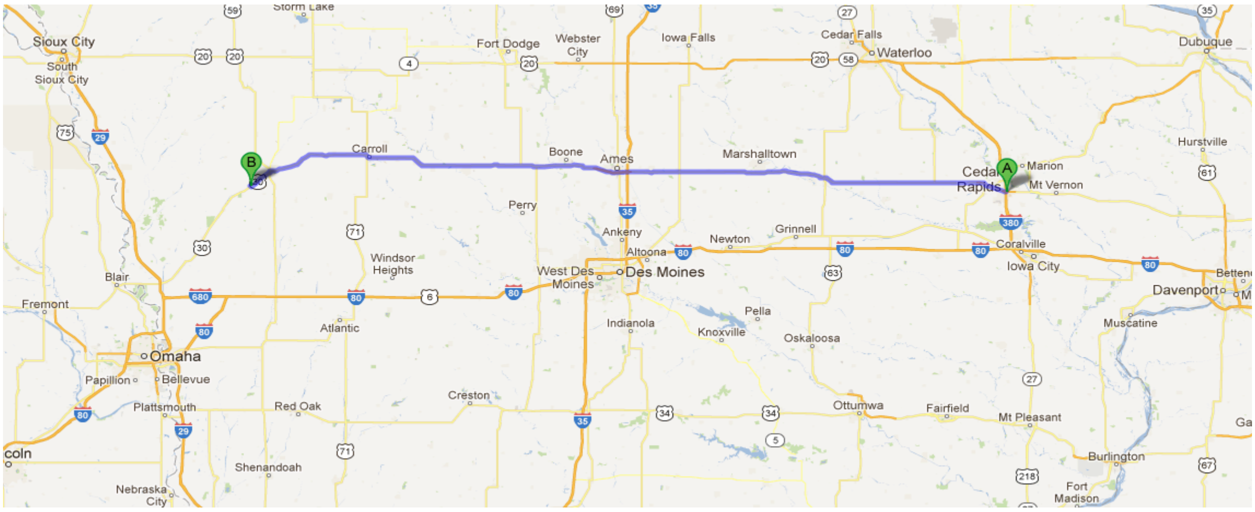

Figure 4 GSVS 14 survey line covering 320 km at 204 official GPS points. GPS, leveling, absolute/relative gravity and astrogeodetic Deflection of the Vertical data were observed along the line.

3.3 GSVS 17

The most difficult survey both for logistics and modeling will be the survey line passing through the Rocky Mountains along US160, from Durango to Walsenburg, in southern Colorado. Elevations will vary from 1.8 km to 3.4 km over two mountain passes. The relief will be very extreme and any errors in underpinning assumptions in physical geodesy will have much greater impact (i.e., density). Most of this survey line's bench marks have been emplaced, and the rest will be set later in 2016. It will be necessary for the marks to go through a freeze-thaw cycle before they can be used for survey purposes. Hence, the soonest this line will be run is 2017.

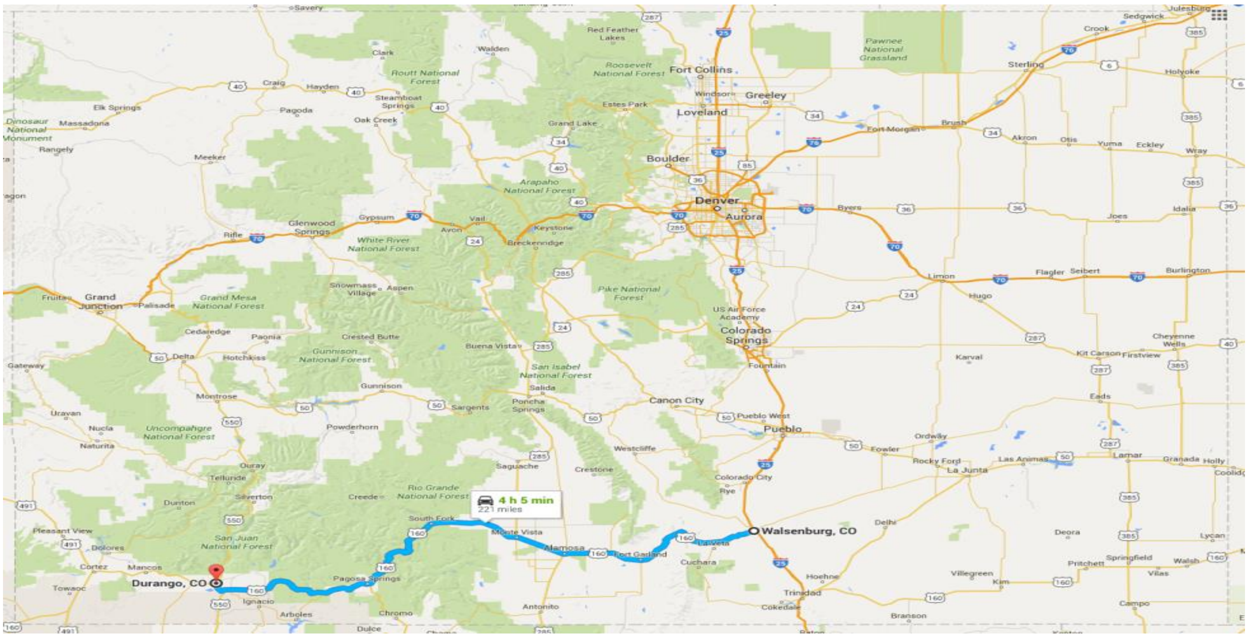

Figure 5 GSVS 17 is planned for about 300 km and 220 BM's with heights ranging between 1.8 – 3.4 km.

4. WATER LEVEL STATIONS

Another external data set for comparison is much more practical and of interest: the surface of bodies of water near the land. In particular, the ocean is of interest since that is the nominal datum selected from which heights are to be measured. Additionally, the Great Lakes are vast bodies of fresh water that serve as a means of navigation for commerce for both the U.S. and Canada. Hence WLS for both ocean tidal bench marks (TBM) as well as those in the vicinity of the Great Lakes were also examined using GPS and derived geoid models. NGS has responsibility for maintaining the datum coordinates on the TBMs, while the Center for Operational Ocean Products and Services (CO-OPS) has responsibility for the WLS.

4.1 Coastal Comparisons

Quantifying the geopotential of the ocean surface has been the subject of much debate (Burša et al. 1999, Sanchez 2007, Dayoub et al. 2011). For practical purposes, it was necessary to establish a value for the U.S. and Canada sooner rather than wait for this debate to be resolved. Canada adopted a geoid based datum in 2013 Véronneau et al. 2013a, 2013b) and needed an agreement on a specific value if the U.S. and Canada were ever going to develop a common datum surface in the future.

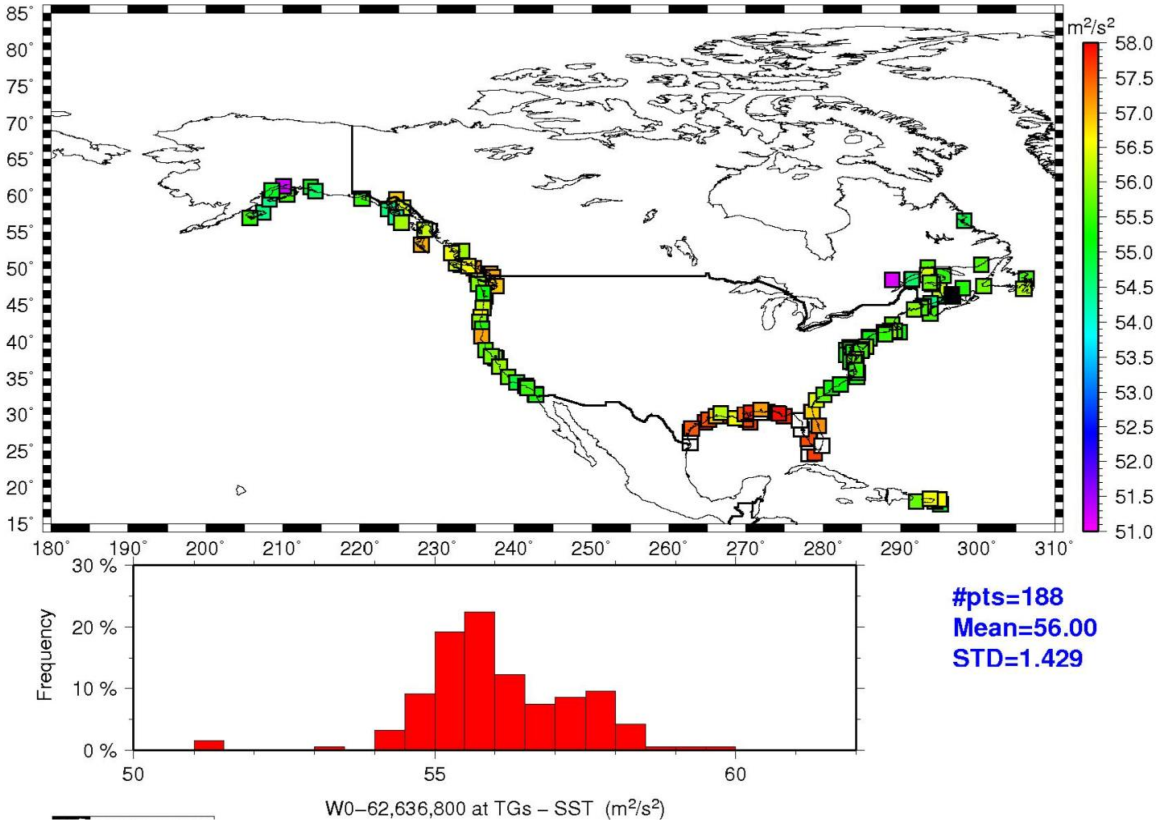

Figure 6 Geoptential numbers (W_i) were determined TBM/WLS along coastal regions of the U.S. and Canada except the Arctic using an enhanced EGM2008 model. To facilitate comparisons, 62,636,800.00 m2/s2 was removed. Add that to the mean above for an average geeoptential surface of 62,636,856.00 m^2/s,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

GPS on WLS located around ocean coasts of Canada and the U.S. (except the Arctic Ocean) were analyzed in 2012. Modeled ocean topography was removed from WLS observations of MSL to account for local MSL variations due to pressure, temperature and salinity variations (e.g. sea surface topography or SST). A geopotential model based on EGM2008 and enhanced by supplemental satellite and terrestrial gravity data was used to calculate the geopotential numbers (W_i) at each of the WLS. The average value was determined to remarkably close to the value adopted by the IERS convention: 62,636,856.00 m^2/s^2. The U.S. and Canada signed an agreement to adopt this value as the official geoid datum surface for both countries. It will be examined in the future, but it will likely stand as the datum surface though corrections may be applied for any time varying aspects of the geoid surface (e.g., Glacial Isostatic Adjustment near Hudson Bay). Figure 6 highlights the residual values at the WLS/TBM sites and emphasizes the dm-level consistency, which is remarkable given the limitations of the models and approach used. See Roman and Weston (2012) for further details.

4.2 Great Lakes Analysis

This final comparison comes after the completion of GRAVD surveys over the Great Lakes. There are numerous sites in the Great Lakes where WLS are situated (Figure 7). NGS conducts GPS campaigns on an annual to biennial basis to collect geodetic coordinates on the TBM's in the vicinity of the WLS. CO-OPS levels between the TBM and WLS to connect the water level datum measurements to the terrestrial datum. These efforts have been ramped up with the impending replacement of the International Great Lakes Datum of 1985 (IGLD 85) concurrent with the release of GRD 22. The data for the 53 NOAA sites are still being processed by NGS and CO-OPS. Both OP and traditional Bluebooking will be followed in an effort to ensure the integrity of the results. In the meantime, a subset of these data will be examined where greater surety of the geodetic coordinates is already established.

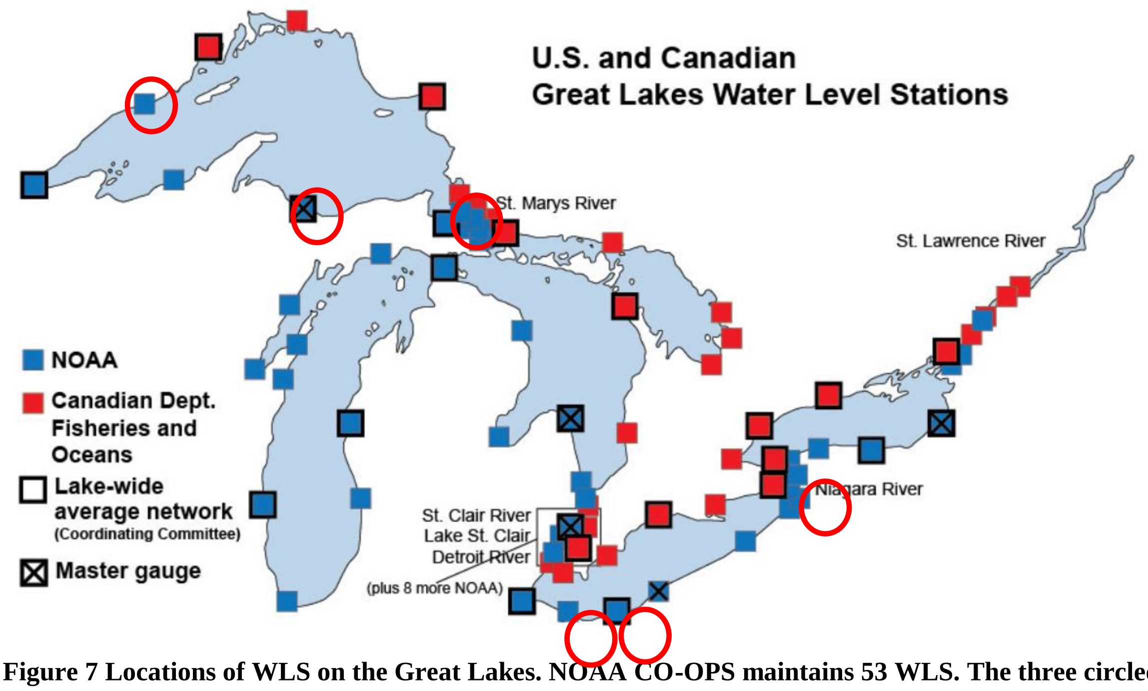

Figure 7 Locations of WLS on the Great Lakes. NOAA CO-OPS maintains 53 WLS. The three circled in red also given in Figuer 8 and will be the focus of further effort.

The CORS network has about 2000 stations. NGS is responsible for 39 with a few of those being WLS. Six were selected: three on Lake Erie and three on Lake Superior at the west, middle and east of each Lake. Figure 7 and 8 have red circles for the following sites moving from east to west: Buffalo, Cleveland, Marblehead (Sandusky), Point Iroquois, Marquette, and Grand Marais. The coordinates or the CORS ARP at each site are available from the site file. The metadata for the WLS provides the distance between the ARP and water level (WL). The ARP-WL value was subtracted from the ARP's height above ellipsoid (HAE) to determine the geodetic coordinates of the water surface as of December 2015. Table 2 shows the dynamic heights developed for these locations using four different geopotential models.

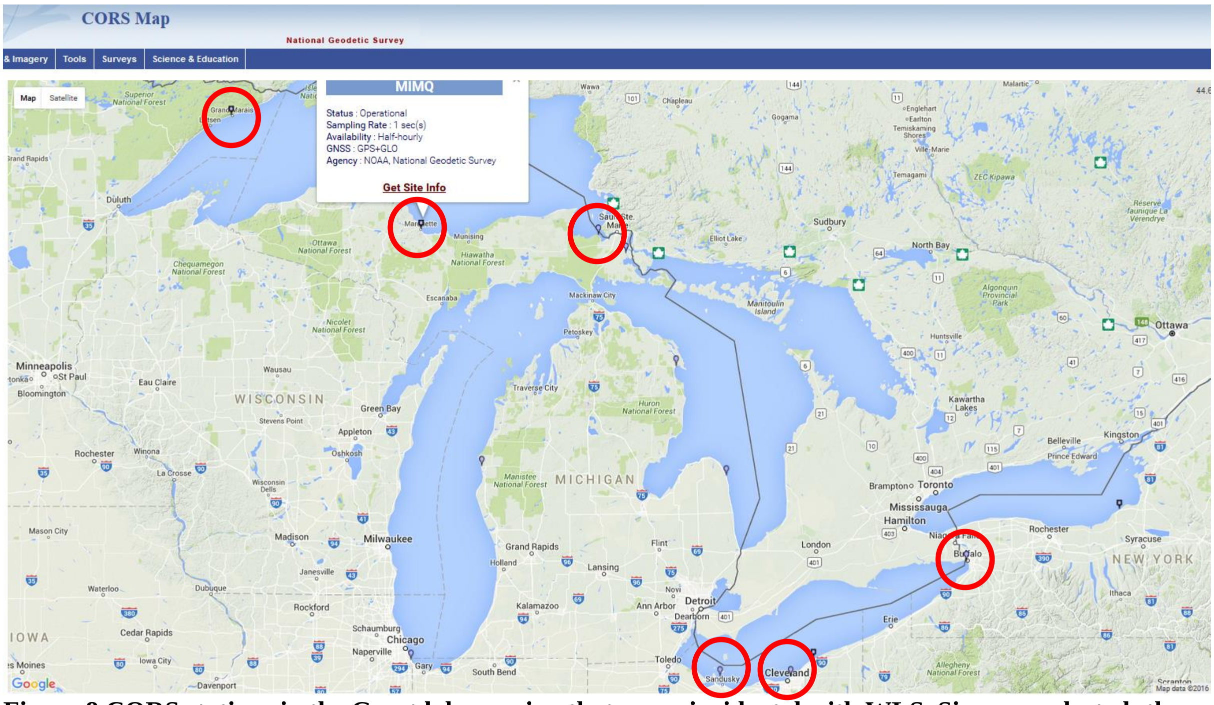

Figure 8 CORS stations in the Great lakes region that are coincidental with WLS. Six were selected: three from lake Erie and three from Lake Superior.

The results given in Table 2 must be considered for each Lake separately. Surprisingly the most agreement occurs on Lake Superior, which is known to have the greatest problems with dynamic heights. Hydraulic correctors are used in IGLD 85 to level the other WLS to the master tide station, but more plainly they are used to account for any misfit in the adjustments. For Lake Superior, the range of hydraulic correctors is from +4.6 cm to -10.0 cm. Yet, the three stations on Lake Superior agree with a few cm. Even the IGLD 85 dynamic heights show a drop of three cm at Point Iroquois, so the behavior there is consistent. Comparing the values for xGEODI15B_REF also shows good agreement. It should be noted that the reference field models all are five arcminute resolution. The derived geoid height model, xGEOID15B, has one arcminute resolution. The missing signal between one and five arcminutes likely must be accounted for if the goal is to achieve mm level consistency.

The case on Lake Erie is less clear. Even the existing IGLD 85 heights show Buffalo at the eastern end as being several centimeters higher than the western end. This is even more greatly exacerbated when looking at the four reference field models. What seems likely is that some static topography may exist on Lake Erie's eastern end. If the water were disturbed from equilibrium, then an underlying assumption in this paper is flawed. It has been assumed that no water surface topography exists other than that determined by the hydraulic correctors.

Table 1 Six CORS sites collocated with WLS on Lake Erie (top three) and Lake Superior (bottom three). Geodetic coordinates were transferred from CORS ARP to WL surface using CO-OPS site metadata.

Site	WLS ID	CORS ID	CORS ARP (IGS08)			ARP toWL (m)	WL HAE (m)
			Latitude (degrees N)	Longitude (degrees E)	HAE (m)		
Buffalo	9063020	BFNY	42.87755697	281.10955496	145.462	-7.610	137.852
Cleveland	9063063	OHCD	41.54074488	278.36485371	144.582	-5.932	138.650
Marblehead	9063079	OHMH	41.54368360	277.26854509	142.866	-5.357	137.509
Pt. Iroquois	9099004	PTIR	46.48458324	275.36915966	151.362	-5.399	145.963
Marquette	9099018	MIMQ	46.54554809	272.62130392	155.102	-7.337	147.765
Grand Marais	9099090	GDMA	47.74855226	269.65874853	157.364	-5.498	151.867

Table 2 The geodetic coordinates in Table 1 were applied to four different reference models and geoptential values calculated. These values were subtracted from the datum value (62,636,856.00 m^2/s^2) and then divided by normal gravity at 45 degrees latitude (9.806199 m/s^2) to determine dynamic heights. For reference, the actual IGLD 85 dynami heights for December 2015 are also given.

Site	IGLD 85 ht	Dynamic Heights (m) from Geopotential Numbers (W_i)			
		EGM2008	EIGEN6c4	xGEOID15A_REF	xGEOID15B_REF
Buffalo	174.197	173.653	173.635	173.652	173.648
Cleveland	174.158	173.582	173.570	173.564	173.586
Marblehead	174.144	173.541	173.544	173.571	173.566
Pt. Iroquois	183.580	182.901	182.897	182.911	182.906
Marquette	183.614	182.916	182.932	182.941	182.931
Grand Marais	183.613	182.890	182.891	182.908	182.919

Table 2 shows the results for comparisons using the EGM2008, EIGEN6C4 (Förste et al. 2014), xGEOID15A_REF, and xGEOID15B_REF models. The first two are self-explanatory. The last two were developed using EGM2008 as well as GRACE and GOCE data. For the xGEOID15B_REF model, the GRAVD aerogravity were also included. This is significant, because the current Canadian datum did not use GRAVD aerogravity largely due to comparisons to WLS in the Great Lakes. The principal reason given for rejecting the data was an apparent 10 cm slope up from the west to east on Lake Erie. It does not appear that the source of this slope lies in the GRAVD aerogravity as was earlier posited, but instead may be a function of physical water surface.

5. SUMMARY AND OUTLOOK

The National Geodetic Survey (NGS) will be replacing the existing North American Datum of 1983 and North American Vertical Datum of 1988 with a single Geodetic Reference Datum of 2022 (GRD 22) that will incorporate all aspects geometric and physical heights. GRD 22 will be accessed using GNSS technology. The specific nature of this access is largely open to debate but will likely involve the use of a suite of tools from the Online Positioning User Service (OPUS) possibly including OPUS-Projects and OPUS-Rapid Static. Further densification through the use of Real Time Networks may be useful though will not be maintained by NGS a core capability. NGS has clear guidance that it will not certify or oversee RTN's though tools will be made available to assist in assessing the quality of positions derived in such networks.

The geometric coordinates will be combined with a geopotential model to estimate physical heights. Providing an improved geopotential model has been a key task for NGS and the motivation for establish the Gravity for the Redefinition of the American Vertical Datum (GRAVD) Project. GRAVD has collected nearly half the required aerogravity necessary for completing a model over the U.S. These data have been combined in a series of experimental geoid models the latest of which is the xGEOID15B. These models were tested against Geoid Slope Validation Survey Studies in 2011 and 2014 with third planned in 2017. These surveys collected different aspects of the gravity field through observations of GPS/leveling, absolute/relative gravity observations, and Deflection of the Vertical along 300 km long profiles. The first two surveys are complete and have demonstrated that geoid models that include GRAVD observed aerogravity can achieve agreement with GSVS survey data at the cm-level.

Additional comparisons were made at Water Level Stations (WLS) along the oceans and on Lake Superior and Lake Erie. Comparisons at the shorelines were earlier and not made against models that incorporated GRAVD aerogravity. Additionally, ocean topography values were first removed – the reliability of which is reduced in nearshore environment. As a result, it is unsurprising that only dm-level comparisons were achieved. For Lakes Superior and Erie, the results were at the multi-centimeter level. This is better, though still not at the cm-level desired for the NGS Ten Year Plan.

Clearly more work is needed on how to better model and remove the disturbing effects on this positioning. For the physical heights, this entails a better understanding of ocean topography. Since GRAVD aerogravity profiles extend at least 100 km offshore, it is very much likely that the comparisons between the gravity geoid and ocean surface will result in improved estimates of ocean topography – thereby affording a better model for removal. Likewise, effects due too short wavelength errors in the gravity field data will be resolved with improved comparison to aerogravity data. Likewise, improvements in the determination of the geometric coordinates will be needed. GSVS studies demonstrated that it is possible to achieve cm-level accuracy for geometric positions using a variety of techniques. However, much work must be completed in order to develop a standard and application that can produce a result from only 15 minutes of data. Research is moving apace and will need to do so in order to implement a new datum in 2022.

REFERENCES

Burša, M., Kouba, J., Kumar, M., Müller, A., Radej, K., True, S. A., Vatrt, V. and Vojtíšková, M., 1999, 'Geoidal Geopotential and World Height System', Studia Geophysica et Geodaetica, 43, 4, pp. 327-337.

Dayoub, N., P Moore, SJ Edwards, and NT Penna (2011) The Geoid Geopotential Value for Unification of Vertical Datums, Paper 5023, presented at FIG Working Week 2011, Marrakech, Morocco, 18-22 May 2011
Förste, C., SL Bruinsma, O Abrikosov, J-M Lemoine, T Schaller, H-J Götze, J Ebbing, JC Marty, F Flechtner, G Balmino and R Biancale (2014) EIGEN6C4, presented at the 5th GOCE User Workshop, Paris, 25. – 28.11.2014.

NGS (2013) National Geodetic Survey Ten-Year Strategic Plan, http://www.ngs.noaa.gov/web/news/Ten_Year_Plan_2013-2023.pdf

Pail R, S Bruinsma, F Migliaccio, C Foerste, H Goiginger, W-D Schuh, E Höck, M Reguzzoni, JM Brockmann, O Abrikosov, M Veicherts, T Fecher, R Mayrhofer, I Krasbutter, F Sansò, CC Tscherning (2011) First GOCE gravity field models derived by three different approaches, J. Geodesy, 85 (11), 819-843, DOI: 10.1007/s00190-011-0467-x.

Pavlis, NK, SA Holmes, SC Kenyon, and JK Factor (2012) The development and evaluation of the Earth Gravitational Model 2008 (EGM2008), JGR, 117 (B4), Article Number: B04406, DOI: 10.1029/2011JB008916.

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.

Schwarz, CR and EB Wade (1990), The North American datum of 1983: Project methodology and execution, Bulletin Géodésique, March 1990, 64 (1): 28-62.

Saleh J, X Li, YM Wang, DR Roman, DA Smith (2013) Error analysis of the NGS' surface gravity database, J. Geodesy, 87: 203¬221.

Sanchez, L., 2007, Definition and realisation of the SIRGAS vertical reference system within a globally unified height system, In Dynamic Planet: Monitoring and Understanding a Dynamic Planet with Geodetic and Oceanographic Tools, 130, pp. 638-645.

Smith D (2007) The GRAV-D project: Gravity for the Redefinition of the American Vertical Datum. Available online at: http://www.ngs.noaa.gov/GRAV-D/pubs/GRAV-D_v2007_12_19.pdf

Smith DA, M Véronneau, DR Roman, J Huang, YM Wang, and MG Sideris (2013a) Towards the Unification of the Vertical Datum Over the North American Continent. Chapter 36 in: Z Altamimi and X Collilieux (eds.), Reference Frames for Applications in Geosciences, International Association of Geodesy Symposia 138, DOI 10./1007/978-3-642-32998-2_36 © Springer-Verlag Heidelberg 2013.

Smith DA, SA Holmes, X Li, S Guillaume, YM Wang, B Bürki, DR Roman, and TM Damiani (2013b) Confirming regional 1 cm differential geoid accuracy from airborne gravimetry: the Geoid Slope Validation Survey of 2011, J. Geodesy, 87 (10-12), 885-907.

Snay R and T Soler (2000) Modern Terrestrial Reference Systems, Part 2: The Evolution of NAD 83, Professional Surveyor, February.

Tapley, BD; Bettadpur, S; Watkins, M; Reigber, C. (2004) The gravity recovery and climate experiment: Mission overview and early results. GEOPHYSICAL RESEARCH LETTERS 31 (9): doi:, 2004.

Véronneau M, Huang J, Smith DA, Roman DR (2014a) Canada's new vertical datum: CGVD2013 (Part 1). XYHT magazine, October 2014, pp 43–45. http://e-ditionsbyfry.com/Olive/ODE/XYHT/Default.aspx?href=XYHT/2014/10/01

Véronneau M, Huang J, Smith DA, Roman DR (2014b) Canada's new vertical datum: CGVD2013 (Part 2). XYHT magazine, November 2014, pp 41–43. http://e-ditionsbyfry.com/Olive/ODE/XYHT/Default.aspx?href=XYHT/2014/11/01

Wang, YM, J Saleh, X Li, and DR Roman (2012) The US Gravimetric Geoid of 2009 (USGG2009): model development and evaluation, J. Geodesy, 86: 165-180.

Zilkoski, DB, JH Richards, and GM Young (1992) Results of the General Adjustment of the North American Vertical Datum of 1988, SaLIS, 52(3): 133-149.

BIOGRAPHICAL NOTES

Daniel Roman is serving as the Chief, Spatial Reference Systems Division at the U.S. National Geodetic Survey, while continuing to serve as the GRAV-D P.I. for development of a geopotential model to incorporate into the Geodetic Reference Datum of 2022 (GRD 22).

Xiaopeng Li is an employee of Data System Technology, Inc. and is contracted to NGS. He assists with spherical/ellipsoidal harmonic modeling efforts as well as geoid modeling efforts for various official and scientific purposes.

CONTACTS

Dr. Daniel Roman
National Geodetic Survey
SSMC 3, N/NGS6, #8813
1315 East-West Highway
Silver Spring MD 20910
U.S.A.
Tel. +1-301-713-3200 x103

Fax + 1-301-713-4324
Email: dan.roman@noaa.gov
Web sites: http://www.ngs.noaa.gov/TOOLS/
http://www.ngs.noaa.gov/CORS/
http://beta.ngs.noaa.gov/GEOID/xGEOID15/
http://www.ngs.noaa.gov/GEOID/GSVS14/
http://tidesandcurrents.noaa.gov/