Implementing Geometric and Geophysical Datums for the United States in 2022

Daniel ROMAN, U.S.A.

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SUMMARY

Use of GNSS-accessed geospatial data has proliferated not only within the surveying community but also into many related and dependent fields of work. These requirements approach the cm-level for coordinate determination with respect to both vertical and geodetic datums – often times with demands for real time or near real time coordinates. GNSS technology and tools have significantly improved in timeliness and accuracy of positioning in a geodetic or geometric datum. New data and processing techniques have also resulted in updated national geoids of increasing accuracy to serve as future vertical or geopotential datums. Such geoid models have been compared to external data sets such as tide gauges and astrogeodetic deflections of the vertical to provide calibration/validation with respect to real physical surfaces such as the ocean surface. This presentation will focus on some of the tasks and plans for developing, implementing and accessing these new datums by 2022 for the United States. The National Geodetic Survey has primary responsibility within the U.S. for developing and maintaining such datums, and has a stated goal of achieving cm-level accurate geometric coordinates and geophysical heights using only 15 minutes of GNSS data in combination with a gravimetric geoid model. To achieve these goals will require the near term definition of the requirements for both the reference frame and the necessary GNSS infrastructure. This process is well under way and tools are likewise being examined that will serve provide for such positional determination. Likewise the Gravity for the Redefinition of the American Vertical Datum (GRAV-D) Project aids the determination of systematic errors in the existing two million gravity points held by NGS. Comparison the National Water Level Observation Network (NWLON) at tide gauges along the U.S Shoreline also aids in determining the fit of the geopotential datum to the real physical heights above the ocean. Comparisons are also planned along river datums such as the Columbia River Datum (CRD). The planning and implementation for these new datums will impact other U.S. agencies (such as FEMA and USACE) but also impacts local and emergency planning at the state and local levels – all of which impacts the surveying, GIS and other industries. Outreach must also begin now to make such a change within the next decade.

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1. INTRODUCTION

The National Geodetic Survey (NGS) is a program office inside of the National Oceanic and Atmospheric Administration (NOAA), which has the responsibility of maintaining the official coordinate system of the United States – the National Spatial Reference System (NSRS). All federal civilian maps and charts refer to the NSRS. Hence most scientific, engineering and commercial applications rely upon it as well to ensure that their products and analyses are consistent within the same geospatial reference. The most recent version of the NSRS is defined by the North American Datum of 1983 (NAD 83) and the North American Vertical Datum of 1988 (NAVD 88).

These two datums are known to be flawed at the meter level and are scheduled to be replaced in 2022 by reference frames that utlize Global Navigation Satellite Systems (GNSS) such as the Global Positioning System (GPS) as the primary means of access (NGS 2013). A geometric datum will be accessed using GNSS data processed through a suite of software on the Online Positioning User Service (OPUS) website. The resulting geometric position will then be used to access a geopotential datum via a geoid height model entirely defined from gravity field data. In turn, the geophysical datum will be compared via vetted models against other physical surfaces such as the tidal datum defined through the National Water Level Observation Network (NWLON).

This paper will first cover the geometric datum including NAD 83 and the likely characteristics of its replacement. Next will be a discussion of the geopotential datum incuding a discussion NAVD 88 and its replacement. Some initial comparison work with the tidal comparisons is covered and then a summary is provided.

2. GEOMETRIC DATUM

2.1 North American Datum of 1983 (NAD 83)

2.1.1 Background

The original North American Datum of 1983 (Zilkoski 1986) was defined strictly as a horizontal network with only latitude and longitude coordinates determined from traditional techniques (e.g., turning angles). Almost as soon as it was defined, GPS arose and a global geocentric model was defined. This model was developed relatively early in the history of GPS and the geocenter of the resulting reference frame was offset by 2.2 m from what is realized by modern reference frames.

Since this model, and the inherent reference frame error, has been adopted into cadastral laws defined by the states in the United States, simply changing the geocenter is not viable. Current realizations of NAD 83 only provide more refined positions within this same reference frame. A new, more geocentric reference frame will need to be developed and adopted to overcome this. Significant legislative action will also be needed to amend cadastral laws defined in the states of the U.S. This will require equally significant outreach and education by NGS.

2.1.2 How it is Currently Accessed

The official values for NAD 83 remain defined at passive bench marks only. Coordinates derived through OPUS and similar software suites provide values that are consistent with but are not definitive within NAD 83. Datasheets can be generated on the fly from the existing NGS database to provide starting coordinates for a survey campaign. A campaign of observations must incorporate many established BM's and then an adjustment completed by NGS staff must be made to develop final NAD 83 coordinates on the new BM's.

2.1.3 Inherent Problems with NAD 83

The primary defect in NAD 83 has been noted above – namely, that its geocenter is offset from what is realized by modern reference frames such as IGS08. Figure 1 highlights the offset and makes clear the impact in a vertical sense caused by this offset. This has caused difficulties in the past when users have entered the wrong reference frame or applied an incorrect geoid height model to derive positions. When overall accuracy of GPS solutions was at the meter level, such errors were generally acceptable. With updated processing techniques and incorporation of other GNSS, the resulting accuracy of the solutions has become much better. This then leads to potential problems where precision navigation is required. Either great care must be taken to account for the datum differences, or a new reference frame must be defined that removes or mitigates the differences by making it consistent with the others.

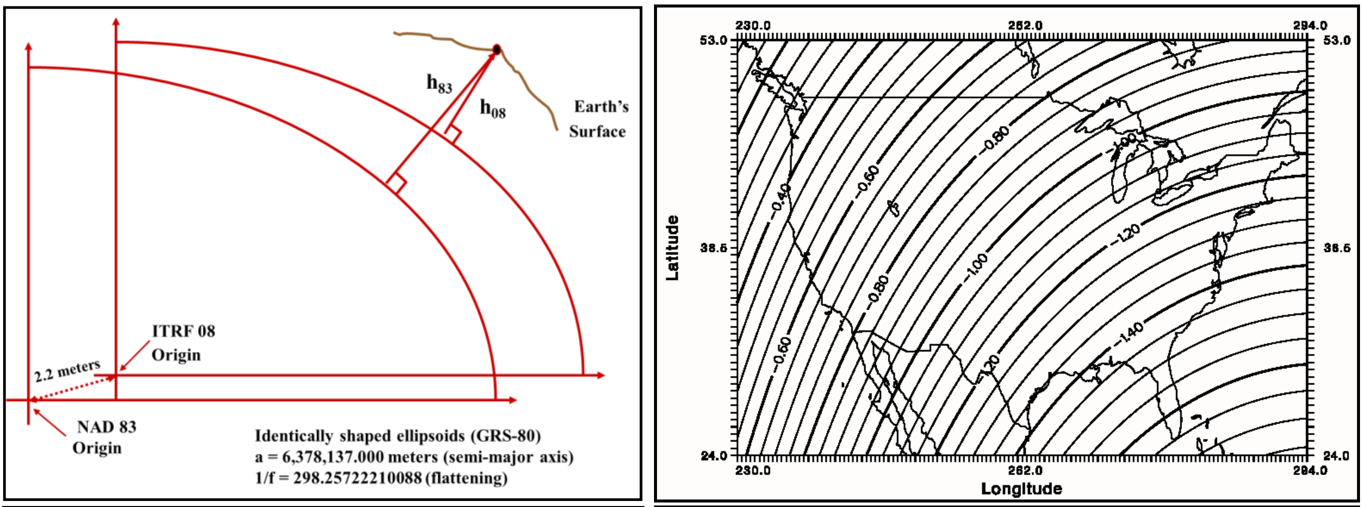

Figure 1. Left image shows depiction of offset between NAD 83 and ITRF00 geocenters. Right image shows impact in vertical across the U.S.

2.2 NAD 2022

2.2.1 Discussions on Replacement Datum

A new geometric datum will be defined in the next few years and implemented in 2022. Nothing definitive has yet been determined regarding the new geometric datum for 2022 though several key internal agreements have been made and these are relayed here. Foremost is that no definitive name has been established for the new datum. NAD 2022, as given in the title of this section is strictly a placeholder for this paper.

NGS will continue to rely on the IGS frames as the foundational geometric reference frame of the NSRS for the foreseeable future. Because NGS relies on IGS coordinates and IGS orbits, NGS will continue the practice (begun around 2008) of stating that coordinates coming out of OPUS (and other tools) will specify the frame as IGS and not ITRF. NGS will continue to use GRS-80 as the default ellipsoid for all official products for the foreseeable future.

NAD 2022 will likely adopt a future IGS reference frame. Subsequent IGS models will have slightly different frames but all will be very close – likely to within the accuracy required for most applications. This will certainly be better than the 2.2 meter offset in NAD 83.

One area that remains open is whether the model will be plate-fixed or have velocities. NAD 83 is plate fixed. However, this is accomplished by solving for IGS08 coordinates and using a velocity model to rotate back to a fixed epoch where the transformation to NAD 83 is accomplished. NAD 2022 could be defined with these velocities as a part of it. To satisfy user needs that positions remain "fixed", a specific epoch (e.g., 2022.0) would be adopted so that any future observations would be rotated back to a fixed point in time. This would be the equivalent of plate fixed model with State Plane Projections would be applied at that epoch.

2.2.2 Likely Implementation

As envisioned at this point, the access will be built from a top-down system starting with a reference frame drawn from the most recent IGS solution to the 2022 publication date. It is speculative to pick a specific date, but IGS publications are roughly every five years. It is expected that IGS will shortly release a 2013 (e.g., IGS13) model. Hence a possible update will follow on in about 2019. If no new model follows after the next release, then we'll use the IGS13 model as a reference for developing NAD 2022.

As a part of defining the IGS model, NGS contributes data into the solution. There are about 14 sites around North America that serve to define this global GNSS-only solution. NGS looks to increase the number of contributed sites by developing the so-called Foundation CORS. After the IGS solution is complete, these Foundation CORS sites, which are inherently defined in the IGS model, will define the positions of the entire CORS Network. In turn then, the CORS Network sites will provide access to NSRS for the user communities.

The newly defined NAD 2022 should have an explicit relationship to the IGS model – possibly exact. As new IGS solutions are generated, a rigorous transformation will continue to exist with the NAD 2022. This transformation will be maintained to ensure that observations in future IGS models will be consistently and accurately transformed into NAD 2022.

Then GNSS observations from a single point or local observation network would be submitted through OPUS to obtain coordinates in NAD 2022 (Weston et al. 2007). In particular, either OPUS-Net or OPUS-Projects or some similar processing software would be utilized to relate the rover points to the geometric datum. Real Time Kinematic (RTK) positioning would also be tied into this framework via RTK Network (RTN) Validation Tool to ensure that derived positions on other networks are consistent within the NSRS and with each other. The net result should be GNSS accessed coordinates processed using CORS data and rover observations. In effect, the CORS Network substitutes for the existing static NAD 83 bench mark data set.

3. GEOPOTENTIAL DATUM

3.1 North American Vertical Datum of 1988 (NAVD 88)

3.1.1 Background

NAVD 88 was developed from over a million kilometers of leveling at 700,000 bench marks tied at one tide gauge (Zilkoski et al. 1992). It was developed to remove the flexures caused by adopting multiple tide gauges, which do not account for local mean sea level variations caused by dynamic ocean topography. Height differences on level loop segments were reduced to geopotential numbers using assumed average gravity values. Geopotential differences on line segments common to different loops were adjusted using Helmert blocking, and a network solution was developed for relative geopotential differences. When the gravity values were reapplied, the resulting relative Helmert orthometric heights were given an absolute value by assuming the height at the tide gauge of Father Point/Rimouski as being the datum.

3.1.2 How it is Currently Accessed

Much as with NAD 83, NAVD 88 is accessed through passive bench mark with values obtained by users from datasheets that are generated on the fly from tables of data stored in NGS servers. As new data are added to the database, they are constrained to fit the existing level BM's and utilize the same gravity field model used in the original NAVD 88 determination. This ensures a consistent result, which can faithfully replicate the datum at new points but does not necessarily mean that it is more accurate.

To expand on the existing data points, Height Modernization techniques are followed. Details for these are given in the NOS/NGS 58/59 Guidelines (NGS 1997, 2008). An example of the complicated and cumbersome procedure for this is laid out in NOS/NGS 58/59 is currently being updated to reflect vastly improved techniques and will likely involve significantly shorter occupation times and observation requirements to establish such control in the future.

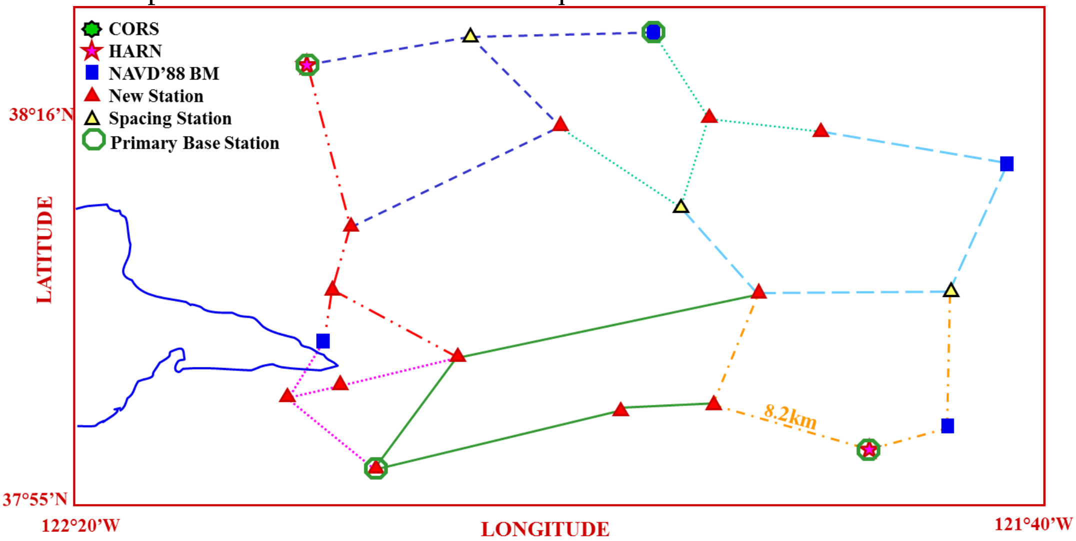

Figure 2 Sample layout for a network that must be established to develop new BM control. New and existing stations must be occupied with GPS & leveling to ensure consistency in the resulting coordinates.

3.1.3 Inherent Problems with NAVD 88

GPS-derived ellipsoid heights on leveled Bench Marks (GPSBMs) provide control for creating hybrid geoid models such as GEOID12A. These data provide point estimates of the separation between NAD 83 and NAVD 88. When a geoid height model derived entirely from GRACE (Tapley et al. 2004) and GOCE (Drinkwater 2006) was compared at these points, the differences reflect the omitted satellite signal and systematic differences between NAVD 88 and the geoid surface reflected by the satellite data.

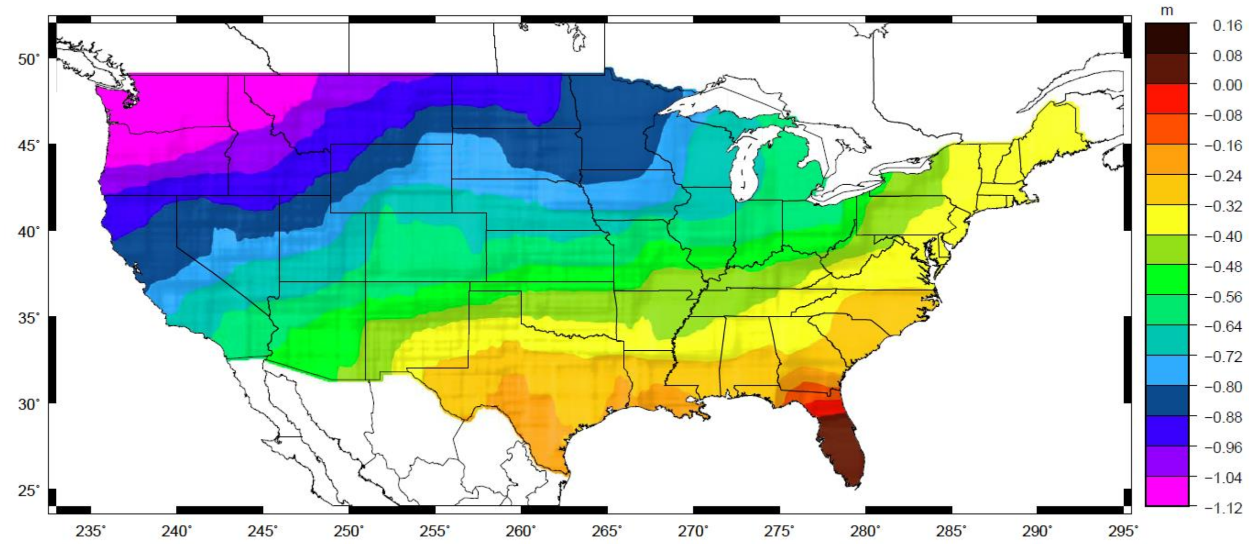

Figure 3 Differences between NAVD 88 and a GRACE-derived geoid at over 25,000 GPS-derived ellipsoid heights on leveled bench marks. Differences were filtered to emphasize those portions of the signal to which GRACE was sensitive (100 km for cm-level accuracy). Note 1.2 m trend and 0.5 m bias.

The combination of GRACE and GOCE are defined to be about cm-level accurate at scales of about 200 km for the most recent versions. By applying commensurate a long wavelength filter to the residual values on the bench marks, the long wavelength systematic differences are highlighted. Figure 3 highlights the 1.2 meter level trend from the Northeast to the Southwest (Smith et al. 2013). The offset of 0.5 meter is based on use of geopotential datum value determined from tide gauges (see section 4).

3.2 NAVD 2022

3.2.1 Discussions on Replacement Datum

The primary means for accessing the geopotential datum will be through a gravimetric geoid that is built on a combination of GRACE & GOCE global models and that incorporates available terrestrial gravity. To ensure continuity in the spectral wavelengths and to correct known errors in the terrestrial gravity data (Saleh et al. 2012), airborne gravity is being flown across the entire U.S. and its territories as a part of the Gravity for the Redefinition of the American Vertical Datum (GRAV-D) Project (NGS 2007). Experimental models have already been developed and are available on the web at http://beta.ngs.noaa.gov/GEOID/xGEOID14/.

Several other factors tmust be assessed on how this model will be developed and maintained. After an episodic-permanent event such as an Earthquake which exceeds some to-be-determined threshold magnitude, NGS will re-fly airborne gravity over the area and compute (at least internally) a new geoid incorporating this change. Episodic-temporary events will not trigger an NGS re-survey in and of themselves. If a satellite mission is flying during such an event, NGS will compute (internally) a geoid using this new data caused by this event.

NGS will not incorporate localized-periodic events into the geoid. If satellite date exists to allow this signal to be averaged out, it will be averaged out and its time dependency not incorporated into the geoid. NGS will incorporate the direct effect (shape change of the geopotential field) of secular mass changes into the geoid. One item that remains open though is in regards to whether the geopotential surface will be updated with sea level change.

3.2.2 Likely Implementation

With GNSS access, a simple linear model will be applied to develop orthometric heights:

$$H = h - N$$

Where: H = orthometric height
h = ellipsoid height from GNSS solution in OPUS
N = geoid height from model

The main difficulty with this process remains the random error associated with the ellipsoid height being generated. Random errors would directly propagate into the solution. However, software such as OPUS-Projects is designed to develop a local network that is tied into the NSRS through CORS. The tie to CORS establishes the coordinates in the new geometric datum, while the local network establishes accuracy and some degree of refinement to mitigate the random component.

However, this is not intended to replace local leveling. This method might establish a local bench mark for control, but local leveling will remain the preferred method for establish local control and determination of fluid flow. By using the geoid based height system, orthometric heights will be determined locally that are consistent with others throughout all of the United States – from Hawaii to Alaska, to the mainland U.S. to Puerto Rico. Further outlying regions such as American Samoa, Guam, and the Commonwealth of the Marianas Islands will have models derived following similar techniques and should have consistent results. Such models will be locally very dense and consistent and will provide an excellent common datum for comparison to other physical surfaces such as river datums or tidal datums.

4. NWLON DATA

To determine which geopotential value to adopt for the geoid surface, several alternatives were examined. There were multiple recommendations made based on various analyses. However, it was decided in the end that the most practical was to use tidal bench marks. Implementing the new datums will require significant outreach. By choosing to use tide gauge data, this was something readily visible to customer communities and with a solid tie to a surface of concern to most of them - the ocean.

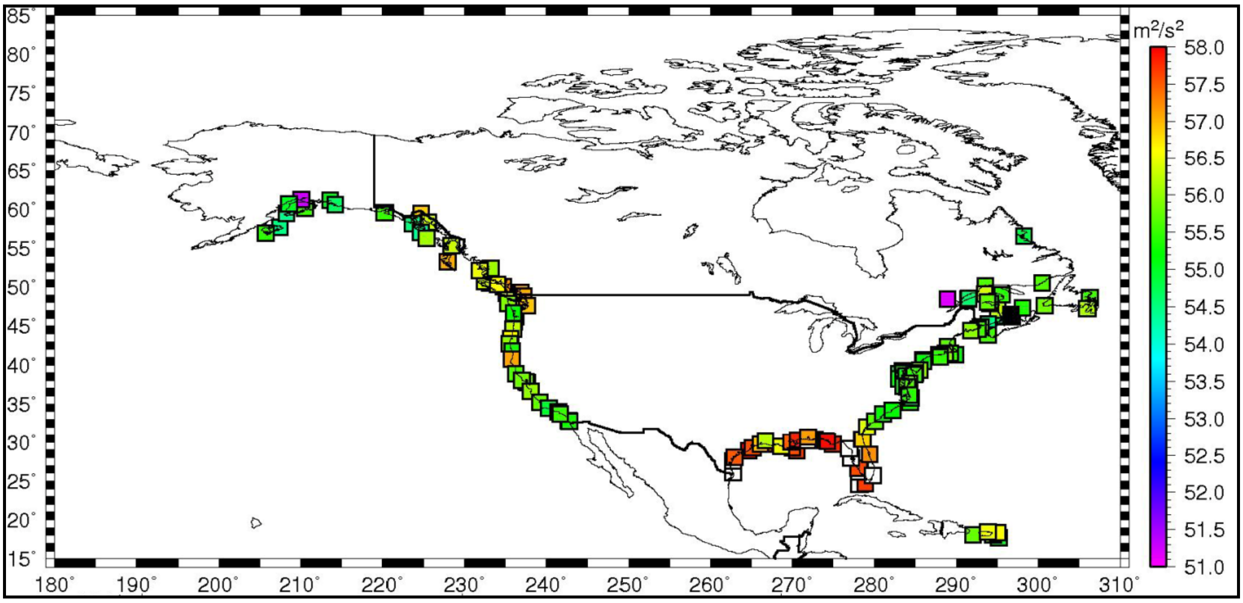

Figure 4 Average geopotential values for 188 tide gauges scattered around the U.S. and Canada where Mean Ocean Dynamic Topography values are modeled. The average value is almost exactly 62,636,856.00 m^2/s^2. Note that the right scale bar only shows the last two digits. The 95% CL is about 3 m^2/s^2 or 0.3 m.

The U.S. and Canada both maintain extensive networks of tidal bench marks. Many of these have been occupied with GPS to determine the local mean sea level (LMSL) in a geometric reference frame. As a first step, mean dynamic ocean topography (MODT) values were removed from the LMSL heights at the tide gauges. MODT models for the Atlantic Ocean and Gulf of Mexico (Thompson and Demirov 2006) as well as the Pacific Ocean (Foreman et al. 2008) were used to remove the effects of sea level variability to better tie to a more correct value for global mean sea level (MSL). The expectation in geodesy has always remained that the geoid would closely approximate global MSL. Hence, the average of this comparison would serve as the datum of choice. Figure 4 highlights the results of this analysis and yielded a result of 62,636,856.00 m^2/s^2. This value was adopted by both the United States and Canada (2012). Subsequently, countries in Central America and the Caribbean have also adopted this same value for a future regional model.

5. SUMMARY

The National Geodetic Survey along has been and continues to be responsible for maintaining the National Spatial Reference System (NSRS) in the United States. The current realizations of the NSRS are the North American Datum of 1983 (NAD 83) and the North American vertical Datum of 1988 (NAVD 88). Both of these datums have known meter level systematic errors that are rapidly becoming a problem for positioning. When GNSS users determine their coordinates using the broadcast signals, their results are consistent with an IGS reference frame. However, maps and other spatial information are provided in NAD 83. For applications that are in real time and may involve sensitivity to positioning at the cm-level, this could be a very significant hazard. Similarly, NAVD88 provides a fair match to tide gauges on the East Coast but is out by over a meter in Pacific Northwest regions.

For this reason, NGS will update the NSRS in 2022 to adopt a new geometric datum accessed using GNSS observations processed on a suite of software available on the Online Positioning User Service (OPUS) website. These positions will then be used to access the geopotential datum by interpolating a gravimetric geoid height model. The resulting orthometric heights will be consistent with leveled heights and provide starting bench mark values for local surveys intended for economic, engineering, and scientific purposes.

It will be necessary to maintain backward compatibility for both datums to ensure that users who have significant investments in their existing passive-control infrastructure will not be unduly hampered. This passive control will assume a secondary role to the active control of Continuously Operating Reference Stations (CORS).

Finally, the close tie between the geopotential datum and tidal datums will provide an enhanced means of linking events transitioning from the oceanographic environment onto shore or into the near shore tidal datums. Flood plain mapping both along the ocean and along rivers will be enhanced by this relationship as will the determination of a ship within a channel and with respect to shore infrastructure (such as bridges).

NGS has begun to prepare the NSRS user community and to engage with our counterparts in neigh boring countries and around the world to ensure that the new NSRS is implemented as smoothly as possible in 2022. The aim is to continue collect necessary data to define two new datums and change the overall reliance on passive control.

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BIOGRAPHICAL NOTES

Daniel Roman is directly involved in the development of both the geometric and geopotential datums that will replace NAD 83 and NAVD 88, respectively, in 2022. He serves as Chief for Spatial Reference Systems Division at the U.S. National Geodetic Survey, where he is responsible for maintaining operations for the CORS sites and OPUS suite of software. He continues to serve as the GRAV-D P.I for development of a geoid height model generated entirely from gravity field data.

CONTACTS

Dr. Daniel R. Roman
Chief, Spatial Reference System Division
NOAA's National Geodetic Survey
1315 East-West Highway
SSMC3, #8813
Silver Spring, Maryland
U.S.A.
Tel. +1-301-713-3200 x103
Fax +1-301-713-4324
Email: dan.roman@noaa.gov
Web site: www.ngs.noaa.gov