The U.S. National Spatial Reference System in 2022

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SUMMARY

In 2022, the National Geodetic Survey (NGS) will be providing updated access to the U.S. National Spatial Reference System (NSRS). The NSRS is currently realized by the North American Datum of 1983 (NAD 83) and the North American Vertical Datum of 1988 (NAVD 88). These older datums have inherent flaws at the meter level and are no longer consistent with efforts envisioned by the United Nations subcommittee for the development of a Global Geodetic Reference Frame (UN- GGRF) nor the International Vertical Reference Frame. The update to the NSRS will involve the development of a new terrestrial frame more closely aligned with recent realizations of International Terrestrial Reference Frame, such as the forthcoming ITRF14. Geometric coordinates defined within this new regional frame would be available throughout Central and North America. The intent is to provide cm- level accurate positioning from 15 minutes of GNSS observations. The observations would be processed using updated Online Positioning User Service software that allow other GNSS data besides GPS to be used as well as incorporating many elements of the existing adjustment software used by NGS. The movement of the frame will largely be captured by an Euler pole with residual velocities being modeled as well. The derived geometric coordinates would then be used to access a geopotential frame for determination of physical heights - both orthometric and dynamic. Again, efforts will be made to develop a geopotential model that is consistent across the region for all countries in Central and North America. Because the U.S. has states and territories outside of the CONterminous United States (CONUS), separate models will be developed for outlying areas including: Puerto Rico and the U.S. Virgin Islands, Hawaii, Guam and the Commonwealth of the Northern Mariana Islands, and American Samoa. To this end, four separate frames will be realized for North America plate, the Caribbean plate, the Pacific plate, and the Mariana plate. Working groups with IAG's commission 1 and 2 have been working to develop these models for broader regional collaboration specifically for Central and North America, but outreach efforts have also begun for collaboration in the Caribbean region as well.

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1. BACKGROUND

The Mission of NOAA's National Geodetic Survey (NGS) is to define, maintain and provide access to the National Spatial Reference System (NSRS) to meet the nation's economic, social, and environmental needs. As these national needs evolve and require improved positional accuracy, NGS must adapt current techniques and data processing.

Currently, official access to the NSRS is through passive control marks established throughout the U.S.A. for both geometric and vertical components. There are over 80,000 benchmarks with coordinates defined in the North American Datum of 1983 (NAD 83) frame and over 500,000 bench marks with leveled heights above the North American Vertical Datum of 1988 (NAVD 88). NGS Policy on submitting data for inclusion into the NSRS is specified in the Federal Geographic Data Committee (FGDC), Federal Geodetic Control subcommittee (FGCS), publication Input Formats and Specifications of the National Geodetic Survey Data Base (September 1994 [updated]) - the so called “BlueBook.” Collection, analysis and processing of this data must follow rigorous standards to ensure the best results. This is a time-consuming process with significant burdens on all involved. Surveyors submitting the data must follow standards during planning, collection, and initial analysis before submission. There is an additional burden on an ever-diminishing and aging NGS staff to finalize the analysis, perform the adjustment, and publish the results.

NGS has also developed the Online Positioning User Service (OPUS) that can ingest GPS observations from surveyors. While GNSS data may be collected, only GPS data are used. GPS data processed through the various suite of tools in the Online Positioning User Service (OPUS) develop coordinates that are only *consistent* with the NSRS but are not defined within it. This is because the official coordinates are defined through BlueBook process given above. Therefore, NGS has moved forward with plans to validate the OPUS approach and implement it as the official means for accessing the NSRS starting in 2022. This will involve refitting some of the algorithms and software that underlie OPUS in order to provide results consistent with currently accepted approaches. This will result in a streamlined method for data collection, submission, analysis, and publication within the NSRS.

In addition, NGS will take the opportunity to update the datums themselves. Both NAD 83 and NAVD 88 have established meter-level datum defects that are inconsistent with modern reference frames or datums. Hence, the geometric frame will likely align with the most recent realization of the International Terrestrial Reference System available before 2022. Currently, this would be ITRF2014, but there may be another release prior to 2022. Vertical control will be defined geometric coordinates and a geopotential or geoid height model using the simple linear relationship between orthometric, ellipsoidal and geoid heights.

This paper presents some fundamental concepts on how NGS currently plans to implement new reference frames in 2022. It represents the culmination of several years' worth of internal discussion and debate on how best to define these datums, and how this access would be realized starting in 2022. The planned structure of the NSRS in 2022 is discussed followed by several subsections focusing on aspects tied to this planned structure. Ongoing and planned efforts from the NGS Ten-Year Strategic Plan (NGS 2013) for developing this new NSRS structure by 2022 are covered last.

2. STRUCTURE OF THE NSRS IN 2022

Reference frames will be developed for four regions based on the existing plates for U.S. states and territories: North America, Caribbean, Pacific, and Mariana plates. Each of these frames will be uniquely identified per ISO standards, but the whole set of frames will be colloquially referred to as the National Spatial Reference Frame for 2022 (NSRF2022) as a realization of the U.S. National Spatial Reference Systems (NSRS).

These frames will be mathematically tied to the most recently available ITRF model in 2022 – this would mean ITRF14, unless some subsequent model is developed. As of this writing, ITRF14 is nearly ready for release. It is entirely conceivable that a new model will be available before 2022. Hence, the term ITRFxx will be adopted to express whatever the most recent realization of the ITRS may be at the time NSRF2022 is adopted. Coordinates derived in the ITRFxx frame would be dynamic and be valid for date of survey. Such coordinates are definitive in their own right, but problematic for many applications desiring some means of connecting prior observations other than through re-occupation on a periodic basis.

A simplified mathematical relationship will be used to convert between ITRFxx and the four respective frames at an as yet to be agreed upon epoch date. This could likely be 2022, but it will likely be tiedclosely to the associated epoch date of the ITRFxx. In the case of ITRF2014, this would mean an epoch date of 2010.0. At that epoch date, the ITRFxx coordinates would be identical in all four eference frames. After that, plate-specific Euler pole rotations would attempt to keep the plates "fixed" in order to simplify coordinates fror most users. Coordinates derived in this frame would be deemed the primary means for accessing the NSRS. However, significant velocities exist within each frame that are not captured in a simple Euler Pole velocity model. Dynamic regions near plate boundaries, such as in southern California, would have significant velocities even with the Euler Pole velocity removed. Additionally, many "stable" areas actually experience systematic vertical movement, such as the Northeastern U.S. where the Glacial Isostatic Adjustment causes subsidence. To accommodate these velocities within the frame, some type of velocity model would need to be applied if it is desired to move from the survey epoch back (or forward to) some other epoch and not break the tie to the point on the ground.

Once geometric coordinates are obtained in the desired frame, a geopotential model will be applied to determine physical heights. This will practically be realized by a geoid height model developed entirely from gravity field data (i.e., not developed from leveling data). Current geoid models blend in leveling data above a vertical datum with known meter-level datum defects (e.g., NAVD 88). The intent of a gravimetric geoid height model would be to develop orthometric heights that are consistent at the cm-level nationally an din regions not connected by land (e.g., Hawaii, to mainland CONUS to Puerto Rico).

2.1 Mathematical relationship between ITRFxx and U.S. frames in 2022

As presently envisioned, an Euler Pole of rotation will be determined between ITRFxx and the new reference frames. Naturally, selection of the CORS sites that determine such Euler Pole velocities is essential to best defining the frame. A working group under IAG Subcommission 1.3c, North American Reference Frame, will be restarted to develop the optimum selection of CORS to develop the best velocities. Similar analyses will be repeated for the other three regions, though there will be notably fewer CORS to select from in those cases. For the Caribbean frame, expansion of the CORS Network to include more of COCONet (UNAVCO 2016) is being explored as well outreach to Caribbean Nations interested in developing a common regional frame. Similar collaborative efforts will be sought for the Pacific and Mariana frames. The Frames and names are given in Table 1.

Table 1. The four terrestrial reference frames for NSRF2022. Each will be closely tied to ITRFxx but with serprate Euler Pole velocties determined.

Plate	Name	Acronym
North America	North American Terrestrial Reference Frame of 2022	NATRF2022
Pacific	Pacific Terrestrial Reference Frame of 2022	PTRF2022
Caribbean	Caribbean Terrestrial Reference Frame of 2022	CTRF2022
Mariana	Mariana Terrestrial Reference Frame of 2022	MTRF2022

2.2 Velocity within the frames

The exact nature of velocity models is still somewhat indeterminate. It could be as simple as interpolating a grid of the CORS velocities or involve more geophysical interpretations such as TRANS4D (Snay et al. 2016). Other options include the use of expanded networks of points beyond just those from CORS such as data volunteered by RTN’s and private networks. Nearly 400,000 OPUS solutions are made each year that can provide supplemental control for determining the efficacy of the velocity models.

The point being made here is that some attempt will be made to account for movement within the frame. However, no such model will be errorless. Through models of residual 3D crustal motions, the new frames will allow users to “virtually” translate their coordinates backwards in time, but at the cost of decreased accuracy. As such, while NGS will offer derived coordinates using such models as a secondary product. If these are used, then necessary metadata must include the applied velocity model. Such models will likely be updated with subsequent versions being released. Hence, knowing which velocity model was applied to mitigate velocity within the frame is essential for the provenance of the coordinates.

2.3 Geopotential or geoid height model

The optimal solution for a geopotential model would have the resolution of the existing geoid height models (e.g., one arc-minute). Previous analysis (Wang 2016) has shown that the omission error from such a grid is under a centimeter - making the overall desired level of cm-level accuracy feasible. However, one arcminute resolution is equivalent to a harmonic model complete to degree and order 10,800. By way of comparison, EGM2008 (Pavlis et al. 2012) is d/o 2160. This may be achievable in 2022 given the expansion and capability computing. For now, the only real option is a geoid height model derived following more classical techniques of remove-compute-restore (Smith et al. 2013). Such models are currently being developed and are available on the web as Beta products for evaluation. The most recent in this series is the xGEOID16 model, available at: http://dev.ngs.noaa.gov/GEOID/xGEOID16/. Taking advantage of a first order relationship between ellipsoid (h), geoid (N), and orthometric (H) heights, GNSS-derived ellipsoid heights can be transformed into orthometric heights:

$$H = h - N$$

For dynamic or other types of heights, a more complicated process must be followed requiring several simplifying assumptions. This will not be covered here, but it is feasible to extract all of the other types of coordinates (e.g., DoV's) in the NSRS beyond just positional coordinates. A great deal of effort was made to ensure consistency in the geoid height model across regions. Satellite gravity missions such as GOCE (Förste et al. 2014) provide long wavelength control. NGS' GRAV-D Project has been systematically collecting aerogravity to help normalize any inconsistencies in the three million surface gravity observations that will be used to make the geoid height models. Note that there will be three different geoid grids produced. The Caribbean and North American plates and even significant portions of the Pacific plate have been captured in the current xGEOID16 model.

The model in 2022 will span a similar range and will be termed GEOID2022-NA. Guam and the Commonwealth of the Northern Mariana Islands as well as American Samoa will require their own geoid models termed GEOID2022-GC and GEOID2022-AS, respectively. These two other regions will follow similar processing techniques and rely on the same long wavelength control. However, NGS does not have the capability or need to develop a global gravity field model. So, the models will be co-defined regional geoid models.

Note that the geoid height models are one arc-minute resolution, which is about 2 km grid intervals. The difference seen in residual velocities are all very small with respect to such an interval. Hence, while different geoid models may be applied in the four different frames, they all yield essentially the same geopotential datum: the North American-Pacific Geopotential Datum of 2022 (NAPGD2022). As such, Table 2 should be used to sort through the planned components of what will be the NSRF2022.

Table 2. Naming conventions between TRF's and geoid models related to geopotential datum name for orthometric heights.

Location	TRF	Geoid Height Model	Geopotential Datum

<table>
<tr><th></th><th></th><th></th><th>Name</th></tr>
<tr><td>Mainland U.S.A.</td><td>NATRF2022</td><td rowspan="4">GEOID2022-NA</td><td rowspan="7">NAPGD2022</td></tr>
<tr><td>Alaska</td><td>NATRF2022</td></tr>
<tr><td>Hawaii</td><td>PTRF2022</td></tr>
<tr><td>Puerto Rico</td><td>CTRF2022</td></tr>
<tr><td>American Samoa</td><td>PTRF2022</td><td>GEOID2022-AS</td></tr>
<tr><td>Guam</td><td>MTRF2022</td><td>GEOID2022-GC</td></tr>
<tr><td>Anywhere, North America</td><td>ITRFxx</td><td>GEOID2022-NA</td></tr>
</table>

2.4 Access

Much as today, a GNSS receiver file would be uploaded onto the NGS website for processing in an OPUS engine. Positions would be defined at the epoch of observation in ITRFxx. This is a dynamic frame and would provide the most reliable positions. However, most applications and users require more continuity with previous observations. To that end, two further processing steps would be applied.

The Euler Pole velocity for the respective frame would be applied to define coordinates within the frame at the epoch of observation. For much of the mainland United States, this would result in plate fixed coordinates and satisfy the bulk of users. These coordinates are still deemed to be at the observation epoch, because no frame velocities have been removed. The final step would then be to apply some type of frame velocity model to best approximate the movement of the position within the frame over time. This would permit moving a point in the same frame to different epochs for comparisons to other data. Necessarily then, coordinates derived via these three steps are in progressively reduced desirability. The dynamic positions from ITRFxx truly indicate the location of a point at the survey epoch, while those with only the Euler Pole are the most accurate. However, a velocity model must be applied to make the connection to the point on the ground.

Finally, a geoid height grid would be interpolated to arrive at orthometric heights if those are desired. The version of the velocity model and the geoid grid must be tracked carefully as a part of the metadata. It is a great likelihood that both may updated and it would be necessary to retain knowledge of the appropriate version so as to remove it back to the Euler Pole only frame.

All of this would be processed using an updated version of OPUS-Projects (OP). Data are uploaded through OPUS-Static and tagged for a specific project. Then OP is used to adjust the data to produce refined positions. The underlying algorithms and software would be updated to incorporate accepted versions currently used in BlueBooking. Additionally, this same scheme would be expanded to perform adjustments for leveling observations, gravity data, etc. In effect, this becomes OPUS-for-everything. All tabs of this analysis would be inter-related, so initial processing of GNSS control would be ported to the leveling page, where a geoid height model would then develop vertical control for adjusting leveling. This will insure continuity of the leveling at the national (and indeed international) level, while still meeting local accuracy requirements.

2.5 Summary and Outlook.

The U.S. will be implementing new datums in 2022 to replace the existing datums (NAD 83 and NAVD 88) as well as the means by which data are submitted and published. This will provide a streamlined means for accessing the NSRS and ensure more continuity in the results. Backward compatibility will be maintained through an update of the NADCON and VERTCON software packages that are currently available. In conjunction with the intra-plate velocity models, it should be easily possible for future surveyors to compare data collected at various times on different realizations of the U.S. datums to future observations at a sufficient level of accuracy to meet their needs.

REFERENCES

Förste, Christoph; Bruinsma, Sean.L.; Abrikosov, Oleg; Lemoine, Jean-Michel; Marty, Jean Charles; Flechtner, Frank; Balmino, G.; Barthelmes, F.; Biancale, R. (2014): EIGEN-6C4 The latest combined global gravity field model including GOCE data up to degree and order 2190 of GFZ Potsdam and GRGS Toulouse. GFZ Data Services. http://doi.org/10.5880/icgem.2015.1

Pavlis N.K., S.A. Holmes, S.C. Kenyon, J.K. Factor (2012) The development and evaluation of the Earth Gravitational Model 2008 (EGM2008) JGR: Solid Earth, Volume 117, Issue B4, April.

Smith DA, SA Holmes, X Li, S Guillaume, YM Wang, B Burki, DR Roman, TM Damiani (2013) Confirming regional 1 cm differential geoid accuracy from airborne gravimetry: the Geoid Slope Validation Survey of 2011, J. Geod, DOI 10.1007/s00190-013-0653-0

Snay R.A., J.T. Freymueller, M.R. Craymer, J Saleh (2016), Modeling 3D Crustal Velocities in the United States and Canada: Modeling 3D Crustal Velocities, JGR, B, DOI: 10.1002/2016JB012884

UNAVCO (2016) COCONet website, http://coconet.unavco.org/

Wang, Y.M. (2016) On the Omission Errors Due to Limited Grid Size in Geoid Computations, NGS Internal Report.

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 assumed duties as Chief of Spatial Reference System Division for the past three years. He is now the acting Chief Geodesist for NGS and involved in developing and implementing the new National Spatial Reference System for 2022.

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