NOAA Technical Report NOS NGS 64

Blueprint for the Modernized NSRS, Part 2: Geopotential Coordinates and Geopotential Datum

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Versions

Date	Changes
November 13, 2017	Original Release
February 5, 2021	• Minor typos corrected • Terminology updated • Reference epoch 2020.00 chosen • Figures updated • Figure and table numbering changed to align with Blueprint Part 1 • Chapters 5 and 6 were mostly moved to Appendices A and B

Contents

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Kevin Ahlgren, Jeff Jalbrzikowski, Dan Roman, Brian Shaw, Dru Smith, Marc Véronneau (CGS), Dave Zenk

Acknowledgements from the 2017 version

A work of this magnitude requires the input of many people. The contents of this document grew out of a long list of scientific meetings inside NGS, beginning in 2014, and grew in scope and frequency through 2015 and 2016. Many scientists inside NGS, and eventually outside of NGS, contributed to the conversations, which ultimately led to this document. Recognition and thanks for their contributions should go to the following individuals (in alphabetical order):

Kevin Ahlgren, Dana Caccamise, Vicki Childers, Theresa Damiani, Michael Dennis, Joe Evjen, Steve Hilla, Simon Holmes, Jianliang Huang (GSC), Nic Kinsman, Xiaopeng Li, Dennis Milbert, Dan Roman, Brian Shaw, Dru Smith, Derek vanWestrum, Marc Véronneau (GSC), Yan Wang, Stephen White, Daniel Winester, Monica Youngman, Dave Zenk

1 Delayed Release of the Modernized NSRS

NOAA's National Geodetic Survey (NGS) is announcing a delay in the release of the modernized National Spatial Reference System (NSRS).

In 2007, NGS began planning for the modernized NSRS, acquiring its first airborne gravimeter, creating and initiating the GRAV-D project and by 2008 had codified its modernization plans into a Ten Year Plan. At that time, the target completion date was 2018. By 2013, that date seemed unlikely, due to both the broadening of the Gravity for the Redefinition of the American Vertical Datum (GRAV-D) coverage area and the experience of five years of operational planning and execution.

In 2013, NGS revised its 2007 Strategic Plan, and targeted 2022 as the date of the release of the modernized NSRS. This date was reinforced with a 2018 Strategic Plan revision. By 2017, confidence in hitting the 2022 target was high enough to reach final agreement with Canada and Mexico on a naming convention for certain components, to include "2022" in their names.

Since 2017, operational, workforce, and other issues have arisen and compounded, causing NGS to recently re-evaluate whether a successful roll-out by 2022 is possible. The most significant impacts have been in workforce hiring and retention, and in meeting GRAV-D data collection milestones, which underpin the NSRS modernization efforts.

NGS is currently conducting a comprehensive analysis of ongoing projects, programs, and resources required to complete NSRS modernization and will continue to provide regular updates on our progress. To get the latest news on NSRS modernization and track our progress, subscribe to NGS News or visit our "New Datums" web pages.

2 Executive Summary

NOAA Technical Report NOS NGS 64

Blueprint for the Modernized NSRS, Part 2:

Geopotential Coordinates and Geopotential Datum

Between 2022 and 2025, the entire National Spatial Reference System (NSRS) will be modernized. This document addresses the *geopotential* aspects of the NSRS, including every vertical datum, the geoid, gravity, deflections of the vertical, and other quantities related to Earth's gravity field. Every one of these related, yet semi-independent sources of information will be replaced with an internally consistent geopotential datum called the North American-Pacific Geopotential Datum of 2022 (NAPGD2022). Within NAPGD2022 four primary, interrelated time-dependent products will exist:

- *A global model of Earth's geopotential field (GM2022)*
- *Regional gridded geoid undulation models (GEOID2022)*
- *Regional gridded deflection of the vertical models (DEFLEC2022)*
- *Regional gridded surface gravity models (GRAV2022)*

The three regions for the gridded models will be North America (covering CONUS, Alaska, Hawaii, the Caribbean, Canada, Mexico, Central America, and Greenland), American Samoa, and Guam/Commonwealth of Northern Mariana Islands (CNMI).

NAPGD2022 will be built upon ITRF2020, as only minor (entirely horizontal) differences will exist between ITRF2020 and the four new terrestrial reference frames developed as part of the NSRS in 2022. Since these differences will be relatively small horizontal displacements (mainly due to Euler pole rotations), NAPGD2022 will operate equally well in any of the four new frames.

Orthometric heights in NAPGD2022 will be defined through ellipsoid heights and GEOID2022. This means NAPGD2022 orthometric heights will primarily be accessed through Global Navigation Satellite System (GNSS) technology. GEOID2022 will be defined in a manner that best fits global mean sea level at the epoch of NAPGD2022. When global sea level changes by a threshold level of 20 centimeters, a new geoid model, and thus geopotential datum, will be released. Until then, updates to any component of NAPGD2022 will result in updating all components of NAPGD2022 using sequential version numbering.

Leveling in NAPGD2022 will retain its current role of providing high-accuracy local differential orthometric heights. The determination of absolute heights, however, which will provide the context of local differential heights, will reside in the Global Navigation Satellite System (GNSS) domain (i.e., will be based on ITRF2020/GRS 80 ellipsoid heights).

The red text in the first three sections of this report is repeated verbatim from NOAA Technical Report NOS NGS 62 (Blueprint for the Modernized NSRS, Part 1: Geometric Coordinates and Terrestrial Reference Frames). The critical nature of this text to both Geometric and Geopotential coordinates, as well as the need for consistency between the documents, is the principal reason for this duplication.

Additionally, due to the large number of similar acronyms found throughout this document, a reference glossary and list of abbreviations is provided at the end of this report.

3 Purpose

The intent of this document is to provide to the public the current status of plans by the National Geodetic Survey (NGS) to modernize the National Spatial Reference System (NSRS). This particular document covers the Geopotential component; that is, the definition and determination of orthometric heights, geoid undulations[1], gravity, deflections of the vertical, geopotential numbers, and any other quantity directly related to the geopotential field[2] of the Earth. Many abbreviations and terminology specific to the new geopotential datum are used in this document. As a convenience to the reader they are defined in the glossary at the end of the document.

This document attempts to be comprehensive, without being unduly lengthy. This is expected to be the last version of this document before release of the modernized NSRS. Once the fully modernized NSRS has been released, a separate report will be issued by NGS describing its creation and serving also as an "as built" description.

4 Introduction

The mission of the NGS is to define, maintain and provide access to the NSRS, to meet our nation's economic, social, and environmental needs. The NSRS is defined by the Office of Management and Budget's (OMB) circular A-16 (Coordination of Geographic Information and Related Spatial Data Activities) as "the fundamental geodetic control for the United States" and is required to be used by all federal government agencies creating geographic information

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[1] The terms "geoid undulation," "geoid height," and "geoid separation" have been used in a variety of sources throughout the years, all with the same meaning: The distance, measured relative to a reference ellipsoid, along the ellipsoidal normal, positive outward, to the geoid. This document will use the term "geoid undulation" exclusively for this quantity.

[2] The term "geopotential" is shorthand for the gravity potential field generated by the masses of the Earth.

within the United States[3]. In fact, the NSRS is also the primary spatial reference framework in the nation for geospatial activities undertaken by regional, state, and local governments, many private sector organizations, and academia.

Datums / reference frames are an essential component for geospatial data, serving as the foundation to help align geospatial data from disparate sources. When performing analysis with geospatial data, using a consistent datum or reference frame assures that different datasets are correctly referenced and decisions made from this analysis are accurate. Consistency in coordinates is a fundamental reason the OMB Circular A-16 mandates federal agencies to use the NSRS to eliminate the significant effort that would be needed if different agencies use different datums and reference frames. Similar to how the concrete foundation helps to keep the frame of a house in place, datums and reference frames help to keep geospatial data properly aligned.

In order to keep up with changing technology and improved accuracy, NGS has planned for a modernization of the NSRS, originally set for 2022 but now slightly delayed (see delay message at beginning of this report). In order that this modernization maintains the usefulness of the NSRS, the function of geodetic control should be clearly articulated first.

5 Geodetic Control

According to OMB A-16, "geodetic control provides a common reference system for establishing coordinates for all geographic data." That is, geodetic control is some system which allows users to determine the latitude, longitude, height, gravity or other coordinate at points in their geographic dataset in such a way that these coordinates are *consistent with* similarly derived coordinates prepared by other users using other datasets, but using the same geodetic control. Therefore, geodetic control must be more accurate than any map or other data set built upon it.

Unfortunately missing from this functional statement is the reality that geodetic control points (and their respective coordinates) can, and do, move over time. A significant portion of this blueprint will be dedicated to addressing why this is true and what can be done about it.

In order to fulfill its function, classical geodetic control was usually a network of metal disks or rods affixed to the surface of the Earth with some associated coordinates such as latitude,

[3] In 2018 a new law, the Geospatial Data Act (GDA) was passed which re-defined parts of OMB A-16 while leaving other parts unaddressed. One of the parts left unaddressed was the NSRS and geodetic control in general. A cross-agency working group continues to work on interpretation and implementation between GDA and OMB A-16. Based on that working group's guidance, NGS's role and authority as per OMB A-16 remains intact.

longitude, height or gravity, and where such coordinates are mutually consistent within the network. Such points served as "starting points" for the *users* of geodetic control to begin their own surveys and thus create their own maps or other geographic datasets. By requiring all federal[4] creators of geographic data to use the same geodetic control network (the NSRS), all geographic data in the USA created at the federal level should therefore be mutually consistent.

As technology has progressed, theability to establish accurate positions has outpaced the accuracy of theunderlying geodetic control. Coordinates change over time due to a variety of factors operating over different spatial and temporal scales. In general, these scales were either spatially small or temporally very long, and were of a magnitude smaller than the accuracy of the surveys which created the coordinates. For example, on a typical engineering timescale, coordinate drift is typically less than the aforementioned 1 meter state-of-the-art absolute accuracy of the mid-late 20th century. Therefore, it was possible for geodetic control to function for decades with the assumption of "fixed" coordinates, only occasionally getting updated in certain locations when movement, exceeding the accuracy of existing surveys, was finally detected.

It should be pointed out that "horizontal control" (a point that provides latitude and longitude) was generally considered stable and reliable for decades, except in locations of known significant crustal deformation, such as in southern California. It was not until the advent of space geodesy that issues such as the rotation of the entire tectonic plate (at centimeters per year) were seen to be affecting such control. Contrast that with "vertical control" (points providing orthometric heights, or "elevations"). Such control was well known from early on to be susceptible to (vertical) motions. Vertical motion, relative to neighboring points, was occasionally detected upon re-surveying. Methods for avoiding such movement have been used for decades, such as setting the points into bedrock or structures with deep foundations, or driving rods to refusal. The success of such methods is not entirely clear, as no comprehensive re-evaluation of the level network in the United States has ever been accomplished. However, even methods that affix a mark to bedrock will be susceptible to vertical motion if the bedrock itself is moving, such as is the case for the entire northeast portion of the North American continent, due to the Glacial Isostatic Adjustment (GIA) centered around Hudson Bay. But as a significant portion of the so-called "passive control" in the United States are poured-in-place concrete markers set into the soil, any subsidence or uplift affecting the soil layer will also impact the elevation of these points.

The purpose of geodetic control is to provide starting points by which geospatial users may define positions with the consistency and reliability of the NSRS. Such starting points should have known coordinates at an epoch that is useful to the geospatial professionals using the control. If those coordinates have changed over time, then it would be convenient if some component of the geodetic control would allow for comparison of previously determined

[4] Non-military, non-intelligence agencies. Geodetic control for those agencies, when used outside of the United States, is the mission of the National Geospatial-Intelligence Agency (NGA)

geospatial coordinates at different epochs. This temporal aspect of geodetic control will play an integral role in the modernized NSRS.

6 The Role of Leveling in Defining Continent-Wide Geodetic Control

Using infrequently surveyed vertical control as a method for defining and accessing a vertical datum suffered not only from the vertical motion of marks (see above), but also from the methodology used to determine the heights on those marks: geodetic leveling. Until the advent of space geodetic positioning techniques (GNSS) and also the advent of accurate modeling of the geoid, the only reliable way to determine heights with geodetic accuracy was to use geodetic leveling, a line-of-sight method generally restricted to approximately 50- to 100-meter sight lengths, depending on the accuracy goal. Additionally, some *absolute* starting height (or heights) had to be predetermined by other methods (e.g. choosing Local Mean Sea Level [LMSL] at a convenient tide gauge, or forcing groups of tide gauges to average their LMSL values to zero), as geodetic leveling is a purely *relative* height-determining process.

Leveling is well known to yield very accurate differential heights[5] in local areas (sub-millimeter over a kilometer). However, it was used to determine continental-scale vertical datums, such as the National Geodetic Vertical Datum of 1929 (NGVD 29) and the North American Vertical Datum of 1988 (NAVD 88). The build-up of errors using such a localized tool in a project of continental size was difficult to gauge, and this was especially true for NAVD 88, which held a single point (Father Point, in Rimouski, Canada) as fixed (Zilkoski et al, 1992). Around 2005 or thereabouts, it finally became possible to independently evaluate the absolute accuracy of NAVD 88 heights. By that time GNSS-derived ellipsoid heights were accurate to centimeters, and the Gravity Recovery and Climate Experiment (GRACE) mission yielded a continental scale geoid model accurate to 1 centimeter over wavelengths longer than approximately 200 kilometers. These could be combined in the classic equation relating orthometric heights (H), ellipsoid heights (h) and geoid undulations (N):

$$H \approx h - N \tag{1}$$

Equation 1 is frequently expressed as being approximate, because H is measured along a curving plumb line, while h and N are on straight lines normal to the reference ellipsoid.

[5] A point on terminology may be worthwhile here: *Accuracy* describes how close a measurement is to truth, while *precision* describes how repeatable a measurement is over time. These definitions will be adhered to, so that "differential *accuracy*" will be the correct term to discuss how well leveling can actually determine the true difference in heights between two points. There are examples in the literature where "precision" is used interchangeably with "differential accuracy," but these examples break from the definition stated above, and precision will only be used to describe *repeatability* of measurements.

However, the error in the approximation never exceeds 1 millimeter anywhere on Earth (Jekeli, 2000, equation 34).

Once N was determined from GRACE and h from GNSS, the GRACE/GNSS orthometric heights could be checked against the leveling-derived NAVD 88 orthometric heights. This revealed that NAVD 88 heights were, on average, biased by 50 centimeters in CONUS and were tilted about 1 meter from the Pacific Northwest to southern Florida. See Figure 1.

This mismatch was determined based (most recently) on the approximately 25,000 points in the NAVD 88 network that also had GNSS-derived heights. Therefore, it does not contain information about the remaining hundreds of thousands of other leveled NAVD 88 points which have never been surveyed with GNSS. Also, most of the NAVD 88 network was leveled during the 1930s through the 1980s, and have not been re-leveled since then. Whether those points have moved, have been destroyed, or are perfectly stable is not known for many of the points.

Figure 1 shows the difference between orthometric heights from satellite gravity, GRACE (circa 2005) and GOCE (circa 2010), and GNSS (circa 1990–2005) and the orthometric heights from NAVD 88 (circa 1930–1990). Therefore, it includes both the error in the NAVD 88 definition *and* any regional *subsidence* or *uplift* of individual bench marks included in estimating the NAVD 88 H = 0 surface (note that effort was made to remove marks suspected of local vertical movement, although it is unlikely all such marks were identified).

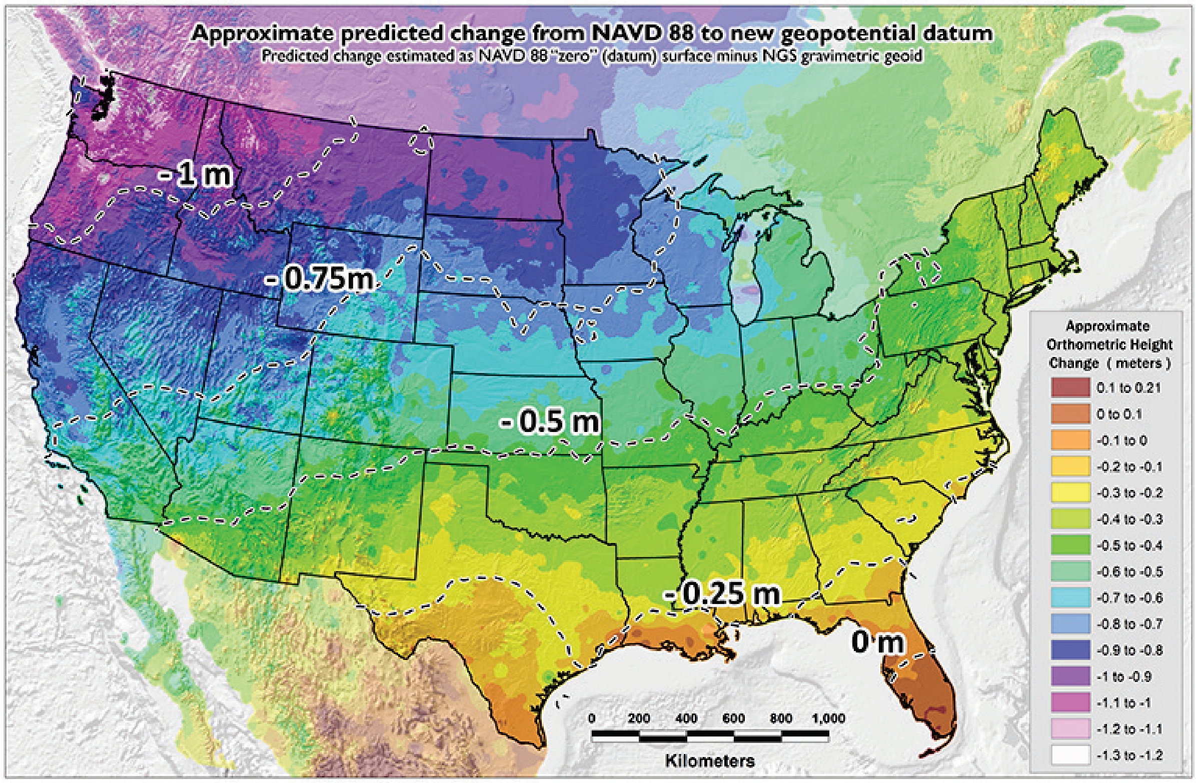

Figure 1: The continental bias and tilt of the NAVD 88 H=0 surface across CONUS as implied by the latest NGS experimental geoid model based on improved gravity data.

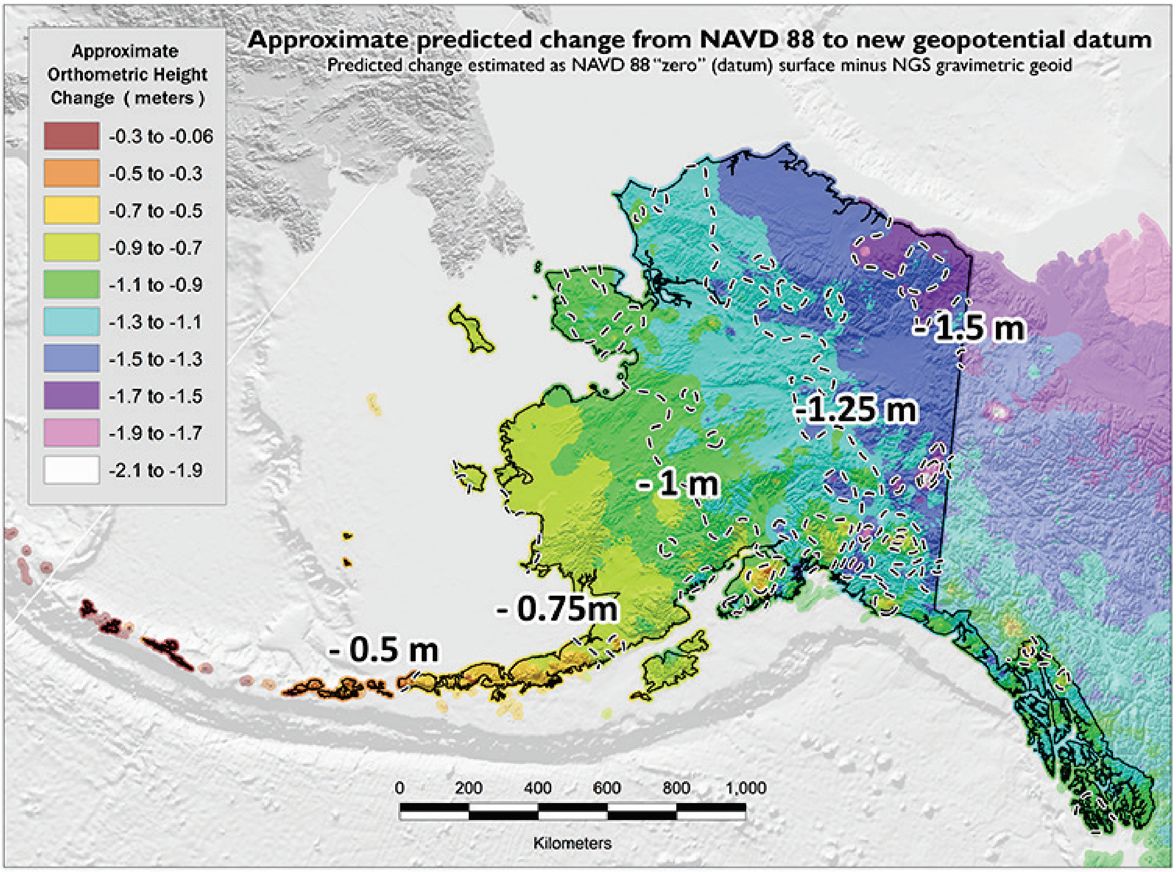

Figure 2: The statewide bias and tilt of the NAVD 88 H=0 surface across Alaska as implied by the latest NGS experimental geoid model based on improved gravity data. Note the tilt is due to the severely poor distribution and quality of GNSS on Bench Mark data

A similar situation exists in Figure 2, however the southwest-northeast tilt in that grid covering Alaska cannot be attributed to a tilt in NAVD 88 itself. This is because the network of NAVD 88 marks was never extended into western Alaska, and only marginally into eastern Alaska. Consequently, the thin concentration of actual points with an NAVD 88 and a GNSS measurement resulted in wild extrapolations of the conversion surface between the gravimetric geoid (USGG2012) and the hybrid geoid (GEOID12B) in those regions. These extrapolations can only be called "the NAVD 88 H=0 surface" ***per se***, as they are a purely statistical anomaly and do not represent any actual leveling-based NAVD 88 data. To summarize: the directionality and degree of the tilt in Alaska is a byproduct of over-extrapolation in a data-sparse region[6] and should not be considered a reflection of any "leveling-based NAVD 88 tilt" in Alaska.

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[6] Local errors (rather than the long wavelength tilt) are primarily caused by the difference between USGG2012 and xGEOID16B and are the result of actual data differences (updated satellite models and xGEOID16B included GRAV-D airborne data, whereas USGG2012 did not).

Knowledge of the bias and tilt problem in NAVD 88, as well as uncertainty about the viability and stability of the network of marks, led NGS to study the problem in preparation of the 2008–2018 NGS Ten-Year Plan (NGS, 2008). Estimates of the resources required to re-level the entire network were extrapolated from existing labor and contracting costs. The estimate to completely re-level NAVD 88 ranged between $200 million and $2 billion dollars. It was concluded that—even if NGS could secure funding at that level—re-leveling would not solve the underlying problems that (a) leveling builds up large systematic errors over a continent, (b) marks can move, unchecked, and (c) marks can easily be destroyed.

An entirely new approach was seen to be the only remaining viable option. Since the approximation in equation 1 does not exceed 1 millimeter, and since GNSS-derived ellipsoid (absolute) heights were accurate to within a few centimeters anywhere in the United States (and differentially accurate to sub-cm: see Smith et al, 2013) the only logical answer was for NGS to pursue the creation of a geoid model more accurate than ever before realized (with a target differential accuracy of 1–2 cm. This is discussed in section 9.1). Furthermore, due to ground motion and stability uncertainty, the reliance on infrequently surveyed marks as having "known heights" had to be replaced, with the determination of up-to-date GNSS-derived ellipsoid heights as the initial step in determining orthometric heights. This is the crux of the NGS statements that the NOAA CORS Network would be the "primary access" and infrequently surveyed marks serve as the "secondary access" to the NSRS in the future.

For an overview on the history of geoid modeling, and the geopotential field as a whole, please refer to Appendices A and B of this document.

7 Time Dependency

Geodetic control marks are set into the crust of the Earth, which can move vertically, sometimes at relatively large speeds (multiple centimeters per year). As such, things set into the crust make a poor choice for geodetic control, unless they are regularly monitored for movement. And while stations in the NOAA CORS Network are monitored regularly for motion, their vertical movements are purely geometric (ellipsoid heights) and—due to the changing nature of the geoid—cannot be directly equated to orthometric height changes (since orthometric height changes are a combination of ellipsoidal height change AND geoid height change).

Although the geoid also changes vertically, its changes (relative to the magnitude of vertical crustal changes) are smaller than ellipsoidal height changes. Geoid change requires large movements of mass, such as the flow of extra material into the mantle below Hudson Bay, or the secular deglaciation of Alaska, for the geoid change to be measurable on a yearly timescale (i.e. over 1 millimeter per year). In addition, secular (relatively constant over time) change, episodic events (certain volcanic eruptions or earthquakes), and some cyclic events (present-day seasonal ice melting and re-freezing of glaciers in Alaska and Greenland) can affect the geoid in a measurable way. The long-term impact of these events can be either permanent or transient. An example of an *episodic* change with a *permanent* impact might be an earthquake, while an example of an episodic change with a *transient* impact might be a multi-year drought.

To account for geoid changes in time, NGS has established the Geoid Monitoring Service (GeMS) in 2019 to investigate all potential physical processes that could modify the geoid over time and how to properly incorporate these changes into the NSRS. Each type of change will be investigated for three components: magnitude, temporal duration, and spatial scale. For more information about GeMS and geoid change, see NOAA Technical Report 69 (Ahlgren, et al. 2019).

An example of some of the physical processes investigated is shown in Table 5-1. Those entries in red have already been determined to be too small for NGS to track. This table is meant to be illustrative, not exhaustive:

Table 5-1: Some of the geophysical drivers of geoid change.

Type of Change	**Frequency**	**Temporal Duration**	**Example**	**Magnitude**	**Spatial scale**
Shape	Secular	Permanent	GIA at Hudson Bay Deglaciation of Alaska	2 mm / year	> 100 km
Shape	Secular	Permanent	Slowing of Earth's Spin Rate	8×10^{-17} mm / y	Pole to Equator
Shape	Periodic	Permanent	Seasonal Freeze/Thaw Cycles	Being studied	> 100 km
Shape	Episodic	Permanent	Certain Earthquakes or Volcanic Eruptions	1-10 cm	Up to 200 km
Shape	Episodic	Transient	Droughts/Deluges	Being studied	Up to 500 km?
Size	Secular	Permanent	Accretion of Space Dust	4×10^{-7} mm / y	Global
Size	Secular	Permanent	Loss of Stratospheric Mass	-10×10^{-7} mm / y	Global
W_0	Secular	Permanent	Global Mean Sea Level Change[7]	1.7- 3.2 mm / y[8]	Global

Another factor to consider while studying sources of geoid change is that the sources can be grouped by the *types of change* they introduce to the geoid. These three types of geoid change are:

[7] This particular signal only affects the value of W_0 for the geoid if the geoid definition remains tied to GMSL.
[8] While 1.7 millimeter per year was the average over the 20th century, the value has been accelerating and is now closer to 3.2 millimeters per year. See IPCC (2014).

1. Shape change: This means a change to the *shape* of the $W=W_0$ surface, without changing W_0 itself and while maintaining the average radial distance from Earth's center to the $W=W_0$ surface. If one considers $W=W_0$ like a balloon, this is analogous to squeezing the balloon. Some new bulges and some new depressions will occur, affecting only the shape of the balloon, not its size.
2. Size change: This means a change to the *size* of the $W=W_0$ surface, effectively increasing (or decreasing) the volume enclosed by the geopotential field itself, without changing the value of W_0. Continuing the balloon analogy from above, this would be akin to inflating or deflating the balloon without squeezing it.
3. W_0 change: This means that the surface which was called "the geoid" and had $W=W_0$ will no longer be the geoid. A new value of W_0 (W_0^{new}) is chosen, and "the geoid" is now the surface $W= W_0^{new}$. Continuing the balloon analogy, consider *two* balloons, a red one inside a green one, where both are inflated, but are not touching one another. A new W_0 means the geoid was the red balloon, but now you have chosen to make it the green balloon, without necessarily changing the size or shape of either.

NGS has set the ambitious target of maintaining geoid accuracy at 1 centimeter (1 standard deviation) in both absolute and differential geoid undulations, but is also interested in balancing practicality against that goal. That means that each of the signals above has been considered both for its spatio-temporal scales, as well as its impact on users to determine which signals will be included in the dynamic portion of the geoid model, DGEOID2022.

8 Sea Level Change

The standing definition of the geoid, as adopted and used at NGS is this:

> ***The geoid is the equipotential surface of the Earth's gravity field which best fits, in a least squares sense, global mean sea level.***

This definition, like many geodetic specifications, was highly suitable and stable for decades. And like many geodetic specifications, the accuracy to which geodesists measure things has made it necessary to re-think this definition. To be specific, over a century of sea level measurements have made it "very likely" that global mean sea level (GMSL) was rising at a rate of approximately 1.7 millimeters per year and is rising at a rate of 3.2 millimeters per year between 1993 and 2010 (IPCC, 2014). Additionally, the geoid definition suffers all the same problems if the situation is reversed in some hypothetical scenario where GMSL is dropping.

NGS has set an accuracy goal for geoid models in the future of 1 centimeter (at 1 standard deviation or "sigma," about 68 percent confidence) in both absolute and relative (over all distances) geoid height. If NGS were to continue to stand by the geoid definition above, then as GMSL rises, so must its best fitting geopotential surface. That is to say, as GMSL rises, so must the geoid; and thus all orthometric heights must get smaller, year by year. To be clear, as GMSL rises, the value of gravity potential which best fits to GMSL (called W_0) will also change.

To be sure, any change of sea level *also* has a component of mass redistribution, which means there is also a component of shape change, not just W_0 change, as part of this. To exemplify the subtlety of the two types of change that will come from the one issue (sea level change), consider the following example.

Figure 3 and Figure 4 illustrate schematically what happens over time with GMSL and the potential field. Specifically, the rise of GMSL is not purely geometric. Masses have re-distributed on the Earth (due to addition of water mass to the oceans, loss of water mass from land ice, and thermal expansion of the ocean waters themselves). Thus the shapes of equipotential surfaces in the old potential field, $W(t_0)$, will not necessarily be the shapes of equipotential surfaces in the new potential field, $W(t_1)$. Furthermore, when selecting the equipotential surface that best fits the new GMSL, there is no guarantee that the previous numerical value of potential, W_0, will be the same as the new numerical value. In fact, it can be proven that the value will change, but that derivation is too lengthy for this report.

There are arguments against maintaining the above definition of "the geoid." The first is simply the disruptiveness of an ever-changing geoid and thus ever-changing orthometric heights. However, since NGS is committed to providing scientific accuracy in its products and services, it seems to be a poor choice to ignore the reality of sea level change.

At first glance, it would seem an argument is being made between two different geoid definition scenarios: one where the geoid is definitionally tied to GMSL, and one where it is not. These two scenarios are outlined in Figure 5 and Figure 6.

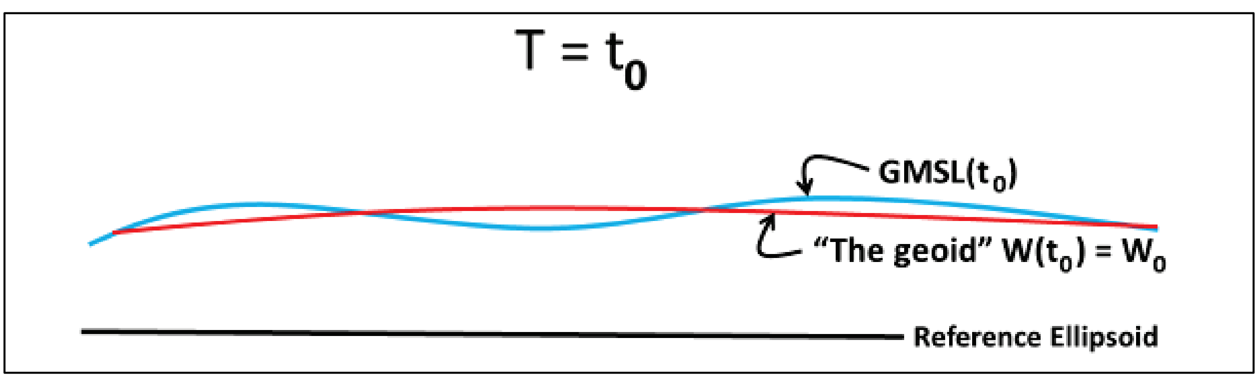

Figure 3: Within the potential field which exists at time t_0, $W(t_0)$, one particular equipotential surface in that field fits to the Global Mean Sea Level at time t_0, GMSL(t_0), has a constant value of potential "W_0," and is called "the geoid."

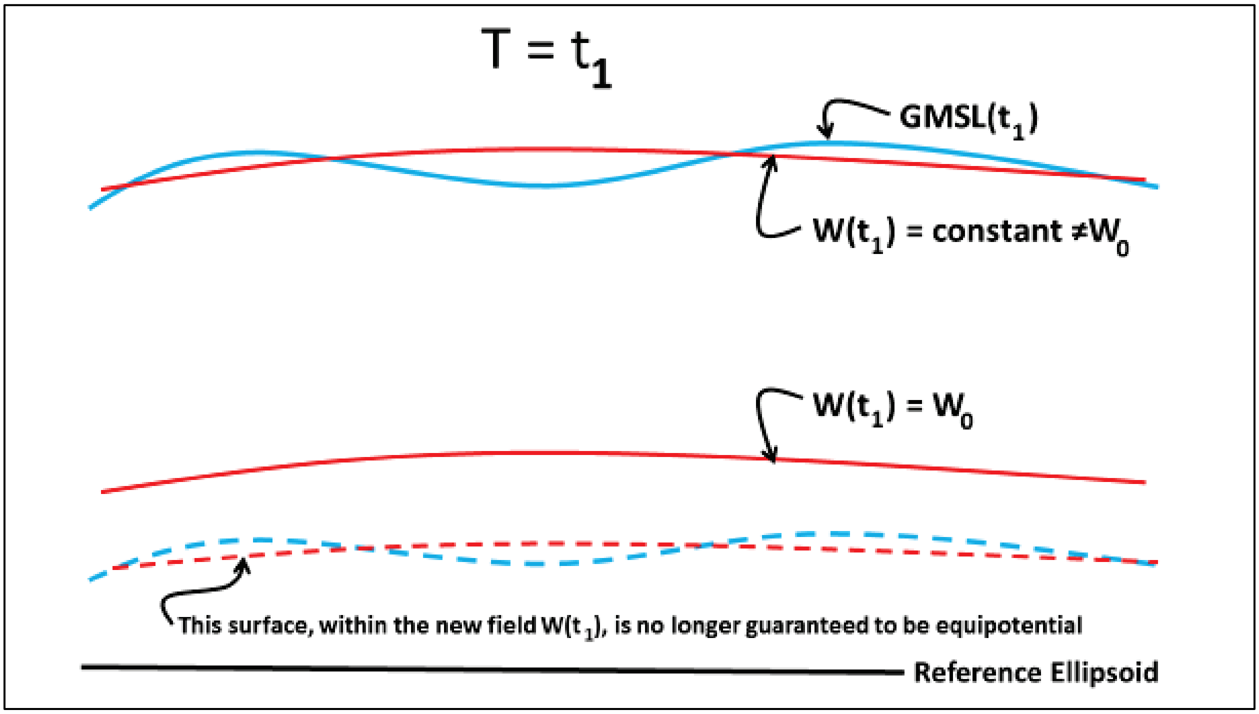

Figure 4: At time T=t_1, GMSL rise comes with a mass re-distribution, so that the potential field now, W(t_1), differs from W(t_0) in its equipotential shapes. Furthermore, the equipotential field which fits to GMSL will no longer have value W_0. The dashed lines represent the lines seen in Figure 3.

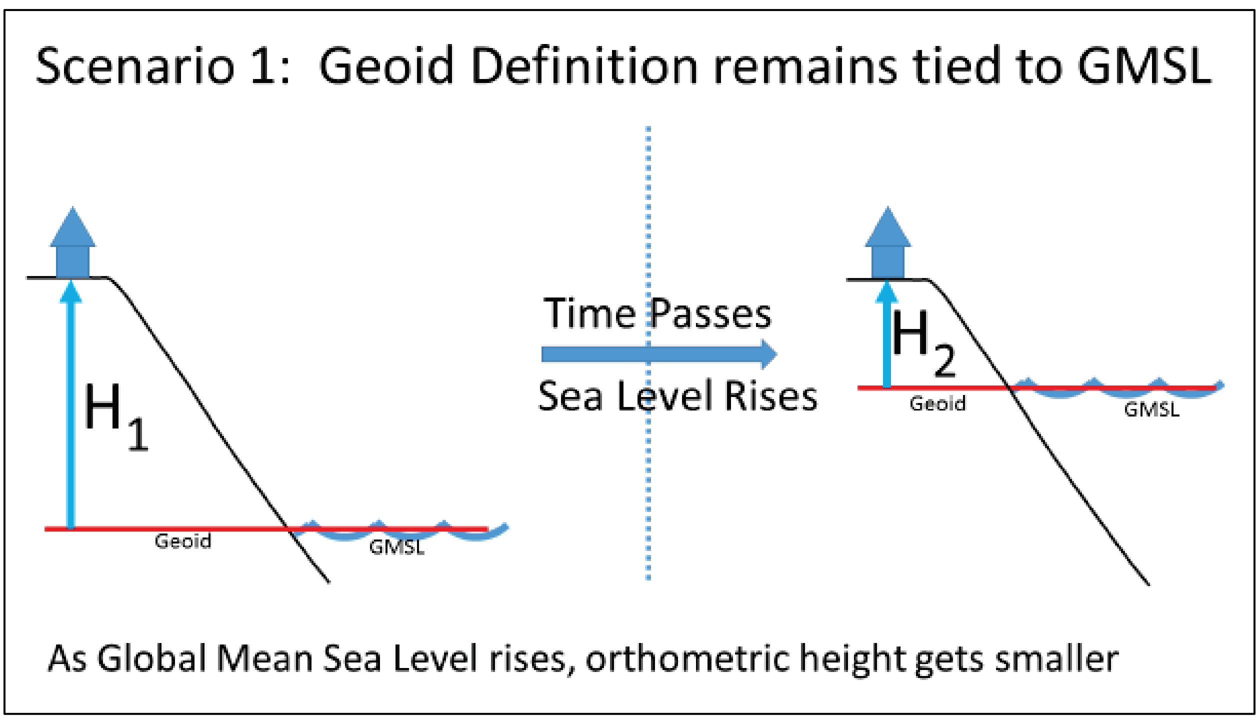

Figure 5: Scenario 1 – the geoid definition remains tied to GMSL

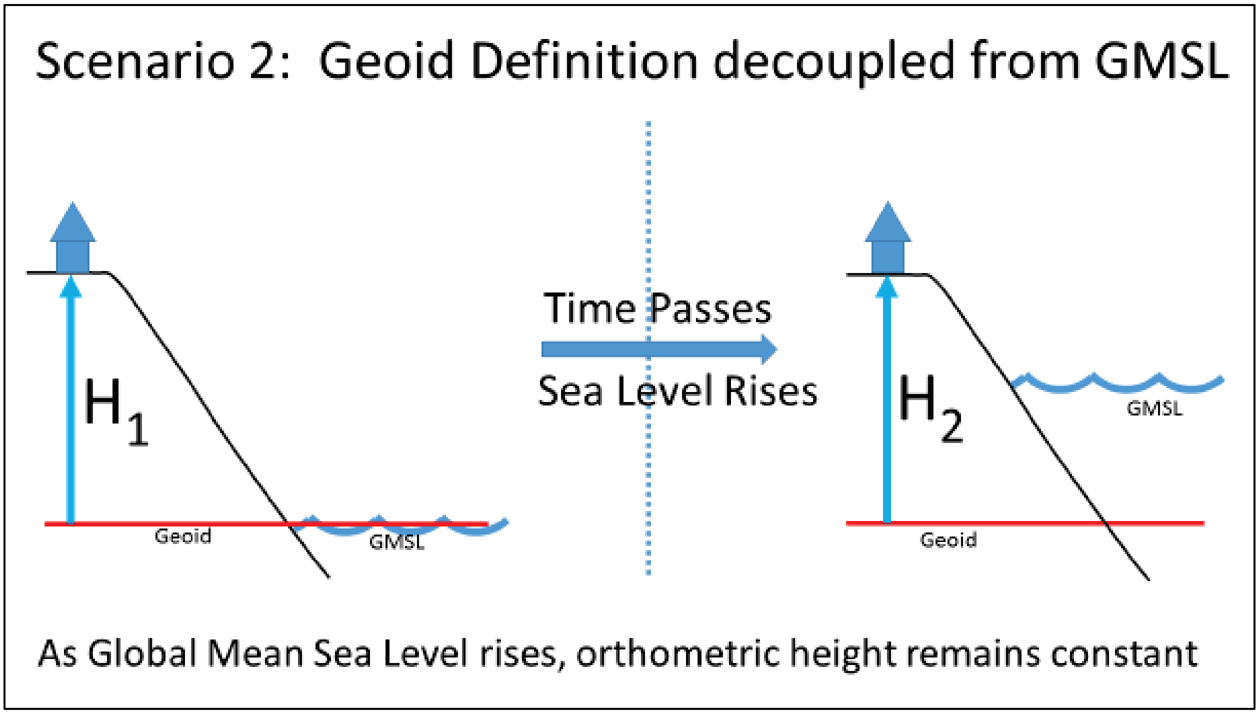

Figure 6: Scenario 2 – the geoid definition disconnected from GMSL

Both methods have advantages and disadvantages.

While there is no international standard, per se—the International Association of Geodesy (IAG) has never defined the geoid—a reasonable way forward has been proposed by the Joint Working Group on Strategy for the Realization of the International Height Reference System (IHRS) of the IAG, in a recent paper (Sanchez, *et al*, 2016):

> "…a suitable recommendation is to adopt a potential value obtained for a certain epoch as the reference value W_0 and to monitor the changes of the mean potential value at the sea surface W_S. When large differences appear between W_0 and W_S (e.g., > ± 2 m^2 s^{-2}), the adopted W_0 may be replaced by an updated (best estimate) value."

This strategy will be adopted at NGS. What this means is that NGS will adopt Scenario 2, above. On a regular basis, NGS will compute a new W_0 value using the method of Roman and Li (2020) and monitor these values until the geoid and GMSL have diverged by a threshold amount of *± 2 m^2 s^{-2}*. When that threshold is reached a new geoid will be defined and held fixed for a number of years. In this way, the impact of the change of GMSL is accounted for in the heights of the NSRS, while the appearance of stability is maintained for decades at a time (See Section 14). A simplistic view of this approach is presented in Figure 7.

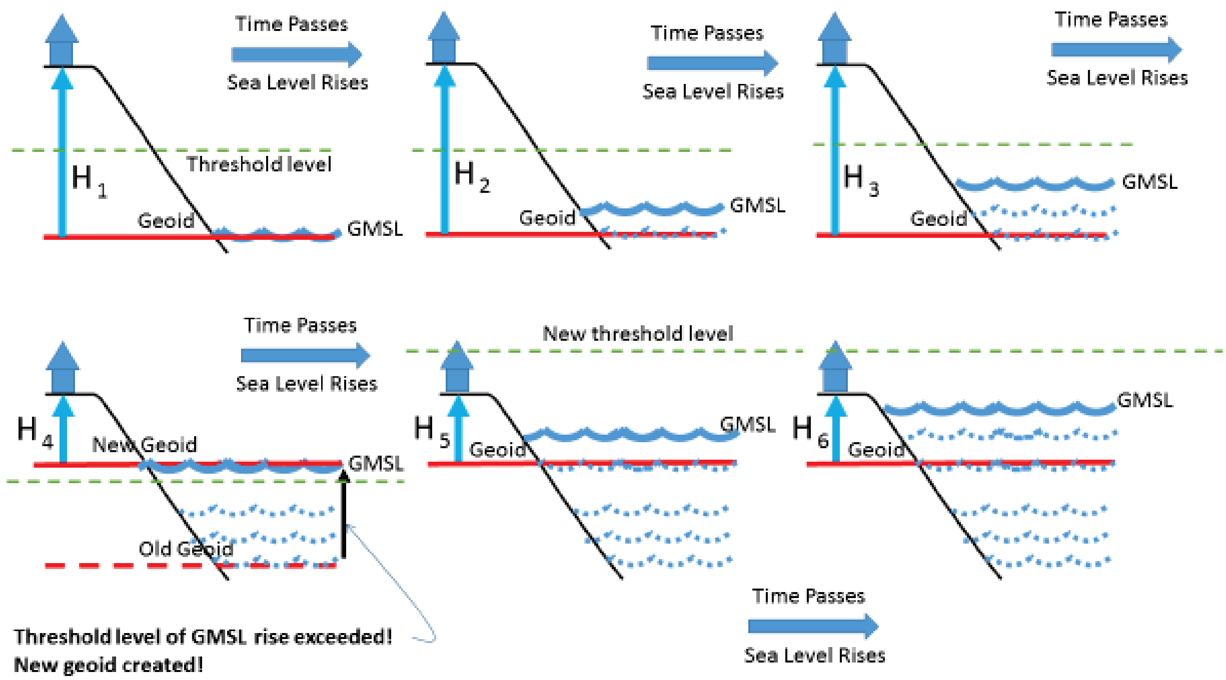

Figure 7: Scenario 3 — A new geoid is introduced whenever GMSL rises above some threshold level

9 The North American-Pacific Geopotential Datum of 2022

The National Geodetic Survey, in preparing for the 2022 replacement of NAVD 88 and all other vertical datums in the NSRS, received user feedback through multiple channels (particularly through three Geospatial Summits, in 2010, 2015, and 2017). In 2016 and 2017, reflecting on user feedback and considering the right mix of science and stewardship, NGS held a number of internal and external debates and discussions in an attempt to rigorously define the new geopotential datum for 2022.
The result of those discussions can be summed up as follows.

Note that many names in this document have not yet been finalized, however working names are provided for clarity of discussion.

1) Upon release, the modernized NSRS will contain one **geopotential datum**, capable of providing (at a minimum) the geoid undulation, acceleration of gravity, geopotential

number, deflection of the vertical and geopotential number at any given latitude, longitude, ellipsoid height, and time in the International Terrestrial Reference Frame (ITRF), specifically ITRF2020. The name of this datum will be the **North American-Pacific Geopotential Datum of 2022 (NAPGD2022).**

2) The foundational component of NAPGD2022 will be a spherical[9] harmonic model of Earth's external gravitational potential, called the **Geopotential Model of 2022 (GM2022).** The GM2022 will be created for the entire Earth and will contain two components:
    a. The first component will be time independent, fixed at 2020.00 to degree and order of 2190, called the **Static Geopotential Model 2022 (SGM2022).** This will be developed in collaboration with the National Geospatial-Intelligence Agency (NGA) as an update to their EGM2020 model.
    b. Complementing SGM2022 will be a *time-dependent* model of Earth's external gravitational potential, capable of capturing both secular and episodic changes of significance. This time-dependent model will be called the **Dynamic Geopotential Model 2022 (DGM2022).**
3) Three derivative products, based upon GM2022, but requiring additional information and providing higher-resolution regional information than is contained in GM2022 will be created:
    a. A gridded geoid model **GEOID2022**[10], which will contain two components:
        i. The first will be time independent, fixed at 2020.00 called the **Static Geoid model of 2022 (SGEOID2022)**.
        ii. Complementing this will be a time-dependent geoid undulation model, encompassing permanent geoid changes ≥1 millimeter per year, called the **Dynamic Geoid model of 2022 (DGEOID2022)**.
    b. A gridded deflection of the vertical, DoV, model (at the surface of the Earth) **DEFLEC2022**, which will contain two components:
        i. The first will be time independent, fixed at 2020.00 called the **Static Deflection of the Vertical model of 2022 (SDEFLEC2022)**.
        ii. Complementing this will be a time-dependent DoV model, called the **Dynamic Deflection of the Vertical model of 2022 (DDEFLEC2022)**.
    c. A model for interpolating surface gravity **GRAV2022**, which will contain at least one, possibly two components:

[9] There is also a chance the model will be developed in *ellipsoidal*, rather than *spherical*, harmonics. Although the basic application is the same, the increased stability of ellipsoidal harmonics at ultra-high degrees makes it an appealing option. This decision will be made and announced prior to the release of the modernized NSRS, pending the results of ongoing research.

[10] The final GEOID2022 model will be a joint effort between the National Geodetic Survey, the Canadian Geodetic Survey, and Mexico's Instituto Nacional de Estadística y Geografía. The final methodology remains to be determined (TBD), but these three agencies have been working closely on this project for years and have mutually agreed to produce one single model for the modernized NSRS.

    i. The first will be time independent, fixed at 2020.00 called the **Static Gravity model of 2022 (SGRAV2022)**.
    ii. As a second, possible component, NGS will investigate the feasibility of a time-dependent surface gravity model. Its name, if created, would be the **Dynamic Gravity model of 2022 (DGRAV2022)**.

4) Software capable of using GM2022 to compute user-requested aspects of the geopotential field existing external to the crustal masses (including, but not necessarily limited to gravity, geopotential/spheropotential separations, surface deflections of the vertical, and geopotential numbers) will be built into NGS products and services.
5) The GM2022 model, being global, can be evaluated to provide estimates of any geopotential-related quantity, within any NGS product or service in the world (such as positioning with the Online Positioning User Service [OPUS]), without regard to its location. Certain geopotential-related quantities, specifically geoid undulations, surface deflections of the vertical and surface gravity will, however, be evaluated with higher accuracy than is possible in GM2022, when within distinct regions (see #6 below). When an NGS product or service is used to provide information outside of these 3 regions, NGS will determine what, if any, GM2022-based quantities to provide.
6) The three derivative, gridded products (GEOID2022, DEFLEC2022, and GRAV2022) will encompass three non-global areas. These three areas will be (latitude and longitude convention being positive north, positive east):

Area	North (°N)	South (°N)	West (°E)[11]	East (°E)
North America	90	0	170	350
Guam and CNMI	22	11	143	148
American Samoa	-10	-16	186	193

For the North American region specifically, boundaries were determined by first assuring that certain areas (CONUS, Alaska, Hawaii, Canada, Mexico, Central America, the Caribbean, and Greenland) were contained in the computational area. Then an appropriate buffer was added to avoid “edge problems” during the computation.

Only within these three regions will an OPUS solution (or other NGS product or service) yield a geoid undulation, deflection of the vertical and surface gravity value in NAPGD2022.

[11] The longitude system chosen here is a 0–360, positive east system. This avoids a few problems, including (a) mixing positive and negative longitude values, (b) using a west longitude system with values larger than 180, which seems to be a United States-specific invention, (c) the need to specify an alphabetic hemisphere and (d) the difficulty of longitudes going “up” (0 to 180) in two opposing directions, depending on one’s hemisphere.

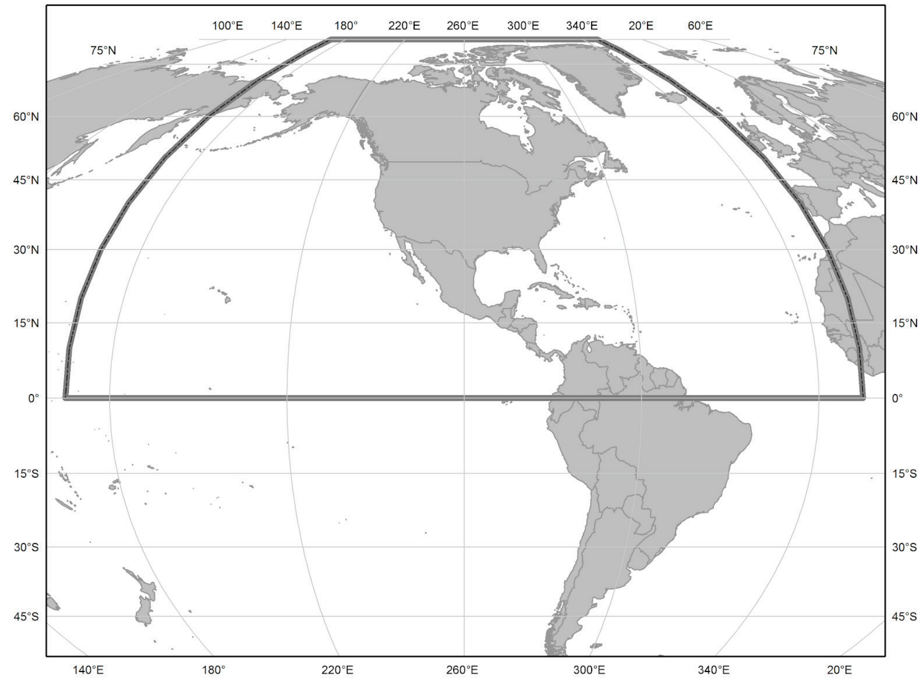

Figure 8: The North American region for GEOID2022, DEFLEC2022 and GRAV2022

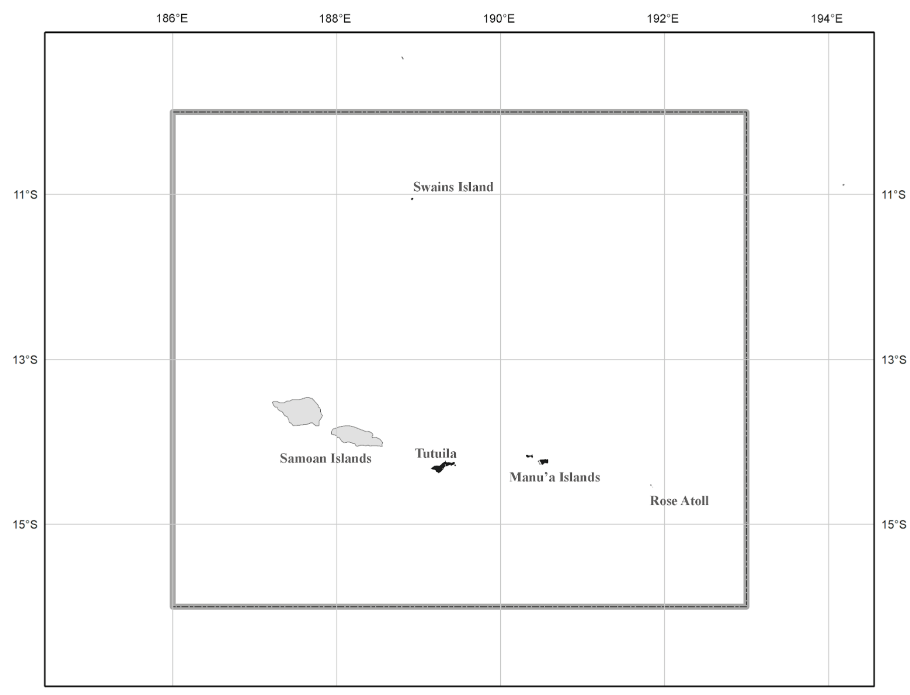

Figure 9: The American Samoa region for GEOID2022, DEFLEC2022 and GRAV2022

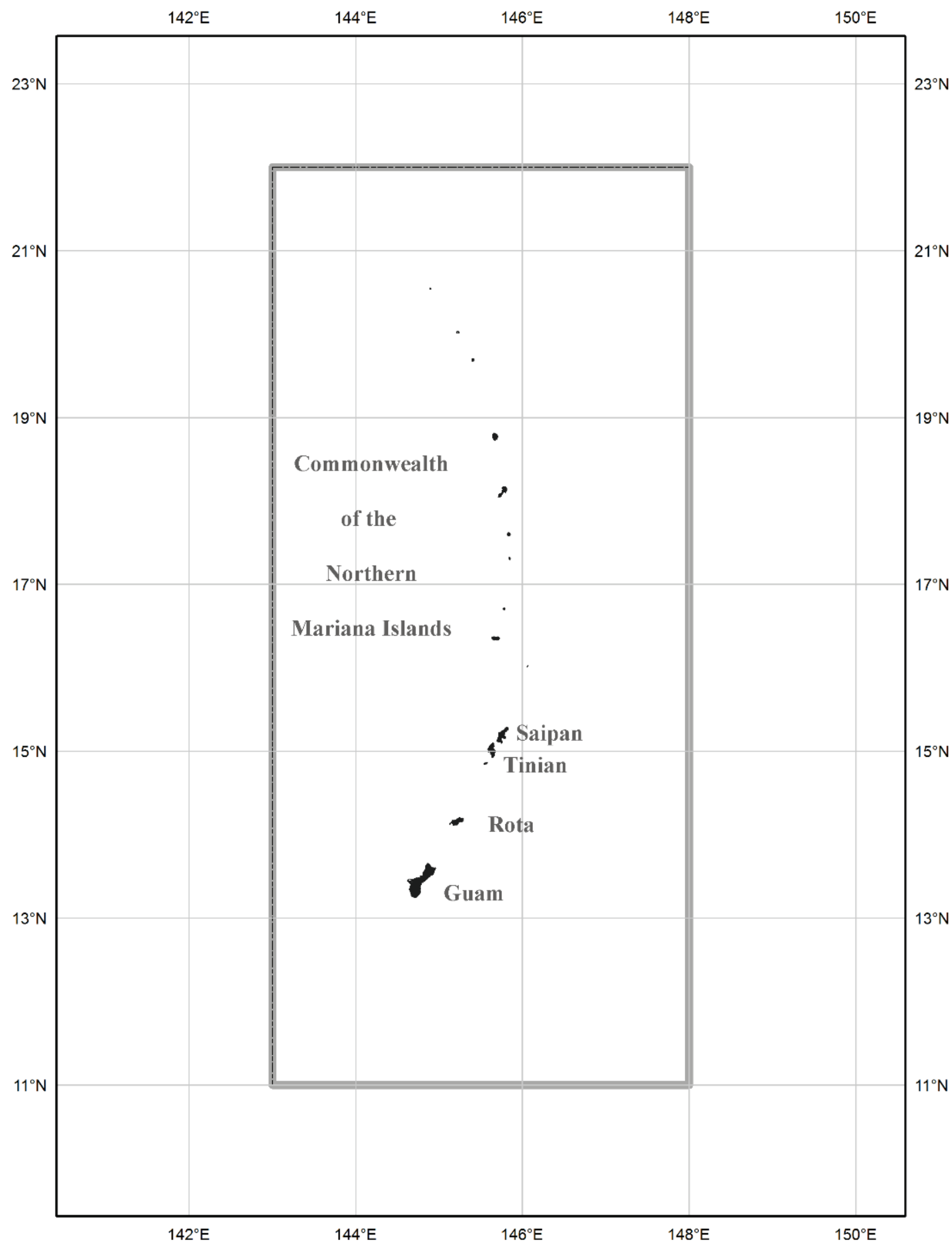

Figure 10: The Guam and CNMI region for GEOID2022, DEFLEC2022, and GRAV2022

9.1 Relationship between GEOID2022 and Other Height Reference Surfaces

GEOID2022 will be the official zero-height surface for orthometric heights within NAPGD2022, and thus within the NSRS. However, other types of heights and other types of reference surfaces are used throughout the world, and their relationship to GEOID2022 should be accurately understood. However, only the relationship between GEOID2022 and certain select height surfaces will be represented in NGS products and tools. The most likely candidates are listed below.

Global Mean Sea Level (GMSL): This was already touched upon, but some further clarification is due. Specifically, the SGEOID2022 portion of GEOID2022 should be considered to best fit global mean sea level at 2020.00, the reference epoch of NAPGD2022, within the bounds of known errors and acceptable error tolerances. The DGEOID2022 portion of GEOID2022 will track changes to the shape of the geoid, but will not contain any element of the approximately 3 millimeters per year GMSL rise (IPCC, 2014; for more details, see sections 6 and 12).

Local Mean Sea Level (LMSL): Local Mean Sea Level can behave very differently from GMSL. Additionally, LMSL behavior can vary significantly between neighboring coastal locations. Consequently, any LMSL change (rise or fall) may be different than the GMSL change rates. Heights above LMSL at various tidal datums (Mean High Water, Mean Lower Low Water, *etc.*) are of critical importance for navigation and flood risk determination. But heights on most topographic maps are generally orthometric, unrelated to LMSL. It is therefore important for a relation to exist between NAPGD2022 heights and LMSL heights. Such ties will best be determined by using GNSS technology at tide gauges. Between tide gauges, NGS will work with NOAA's Center for Operational Oceanographic Products and Services (CO-OPS) to provide interpolation tools (akin to the current VDatum tool). The LMSL heights are usually tied to a group of local tidal benchmarks through a short leveling survey. Using GNSS surveying at the same points, NAPGD2022 orthometric heights can be determined.

North American Datum of 1988 (NAVD 88), *et al*: Until replaced, NAVD 88 is the official vertical datum of the NSRS in CONUS and Alaska. Other official vertical datums exist in Puerto Rico (PRVD 02), the U.S. Virgin Islands (VIVD 09), American Samoa (ASVD 02[12]), The Commonwealth of the Northern Mariana Islands (NMVD 03), and Guam (GUVD 04). A transformation tool (an update of the existing VERTCON tool) will be built that transforms orthometric heights in each of these datums into heights in NAPGD2022 at epoch 2020.00. A campaign is underway, organized by NGS but executed by several hundred surveyors nationwide, to collect GNSS data on benchmarks in each of these datums to assist in building the new version of VERTCON[13].

International Great Lakes Datum (IGLD): The IGLD is an international vertical datum jointly defined and realized by the United States and Canada. The IGLD uses dynamic heights[14], which

[12] Currently deprecated. See Federal Register Volume 74, Number 13 (Thursday, January 22, 2009).

[13] Hawaii has never had an official vertical datum defined as part of the NSRS. However, there is an effort underway (circa 2017) to define a leveling-based datum in the state, on an island-by-island basis. Should any component of that datum become an official part of the NSRS (either before or after the release of the modernized NSRS), then VERTCON will also have a transformation tool from that Hawaiin vertical datum to NAPGD2022 at epoch 2020.00.

[14] It is unfortunate, but unavoidable, that the term "dynamic" appears in two different contexts in this report. For the most part, "dynamic" has been used herein in direct contrast to "static" to distinguish between "time varying"

are relative geopotential values converted to units of length (equivalent to "hydraulic head" used in engineering). The reason for this type of height is that a change in dynamic height equals a change in hydraulic head, which more accurately indicates water levels and flow than orthometric height differences—an important characteristic for the Great Lakes. The current realization, IGLD 85, was co-defined with NAVD 88 (they both are derived from the same set of geopotential numbers, adjusted from geodetic leveling and surface gravity measurements), although NAVD 88 dynamic heights are generally not numerically equal to those of IGLD 85. The reason for the difference is that IGLD 85 dynamic heights are "corrected," so that they match lake levels at official water level stations at an epoch of 1985 (the mid-year of a standard seven-year observation period). This was necessary mainly due to inherent issues in the NAVD 88 datum. A new realization, IGLD2020, will be centered on water level epoch 2020, so it will not be available until after the end of the water level observation period (in late 2023). IGLD2020 will be consistent with NAPGD2022, and NGS is currently working on a method for deriving accurate (relative and absolute) dynamic heights using GNSS. It is still being investigated as to whether a water surface correction will be needed to account for any standing (mean) water topography issues (e.g., wind-driven set up on SE sides of the Lakes).

International Height Reference System (IHRS): The IHRS is not yet a realized entity, but the International Association of Geodesy has been working for over a decade on the realization of this global height standard. When realized, it will likely have a bias from GEOID2022 and possibly higher frequency terms. At that time, a conversion from NAPGD2022 heights to IHRS heights will be determined and provided in all NGS products and services.

EGM96, EGM2008, and EGM2020: The NGA has produced these three global Spherical Harmonic Models (SHMs) in the last 3 decades. Companion geoid grids were provided with each SHM. When GEOID2022 is produced, NGS will also be able to provide direct comparisons between the GEOID2022 grids and the EGM96, EGM2008 and EGM2020 geoid grids, in the areas where GEOID2022 is defined. With the cooperation and permission of NGA, NGS can incorporate all three of the NGA geoid grids into NGS tools such as OPUS, NCAT, and VDatum.

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and "time independent" parts of the geopotential field. However, the term "dynamic height" is actually a long-established geodetic quantity where "dynamic" does not mean "time varying". Even more confusing, "dynamic heights" aren't even heights, but are rather geopotential numbers that have been scaled from their usual units (m^2/s^2) by dividing by some constant value of gravity (m/s^2) to yield a value in meters that is in the same ballpark as true heights (ellipsoidal, orthometric). They are used to regulate water levels and aside from this use, they are rarely used in geodesy.

10 Creating and Using NAPGD2022

A variety of new terms were introduced in the previous section, and their relation, interaction, and use may not be immediately clear. Therefore, this section will attempt to provide some clarity.

10.1 Selection of the Geopotential Datum value (W_0) for NAPGD2022

The most fundamental aspect of any geopotential datum is the selection of the geopotential value (W_0) to serve as the geoid, which is the best approximation of global mean sea level. The International Association of Geodesy (IAG) adopted a value of 62,663,853.4 $m^2\ s^{-2}$ based on evaluation of global satellite altimetry (IAG Resolution No. 1, 2015). The value of 62,636,856.0 $m^2\ s^{-2}$ (Burša *et al.*, 1999) was adopted by the International Astronomical Association (IAU), the International Earth Rotation and Reference Systems Service (IERS) and the Bureau International des Poids et Mesures (BIPM). Other values have been suggested globally as well (Sevilla *et al.* 2008, Dayoub *et al.* 2012). In the end, the NGS decided to determine the best value from comparisons at tide gauges around North America (Roman and Li, 2020). This will tie more closely to the mission of the National Ocean Service inside of NOAA and provide enhancements to products such as VDatum and the Sea Level Rise viewer. It will also better serve the American public by making a more explicit link between the ocean surface and places on land in the form of relative sea level (e.g., how high is my house above the next storm surge or King tide?).

Mean Ocean Dynamic Topography (MODT) represents a disturbing force from the ideal equipotential surface of the geoid. It is caused by variations in pressure, temperature, and salinity of the ocean waters and is usually associated with the well established ocean currents. MODT values range over 1.5 meters along the eastern North American shoreline ranging from the higher, warmer, rapidly moving Gulf Stream in the South to the lower, colder, denser waters of the Labrador Current in the North. Removal of estimated MODT values at nearly 200 tide gauges in the U.S. and Canada determined residual values that averaged out to the value adopted by the IAU and the IERS. This test was completed by NGS for the U.S. and also by the Canadian Geodetic Survey, and both agencies agreed on the results. Therefore, the U.S. and Canada agreed to adopt the common value of 62,636,856.00 m^2/s^2 to serve as the common geoid.

10.2 *Creating* NAPGD2022

The creation of all components of NAPGD2022 begins with the creation of GM2022. That model has the advantages of being global and providing information in three dimensions, as long as the point being evaluated is at or above the surface of the Earth. It has the disadvantage of being "spectrally limited," which is to say that it suffers omission error (lack of high-frequency information below a certain wavelength, determined entirely by the highest degree to which GM2022 is modeled, somewhere between 2190 and 10,000[15]).

GM2022 will be built from a variety of input data sources (gravity, digital elevation models or DEMs, Satellite Altimetry, and models of the geodynamics of the Earth). There will be a fixed component (at reference epoch 2020.00) called "SGM2022" and a time-variable component (reflecting changes to the potential field relative to that same reference epoch) called "DGM2022." The most probable final mix of input data is seen in Figure 11.

Note the dashed lines in Figure 11, contributing to the creation of DGM2022. They are dashed to indicate they are not likely to contribute to the first DGM2022 version. As the secular and episodic changes to each of those data sets becomes well known, they may contribute to future DGM2022 versions. The most likely example of this is that episodic changes, such as certain earthquakes, may see contributions to DGM2022 from a new surface gravity or airborne gravity survey in a local region.

Because GM2022 has the disadvantage of being spectrally limited, and because that disadvantage can be overcome by creating high-resolution gridded models of certain aspects of the potential field (such as geoid undulations, deflections of the vertical, or surface gravity), three products in grid form will be created, using the same input data, and built upon SGM2022 and DGM2022. These three products will be GEOID2022, DEFLEC2022, and GRAV2022, the first two of which will have time dependency. See Figure 12.

[15] As mentioned earlier, state-of-the-art SHMs tend to have a maximum degree of at least 2,190, though some have expanded past 10,000.

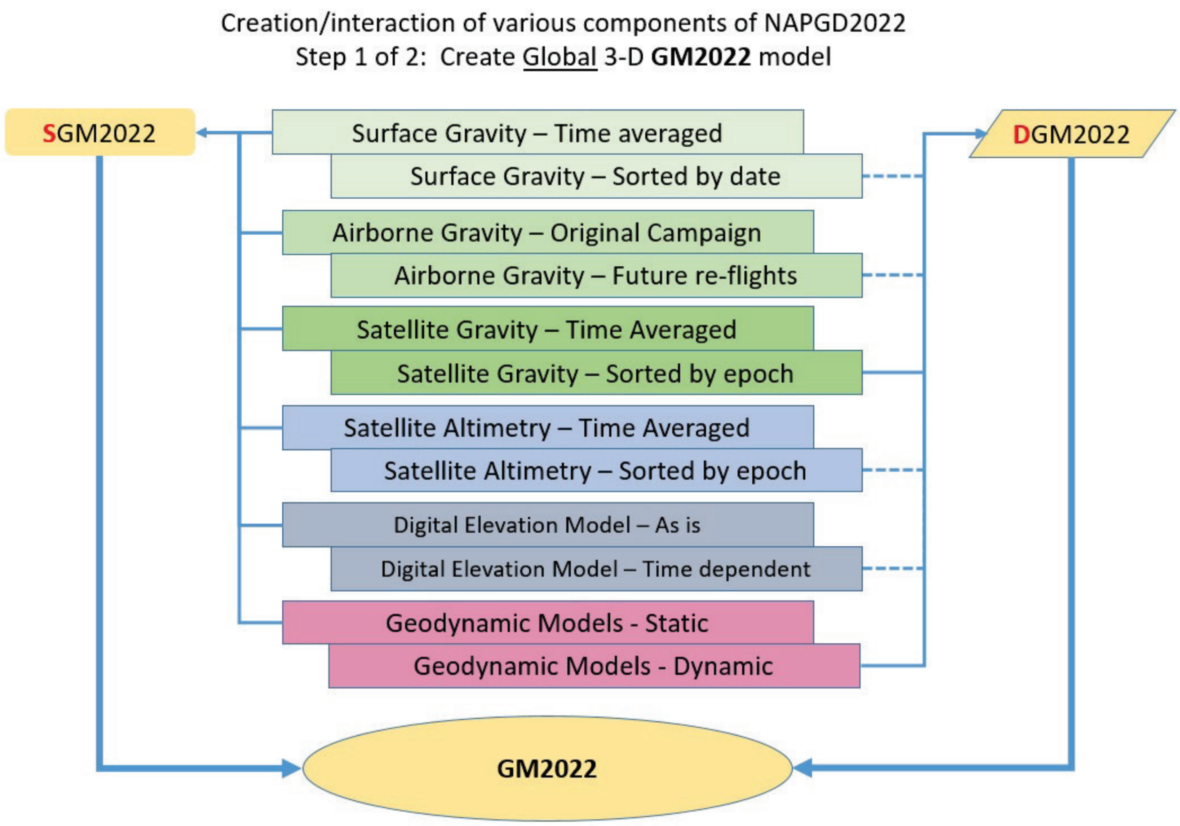

Figure 11: Creating NAPGD2022, Step 1: Create GM2022

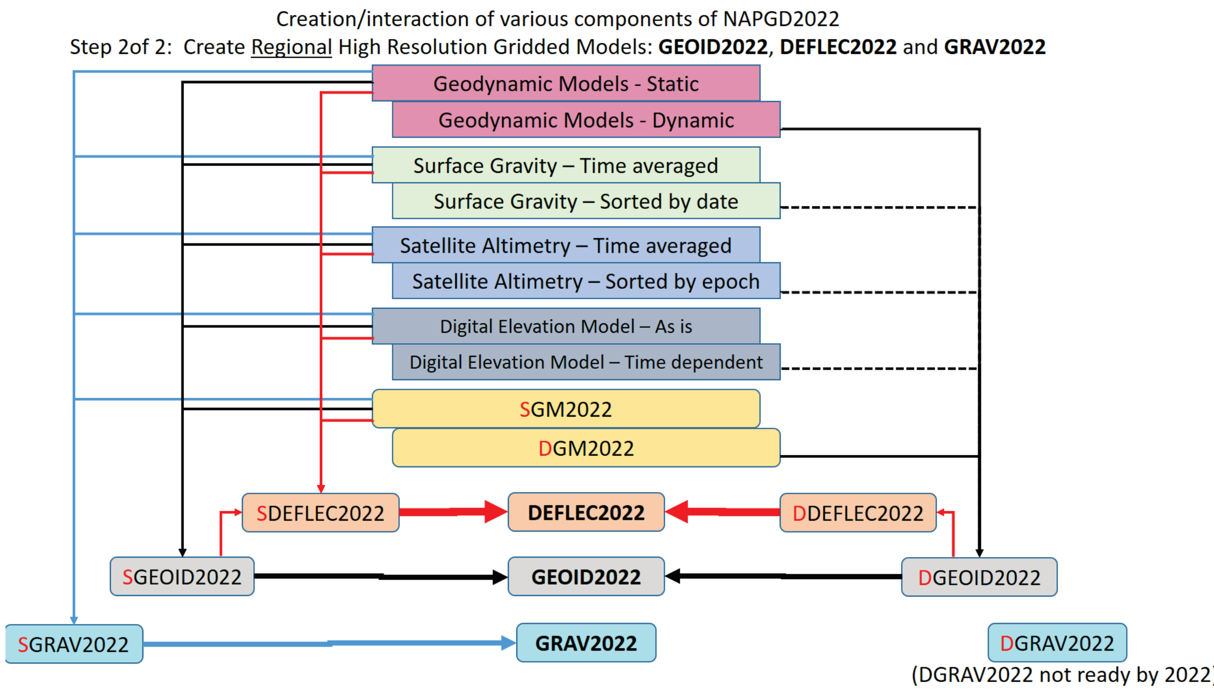

Figure 12: Creating NAPGD2022, Step 2: Create GEOID2022, DEFLEC2022, and GRAV2022

As in Figure 11, the dashed lines in Figure 12 indicate potential future sources of information for the dynamic geoid model, but those sources are not expected to be part of the initial roll-out of the modernized NSRS.

It is critical to point out that the two components of GM2022, GEOID2022, and DEFLEC2022, will generally not be treated as separate products to users. For example, GEOID2022 is a time-dependent model of the geoid, and that means a geoid undulation from GEOID2022 is time dependent. Users needing a geoid undulation in 2025 will get a different geoid undulation from GEOID2022 than those who need a geoid undulation in 2030.

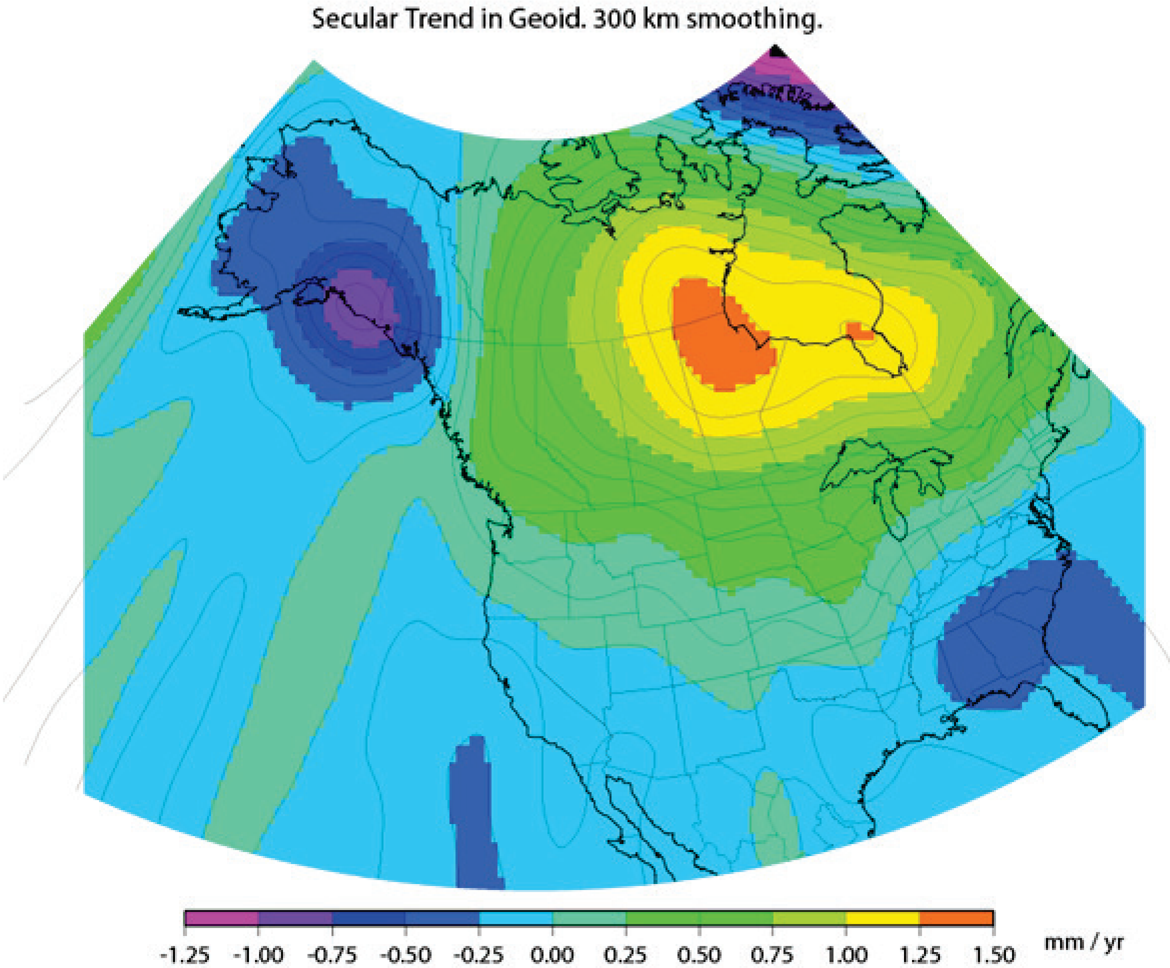

Figure 13: Secular geoid change

However, NGS is aware of the uses of time-invariant values at fixed epochs, and so NGS will provide not only time-dependent values, but will also provide estimates of time-invariant coordinates at reference epochs, as well, such as the time-dependent geoid change seen in Figure 13. This was originally addressed in NGS (2019), but will be further discussed in the next sub section.

10.3 *Using* NAPGD2022

When one considers the issue of time-dependent geodetic control, a number of heretofore unasked questions arise. That is, the single question of “What is the coordinate of this point?” must be discarded and replaced with the more scientifically accurate question of “What is the coordinate of this point *at this time*?” Furthermore, the equally relevant questions of “Which version of the datum does this refer to?" (see Section 12) and "Which version of the software was used to create that coordinate?" must also be asked. Thankfully, with a new version of OPUS being part of the modernized NSRS, many important metadata questions such as these will be more easily resolved. In contrast to the current method of bluebooking, which allows for a wider variety of file names and directory structures when data are turned in to NGS, the future of data submissions through OPUS will enforce specific metadata storage, allowing for easier re-processing of data in the future. For a thorough discussion on using NAPGD2022 and the modernized NSRS, please see NGS (2019).

As mentioned previously, both in this document as well as others, the determination of most coordinates in the geopotential datum begins with the determination of geometric coordinates in terrestrial reference frames.

The previous Blueprint document (NGS 2020), showed the determination process for geometric coordinates, using (for example) a simple OPUS tool akin to today's OPUS-S, but in the modernized NSRS. The determination of geopotential coordinates through tools like OPUS will begin with that method, arriving at geometric coordinates. Those will then be used to derive geopotential coordinates, as per the following:

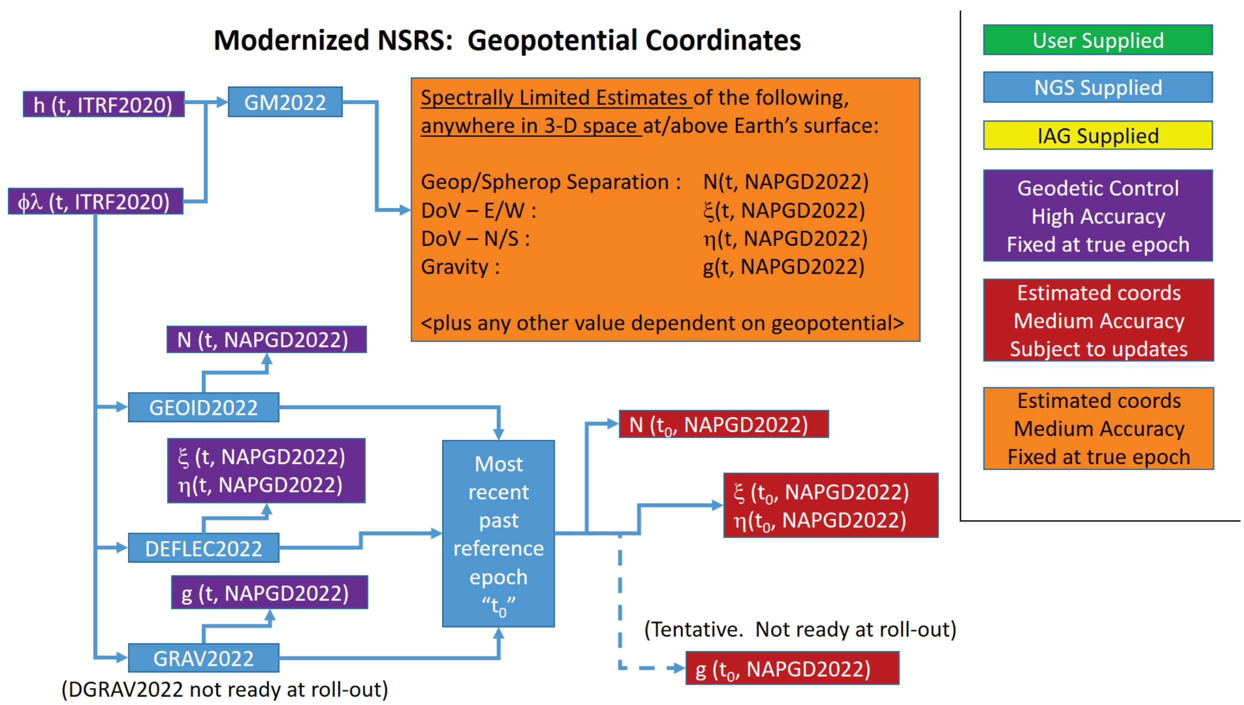

Figure 14: Flowchart for the determination of geopotential coordinates in the modernized NSRS

One might then ask "What geometric reference frame should be used in conjunction with NAPGD2022?" The answer to that question is simple: "any". Specifically NAPGD2022 works in perfect conjunction with ITRF2020, NATRF2022, PATRF2022, CATRF2022 and MATRF2022.

Therefore, OPUS, and all other NGS products and services will solely use IGS values of ϕ and λ to compute values in NAPGD2022, regardless of the geometric frame being used.

11 Quantification and Use of Uncertainty in GEOID2022

11.1 Quantification of Uncertainty

GEOID2022, like any model, will be imperfect. It will be built on imperfect data, imperfect theories and imperfect software. However, NGS (along with the geodetic community as a whole) has been improving all of these for decades. Some fifty years ago a geoid uncertainty of 1 meter was considered state of the art (see Appendix A). Since then, data, theory and software have driven that down by orders of magnitude.

While a geoid model can be used to convert one ellipsoid height into one orthometric height (or vice versa), that ignores the fact that height determination in surveying is most often about *relative* relationships. To paraphrase from Smith et al (2013) it is an academic and somewhat unimportant question about whether one can determine the absolute accuracy of the geoid undulation at a single point. The more pressing question is how well can you determine the difference in geoid undulations between two points? In this way differential ellipsoid heights yield differential orthometric heights, and differential orthometric heights almost always[16] determine the direction of water flow, a critical piece of information to USGS, FEMA, and others.

Aside from theory and software improvements, NGS knew that flying GRAV-D would mean improving the overall gravity data holdings at NGS. NGS wished to quantify how much improvement to the geoid was gained with GRAV-D. Therefore, three studies were stood up under the titles Geoid Slope Validation Survey (or GSVS). Each survey was approximately 300 km in length, incorporated GPS, leveling, gravity, and deflection of the vertical measurements with the express intent of developing two mutually independent but compatible calibration lines of differential geoid undulation (one from mixing differential GPS and differential leveling and the other from the DoV measurements). With these two calibration profiles available, NGS was able to compare them against geoid models computed with and without GRAV-D, using otherwise identical data, theory and software. This allowed for NGS to quantify not only how much improvement was gained but also a general rule of thumb for differential geoid accuracy in particular terrain types. The three terrain types studied were low and flat, in Texas for GSVS11 (Smith et al, 2013), high and flat with some complex geoid signals in Iowa for GSVS14

[16] Full clarification of this not-quite-absolute statement is beyond this document, but readers so interested in pursuing it are pointed to the difference between water moving “down hill” and water moving “up potential”.

(Wang et al, 2017) and high and rugged in Colorado for GSVS17 (van Westrum et al, 2021). A summary of the findings, which NGS anticipates will serve as general rules of thumb for the overall GEOID2022 expected accuracy are seen in the table below. These are differential accuracies for distances between points ranging from 0 to 300 km or so.

Table 2: Generalized geoid accuracy results from the three GSVS research projects

Survey	Accuracy without GRAV-D	Accuracy with GRAV-D
GSVS11	1-3 cm	1 cm
GSVS14	2-4 cm	2-4 cm
GSVS17	3-5 cm	3-5 cm

The most significant improvement from GRAV-D was seen in flat coastal areas, which is not completely surprising. Such areas frequently have a gap of gravity data in the near-shore littoral regions which contributes to poor geoid modeling. However, it was somewhat surprising that neither GSVS14 nor GSVS17 showed a statistically significant improvement in geoid modeling with the addition of GRAV-D data. Because of this, NGS has initiated an investigation into our current geoid modeling techniques and software. This investigation will take the place of NGS's annual "experimental geoid" (or "xGEOID") production in 2021. Before GRAV-D was flown, it was safe to say that NGS did not have a comprehensive picture of where terrestrial data was incorrect and where it was still viable. These GSVS experiments helped to verify that terrestrial data is still good in parts of Iowa and Colorado, but it does not mean that the terrestrial data is good everywhere.

The values in the above table are rules of thumb. The actual GEOID2022 model will also have geographically dependent formal accuracy estimates released as part of the model. Those formal accuracy estimates will be calibrated to the actual empirically determined estimates in the table above.

11.2 Use of Uncertainties

Although GEOID2022 will come with a companion set of geographically dependent uncertainties, the treatment of uncertainties in GEOID2022 will be done in a very specific way. On the one hand, geoid modeling, similar to any model built upon theory and measured data, must contain uncertainties. On the other hand, if NGS were to modify the geoid every time new survey data or new theories were available, the model would change multiple times every year. Based on user feedback over the last two decades, even the approximate three-year update cycle of NGS hybrid geoid models (1996 to 2018) was seen to be somewhat disruptive. The good news is that the primary driver of the NGS hybrid geoid model's approximate three-year update cycle was the accumulation of new GNSS data on leveled benchmarks. As these data will not be the basis of creating GEOID2022, that driver has been entirely removed.

Furthermore, the need for periodically creating new geoid models is lessened, due to the availability of satellite gravity global data from GRACE and GOCE, the systematic and mutually-consistent GRAV-D airborne surveys, millions of historic terrestrial gravity survey points, and Digital Elevation Models (DEMs) with better accuracy and consistency. The main remaining driver of change will be improvements in future geoid modeling theory. A significant portion of NGS' geoid-related work leading up to the modernized NSRS has been toward refining the theory and coming to agreement on that theory with colleagues in Canada and Mexico.

Therefore NGS has adopted as its initial standard operating procedure, that surveys making use of GEOID2022 will not be used to *alter* GEOID2022.

That is, leveling surveys will always be adjusted while holding GEOID2022 fixed at the epoch of the adjustment. However, if a critical mass of new gravity information or improved geoid modeling theory accumulates at NGS, then newer versions of GEOID2022 will likely be issued (see Chapter 12). NGS will be very clear on versioning all changes to all components of NAPGD2022, so that users will be able to retrace historic computations as necessary.

However, that is not to say GEOID2022 is *actually* known perfectly. But to provide consistent customer service for the foreseeable future, NGS will treat GEOID2022 as a convention, very much in the same light as the GRS 80 ellipsoid—it will be considered a fixed surface at any given epoch when transforming values (though, to be complete, GRS 80 has no time dependency, whereas GEOID2022 does). To clarify, consider this transformation of coordinates in any of the new *TRF2022[17] frames:

$$\begin{bmatrix} x_{*TRF2022} \\ y_{*TRF2022} \\ z_{*TRF2022} \end{bmatrix}_t \xrightarrow[GRS-80]{} \begin{bmatrix} \phi_{*TRF2022} \\ \lambda_{*TRF2022} \\ h_{*TRF2022} \end{bmatrix}_t \qquad (2)$$

In performing that transformation, the *x*, *y*, *z* values come from a GNSS survey, and they do have error. But when converting *x*, *y*, *z* to *φ*, λ, and *h*, no *additional* error is added to the *φ*, *λ*, *h* coordinates simply because they rely on GRS 80. This would not be true if, for example, parameters like the semi-major axis "*a*" and flattening "*f*" for GRS 80 were considered to have

[17] *TRF2022 means any of these: NATRF2022, CATRF2022, PATRF2022, or MATRF2022. See also NOAA Technical Report NOS NGS 62, "Blueprint for the Modernized NSRS: Part 1, Geometric Coordinates and Terrestrial Reference Frames." (2020)

some uncertainty. In that case, the additional uncertainty of the "*a*" and "*f*" values would mean the error estimates of the φ, λ, h coordinates would be a combination of the errors in x, y, and z, as well as the errors in the "*a*" and "*f*" of GRS 80. Note though, in either case, the actual φ, λ, h coordinates would still come out the same. It is just that the *errors* on those coordinates would be larger if there were errors in the ellipsoid.

However, the treatment of GEOID2022 will not be exactly the same as GRS 80. The uncertainties in GEOID2022 will be acknowledged when computing orthometric heights. That is:

$$[h_{*TRF2022}]_t \xrightarrow[GEOID2022]{} [H_{NAPGD2022}]_t \tag{3}$$

or, with the appropriate detail:

$$H_{NAPGD2022}(t) \equiv h(t) - N_{GEOID2022}(t) \tag{4}$$

Note that this equation is **definitional** (and also that h(t) can be in any of the frames ITRF2020, NATRF2022, CATRF2022, MATRF2022 or PATRF2022, provided they all use the GRS 80 ellipsoid). It is exact (the approximation sign seen in equation 1 has been removed) and time dependent. But, unlike the GRS 80 example, NGS will not treat GEOID2022 as errorless when computing the uncertainties of orthometric heights. On the contrary, ***there will be a very rigorously computed geographically dependent model of geoid errors in GEOID2022*** used to contribute to the uncertainty in orthometric heights in NAPGD2022. This will be the first time that such an error model will be provided as part of an NGS geoid product. It will be applied as follows:

$$\sigma_{H_{NAPGD2022}}(t) = \sqrt{\sigma^2{}_h(t) + \sigma^2{}_{N_{GEOID2022}}(t)} \tag{5}$$

What this means, from a practical standpoint is that NAPGD2022 orthometric heights determined by equation 4 will, as a rule, have larger uncertainties than *TRF2022 ellipsoid heights. As in the remainder of this document, NGS is using 1 sigma (1 standard deviation) as the basic unit of uncertainty. This is also definitional and reflects the fact that GNSS-derived orthometric heights should reflect a greater uncertainty than GNSS-derived ellipsoid heights, due to the imperfect nature of geoid modeling.

12 Scientific Aspects of NAPGD2022

Certain scientific and practical decisions have been made regarding the new geopotential datum and its derived geoid, deflection of the vertical, and surface gravity models, while others remain to be determined (TBD). A list of decisions to this point is found in Table 3. All of the listed non-TBD decisions should be considered fixed for the initial release of NAPGD2022 and its derivative products (GEOID2022, DEFLEC2022, GRAV2022), but NGS reserves the right to modify any of them in future datum and geoid updates.

Table 3: Decisions on characteristics of NAPGD2022 and its derivative products

Subject	**Decision**
Permanent Tide System	Tide Free (aka "Non-Tidal")[18]
W_0 of GEOID2022	62,636,856.0 $m^2\ s^{-2}$
Epoch of SGEOID2022	2020.00
Reference Frame	ITRF2020
Ellipsoid shape (a, f)	GRS 80
GM of normal Field[19]	398,600,500,000,000 m^3s^{-2}
"a" of normal Field	6,378,137 m
GM of true field	TBD
"a" of true field	TBD
Maximum degree of GM2022	2190 (Spherical Harmonics)
Rotation rate of normal field (ω)	0.00007292115 rad s^{-1}
Rotation rate of full field	Identical to rotation rate of normal field
Grid Spacing of SGEOID2022	1 arcminute
Grid Spacing of SDEFLEC2022	1 arcminute
Mean gravity on the plumbline computed from GRAV2022	Method of Flury and Rummel (2009)
Grid formats	GeoTIFF
Interpolation method of GEOID2022	Biquadratic

13 The Role of Leveling in NAPGD2022

Geodetic leveling has been, and is expected to continue to be, the most accurate method to determine differential orthometric heights over distances of 50 kilometers or less (Smith, et al, 2013). Beyond that, the build-up of error in leveling will begin to approach the combined errors of GNSS-derived ellipsoid height differences and geoid undulation differences. Therefore, the continued use of leveling is necessary for many applications. However, leveling will not be used

[18] This is applied on the C20 term of GM2022 (Mäkinen and Ihde, 2009)

[19] For complete details regarding the differences between the "a" and "GM" values chosen for the normal geopotential field and the full geopotential field and their varied impacts, see Smith (1998). Also, this GM value includes the mass of the normal atmosphere.

in the definition of the geopotential datum, but only in the dissemination of differential orthometric heights within that datum.

The primary issue with using leveling remains the same as it always has been: it is a differential survey method only. In the past, this meant that some starting point, or points, would need to be chosen, either to create a vertical datum or to perform a local survey within a given datum. In the case of creating a datum, one point was chosen for NAVD 88. In the case of a local survey, current geodetic leveling specifications require finding a certain number (usually 3) of known points and tying a local leveling survey to them.

This issue will remain the same for local surveys in NAPGD2022—to perform a survey, users will need to have some known starting height or heights. The finding and/or determining of such points and their quality will be part of a new leveling manual. The most reliable method will be to use GNSS to determine orthometric heights on points contained within the leveling survey near the time of the leveling survey itself. Other, less reliable methods will be investigated, and NGS will eventually provide specifications on their overall reliability. For example, taking the results of someone else's GNSS survey or GNSS/leveling survey from days, weeks, months, or years prior will all be considered, within the context of provable mark stability. NGS will investigate not only the likelihood of such points being reliable, but also the error estimates derived from using them.

In summary, for any geodetic leveling survey, NGS is leaning toward the following standard operating procedure: "The first step is to use GNSS to acquire your starting orthometric heights." Whether that GNSS consists of short sessions using a tool such as OPUS, or even RTK/RTN technologies (aligned to the NSRS), as well as how much time should pass between the GNSS survey and the beginning of leveling, all remain part of the ongoing research into this topic.

14 Updating and Replacing the Geopotential Datum

All of the preceding information has dealt with the initial roll-out of NAPGD2022. However, a variety of things will drive *updates* to NAPGD2022, while only certain severe threshold changes to the Earth would drive a complete *replacement* of NAPGD2022.

14.1 *Updating* the Geopotential Datum

The year "2022" occurs in many names listed above. Having that year in all of the various names reflects the fact that this geopotential datum (NAPGD2022) with its four primary components (GM2022, GEOID2022, DEFLEC2022, and GRAV2022) were originally created for rollout in 2022. *The year 2022 does not imply an epoch of the static components of any of the* *data.* Nor does it imply that coordinates in that geopotential datum will refer to the year 2022. But the common "2022" ties the datum and its four components together, and NGS plans to always have this five-way common "rollout year" in the names for the foreseeable next few decades.

What this means is that NGS will adopt *version numbering* for updates, rather than changing the actual name of the datum or any component of the datum. Therefore, the official name of the new datum and of all its components, upon their initial release, will come with a version number parenthetically on the end:

- NAPGD2022 (v01), composed of:
    - GM2022 (v01) (made up of SGM2022 (v01) and DGM2022 (v01))
    - GEOID2022v01 (made up of SGEOID2022 (v01) and DGEOID2022 (v01))
    - DEFLEC2022v01 (made up of SDEFLEC2022 (v01) and DDEFLEC2022 (v01))
    - GRAV2022v01 (made up of SGRAV2022 (v01) and, in theory, *DGRAV2022(v01)*[20])

These version numbers will remain consistent across every component of NAPGD2022. For example, say that in the year 2025 something drives NGS to consider an update to SGEOID2022. Such a driver might be an error detection or some significant improvement in static geoid modeling theory, etc. No matter which component of NAPGD2022 needs an update, the exact rollout will always be as follows:

1) NGS will always begin by taking this as an opportunity to update GM2022. The most likely change will be the incorporation of any post-2022 gravity collected into the geopotential model. Thus, the first update of any component will begin by creating GM2022 (v02.)

2) As all models are built upon the geopotential model, they will then be built based on GM2022 (v02) to create a SGEOID2022 (v02), DGEOID2022 (v02), GEOID2022 (v02), etc.

3) As all models comprise the geopotential datum, the updated datum name would be NAPGD2022 (v02).

When an update occurs, the *epoch* of the static field is not changed. That is, the epoch used for SGEOID2022 (v01) will be the same as that for SGEOID2022 (v02) (being 2020.00). This updating of the vertical datum with version numbers, rather than name changes, is a new policy at NGS. Only an actual *replacement* of the entire geopotential datum itself (see section 12.3) will trigger a name change. That is, should the first *update* to the geoid (not a *replacement*) occur in 2030, NGS will issue "GEOID2022 (v02)" (as part of "NAPGD2022 (v02)") and not "GEOID2030."

[20] As mentioned previously, the concept of a time-dependent surface gravity model will be investigated, but is not viewed as a likely part of the initial roll-out of NAPGD2022. If it is not released, then it will be assumed zero and SGRAV2022v01 and GRAV2022v01 will be identical.

The capability to access prior versions of NAPGD2022 and all its components will be built into NGS products and services. The initial versions of NAPGD2022 and all its components will therefore have version "(v01)" upon initial rollout.

14.2 Drivers of Updates

An illustrative, but not exhaustive list of the sort of things that may drive an update would be:

- Events (earthquakes, volcanic eruptions, etc.)
- Improved knowledge (new satellites, significant new surveys, new theories)
- Fixing errors in earlier versions (bug fixes, etc.)

NGS has set the goal of maintaining the geoid at 1 centimeter (1 standard deviation) in both absolute and differential accuracy. This goal, however, should not be interpreted to mean that, were a single grid node with an error of 1 centimeter be detected, an update to the geoid model is required. Rather, as NGS continually performs geoid research, there will be checks on the most current version of GEOID2022. Some TBD threshold geographic region (e.g. 20 km x 20 km) in GEOID2022 would need to exceed 1 centimeter to trigger an update. As such, the ***update threshold*** for the geoid model is not simply "whenever any point is off by 1 centimeter," but rather when some significant geographic region is off by 1 centimeter. Furthermore, to minimize disruption to the user community, decisions on updating the geoid must take into consideration their practical impact, such as whether they would only impact remote or less populated areas.

14.3 Replacing the Geopotential Datum

NGS plans to maintain the geopotential datum under the name "NAPGD2022" for the foreseeable next few decades. However, as mentioned earlier, the geoid is (strictly speaking) defined as best fitting to global mean sea level which is known to be rising by over 3 millimeters per year, and possibly accelerating. Rather than having the public adapt to a rising H=0 surface, NGS will specifically hold the H=0 surface at one $W=W_0$ value, with $W_0=62{,}636{,}856.00\ m^2/s^2$ at first.Changes to the shape of this surface will be tracked and monitored, but that surface and sea level will obviously diverge over the years (by the aforementioned 3 mm/year or so). Only when the Global Mean Sea Level (GMSL) has risen above some threshold amount will a *new* geoid model be released, and that new geoid will require the definition (and renaming of) an entirely new geopotential datum. The new geoid model will have a variety of changes from the previous model. Changes to expect:

1) The static geoid model will be replaced (SGEOID2022 gets replaced with SGEOIDyyyy)
2) The epoch of the static geoid model will change (2020.00 to ?)
3) The W_0 value of the static geoid model will change
4) The name of the *entire* geoid model will change (GEOID2022 gets replaced with GEOIDyyyy)
5) The name of the entire geopotential datum (and all its components) will change, so NAPGD2022 is replaced with NAPGDyyyy.

NGS and the Canadian Geodetic Survey have jointly adopted the value of 2.0 m^2/s^2 as the **replacement threshold** for a new geoid model (and new geopotential datum). This represents approximately 20 centimeters of GMSL (and thus geoid) rise. At the current rate of sea level change of about +3 millimeters per year (IPCC, 2014), this means NGS expects to replace NAPGD2022 in approximately 60 to 70 years.

15 Bibliography

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

Dayoub, N., S.J. Edwards, and P. Moore, 2012. "The Gauss-Listing potential value W0 and its rate from altimetric mean sea level and GRACE," *Journal of Geodesy*, 86(9): 681–694, https://doi.org/10.1007/s00190-012-0547-6 .

Flury, J., and R. Rummel, 2009. "On the geoid–quasigeoid separation in mountain areas." *Journal of Geodesy*, 83(9), 829–847.

Fowles, G. R., 1970: *Analytical Mechancs,* 2nd ed., Brooks Cole, Pacific Grove, CA.

Gauss, C.F., 1828: *Bestimmung des Breitenunterschiedes zwischen den Sternwarten von Göttingen und Altona*, Göttingen.

Heiskanen, W.A., and H. Moritz, 1967: *Physical Geodesy*, W.H. Freeman and Co, San Francisco.

Hofmann-Wellenhof, B., and H. Moritz, 2006: *Physical Geodesy*, Springer Science & Business Media, New York.

Hsu, S-W., 2010: "The Palermo Stone: The Earliest Royal Inscription from Ancient Egypt," *Altorientalische Forschungen*, v. 37, pp. 68–89.

IAG Resolution No. 1, 2015: *IAG Resolution (No. 1) for the Definition and Realization of an International Height Reference System (IHRS)*, IAG Resolutions adopted by the IAG Council at the XXVI th IUGG General Assembly, Prague, Czech Republic, June 22–July 2, https://iag.dgfi.tum.de/fileadmin/IAG-docs/IAG_Resolutions_2015.pdf .

IPCC, 2014*: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* https://www.ipcc.ch/report/ar5/ .

Jekeli, C., 2000: " Heights, the Geopotential, and Vertical Datums," *Department of Civil and Environmental Engineering and Geodetic Science Report* 459, The Ohio State University. https://earthsciences.osu.edu/sites/earthsciences.osu.edu/files/report-459.pdf .

Lemoine, F.B., S. C. Kenyon, J. K. Factor, R.G. Trimmer, N. K. Pavlis, D. S. Chinn, C. M. Cox, S. M. Klosko, S. B. Luthcke, M. H. Torrence, Y. M. Wang, R. G. Williamson, E. C. Pavlis, R. H. Rapp, and T. R. Olson, 1998: *The Development of the Joint NASA GSFC and NIMA Geopotential Model EGM96*, NASA Goddard Space Flight Center, Greenbelt, Maryland, 20771 USA.

Listing, J.B., 1873: *Über unsere jetzige Kenntnis der Gestalt und Größe der Erde*, Nachr. D. Kgl. Gesellsch. D. Wiss. Und der Georg-August-Univ., 33–998, Göttingen 1873.

Mäkinen, J., & J. Ihde, 2009. "The permanent tide in height systems." *In Observing Our Changing Earth* (pp. 81–87). Springer, Berlin, Heidelberg.

Marion, J.B., 1970: *Classical Dynamics of Particles and Systems*, 2nd ed., Brooks Cole, Pacific Grove, CA.

Milbert, 1991: *Computing GPS-derived orthometric heights with the GEOID90 geoid height model*, GIS/LIS 91 proceedings.

National Geodetic Survey, 1993: *GEOID93 / ALASKA94*, https://www.ngs.noaa.gov/GEOID/GEOID93_ALASKA94/, downloaded 2017 03 03.

National Geodetic Survey, 2007: *The GRAV-D Project: Gravity for the Redefinition of the American Vertical Datum*. National Oceanic and Atmospheric Administration, National Geodetic Survey, Silver Spring, MD, http://www.ngs.noaa.gov/GRAV-D/pubs/GRAV-D_v2007_12_19.pdf, downloaded 2017 08 07.

National Geodetic Survey, 2008: *The National Geodetic Survey Ten-Year Plan 2008–2018*, available at: http://www.ngs.noaa.gov/INFO/NGS10yearplan.pdf, downloaded 2017 03 02.

National Geodetic Survey, 2013: *The National Geodetic Survey Ten-Year Strategic Plan 2013-2023*, available at: https://www.ngs.noaa.gov/web/news/Ten_Year_Plan_2013-2023.pdf, downloaded 2017 03 03.

National Geodetic Survey, 2017: *Blueprint for 2022, Part 1: Geometric Coordinates*, NOAA Technical Report NOS NGS 62, available at: https://www.ngs.noaa.gov/PUBS_LIB/NOAA_TR_NOS_NGS_0062.pdf, downloaded 2017 05 18.

National Geodetic Survey, 2019: *Blueprint for 2022, Part 3: Working in the Modernized NSRS*, NOAA Technical Report NOS NGS 67, available at: https://www.ngs.noaa.gov/PUBS_LIB/NOAA_TR_NOS_NGS_0067.pdf, downloaded 2020 04 15.

Pavlis, N.K., S.A. Holmes, S.C. Kenyon, and J.K. Factor, 2012: “The Development and Evaluation of the Earth Gravitational Model 2008 (EGM2008),” *Journal of Geophysical Research,* Volume 117, Issue B4, pp. 1–38.

Smith, D.A., and D.R. Roman, 2001: “GEOID99 and G99SSS: 1-arc-minute geoid models for the United States,” *Journal of Geodesy,* Vol. 75, No. 9, p. 469–490.

Roman, D. R., and X. Li, 2020: *Analysis of a Geopotential Datum at Tide Gauge Stations*, Paper 10426, Proceedings of the FIG Working Week (virtual), Amsterdam, the Netherlands, ISBN 978-87-92853-93-6, ISSN 2307-4086.

Roman, D. R., Y. M. Wang, W. Henning, and J. Hamilton, 2004: “Assessment of the New National Geoid Height Model GEOID03,” *Surveying and Land Information Science*, Vol. 64, No. 3, 2004, pp. 153–162.

Sevilla, M., M. Burša, D. Dušátko, S. Kenyon, J. Kouba, Z. Šíma, Z., V. Vatrt, and M. Votjiĺšková.. (2008*). Determination of Geopotential W0,ALICANTE and its Connection to W0,NAVD88*.

Smith, D.A., 1998: “There is no such thing as ’The‘ EGM96 geoid: Subtle points on the use of a global geopotential model,” *IGeS Bulletin* No. 8, International Geoid Service, Milan, Italy, p. 17–28.

Smith, D.A., and D.G. Milbert, 1999*: “*The GEOID96 high resolution geoid height model for the United States,” *Journal of Geodesy*, Vol. 73, No. 5, p. 219–236.

Smith, D.A., S.A. Holmes, X. Li, S. Guillaume, Y.M. Wang, B. Bürki, D.R. Roman, and T. Damiani, 2013: “Confirming regional 1 cm differential geoid accuracy from airborne gravimetry: the Geoid Slope Validation Survey of 2011,” *Journal of Geodesy*, V. 87, No. 10–12, pp. 885–907.

Stokes, G.G., 1849: *On the variation of gravity on the surface of the Earth*, Transactions of the Cambridge Philosophical Society, v. 8, pp. 672–695.

van Westrum, D., K. Ahlgren, C. Hirt, and S. Guillame, 2021. “A Geoid Slope Validation Survey (2017) in the rugged terrain of Colorado, USA.” *Journal of Geodesy* 95, 9, https://doi.org/10.1007/s00190-020-01463-8 .

Wang, Y.M., J. Saleh, X. Li< and D. R. Roman, 2011: “The US Gravimetric Geoid of 2009 (USGG2009): Model Development and Evaluation,”*Journal of Geodesy*, 86, 165–180, https://doi.org/10.1007/s00190-011-0506-7 .

Zilkoski, D. B., J.H. Richards, and G.M. Young, 1992: “Results of the General Adjustment of the North American Vertical Datum of 1988.” *Surveying and Land Information Systems*, 52(3), 133–149, http://www.ngs.noaa.gov/PUBS_LIB/NAVD88/navd88report.htm, downloaded 2017 08 05.

16 Glossary and Abbreviations

DDEFLEC2022	**Dynamic Part of DEFLEC2022** Six models (likely in grid form, covering three areas) of time-dependent modeled changes to deflections of the vertical (angle between the ellipsoidal normal and the plumb line), in the North/South and East/West directions, at the surface of the Earth, relative to reference epoch 2020.00.
DEFLEC2022	Six grids (covering three areas) of time-dependent modeled deflections of the vertical (angle between the ellipsoidal normal and the plumb line), in the North/South and East/West directions, at the surface of the Earth.
DGEOID2022	**Dynamic Part of GEOID2022** Three models (likely in grid form, covering three areas) of time-dependent modeled changes to the differences between the GRS-80 ellipsoid and the geoid, relative to reference epoch 2020.00.
DGM2022	**Dynamic Part of GM2022** A time-dependent global model of the changes to the three-dimensional gravity potential field of the Earth, for all points on or above the crust of the Earth, relative to reference epoch 2020.00.
GEOID2022	Three grids (covering three areas) of time-dependent modeled differences between the GRS-80 ellipsoid (centered at the origin of ITRF2020) and the geoid. The geoid surface of GEOID2022 is the surface of zero elevations (orthometric heights) within the NSRS.
GM2022	**Geopotential Model of 2022** A time-dependent global model of the three-dimensional gravity potential field of the Earth, for all points on or above the crust of the Earth. This model is capable of estimating a variety of geopotential-related quantities, such as gravity and deflection of the vertical anywhere on or above the crust of the Earth, albeit with errors (commission and omission both).
GRAV2022	**Surface Gravity Model of 2022** Three models (covering three areas) of the acceleration of gravity, pointed along the plumb line, at the surface of the Earth. Although NGS is investigating the capability of GRAV2022 to reflect time dependencies, the initial release of the model will be time invariant.
NAPGD2022	**North American-Pacific Geopotential Datum of 2022** The official datum for all physical (related to gravity) coordinates within the NSRS in 2022. It is composed of four primary elements: GM2022, GEOID2022, DEFLEC2022, and GRAV2022.

NGS	**National Geodetic Survey (NGS)** An office within the Department of Commerce, National Oceanic and Atmospheric Administration, National Ocean Service, charged with the creation and maintenance of the National Spatial Reference System.
NSRS	***National Spatial Reference System*** A coordinate system established and maintained by NGS and serving as the official geodetic control for the civilian federal government of the United States.
SDEFLEC2022	**Static Part of DEFLEC2022** Six grids (covering three areas) of time-invariant deflections of the vertical (angle between the ellipsoidal normal and the plumb line), in the North/South and East/West directions, at the surface of the Earth, fixed at reference epoch 2020.00.
SGEOID2022	**Static Part of GEOID2022** Three grids (covering three areas) of time-invariant modeled differences between the GRS-80 ellipsoid and the geoid, fixed at reference epoch 2020.00.
SGM2022	**Static Part of GM2022** A time invariant global model of the three-dimensional gravity potential field of the Earth, for all points on or above the crust of the Earth, fixed at reference epoch 2020.00.
SGRAV2022	**Static Part of GRAV2022** Three models (covering three areas) of the time-invariant acceleration of gravity, pointed along the plumb line, at the surface of the Earth. Although NGS is investigating the capability of GRAV2022 to reflect time dependencies, the initial release of the model will be time invariant, therefore "SGRAV2022" will be identical to "GRAV2022" upon initial roll-out in 2022.

17 Appendix A: History of Geoid Modeling

For over 4,000 years, humans have been referring to "heights" above the surface of some body of water. One of the earliest extant records of this comes from about 2300 B.C.E. when, according to the Palermo Stone (Hsu, 2010), the Egyptians regularly noted the "height" of the Nile River's annual inundation. While the exact datum those heights referred to is unclear, what is clear is that humankind has a long history of thinking about heights relative to a body of water. But it was not until the 1800s that a mathematical foundation for describing global mean sea level was developed. C.F. Gauss proposed a "mathematical figure of the Earth" (Gauss, 1828), and G.G. Stokes built upon that idea to compute the "surface of the Earth's original fluidity" (Stokes, 1849). A few decades later, this mathematical representation of sea level was given the name "geoid" (Listing, 1873).

For the better part of a century, modeling the geoid was pursued by mathematicians and geodesists, though the practical application of that pursuit (using the modeled geoid as a reference surface for heights) was limited by both data and theory. As late as 1967, one of the best known treatises concerning the theory of geoid modeling claimed that "…an error of probably less than 1 meter in [geoid undulation]…can be neglected for most practical purposes…" (Heiskanen and Moritz, 1967, p. 94). Great strides have been made in data collection, computational power, and geoid modeling theory in the intervening decades, to the point that negligible errors are now closer to the 1 millimeter to 1 centimeter level.

Because the geoid is a surface of equal gravity *potential* (see also section 6), spherical harmonics became a favored tool for modeling the geoid[21]. Essentially, spherical harmonics allow modelers to easily represent a planetary-sized signal of infinite complexity with a simple series of numbers; each number represents the power of the signal at a given spatial scale. The more numbers used, the more detail is captured by the model. Readers interested in more detail are directed to Part 4 of this blueprint document and to Chapter 1 of Heiskanen and Moritz (*ibid*) or Hofmann-Wellenhof and Moritz (2006). Through the 1970s and into the 1990s, a variety of ever-improving spherical harmonic models (SHMs) were developed to describe the geoid. In the late 1990s, when the drive for centimeter-accuracy in geoid models became a realistic goal, one of the weaknesses of SHMs became apparent—the geoid exists *within* continental masses, in a place where potential fields are *not* harmonic (and thus any "*harmonic* model" breaks down). SHMs were thus appended to include "correction coefficients" to account for this non-harmonicity. One of these first examples was the Earth Gravity Model 1996 (EGM96; Lemoine, *et al*, 1998).

While SHMs continued to improve *global* models of the geoid, many countries were pursuing ever more accurate geoid models for their particular *region*. In the United States, NGS developed GEOID90 (Milbert, 1991) and GEOID93 (NGS, 1993). The accuracy of these U.S.-specific geoid models could be checked by using a significant amount of GNSS-derived ellipsoid heights in the NAD 83 reference frame and leveling-derived orthometric heights in the NAVD 88 datum (see equation 1). It soon became apparent that the geoid model based on gravity data and theory disagreed with the NAD 83 and NAVD 88 data at the level of a few meters. The reasons for this were determined to be: (1) the NAD 83 reference frame had a non-geocentricity of over 2 meters, (2) the leveling-based heights were showing regional biases and tilts, and (3) an overall bias was introduced by fixing the zero point of all of NAVD 88 to Local Mean Sea Level at just one point on the St. Lawrence River (tidal station Father Point, Rimouski, Quebec, Canada). The conclusion drawn by NGS was clear: if surveyors are using GNSS to obtain ellipsoid heights, and they want to use a geoid model to transform those into

[21] The equation describing a 3-D gravity potential field is a *differential* equation. Spherical Harmonics are but one kind of tool which can be chosen to solve this kind of differential equation. Other tools exist, such as ellipsoidal harmonics. Further details are beyond the context of this document. Interested readers are directed to Chapter 1 of Heiskanen and Moritz (1967) or Hofmann-Wellenhof and Moritz (2006).

orthometric heights, and if the surveyor is working in NAD 83 and NAVD 88, then a purely gravimetric geoid model will not suffice.

In 1996, NGS began developing a two-track geoid modeling program. The best gravimetric geoid model would be developed, but would then be modified to fit data from GNSS, and leveling in NAD 83 and NAVD 88. This modified geoid would be called a "hybrid geoid." The first instance of this was the paired G96SSS and GEOID96 models (Smith and Milbert, 1999). The pursuit of hybrid geoids has continued for 20 years, as NAD 83 and NAVD 88 remain the official datums of the NSRS. Hybrid geoids have served many NSRS users well, yielding accurate NAVD 88 heights from GNSS (Roman and Smith, 2001; Roman, *et al,* 2004; Wang, *et al*, 2011).

In 2007 NGS recognized both the growing trend of improved GNSS accuracy and the availability of that accuracy to a broader range of users, as well as a significant new tool in the increased accuracy of geoid modeling: airborne gravity. Furthermore, the national consistency and availability of a gravimetric geoid model far surpasses the capabilities of infrequently surveyed marks connected by leveling. Due to these factors, the *NGS Ten-Year Plan 2008–2018* (NGS, 2008) first laid out plans to replace NAVD 88 with a vertical datum based on a gravimetric geoid model. The plan was described in the next *NGS Ten-Year Plan for 2013–2023* (NGS, 2013). Since that time, NGS has fleshed out how the entire ***geopotential datum*** (including, but not limited to, using a gravimetric geoid as a zero-height surface) will be created and will function, and the main body of this blueprint document is dedicated to presenting those details.

18 Appendix B: The Geopotential Field

Some additional words should be said about a Spherical Harmonic Model (SHM) of Earth's external gravitational potential field in deference to the critical importance it has on the geoid model and many other NGS products and services. However, a *lengthy* foray into this subject is inappropriate for the scope of this document. Readers interested in greater detail or derivations are directed to the opening chapters of Heiskanen and Moritz (1967) and Hofmann-Wellenhof and Moritz (2006) or any standard textbook on physics. Details in the remainder of this chapter are therefore limited to those essential to the basic understanding of Earth's geopotential field[22].

Let us begin with a few definitions:

Gravitation: The force of attraction between two masses

[22] Further details can be found in an NGS educational video "Gravity for Geodesy I: Fundamentals" available online at https://www.ngs.noaa.gov/web/science_edu/online_lessons/

Centrifugal force: A fictitious force caused by the uniform circular motion of a body about some fixed point

Gravity: The force acting on a body on or near Earth's surface, which is a combination of the gravitational force and centrifugal fictitious force of Earth's rotation

As evidenced by the above definitions, geodesists draw a clear distinction between gravitation and gravity. This distinction will be important to note in this section.

Additionally, one must be cautious to draw a distinction between the terms *force, acceleration, potential energy,* and *potential*.

18.1 Gravitation

The first force (of two which make up that which is called "gravity") is gravitation. According to Newton's Law of Universal Gravitation, two point masses attract one another with a *gravitational force (F)*, directly proportional to the product of the two point masses (m_1, m_2) and inversely proportional to the distance between them (s), squared, and directed along the straight line between the two masses. Gravitational force therefore is a three-dimensional vector.

Geodesists have found it easier and more convenient to work with a related value, called *gravitational potential*, (also called the *gravitational potential energy per unit mass*.) *Gravitational potential* is a scalar value, directly proportional to some attracting mass, and inversely proportional to the distance to that attracting mass:

$$V = G\frac{m}{s} \tag{6}$$

The convenience of this quantity is that, being a scalar, it represents a single value (rather than vectors, which would require magnitude and direction) in a *field* surrounding a mass. That statement is equally true for a point mass or a set of point masses (such as a body, planet Earth, for example). That is, if one added up equation 6 for every point mass that made up the Earth (using all the various distances to those point masses), one can say that the Earth's masses generate a gravitational potential field.

$$V(r,\theta,\lambda) = G\sum_i \frac{m_i}{s_{i,(r,\theta,\lambda)}} \tag{7}$$

Equation 7 is the simplest form of the gravitational potential field of a body (such as the Earth), but is effectively impractical to use as is.

Related to gravitational potential is *gravitational acceleration*. Similar to gravitational force, gravitational acceleration is a three-dimensional vector, directed along the line between two point masses. It is directly related to gravitational potential through the derivative with respect to the separating distance *s*:

$$g^{*}(r,\theta,\lambda) = G\sum_i \frac{m_i}{\left[s_{i,(r,\theta,\lambda)}\right]^2} \tag{8}$$

To summarize this section: Gravitational force (*F*) induces gravitational acceleration ($g*$), which is also the gradient of gravitational potential (*V*).

18.2 The Spinning Earth

In addition to experiencing the gravitational pull of the Earth, a body at rest on the Earth is also experiencing a *centrifugal fictitious force*[23], because it is moving in uniform circular motion as the Earth rotates. This fictitious force acts to thrust the body away from the point about which the circular motion is happening (such as Earth's axis of rotation.) Such a fictitious force would not exist if, for example, the body were able to independently maintain its position in space while the Earth spun nearby.

Like gravitational potential, it is convenient for geodesists to refer to *centrifugal potential*:

$$\Phi(r,\theta,\lambda) = \frac{1}{2}\omega^2 p^2 \tag{9}$$

Where ω is the angular velocity of the Earth and *p* the distance along a line normal to Earth's spin axis to the point. The acceleration due the centrifugal force is:

$$\mathrm{a}_c(r,\theta,\lambda) = \omega^2 p \tag{10}$$

[23] This quantity is traditionally called the "centrifugal force," although it is not a "force" in the ordinary sense of the word. "Fictitious forces or inertial forces arise from the inertial properties of matter rather than from the presence of other bodies." (Fowles, 1970). To put it another way, "Newton's equation, F=ma, is only valid in an inertial frame. A rotating reference frame is not inertial. If we transform Newton's equation into a rotating frame, additional non-inertial terms arise. These terms are not induced by any form of physical attraction, nor any physical body. They arise due to the non-inertial motion of an observer." (Marion, 1970).

18.3 Gravity

The combination of gravitational acceleration and centrifugal acceleration is called *gravity acceleration*:

$$\mathrm{g} = \mathrm{g}^* + \mathrm{a}_c \tag{11}$$

Just as *gravity acceleration* (*g*) is the combination of *gravitational acceleration* (*g**) and *centrifugal acceleration* (a_c), so too is *gravity potential* (*W*) the combination of *gravitational potential* ($V^{(1)}$)[24] and *centrifugal potential* (*Φ*):

$$W = V^{(1)} + \Phi \tag{12}$$

For the remainder of this report the stand-alone use of "gravitation" will refer to *gravitational acceleration,* and the stand-alone use of "gravity" will refer to *gravity acceleration*.

Spherical harmonic models (SHMs) of Earth's external (specifically "above the masses") gravitational potential, such as EGM96 and EGM2008 (Pavlis, *et al*, 2008) are three-dimensional models of the scalar potential, *V*, as seen in equation 3. These models are valid everywhere the potential is harmonic -- everywhere where no solid mass exists (a.k.a. "outside the crust" or "external"[25]). SHMs are a common (probably the most common) representation of the global gravitational potential field and fulfill this equation (Smith, 1998):

$$V^{(1)}(r,\theta,\lambda) = \frac{(GM)_1}{r}\sum_{n=0}^{N}\left(\frac{a_1}{r}\right)^n\sum_{m=0}^{n}\left(\bar{C}_{n,m}cos(m\lambda) + \bar{S}_{n,m}sin(m\lambda)\right)\bar{P}_{n,m}(cos\theta) \tag{13}$$

An SHM is a collection of fully normalized coefficient (Cn,m and Sn,m) and Legendre function (Pn,m) values for every degree and order (n and m), up to some maximum degree n=N value chosen by the model-maker, as well as the GM_1 and a_1 values[26]. (See also Heiskanen and Moritz, 1967, Figure 1–9, or Hofmann-Wellenhof and Moritz, 2006, Figure 1.5). Equation 13 can

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[24] The superscript (1), in $V^{(1)}$, distinguishes the *true* gravitational potential from a simpler version called the "*normal* gravitational potential," designated $V^{(2)}$. See also Smith (1998) for details.

[25] Astute readers will note that the atmosphere is not massless, nor are all of the astronomic bodies outside the Earth. These issues are known and carefully accounted for, but details are not appropriate for this document.

[26] The values of ***GM*** and ***a*** do, ostensibly, have physical meaning. But ultimately, they function as scale factors in equation 13 and therefore need not be perfect for equation 13 to be useful. Nevertheless, for completeness, the value of ***GM*** has historically been the product of Newton's gravitational constant times the mass of the Earth, while ***a*** should be the radius of a sphere (such as Earth's radius at the equator), outside of which there are no masses. It should be pointed out that equation 13 tends to yield valid results for points *inside* a sphere of radius ***a,*** provided there are no masses at, or above, the points being evaluated

be used to calculate the gravitational potential (up to that maximum degree N) at any point in spherical three-dimensional space (geocentric radius r, spherical colatitude θ, longitude λ).

When geodesists speak of “equipotential surfaces” such as the geoid, they refer to surfaces of equal *gravity potential*. That is, on the geoid, gravity *potential* (equation 12) is a constant, but not *gravity* (equation 11).

What is elegant about an SHM (used in combination with equation 9, the centrifugal potential equation) is that it can be used to calculate anything that is a *function of* gravity potential. In other words, once you have an SHM of the gravitational potential, then you can also calculate the acceleration of gravity (in all three directions), deflections of the vertical, and other related quantities. However, equation 9 is an imperfect representation of Earth’s gravitational potential and is limited by three factors: first, it only yields correct results at points that are in harmonic space (outside of the solid masses); second, it is necessarily limited in spectral content (and therefore spatial resolution) by that maximum “n=N” value; and third, the $\bar{C}_{n,m}$ and $\bar{S}_{n,m}$ values themselves are not perfectly determined and have errors. That second limitation is called “omission error,” while the third limitation is “commission error.”

The first limitation is dealt with, in part, by using digital elevation models (DEMs) to compute the gravitational potential of topographic masses outside the geoid. This potential is “removed” to make the field harmonic outside the geoid, and then “restored” after performing SHM computations.

One way to address the second limitation is to increase the N value, so that more detail is included in the model, and it produces a better (in theory) representation of Earth’s gravitational potential. In practice, “high-degree expansions,” with *N* = 20,000 or more, push the limits of current computing power and challenge the integrity of equation 13. SHMs in use at NGS routinely use *N* values closer to 2,000 to balance the practical time needed to do the computations, versus the resulting model spatial resolution. Switching from spherical to ellipsoidal harmonics has been shown to be a more stable approach when dealing with such large-degree harmonic models.

The third limitation (“commission error”) is mitigated by using a complete spectrum of accurate sample gravity data for determining the coefficients. That includes using satellite data for the long wavelength field (≥ 250 kilometers), terrestrial gravity (and DEM computations) for short wavelengths (< 100 kilometers), and aerial gravity measurements for the medium wavelength field (20 to 300 kilometers). Indeed, one of the main reasons for the Gravity for the Redefinition of the American Vertical Datum (GRAV-D) project is to provide accurate measurements of the medium wavelength field (NGS, 2007). GRAV-D is thus an essential part of creating the new geopotential datum.

Despite these limitations, an SHM is an incredibly powerful and fast tool for yielding a variety of gravity-potential-related quantities anywhere on or outside the Earth’s crust. In the overwhelming majority of regional geoid modeling efforts, such as GEOID93, etc., an SHM serves as the foundation of the model. However, because the geoid itself resides in non-harmonic space, an SHM can never, by itself, yield a model of the geoid, even if it were possible to set $N=\infty$.

Because an SHM describes potential at any point (r, θ, λ), it can be used to locate a surface of constant potential. That is, given an SHM and equation 9, one can solve for the coordinates (r, θ, λ) of all points fulfilling this condition for any given constant:

$$W = constant \tag{14}$$

Surfaces fulfilling equation 14, having equal gravity potential, are referred to as *equipotential* surfaces. The geoid, by definition, is that one equipotential surface which best fits global mean sea level[27]. When a model of the geoid is created, one often begins with an SHM, which means a choice must be made concerning which (of the infinitely many) equipotential surfaces is actually being modeled as "the geoid" (Smith, 1998). Once such a choice is made, the numeric value of the constant must be chosen. That value is often given the name W_0, so that the geoid fulfills this condition:

$$W = W_0 \tag{15}$$

The role of SHM in the modernized NSRS will therefore be critical, as well as the role of W_0, and both is discussed in section 12.3.

[27] The fact that global mean sea level is changing is discussed in Section 6.