NOAA Technical Report NOS NGS 67

Blueprint for 2022, Part 3: Working in the Modernized NSRS

Initial draft released April 25, 2019

Versions

Date	Changes
April 25, 2019	Original Draft Release

Notes

On the use of "TBD": This document is an initial draft of policies and procedures the National Geodetic Survey (NGS) is refining as we prepare to define the modernized National Spatial Reference System (NSRS) in year 2022. The intent of releasing this document so many years in advance is so we may provide the NSRS user community with insight and as many details as are currently available, as well as to give time for these details to be read and understood and for feedback to be provided back to NGS. The early release of this document, therefore, naturally comes with certain unresolved decisions. Rather than delay the entire document, the term TBD (To Be Determined) has been used herein to indicate where a decision is pending.

On the use of the terms "datums" and "reference frames": Entire chapters of books could be dedicated to the distinction, or lack thereof, between the terms *datums* and *reference frames,* however for this paper we will define these terms in this way: In 2022 the NSRS will consist of four **terrestrial reference frames** and one **geopotential datum**. From time to time and for the sake of brevity, the four terrestrial reference frames and the one geopotential datum may be clustered under the general term "new datums." For example, NGS has put information concerning the NSRS modernization on a "New Datums" web page. This form of shorthand should not be taken as anything other than an easy way for us to quickly speak of these four frames and one datum.

On the use of the words "you" and "your": This document will be providing instructions to a variety of NSRS users. Rather than employing the somewhat awkward and unwieldy generic terms of "someone" or "a user of the NSRS," we chose to use a more conversational tone. Consequently, "you" and "your" shall refer to the readers of this document or, more generally, to anyone who uses the NSRS.

On the mention of specific commercial vendors: Mention of a commercial company or product does not constitute an endorsement by the National Oceanic and Atmospheric Administration (NOAA). Furthermore, the use of this document for publicity or advertising purposes concerning proprietary products, or the test of such products, is strictly unauthorized.

On the use of "OPUS": Beginning with this document, the entire suite of products and services which previously fell under the various names of "OPUS" (OPUS-S, OPUS-RS, OPUS-Share, OPUS-Projects, etc.) will herein simply be referred to by the overarching term "OPUS."

On the use of "CORS," including its singular, plural, and network versions: "CORS" is an *acronym* which stands for "Continuously Operating Reference Station," with the *initialism* "GNSS" implied, and sometimes explicitly inserted, between Operating and Reference. Therefore, by definition, CORS refers to a *single* station. In the past, NGS has also used "CORS" to mean "the network of all CORS." We have abandoned this confusing language, and (for now) the complete phrase "the NOAA CORS Network"[1] will mean the network of all CORS managed by NGS. Furthermore, "CORS" can be pluralized, and according to the AP style guide, Chicago Manual of Style and the NY Times, the plural version of an acronym which ends in a capital "S" is to simply add a lowercase "s" to it (with no apostrophe.) To summarize, throughout this document you will find the following variety of usages:

GODE is a CORS

GODE and 1LSU are CORSs

GODE and 1LSU belong to the NOAA CORS Network

Terminology Guide: In an attempt to be as precise in our language as possible, this document and certain documents still in the planning stages, should contain language that is both consistent within NGS and (if possible) with the international community, as well. The use of CORS, above, is one such example. A terminology guide of such terms is found near the beginning of this document. ***Readers of this document are strongly encouraged to familiarize themselves with the terminology guide before reading the rest of the document.***

[1] This term is tentative. Because the term "CORS" is commonly used by many groups around the globe, "the NOAA CORS Network" has now been adopted, as it does describe who manages the network. Thus "the NOAA CORS Network" will be used to refer to the network of stations organized and processed by the National Geodetic Survey, an office within NOAA.

Acknowledgments

A work of this magnitude requires the input of many individuals. The contents of this document grew out of an extended series of meetings within NGS, beginning in 2017 and growing in scope and frequency through 2019. Many employees and former employees contributed to conversations, which ultimately led to the completion of this document. Recognition and thanks for their contributions should go to the following individuals (in alphabetical order):

Kevin Ahlgren, Andria Bilich, Steve Breidenbach, Dana Caccamise, Vicki Childers, Kevin Choi, Theresa Damiani, Michael Dennis, Ben Erickson, Joe Evjen, Kendall Fancher, Pam Fromhertz, Charlie Geoghegan, Dan Gillins, David Grosh, Tim Hanson, Jacob Heck, Philippe Hensel, Steve Hilla, Ryan Hippenstiel, Kevin Jordan, Boris Kanazir, Nicole Kinsman, Phillip McFarland, Nagendra Paudel, Julie Prusky, Dan Roman, Jarir Saleh, Mark Schenewerk, Michael Silagi, Ajit Singh, Burt Smith, Dru Smith, Bill Stone, Lijuan Sun, Steve Vogel, Maralyn Vorhauer, Brian Ward, Daniel Winester, Sungpil Yoon, Dave Zenk, Dave Zilkoski

Executive Summary

NOAA Technical Report NOS NGS 67
Blueprint for 2022, Part 3: Working in the Modernized NSRS

In year 2022, the National Spatial Reference System (NSRS) will be modernized. This document addresses how geospatial professionals can expect to work within the newly-modernized NSRS.

At the forefront of these NSRS changes, we will embrace time-dependency, an issue NGS has not completely implemented as of yet. Beginning in 2022, points in the NSRS with defined coordinates will have epochs associated with them, based upon the time actual data were collected at those points. Such coordinates will be known as “Final Discrete” coordinates (if associated with finite timespans of data collection) or “Final Running” coordinates (if associated with continuous data collection). Consequently, passive control will have less reliability than active control, and NGS will treat the NOAA CORS Network as having the definitive, up-to-date coordinates within the NSRS. A change of business will result: both leveling and classical surveys will require Global Navigation Satellite System (GNSS) components to ensure coordinates computed in those surveys are up-to-date and are connected to the NSRS through the NOAA CORS Network.

In order to bridge users into a time-dependent NSRS, NGS will also be estimating, and providing to the public, coordinates on points at five-year reference epochs. While such *estimates* will mimic the current status quo [the 2010.00 epoch of NAD 83(2011), for example], they will not be considered the “definitive” NSRS coordinates. Whereas users will have the option, via an updated OPUS, to take any campaign survey at any date and adjust their surveys to such reference epochs, we at NGS will not do this. Rather, if your survey data is submitted to NGS, we will compute Final Discrete coordinates at the epoch of your survey. Then, in the future, those Final Discrete coordinates will be used to estimate Reference Epoch coordinates.

We will be providing tools to users, under the catch-all name “OPUS,” for uploading, processing, analyzing, and submitting survey data of all types, such as: GNSS, RTK (Real Time Kinematic), RTN (Real Time Network), leveling, gravity, or classical. Additionally, OPUS will have tools for ingesting and analyzing continuous data (e.g. GNSS, gravity). The tool will be browser-based and will fully integrate all data types, whereby a single project, containing both GNSS and leveling could be uploaded and processed under the same project name. Users processing their data in OPUS will always receive “Preliminary” coordinates from OPUS. We hope to encourage users to submit that data so that NGS can provide quality control, internal national processing, and creation of Final Discrete coordinates from their data. Only data submitted to NGS will make it into the NSRS database and be processed and re-distributed to the public using an updated Data Delivery System, previously known as “datasheets.”

Please find this entire report here:
https://geodesy.noaa.gov/PUBS_LIB/NOAA_TR_NOS_NGS_0067.pdf

Contents

Terminology Guide

Throughout this document, many of the following terms are used. For purposes of definition consistency, we shall adhere to the usages found in this guide. Readers are strongly encouraged to familiarize themselves with the definitions described below before reading the remainder of the document. Additionally, these terms are defined in consideration of their *geodetic* usage, not within their *broader* usage within the English language.

Antenna Reference Point (or ARP): The antenna reference point (ARP) is the **point** on a GNSS antenna from where antenna calibration values are referenced. The **ARP** is preferably, but not always, an easily accessible **point** on the plane that contains the antenna's lowest non-removable horizontal surface. The ARP could be physically identifiable on that (above-mentioned) surface of the antenna; or it may be the center of a mounting axis, and thus co-planar with that surface, without being on the surface itself. The **ARP** can, but is not required to, coincide (in space) with the geometric reference point (**GRP**) when the antenna is mounted as part of a **CORS**. For this reason, NGS has for decades erroneously described the coordinates at a **CORS** as referring to the **ARP**, and not the **GRP**, a practice we ceased in 2019. Note that the **ARP** is a **point** that is part of an antenna, but it is *not* a point on a **mark**. Therefore, a **CORS** only has an **ARP** at those times when an antenna is mounted at it, whereas a **CORS** always has a **GRP**.

Bluebooking: A phrase used to describe how geodetic survey data were formatted and submitted to NGS using *Input Formats and Specifications of the National Geodetic Survey Data Base* (FGCS, 2016) so they could be checked and included in the National Geodetic Survey's Integrated Database **(NGS IDB)**. The term **Bluebooking** was derived from the original document that had been distributed with a blue cover.

Continuously Operating Reference Station (CORS): A **station**, composed of a variety of equipment, but usually including at least one **mark** (containing one **geometric reference point**, or **GRP**), as well as a GNSS antenna and receiver, as well as some source of power and communications. The purpose of a CORS is to continuously collect and distribute GNSS data so as to monitor the coordinates of the **GRP**. The term **CORS,** however, has grown to acquire a general use worldwide, therefore, there is no guarantee a station being referred to as a **CORS** is actually part of **the NOAA CORS Network** (plural: CORSs).

Also referred to as: *Continuously Operating GPS Reference Station, Continuously Operating GNSS Reference Station, Active Control Station*

Coordinate Function: A set of three piecewise continuous functions (one for each of the X, Y or Z coordinates with respect to time), fit to the daily or weekly coordinates implied by analyzing daily or weekly data collected at a **CORS**. Serves as the official time-dependent NSRS coordinates of the **GRP** of each **CORS**. Specific to **CORS** only, the coordinate function is identical to Final Running Coordinates (see Section 2.5).

Geometric Reference Point (or GRP): A unique **point** that is part of a particular **station**. The **GRP** is the **point** to which any coordinates of the **station** refer. The operator of each **station** identifies the **GRP** of that **station**. The GRP is sometimes independent of equipment, such when it is contained within a **mark** at a **CORS** (and thus it exists even when the antenna is removed). In other cases, such as with very long baseline interferometry (VLBI) and satellite laser ranging (SLR), the GRP is a **point** in space defined by the motion of the telescope, typically the intersection of the azimuth axis with the common perpendicular of the azimuth and elevation axis, and thus it only exists when that particular set of equipment is at that **station**.

Local Site Survey: A survey—often consisting of GNSS, leveling, and classical observations using survey-grade instruments—at one **site.** High-precision local tie vectors are determined between the **site marker** and the **geometric reference points** of co-located space geodetic technique (SGT) **stations** on that **site** so as to contribute to realizations of the International Terrestrial Reference Frame (ITRF).

GPS Month: Four consecutive GPS weeks, with the first week in the **GPS month** having a GPS week number that is a multiple of four. Thus, **GPS month** 'zero' is the consecutive period spanning GPS weeks zero, one, two, and three; **GPS month** 'one' is the consecutive period spanning GPS weeks four, five, six, and seven, etc.

Mark (or Marker): A physical structure of varying size or construction, attached to Earth's crust in some way that is presumed to be stable throughout years (or decades) and whose function is to contain a single, unique, identifiable **point** in a stable location. Such **points** are often a small divot or cross on the top of the **mark** (though even the smallest divot is not zero-dimensional, so for highest accuracy, one must clearly identify which part of the divot is the **point**. For example, the **point** on the **mark** might be the bottom of such a conical divot). Common forms of a **mark** include:

> A metal (often brass or aluminum) disk (often about 3 inches in diameter but varying from 0.5 inches to more than 12) with a stem underneath which keeps it mounted in stone, masonry or concrete.
>
> A metal rod (usually 1-2 centimeters in diameter) driven into the ground and rounded on the top.

When NGS refers to the "coordinates of a **mark**," we are referring to "the coordinates of the **point** on the **mark**."[2]

[2] To that end, NGS plans to change our official policy (from an unofficial practice that has been in place for approximately 10 years) that all surveying to a mark, and all coordinates of a mark, should refer to one uniquely identifiable point on that mark. This policy will be necessary to

Also called: *Bench Mark, Control Mark(er), Disk, Geodetic Control Mark(er), Monument, Passive Mark(er), Physical Mark(er), Rod, Survey Mark(er)*

See Figure 1 below.

NGS IDB (or IDB): The National Geodetic Survey Integrated Database. Prior to the modernization of the NSRS, the NGS IDB was the definitive storage place for all NSRS data. Datasheets were generated only from this database. It was "Integrated," because two separate databases (one for horizontal and one for vertical) were combined into the **NGS IDB** in the 1990s.

The NOAA CORS Network: The name of the collection of **CORSs** whose data are collected and processed by the National Geodetic Survey. Note that many other countries and agencies around the world refer to their individual **stations** as being **CORSs**. This generic use of the term **CORS** does not, however, mean their **stations** are in **the NOAA CORS Network**.

NSRS Database (or NSRS DB): The official database built to house the modernized NSRS. Some information from the **NGS IDB** will be converted directly into the **NSRS DB**. For example, the Permanent Identifier **(PID),** of a **mark**. Other information, such as coordinates, will be re-computed from raw measurements using the modernized NSRS as their foundation.

PID: Abbreviation for 'Permanent Identifier,' the unique six-character alphanumeric code assigned to each **point** included in the **NGS IDB** or **NSRS DB** and residing on a **mark.**[3]

Point: A zero-dimensional location. Two **points** cannot exist in the same space at the same time. A **point** might be physically "touchable" (such as the bottom of a small conical divot on top of a **mark**) or it may not be (such as the location of an airborne gravimeter's sensor at any given moment during a flight). *See Figure 1 below.*

Redundancy: Taking the same measurement more than once, where each measurement is taken separately and independently of the other. Strictly speaking, this is impossible, as anything measurable in the universe changes to some degree or another from one moment to the next. However, in the context of this document, **redundancy** will generally mean "collecting GNSS data at a **point** during two different occupations within the same **GPS month**."

Site: The smallest civil location name of the area where (one or more) **stations** are located. (Legal, i.e., recognizable by deed; national- or state-recognized city, town, village, or hamlet; or geographic feature). Multiple **stations** can be on one **site**. (Example: "MacDill Air Force

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undo the official policy from the NOAA leveling manual (Schomaker and Berry, 2001) that states, "Place the rod so that the exact center of the base plate rests on the highest point of the turning point or control marker." Such a practice meant that, on any sort of tilted mark, the "highest point" might not be the same as the point at the center of the disk to which, say, a classical or GNSS survey might refer. Furthermore, as "depth of dimple" becomes an issue (particularly with using pointed fixed-height poles in GNSS surveys), the unique point of any given mark may need to be identified as the bottom of the dimple (or cross mark).

[3] Recall, **points** exist in the **NSRS DB** that are not on **marks**, such as the **points** an airborne gravimeter's sensor may have occupied during a flight. As each **mark** should hold only one unique **point**, the **PID** of a **point** may equally be considered to be the **PID** of the **mark** upon which that **point** resides.

Base" is a **site**, and it happens to contain two **stations**, which are the **CORSs** known as MCD5 and MCD6). *See Figure 1 below.*

Site Mark(er): A single, unique **mark**, installed one per **site**. All vectors from the **geometric reference points** of every **station** on that **site** are tied to that single mark within a **local site survey**. Note that **local site surveys** often use *many* **marks,** and all may be located at a **site** (for the purpose of **redundancy** and to provide a backup of the **site marker**), but only one can be (and must be) designated as the **site marker**. *See Figure 1 below.*

Station: A collection of equipment located at one **site** to collect one specific type of data for a particular geodetic purpose. Within the geodetic community there are many types of **stations**, and most common are:

Continuously Operating GNSS Reference Station (**CORS**)

Satellite Laser Ranging (SLR) Station

Very Long Baseline Interferometry (VLBI) Station

Doppler Orbitography and Radiopositioning Integrated by Satellite DORIS) Station

Continuously Operating Relative Gravimeter Station

Two or more **stations** located on the same **site** may share some pieces of common equipment, but at least one unique thing should distinguish one **station** from another. *See Figure 1 below.*

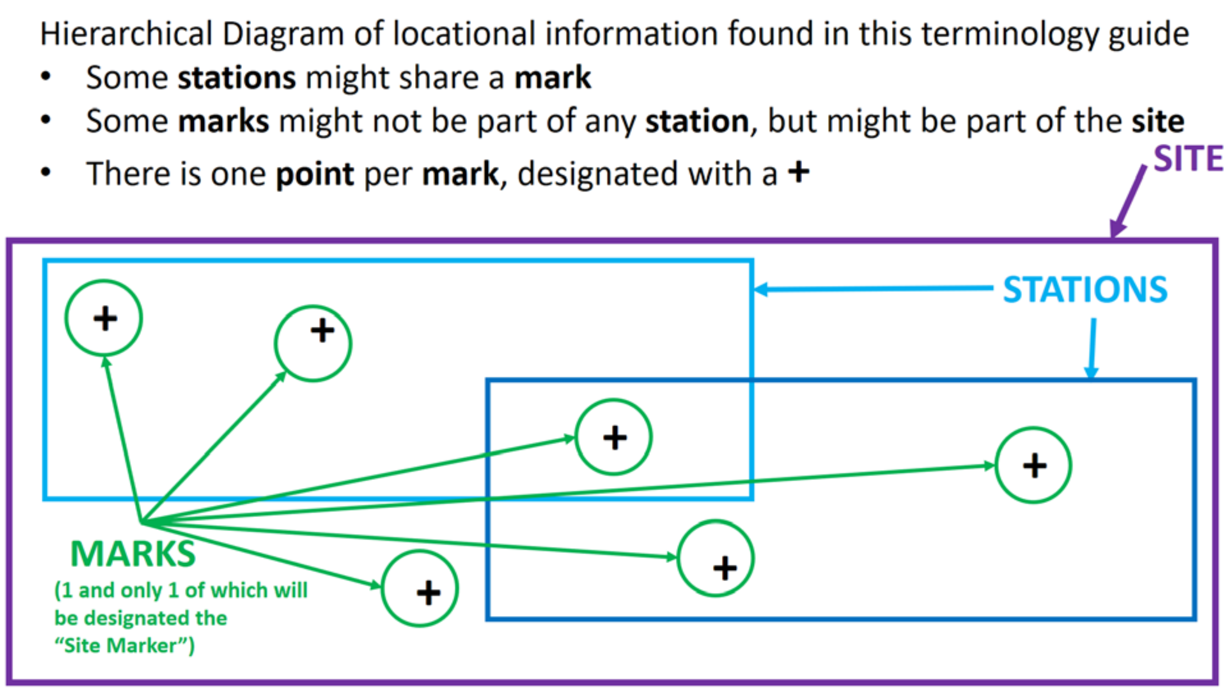

Figure 1: Site, Station, Mark, Site Marker, and Point Hierarchy

1 The Past and Present

1.1 Introduction

In 2022, the National Geodetic Survey (NGS) will introduce a modernized National Spatial Reference System (NSRS). The NSRS is the positional framework used by all non-military federal agencies for geospatial data, information, and products, so that all federal maps, surveys, etc. are mutually consistent. However, while it is a federal system established for federal users, most private and local/regional public-sector geospatial users and applications across the country also rely on the NSRS for their positioning framework. Whereas NGS performs the task of NSRS stewardship, the official adoption of changes to the NSRS has most recently been conducted via approval by the Federal Geodetic Control Subcommittee (FGCS), the organization issuing decisions in Federal Register Notices (FRN).[4]

The definition of the ***geometric*** component (latitude, longitude, ellipsoid heights, etc.) is found in *Blueprint for 2022, Part 1: Geometric Coordinates* (NGS, 2017a). The definition of the ***geopotential*** component (heights, gravity, etc.) is found in *Blueprint for 2022, Part 2: Geopotential Coordinates* (NGS, 2017b). With these two documents, four geometric reference frames and one geopotential datum were named and defined, as follows:

North American Terrestrial Reference Frame of 2022 (NATRF2022)

Pacific Terrestrial Reference Frame of 2022 (PATRF2022)

Caribbean Terrestrial Reference Frame of 2022 (CATRF2022)

Mariana Terrestrial Reference Frame of 2022 (MATRF2022)

North American-Pacific Geopotential Datum of 2022 (NAPGD2022)

Readers interested in the technical details of these frames and datum are encouraged to read the aforementioned documents. We also have provisions for the modification of these frames and the datum in the future.

This report is a companion to the previous two documents, but its focus is less on definition and more on practical use. Specifically, this document attempts to describe how to use the new frames and the geopotential datum as geodetic control. For users unfamiliar with geodetic control, a simple tutorial is provided in Appendix A.

Historically, the impact of Earth's movements on geodetic control was either ignored outright or dealt with on an ad-hoc basis. For example, a leveling survey performed in the 1950s may have been included in a nationwide adjustment consisting of decades of leveling data, with systematic

[4] Much of the mandate for the NSRS in the last two decades came from the Office of Management and Budget (OMB) circular A-16. However, in 2018, a new law, the Geospatial Data Act (GDA), was passed, and it overlapped and re-defined certain aspects of OMB A-16. As of the release of this document, the full implications of the GDA on the NSRS has not fully been analyzed, though it is not expected to have significant impact.

errors that were only partially accounted for, and computed in 1991, but kept as-is into the 2010s.

Survey accuracy has improved such that what were historically considered “small” coordinate changes in time are no longer considered small, but rather are well within the range of detectability. For instance, the 1-3 centimeters-per-year counterclockwise rotation of the North American plate can easily be seen in coordinate changes computed from Global Navigation Satellite System (GNSS) data, such as from the Global Positioning System (GPS). Historic, local, optical surveys may have dealt with corrections such as Earth tides quite crudely, if indeed they dealt with them at all. Modern geodetic surveying using satellite and astrogeodetic techniques must utilize the latest models for a variety of corrections, and they must be considered within a global context.

The only way to know whether your geodetic control is up to date is to track it continuously. Yet, very few marks in the NSRS have equipment installed to monitor a geodetic coordinate on that mark 24 hours a day, seven days a week. The exception to this rule are marks at tide gauges, continuously operating relative gravimeters, and continuously operating GPS/GNSS reference stations (CORS). Without installed equipment to monitor their position, the majority of passive marks—historically known as the workhorse of the geodetic control community—will be acknowledged as a secondary source of “known” coordinates.

Thus, in the modernized NSRS, NGS will provide geodetic control through the NOAA CORS Network as our primary service. The most accurate information NGS can provide will be by using NGS geodetic control, NGS software, and your survey measurements to produce coordinates on those points you have measured at the epoch of your survey.

By way of answering the question, “Why is NGS bothering with all this?,” our best answer can be summed up thusly, “To save lives and property.” Perhaps the best, most recent illustration of that answer comes from the report prompted by the devastation caused by Hurricane Katrina (U.S. Army Corps of Engineers, 2006):

> *“The floodwalls along the outfall canals were constructed to elevations nearly 2 feet below the original intent because of errors in relating the local geodetic datum to the water level datum.”*

Certainly, the surveyors of levees were not so incautious as to make a 2-foot error. However, decades of unchecked subsidence undoubtedly contributed to geodetic control that was woefully inadequate for the task of protecting the city of New Orleans.

Heights, however, are not the only problematic issue. As we enter the era of self-driving cars, if not accounted for, datum inconsistencies between navigation equipment (most likely in a geocentric system such as WGS-84) and pre-existing road data (most likely in a non-geocentric system such as NAD 83) could yield up two meters of error in parts of the continental United

State (CONUS) and up to four meters in Hawaii. By switching to a more geocentric reference system, we hope to alleviate this issue.

Due to high user demand and practical considerations that compel some level of constancy in NSRS positions over time, NGS will develop and provide certain components in the modernized NSRS in an attempt to alleviate the impact of coordinate changes over time. The two primary components are:

1. Plate-fixed frames
2. Intra-frame Velocity Model

The Plate-fixed frames are those four terrestrial reference frames mentioned previously in this document. Whereas the International Terrestrial Reference Frame (ITRF) is not fixed to any plate, each of the four TRFs of the modernized NSRS will rotate at the average rate of the plate bearing its name, thus alleviating the dominant source of latitude and longitude change over time.

The Intra-frame Velocity Model is intended to describe the motions of geodetic control points between the times those points were measured. In effect, the job of the Intra-frame Velocity Model is to capture all *residual* changes in latitude and longitude, when dealing with the plate-fixed frames (above), as well as *all* vertical motion.[5]

Further details are presented in the two previous Blueprint documents (NGS, 2017a and NGS, 2017b).

1.2 Types of geodetic control and their relationship to the NSRS

At the most basic level, there are currently four types of geodetic control that allow a user to access the NSRS:[6]

1. GNSS satellites,
2. the NOAA CORS Network,
3. other continuous GNSS stations, and
4. passive marks.

Each of these types of control can be considered to have some zero-dimensional point, and, relative to that point, another point of interest that can be located using direct or indirect measurements.

[5] This is because the removal of plate rotation only takes away horizontal signals, leaving (for the IFVM to model) the entirety of any vertical motion, since no vertical motion is removed by removing the plate rotation.

[6] The term, "access the NSRS" can be used interchangeably with the longer phrase, "Take some observations at a point of interest, and perform some computations on those observations in order to determine the NSRS coordinate at that point of interest."

The following sections discuss the ***current situation*** for each type of control. The specifics of using the control ***in the future*** will be covered in Section II of this document.

1.2.1 GNSS satellites

The GNSS satellites themselves serve as "monuments in the sky," and the geodetic control point is the center of mass of each satellite. Knowing the location of the satellites,[7] as well as having a way of receiving and interpreting the data they broadcast, allows a user to compute some form of geodetic coordinates at the user's point of interest.

There are generally two ways to use the GNSS satellites directly as geodetic control.

The first way to use the satellites as geodetic control is by using only the broadcast signal, for example, the GPS chip in a smartphone. Users gain access to a location in the latest frame for that particular constellation (e.g., the WGS 84 frame, if GPS is used). As none of the constellation frames are part of the NSRS,[8] **this form of using the GNSS satellites does not allow direct access to the NSRS.**

However, there is a more accurate way to use, more or less independently, the GNSS satellites alone, and that is via a method called "Precise Point Positioning," or PPP.[9] PPP relies on determining more accurate orbits and clocks than are found in the broadcast GNSS signals. However, PPP does not directly position the user relative to anything other than the satellites themselves (i.e., it does not differentially position you, the user, relative to ground stations). So, the frame of the derived coordinates will be the frame of the orbits themselves, as NSRS coordinates are mathematically defined relative to the ITRF2014 reference frame.

NGS does not, however, operate PPP services, nor do we provide a service to quantify the alignment of PPP services with the NSRS. ***Therefore, NGS can provide no explicit guarantee that NSRS coordinates derived from this method will actually be aligned with the NSRS at any particular level of accuaracy.***

1.2.2 The NOAA CORS Network (NCN)

The NOAA Continuously Operating Reference Station (CORS) Network (or NCN) is an NGS-managed network of stations, with each station being comprised of a static continuous GNSS antenna and related equipment, and each independently referred to as "a CORS." At each

[7] It is critical to be clear regarding to what point an orbit refers. The "broadcast orbits" from GPS refer to the antenna phase center of the broadcasting antenna. However, precise orbits ("SP3 precise ephemeris files") refer to the center of mass of each satellite, and the antex file provides the offset (or "lever arm") between the two.

[8] NGS will establish a strict mathematical relationship between the NSRS frames and the ITRF2014 frame in 2022, and this is what allows direct access to the NSRS. Frames such as WGS 84 may have relationships to either an IGS frame, an ITRF, or even an NSRS frame, to allow access to the NSRS through WGS 84, but those relationships are not currently known. See NGA (2014) for a description of the relationship between WGS 84 and ITRF2008 (and prior).

[9] To be complete, any PPP method in use today requires some form of network of terrestrial GNSS stations to assist in computing corrections, such as to orbits and clocks. But the user of PPP is not being "differentially positioned" from their own antenna directly to one of those terrestrial stations.

station is a unique, permanent, antenna-independent, physical point[10] called the Geometric Reference Point (GRP).[11] NGS regularly collects data from each CORS and uses these data to perform many functions, including GNSS orbit determination, as well as to keep track of the location of each CORS (meaning the coordinates of each GRP).

Because the CORS Network is managed by NGS, the station coordinates are computed in NSRS datums and they have always ***provided direct access to the NSRS***.

There are three ways a CORS currently may be accessed for use as geodetic control. Before discussing them, however, one critical point must be made:

> ***No one should ever remove, alter, or modify the equipment at a CORS in an attempt to access the GRP.***

With the above-mentioned rule in mind, the first and most common way a CORS is used as geodetic control is when a user operates a GNSS receiver at a point of interest, they process received data in coordination with the CORS data, and then they yield a differential vector between the CORS GRP and their point.[12] Whereas NGS offers software to accomplish this task, it is not necessary for the user to rely only on our NGS software to arrive at an NSRS coordinate. ***However, currently, NGS does not provide a service to quantify the alignment of NSRS coordinates computed from non-NGS software*.**

The second method—less disruptive but also difficult in many cases—is to use the GRP (if visually identifiable) in an indirect fashion. That is, to set up, for example, a total station near the GRP, and sight to it without physically touching it.

A third method, not generally endorsed by NGS **(see warning above),** is to occupy the GRP as one would occupy any passive mark (see section 1.2.4). By this we mean, a level rod might be placed on the GRP to perform leveling (assuming it is a "touchable" point, but this is not always the case), or a total station set up on a tripod over the GRP for performing classical surveying. Aside from the fact that this is impossible for a vast majority of CORS (mounted on roofs, etc.) it is also dangerous and disruptive to the CORS data time series to touch the GRP or any other part of the CORS equipment while it is 'up and running.' The only exception to this rule would be during times when the antenna has been removed (such as upon the first installation of the CORS or between antenna changes).

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[10] Such points are not always "touchable." That is, they may be defined as the center of a threaded rod, at the intersection of such a rod with a particular plane. This is not uncommon and does not break the definition, but it does not allow an instrument, such as a level rod, to directly touch the GRP.

[11] Although this term is new, it is introduced in this document for the explicit reason of avoiding long-standing confusion over previous terms "ARP," "MON," or "L1 Phase Center." NGS has been inconsistent in identifying (and giving one name to) a unique, permanent, antenna-independent point at each CORS in the past. Therefore, the term "GRP" is introduced to refer to such a point and identified for EVERY CORS. Relationships between this term and MON or ARP will be clarified in a separate document.

[12] Further refinement of this process can be done by operating multiple receivers and performing a least squares adjustment of all the data.

In all these cases, the CORS coordinate function is key to computing time-dependent coordinates on their own points of interest in the NSRS.

1.2.3 Other Continuous GNSS Stations

Whereas the NCN represents a large proportion of the available continuous GNSS stations in and near the United States, they are by no means *the total sum of all* such stations.[13] In much the same way as a CORS in the NCN, a non-NCN station ***can be used to access the NSRS*.** However, as we at NGS neither compute nor track the coordinates of these stations, ***the veracity of their coordinates is outside of our control***. This means that, despite the fact that coordinates derived from such stations may be listed as being part of the NSRS, we cannot judge or comment on the accuracy of those coordinates. Within that caveat, they can be used in one of the three ways mentioned above, under "the NOAA CORS Network." However, if these stations make their GNSS data available to the public, then their NSRS coordinates can also be re-determined by processing those data relative to the NCN, and those *re-determined* coordinates could then be used as geodetic control for relative GNSS positioning.

There is a *fourth* way to access and use other continuous GNSS stations as geodetic control that is *not* available through the NOAA CORS Network, and that is if such stations are part of a Real-time Network (or RTN). RTNs exist in nearly every state, with some operated by private companies, and others run by state government agencies, such as departments of transportation. In these specific cases, the RTN operators will not only compute the coordinates (and possibly velocities) of their own continuous GNSS stations (usually referred to as "base stations" in this case), but they will also broadcast that (and other) information to users of the RTN who have a specific GNSS antenna (called a "rover" in this case). The hardware and software in a rover will use those broadcast base station coordinates and correctors to determine a coordinate with respect to whatever coordinate frame the RTN operator has chosen for their work. In many cases in the United States, the RTN operator will operate in some frame of the NSRS, thereby ***allowing users of the RTN access to the NSRS***. However, as NGS neither computes nor tracks the coordinates of these stations, ***we cannot (currently) comment on the accuracy of RTN coordinates.*** However, unlike all other non-NGS approaches mentioned thus far, we do have plans to modify and improve this current situation for our user community. See Section II for details.

1.2.4 Passive Marks

Passive marks come in many varieties. The most common of these are a metal (often brass, bronze, or aluminum) disk set into stone or concrete, or a deep-driven rod. Whatever their

[13] The University of Nevada at Reno has a website listing many of these stations, for example: http://geodesy.unr.edu/NGLStationPages/gpsnetmap/GPSNetMap.html

design, they all have one thing in common; unlike the previous three types of geodetic control, up-to-date, time-dependent coordinates on passive marks are generally not available.

Prior to the 2022 NSRS modernization, NGS delivered the NSRS through passive marks by publishing the "official" coordinates on each mark. In the case of latitude, longitude, and ellipsoid height, marks with the most up-to-date coordinates come from a single adjustment of all GPS vector data spanning more than three decades to yield an estimate of coordinates at epoch 2010.00.[14] In the case of orthometric heights, the situation is generally one of publishing the last known height on the point, whether that be from a survey 5 or 55 years in the past. No attempt to provide time-dependent coordinates, based on actual time-spanning surveys on these points is currently available.

However, as these "official" coordinates are included in the NSRS, ***passive marks do provide access to the NSRS*****.**

As Earth deforms (relatively) slowly, the coordinates computed for passive marks might be "usable" for "long stretches of time,"[15] depending on one's location. That, at least, has been our philosophy at NGS until our decision came to modernize the NSRS. Small deformations, of just a few millimeters a year, for example, are noticeable to certain users, and, particularly when considering heights, may have significant impact on issues such as flooding.

This transformation of passive marks from *one* official coordinate set to a *set* of official time-dependent coordinates is indeed one of the more startling aspects of the modernized NSRS, and it warrants an explanation regarding the subject of stability and instability.

Why coordinates of passive marks might be considered "stable": At the moment, the NAD 83(2011) reference frame does not seem to be rotating at the exact speed the North American tectonic plate is rotating. However, if it were rotating at the same speed, it would be a "plate-fixed" frame, and the latitudes and longitudes in NAD 83 would not change over time for

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[14] In the previous NSRS, adjusted coordinates were computed at reference epochs, not survey epochs. That is, though a survey took place on a particular day, those observations were "transformed through time" (sometimes years) to some reference epoch using Horizontal Time-dependent Positioning, or HTDP (a model of horizontal, but almost exclusively not vertical) motion, before being adjusted to all other such data at all other survey epochs that had been similarly moved through time to that reference epoch. This practice is now removed from the current NSRS, and surveys will be adjusted at their survey epoch, with final coordinates reported at those survey epochs. From a general standpoint, the "survey epoch" should be thought of as "that specific and exact time NGS feels the coordinate is valid." The actual computation of the survey epoch will be dependent on many factors, including the type of coordinate, type of survey, the data collected, and the age of the data collection. This will be detailed in sections 2.13.2, 2.13.3 and 2.13.4).

[15] These two terms are left purposefully vague. Coordinates in the NSRS are all time-dependent, and therefore the highest accuracy achievable on a passive mark will be the epoch when an actual survey was performed to the mark itself. Outside of that epoch, Earth's deformation being generally systematic, will cause changes to the coordinate, but without a new survey, such knowledge of these changes can only be modeled from other independent sources (such as geodynamic models, or perhaps from interpolating from CORS stations or from radar-mapped changes to the local topography). Since these deformations are geographically and temporally dependent, and since the coordinate accuracy needs of each user are different, it is impossible to know what "long stretch of time" will deform a point's coordinate to such a level that a particular user might find the mark no longer "usable." In a dystopian situation wherein, there is no communication from GNSS satellites, passive marks can retain coordinates.

much of the plate. Getting that rotation right stabilizes coordinates, so trusting an "old" coordinate on a passive mark would be justified. Getting that rotation right is a cornerstone of the modernized NSRS.

Why coordinates of passive marks might be considered "unstable": Aside from plate rotation, many things can move a passive mark and impact its coordinate enough to make it unusable. Without creating an exhaustive list, following are a few examples. Horizontally, areas west of the Rocky Mountains (particularly the west coast) are deformed as the North American plate attempts to rotate counterclockwise but is impeded in its progress by the Pacific plate. These deformations can cause residual (non-rotational) horizontal velocities that approach a few centimeters per year. On a smaller scale, Glacial Isostatic Adjustment (GIA) can pull a point toward the center of uplift by millimeters every year. Additionally, plates are not *truly* rigid. Even so-called "stable" parts of the plate can have small residual horizontal velocities which, even at sub-millimeter per year levels, can make a point unusable if it was last surveyed a decade or more ago.

Things are significantly more problematic in the vertical, however. Vertically, *all* motions make a point's last known height coordinate out of date, since the removal of the tectonic rotation does not attempt to remove any vertical motion. Among those phenomena which impact a height are processes from deep continental secular scales (such as the aforementioned GIA and faults), to localized crustal issues (including subsidence due to fluid withdrawal). In certain parts of the United States, subsidence has been documented at many centimeters per year. In the San Joaquin Valley in California, subsidence in the later 20th century was recorded as 17.5 centimeters per year. That measure has since slowed to approximately 6 centimeters per year (see below). Marks set in concrete posts or on structures can settle into the local soil over time or be subject to frost heave.

So, with full knowledge of these reasons for considering a passive mark stable or unstable, a user who either *chooses* to, or is *required* to use the "official NSRS coordinates" on passive marks as geodetic control has little choice today other than to trust an old coordinate. Of course, users are encouraged to *update* coordinates on passive control whenever possible and to exercise professional judgement in their election to use 'stale' coordinates.

Figure 2: Subsidence in California (photo credit: USGS)

1.3 NGS Operations Today

NGS operates the NSRS currently in ways that will be changed when the NSRS is modernized. Below is a brief summary of how things stand today.

1.3.1 The NOAA CORS Network

The CORS (Continuously Operating Reference Station) Network began with three stations, called the “Cooperative International GPS Network (“CIGNET"), in the fall of 1986 (Snay and Soler, 2008). The original intent was to have ground GPS tracking stations capable of assisting in accurate orbit computations, as well as to provide support for the then-proposed High Accuracy Reference Network (HARN) surveys. This concept eventually blossomed into a global tracking network and morphed into the International GNSS Service (IGS). However, it wasn't until 1994 that a second function, to "enhance" (which eventually became "supplant") the passive mark network known as the NSRS, was proposed (Strange, 1994; Strange and Weston, 1995).

The NOAA CORS Network has now grown to more than 2700 stations (with more than 1800 of them currently active), including 200 partners in 25 countries. With the growth of the NOAA CORS Network has come a related number of challenges. Managing data feeds from disparate sources and attempting to maintain useful coordinate functions (currently starting conditions, linear velocities, and discontinuities) on the network has slowly allowed small deteriorations to appear at the fringes. It is not difficult to find examples of CORSs with daily coordinates showing regular and systematic deviation from their velocity-predicted coordinates. And whereas a truly "standard" CORS construction does not exist, there are commonalities. Yet there are CORSs that deviate wildly from such common constructions, and there are certainly other challenges associated with maintaining an up-to-date record of the equipment actively in use at every site. For this reason, when users rely on the NOAA CORS Network for processing their GPS data, they have found that their choice of which CORS to use will impact the output coordinates by multiple centimeters, a decidedly undesirable situation.

Further complicating the situation is the lack of resources and automated tools for processing GPS data in the NOAA CORS Network. As an example, NGS' latest effort to reprocess all historic data—called "MYCS2" (for Multi-Year CORS Solution 2)—was an effort to support the IGS's transition to ITRF2014, and it required two years to complete. The effort yielded, for each CORS in the NOAA CORS Network, a triad of piecewise coordinate functions (one each for X, Y, and Z), where the individual pieces of each function were linear and defined through two parameters: a coordinate at epoch 2010.00 and a slope of the line. Upon release in 2019, these coordinate functions were only based on data through January 28, 2017. While that work was important for moving NGS onto ITRF2014, the long timeline to completion has forced us to re-evaluate exactly how coordinate functions could and should be computed going forward into the modernized NSRS. In the current method there is no automated process to respond to a CORS when its daily solutions are persistently deviating from its assigned coordinate function; that simply cannot be sustained in the modernized NSRS.

Despite these difficulties, the potential power has always existed for the NOAA CORS Network to serve as a mutually self-consistent and highly accurate foundation for the NSRS. Major changes in construction, data delivery, and data processing are expected to unleash that potential as part of our NSRS modernization.

1.3.2 OPUS

Originally, the Online Positioning User Service (OPUS) was a GPS processing tool NGS built to invoke our Program for the Adjustment of GPS Ephemerides (PAGES) in a user-friendly way. Over the years, "OPUS" was renamed "OPUS-S" (S for "Static") when a second user-friendly tool became available, followed by OPUS-RS (RS for "Rapid-Static"). Other OPUS "flavors" were subsequently developed. OPUS-DB (which became OPUS-Share) was a place for NGS to highlight the good efforts of users working with OPUS-S, as we had not developed a path for loading OPUS-S data into the NGS IDB. Then OPUS-Projects was developed as a way to combine multiple occupations into a project. Although OPUS-Projects performed similar tasks as "Bluebooking," it was (like OPUS-DB) not originally built with a path to the NGS IDB.[16]

So, while the intent of all versions of "OPUS" was simplicity and user-friendliness, NGS did not fully integrate them into the NSRS. Examples of current difficulties with everything "OPUS" are:

- OPUS-S requires 2-hour sessions, even though its core (PAGES) can process as little as 15 minutes of data (though usually over fairly short baselines).
- Choosing different CORSs in OPUS results in different positions.
- OPUS-RS doesn not consistently agree with OPUS-S.
- OPUS-Share does not have any relationship to the NGS IDB.

Whereas these issues are discouraging, NGS is building the future "Bluebooking" process around OPUS, and we will not only be correcting each of these deficiencies, but we will be addressing much more, as well.

1.3.3 Crustal Dynamics

In 1999, NGS introduced the Horizontal Time-Dependent Positioning (HTDP) software. The intent of that software was to provide users with the ability to model horizontal crustal motion across epochs, with the express purpose of applying those models to geodetic control. Since then, the use of HTDP has been integrated into the standard "Bluebooking" process. For example, GPS-based differential vectors, collected in a survey in 2018, could be "moved in time" (using HTDP) back to epoch 2010.00 and adjusted to other geodetic control in the NSRS in NAD 83(2011) epoch 2010.00.

Updating HTDP requires updating geophysical models of physical structures of the Earth (faults, earthquakes, etc.). The result should provide a model of actual motion of points on the Earth's surface. The complicated nature of HTDP, however, has led to it being updated on a less than optimal schedule. Additionally, NGS researched a tool, Vertical Time-Dependent Positioning (VTDP), to address vertical motion; however, that tool was never fully developed.

[16] This changed in 2018 with the completion of the "OP2IDB" project, with a beta release of a version of OPUS-Projects which did, in fact, perform many of the functions of Bluebooking, including loading data into the IDB. This was intentional, as the ultimate path forward for NGS, as this document will show, is for OPUS to be the single-entry point for all geodetic data, leading to the new NSRS Database.

1.3.4 Passive Marks

Prior to 2022, NGS relied on passive marks and the NOAA CORS Network as effectively being equal in providing users access to the NSRS. Viewing passive marks and the NOAA CORS Network as equals was primarily due to the fact that NGS defined a "reference epoch" (2010.00) for the last realization of the datum, NAD 83(2011), thereby "freezing" the datum in time, and we used HTDP to bring observations back to that epoch. This method has had a mix of successes and failures.

On the success side, consider the adjustment of all GPS vectors in the creation of NAD 83(2011), epoch 2010.00. Using HTDP to move vectors as far back as 1983 to epoch 2010.00 yielded an adjustment with remarkable statistics. In the CONUS portion of that adjustment, 21,231 vectors out of 420,023 (5.1 percent), were rejected as outliers. Of those retained, the median horizontal residual was 0.46 centimeters, and the median ellipsoid height residual magnitude was 0.51 centimeters (Dennis, 2019). This result speaks well to both the quality of GPS work in the NSRS user community, the viability of HTDP, and/or the generally stable nature of the crust in CONUS.

On the less than successful side, however, HTDP does not account for vertical motion, except in central Alaska. Thus, it effectively "hides" any subsidence (along the Gulf Coast or California's Central Valley, for example) by treating such systematic changes to the ellipsoid height of a point as part of the random measurement errors. This is both mathematically incorrect and disingenuous.

An additional difficulty with passive marks is that they remain the primary access to orthometric heights, for example, in NAVD 88. The NAVD 88 was created in 1991 based upon leveling data spanning nearly a century. In many cases, those initial NAVD 88 heights have not been checked, and they continue to be disseminated as the official NSRS heights on datasheets. Even so-named "Height Modernization" surveys using GNSS technology suffer, as they do not measure updated absolute orthometric heights, but rather propagate differential heights relative to existing NAVD 88 bench marks (although most Height Modernization surveys do attempt to identify and correct NAVD 88 heights on marks that may have changed relative to others within a project area).

1.3.5 Accepting Surveys into the Database ("Bluebooking")

An important part of our past (and present) products and services was a procedure for the submission of high-quality passive mark geodetic surveys to NGS. The purpose of these submissions was for us to perform our quality assurance on the survey, and eventually include the information in the NGS Integrated Database, the repository for passive mark information concerning the NSRS prior to 2022. Officially, the procedure had no formal name other than "data submission," but those data were submitted under very specific rules as originally laid out in the document "Input Formats and Specifications of the National Geodetic Survey Data Base"

(Yeager, 1980), which was revised and updated many times over the subsequent 30-plus years. Because the first versions of that document were distributed in a multi-ring binder with a dark blue cover, the procedure came to be called “Bluebooking.”

Originally Bluebooking was developed in the 1980s so that the various field crews (both inside and outside of NGS) could turn data in to the office analysts in a common and consistent format that could be fed into computer programs and databases. For decades, surveys continued to expand the passive NSRS network via the Bluebooking standard.

The time-dependency of passive mark coordinates was originally solved primarily through the process of “superseding” coordinates. Significant human analysis was required to get new measurements to fit to old coordinates. Sometimes the new measurements would lead to a new coordinate that superseded the old. Sometimes the new measurement would be rejected as an outlier. Such decisions happened regularly as projects were turned in; however, our pervasive attitude was to first attempt to fit new data to the old network.

As time progressed, NGS developed HTDP, a program with two primary functions: first, to provide access to 14-parameter Helmert transformations between global reference frames (such as those of the ITRF, the IGS, WGS 84, and the original NAD 83), and second, to provide access to models of crustal dynamics. The second function (of providing models of crustal dynamics) became a standard tool in Bluebooking in the early 2000s (Prusky, 2018). In this way, prior information about horizontal crustal movement was added to the project’s analysis, and decisions concerning superseding older coordinates could be better informed.

Bluebooking performed its one task, of promoting consistency of data submissions, quite adequately for decades. This consistency was critical, so that software only needed to support one data format (important as resources dwindled). Yet, its continued reliance upon not very modern computer technology (DOS, FORTRAN, 80-character ASCII files), as well as its somewhat complicated rules and jargon gave Bluebooking the reputation of being “onerous” to many users.

Bluebooking tended to focus on so-called “reduced observations.” That is, each individual angle turned by a total station wasn not stored in a “Bluebook file.” Rather, the average of multiple angles turned would be stored. Similarly, this was true also for distances, azimuths, and (eventually) differential vectors between two points each occupied by GPS. While those GPS files were often turned in to NGS with the bluebook submission, they were archived and (until the 2010s) forgotten. The vectors derived from the GPS data (whether from NGS software—PAGES, for example—or vendor software, such as Trimble Business Center) were turned in and stored. This, of course, led to inconsistencies depending on both the age and source of the software. Fortunately, such inconsistencies tend to be small (Dennis, 2019), but they do exist and furthermore, without the ability to quickly re-process the raw observables, they will continue to exist.

One additional requirement of Bluebooking was that all data needed to be adjusted using either the software package **ADJUST** (for geometric data, such as GPS vectors, as well as classical surveying data) or **ASTA** (for leveling). These two programs are among the many independent programs NGS had for various statistical and least-squares computations (others still in use are **GPSCOM**, used within OPUS; **NETSTAT**, used exclusively for national adjustments such as those completed in 2007 and 2011; and **CALIBRATE** used in the adjustment of measurements at Calibration Base Lines. In addition to these, NGS has over the years developed, and mothballed, numerous other least squares adjustment packages).

2 The Future

2.1 Introduction

The previous section described NGS' standard operating procedure (SOP) regarding the NSRS prior to 2022. The primary philosophy driving that SOP was to assume a coordinate is unchanging, and to update that coordinate only when enough data warranted it. As knowledge of the deforming crust became more available (and measurement techniques improved to the point where this deformation could be more accurately measured), that philosophy morphed into "pick an epoch, and serve up the NSRS as a set of coordinates on points at that epoch." In this way, the dynamic Earth was acknowledged, but fixing an epoch meant that the NSRS effectively was just a snapshot of Earth at that epoch.

Continuing this analogy, the modernized NSRS will embrace that "snapshots" take place at fixed epochs, but rather than just one snapshot, the NSRS will be served up as a *series* of snapshots over time (for occupations on passive marks), as well as a continual "movie" (for continuously tracked stations, such as CORSs and continuously operating relative gravimeters).

Further, the pre-2022 NSRS treated stations in the NOAA CORS Network (NCN) as having purely linear velocities, rarely corrected when a CORS showed data that deviated regularly away from its linear velocity. Post-2022, the NCN will serve up coordinate functions at each CORS which may be non-linear, and which will be monitored daily for any persistent discrepancies between that coordinate function and the daily data collected at that station.

This section deals with the future. In order to describe both the modernized NSRS and how users will utilize it, some terminology and basic information must first be presented.

2.2 Definitional Constants and Models

The modernized NSRS will begin with definitional constants and models. As this was mentioned in the previous two Blueprint documents, they are simply listed for completeness in Section 3.6 (Appendix F).

2.3 Definitional Data

Using the modernized NSRS will rely, almost to the point of exclusion, on modernizing the NOAA CORS Network, and explicitly upon the coordinate functions NGS assigns to each CORS. Definitional data can be summed up as a 'list' with the following single item:

CORS coordinate functions in the ITRF2014 frame

Further information is found in Section 2.7.

2.4 A New Database

It may seem odd to put a discussion of a new database so close to the beginning of this section, but that was indeed done on purpose. One of the main contributors to confusion and an inability to keep information up to date has been our reliance on a database built neither for geospatial relationships, nor one that holds time-dependent data. For this reason, and others, NGS had stored information in a variety of locations outside of, and inaccessible to, the pre-2022 database (the "NGS IDB").

One might think of the pre-modernized NSRS as "whatever was in the NGS IDB," and that would have been reasonable based on NGS' own public information. As of 2019, "OPUS-Share" (a current location for users to share their OPUS-S solutions) is stored outside of the NGS IDB. And since it is neither in the NGS IDB, nor checked against it, these solutions (while useful) are not considered "**part** of the NSRS," but rather "**tied** to the NSRS." And whereas parts of CORS coordinate functions are stored in the NGS IDB, they are derived from a richer data stream containing much more information than is in the NGS IDB.

Post-2022, all data collected by or submitted to NGS will be quality checked and stored in a new database called the "NSRS Database." It will be a geospatial database (meaning the database is built with geo-relationships between data for fast, spatial queries).

2.5 New Types of Coordinates

It is probably not very debatable that the primary information of interest stored at NGS (in the IDB before NSRS modernization and in the NSRS DB after modernization) are *coordinates*. Coordinates come in a variety of types, but all serve a similar purpose—to uniquely identify the location of a point within some coordinate frame at some time. The "at some time" phrase is fairly new to geodetic control, relatively speaking, and prior to the NSRS modernization, it was never fully embraced at NGS.

With the modernization of the NSRS comes a number of new ways NGS will perform our primary mission. One of those new changes will be how coordinates are computed, stored, and disseminated. Going along with that will be a somewhat more precise nomenclature relating to the types of coordinates we will produce. Many of these details are outlined in the following sections. A description of how accuracy reporting will be standardized is included in Appendix B. However, it will be instructive to first define the five new types of coordinates.

1. ***Reported*** coordinates. These are from any source where the coordinate is directly reported to NGS without the data necessary for us to replicate the coordinate. Examples include coordinates scaled off a map, coordinates reported from a smartphone, or even coordinates reported directly from an RTN rover without supporting vectors. Additionally, any coordinates transformed from one datum to another (such as through the use of NADCON or VERTCON) will automatically be placed in this category. While such coordinates are useful and can be used in computations of no better accuracy than

the coordinates themselves, NGS will not apply the term "geodetic control" to such coordinates.[17]

2. ***Preliminary*** coordinates. These are coordinates at either survey epoch or some other epoch of a user's choice that have been computed from OPUS (and only from OPUS), but either (a) have not yet been quality checked and loaded into the NSRS DB, or (b) have no redundancy within the same GPS month ("redundancy" and "GPS month" are defined in the terminology guide). Users can quickly determine such coordinates in this way and may (at their own risk) use them as geodetic control. However, unless such projects are submitted to NGS for quality control and database loading, we will be unable to compute "Final Discrete" coordinates for them and we do not recommend control. It should be noted that, whereas only OPUS will provide these coordinates, they can be computed from vectors which may have been processed outside of OPUS. For instance, presume a user collects vectors from an RTN operator or perhaps a user does four-hour sessions, but computes the vectors using Trimble Business Center. In either case, those vectors can be uploaded to OPUS, and the resulting coordinates will be labeled "Preliminary."

3. ***Reference Epoch*** coordinates. These are coordinates computed by NGS in an adjustment to estimate the coordinates at one of the official (every five years) "reference epochs" NGS will define (NGS, 2017a).[18] As (generally) all such coordinates come from observations that did not take place at the reference epoch, such coordinates require the introduction of the Intra-frame Velocity Model (IFVM) into the adjustment, and thus the coordinates so computed are subject to all uncertainties and assumptions in the IFVM.[19] For this reason, they are considered a lower accuracy than coordinates computed at the survey epoch itself.

4. ***Final Discrete*** coordinates. These are coordinates computed by NGS using submitted data and its metadata, then checked, adjusted and *defined at one "survey epoch*." These represent the best estimates we have of the coordinates at any mark at some specific point in time. However, we feel it is important to point out that the largest source of adjusted coordinates are not from NGS, but instead come from ***user-submitted*** survey data at passive marks. See section 2.11[20].

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[17] This is a broad category, reflecting coordinates from a variety of sources, but with one thing in common: the observational data, metadata, computational process, or some combination of all three are missing from NGS archives. Consequently, they cannot be replicated at NGS and thus we cannot verify them. In the past, examples of such coordinates might have been labeled "SCALED" or "HAND HELD."

[18] The OPUS software can be used by users to compute coordinates at any epoch of their choosing. However, such coordinates will be labeled to the user as "Preliminary Coordinates," without regard to the chosen epoch.

[19] The HTDP software, which served in a capacity similar to what IFVM2022 will do, had no formal accuracy estimates. Observations taking place at different times from a reference epoch were given no difference in their weights based on age. This will not be the case for IFVM2022.

[20] NGS will use the overarching label of "Final Discrete" coordinates, but we will also consider either sub-categories of coordinates, or at least provide explicit metadata regarding how each coordinate was computed. For instance, if a user provides us with vectors between some CORS and some passive marks in a way we are unable to verify (either because they come from an RTN survey or because they came from static sessions, but the user did not provide the data files to us), we can still compute Final Discrete coordinates from what we are given. However, as

5. ***Final Running*** coordinates. Of all types of coordinates on a mark, these are the only ones which *will have a coordinate at any time*. On a CORS, they will be identical to the coordinate function (see Terminology Guide). On passive marks not associated with continuous data collection, decisions on Final Running coordinates remain TBD, though current plans call for NGS to have the capability to generate them (from a mixture of Final Discrete coordinates and the IFVM) and plot them on a data delivery system.[21] In both such cases, this holds for latitude, longitude, and ellipsoid height. However, for orthometric heights and other geopotential related quantities, additional information will come from the Geoid Monitoring Service, or GeMS (NGS, 2017b). The Final Running coordinates should match the Final Discrete coordinates within the uncertainty of the Final Discrete coordinates. These running coordinates could be extrapolated forward and backward in time, regardless of how many Final Discrete Coordinates a mark has.

Note that each type of coordinate (except Final Running) listed above will also be identified with some "epoch." The epoch is the "representative time" of the observations(s) used to determine any coordinate and it corresponds to NGS' most accurate estimate of that coordinate. The representative time of a survey epoch depends on many factors as will be detailed for various survey types later in this document (sections 2.13.2, 2.13.3 and 2.13.4).

2.6 New Types of Non-coordinate Information

Geodesy and surveying are, by their very nature, frequently concerned with differential, not absolute, measurements. GNSS-derived coordinates often rely on *differential* vectors from a-priori known (fixed or stochastic) points. Leveling yields *differential* heights between points. Relative gravity, as its name implies, is about gravity *differences* between points. Such differential measurements are usually used in an adjustment to determine absolute coordinates. However, such adjustments can (and will in the future) always predict the best value for the differential vector.

In the past, we have stored the differential measurements, but rarely has NGS stored the a-posteriori (predicted) differential vectors. Neither the measured differences nor the a-posteriori differences have regularly been presented to the NSRS user community. This is unfortunate, as such information comes with its own information content. The measurements help determine how the coordinate was determined, and the a-posteriori differences reflect NGS' best estimate of the coordinate differences between points—information that cannot be gained simply by differencing the absolute coordinates of two points. See, for example, section 2.11.5.

NGS cannot verify the vectors, such Final Discrete coordinates will be (TBD) labeled differently and include metadata to distinguish them from those which come from a survey with data we are able to completely replicate and verify.

[21] Previously called "datasheets"

Although the exact names for, and types of, non-coordinate information to be presented to users hasn't been decided, certain decisions are known. NGS plans to build the NSRS database so that our users in the future should be able to access any of the following values:

1. Geometric vectors between points, at survey epoch
   Including ΔX, ΔY, ΔZ and $\Delta \phi$, $\Delta \lambda$, Δh
2. Geopotential differences between points, at survey epoch
   Including differential orthometric heights and differential gravity

Such values will come with uncertainty estimates, as well. It is likely such differential relationships will only be between so-called "directly connected" points. That is, between points observed in a common surveying project. Computing such values is otherwise fraught with scientific and technical complexity that may be insurmountable.

2.7 The NOAA CORS Network

First and foremost, NGS processes the collective data from the NOAA CORS Network (NCN) into "coordinate functions," one for each CORS. Whereas we do many other things with those data, it is the coordinate function which allows a CORS to serve as geodetic control. That coordinate function is simply ***a function, in time, of the ITRF2014 X, Y and Z values of the GRP*** of that CORS, from the moment of the first GNSS observation at that CORS up to the current moment, with a slightly forward-looking predictive capability.

The coordinate function is *piecewise continuous without gaps*. During times when a GNSS antenna is installed at the CORS, the collected GNSS data will drive the coordinate function. During time spans when there is no installed antenna, the coordinate function on either side of that time span, (plus the IFVM) will be used to build a bridge for the coordinate function across the gap.

Examples of piecewise continuous coordinate functions are shown below (from Bevis & Brown, 2014).

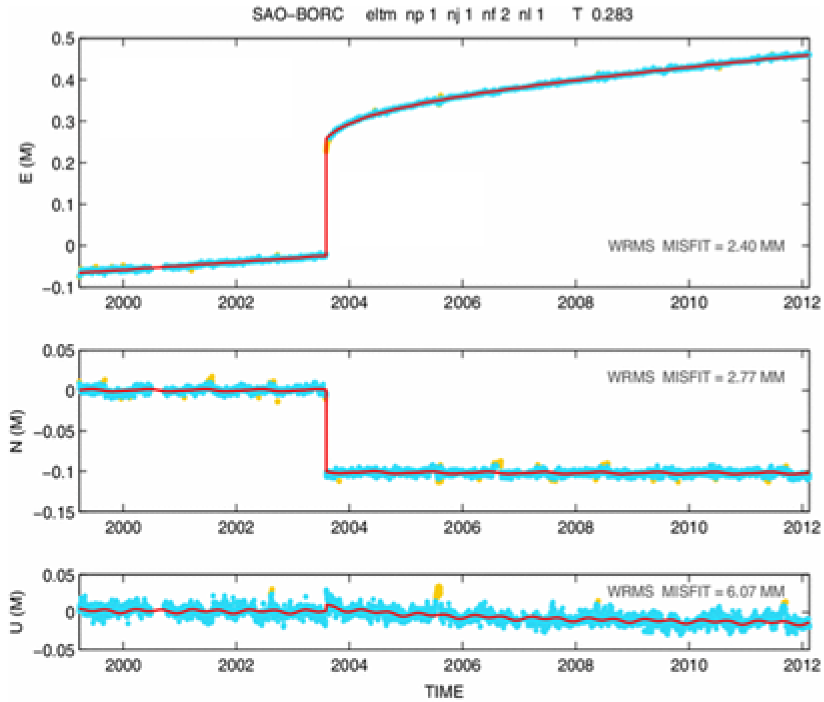

Figure 3: Example of non-linear coordinate functions

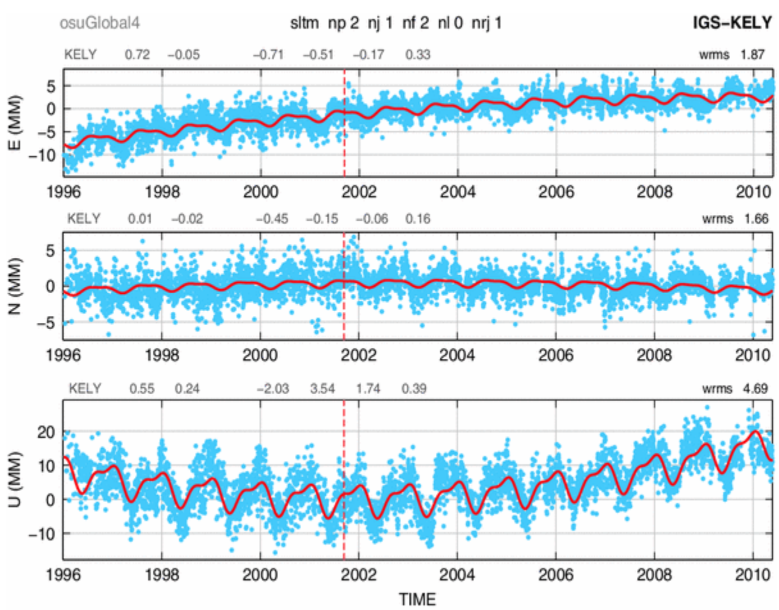

Figure 4: Example of non-linear coordinate functions

Note, these functions are not linear, though a linear trend is a component of each function. Exactly how we will compute, monitor, and update coordinate functions is TBD and will be decided through a series of ongoing scientific discussions within NGS.

2.8 The Twin Pillars of the Modernized NSRS

The two major pillars of the modernized NSRS will be a set of four terrestrial reference frames (NGS, 2017a) and a geopotential datum (NGS, 2017b). Due to the fact that these documents we refer to already contain substantial detail, the following sections will only briefly re-iterate the key points necessary for this document.

2.8.1 Terrestrial Reference Frames

First, NGS will perform most geometric computations in time-dependent Cartesian coordinates in the ITRF2014 reference frame. All coordinates (and other information, such as accuracies, correlations, etc.) will be served up to users in that frame.

From the time-dependent Cartesian coordinates in the ITRF2014 frame, the four sets of EPPs in EPP2022 will yield the same information in four terrestrial reference frames:

- North American Terrestrial Reference Frame of 2022 (NATRF2022)
- Pacific Terrestrial Reference Frame of 2022 (PATRF2022)
- Caribbean Terrestrial Reference Frame of 2022 (CATRF2022)
- Mariana Terrestrial Reference Frame of 2022 (MATRF2022)

From these five sets of Cartesian coordinates (and related information) will be derived five sets of curvilinear geodetic coordinates (geodetic latitude, geodetic longitude, and ellipsoid height) using the GRS 80 ellipsoid.

All the above information will be available through OPUS. Additionally, this geometric location information will be used to determine a variety of geopotential-based coordinates. See the next section for details.

2.8.2 Geopotential Datum

The entry point to the modernized NSRS is, for the most part, through geometric channels—geometric coordinate functions at all CORSs in the CORS network and the use of GNSS and OPUS. That means, access to absolute *orthometric* heights initially comes from *ellipsoid* heights, minus GEOID2022. However, for the highest accuracy *differential* orthometric heights, leveling will remain the primary tool. The following sections will delve into the method GNSS and leveling will be combined in projects to provide both absolute orthometric heights (at GNSS levels of accuracy) and differential orthometric heights (at leveling accuracy).

Any other type of surveying having to do with the geopotential field (deflections of the vertical, astronomic positioning, relative and absolute gravity, etc.) will be performed through OPUS and will be referenced as being part of NAPGD2022. And, as all other quantities, these values will be time-tagged to their survey epoch.

Finally, certain physical quantities will be readily available only to GNSS users and will be provided as part of any quick GNSS positioning solutions yielding preliminary coordinates (such as the pre-2022 OPUS-S and OPUS-RS). That means a so-called "OPUS-S" solution will yield not only geometric coordinates (both Cartesian and geodetic), but also the following:[22]

- Geoid undulation (also called "geoid height")
- Orthometric height
- Acceleration of gravity
- Deflections of the vertical
- Laplace corrections

These values will be interpolated and/or computed from interpolated values.

2.9 Intra-frame Velocity Model

NGS is committed to providing an Intra-frame Velocity Model (IFVM) to capture the residual horizontal motions and complete ellipsoid height motions of geodetic control points within all four terrestrial reference frames of the modernized NSRS (NGS, 2017a). The exact nature of the IFVM is being developed in 2019, but its use inside of the modernized NSRS is already clear.

The IFVM can be used in the following ways:

1) It can be plotted on time-dependent coordinate graphs of passive control, so that the Final Discrete Coordinates can be compared visually to the estimated movements in the IFVM. It is unlikely such presentation would show perfect agreement between the Final Discrete Coordinates and the IFVM, but rather agreement to a general statistical level.
2) It will serve as "stochastic prior information" in adjustments of geometric data which perform Least Squares Adjustment, attempting to estimate coordinates at an epoch different from the epoch the data were collected. Such adjustments might be done by NSRS users as part of a project. They will definitely be performed by NGS on a repeating schedule of every five years (2020.0, 2025.0, etc.) in the creation of official NSRS Reference Epoch Coordinates.
3) It will serve as the official transformation tool for all geometric coordinates in the modernized NSRS, connecting the above mentioned Reference Epoch Coordinates every five years. Pre-modernized NSRS geometric coordinates (NAD 83(2011/PA11/MA11) epoch 2010.00) will be connected to NATRF2022/PATRF2022/CATRF2022/MATRF2022 at epoch 2020.0 by *NADCON*. However, to connect the 2020.0 coordinates to 2025.0 coordinates, *IFVM2022* will be used, as it will be used for connecting 2025.0 to 2030.0, etc. This distinction between using NADCON or IFVM2022, however, will be invisible to

[22] If the point is not on the surface of the Earth, a slight degradation in accuracy of the listed quantities will occur, as they will all need to be derived solely from the global GM2022 model. If, however, the point is effectively at the surface of the Earth, then using only the geodetic latitude and longitude of the surveyed point, and interpolating from gridded products such as GEOID2022, GRAV2022, and DOV2022, NGS can provide improved estimates of the listed quantities.

users, as both NADCON and IFVM2022 will be encompassed within the two NGS transformation tools "NCAT" and "VDatum," and will seamlessly interact. In this way, for example, a user at some point in the future may ask for NAD 27 latitudes and longitudes to be transformed into NATRF2022 coordinates at epoch 2035.0, and NCAT or VDatum will do so without the user realizing that NADCON did part of the work and IFVM2022 did another part. With equal correctness, one might think either that there is no NADCON after 2020.00, or that NADCON and IFVM2022 will be identical after 2020.00.

More information regarding the IFVM will be forthcoming in our updates to the Blueprint for 2022, Part 1 document (NGS, 2017a).

2.10 New Surveying Specifications

NGS has a long history of publishing best survey practices, and that tradition will continue in the modernized NSRS. In fact, because of some substantial changes in how we will process and serve up survey data (specifically to support time-dependent coordinates), some new ways of planning and executing surveys must be disseminated to the NSRS user community. The following sections describe manuals we have planned to support these changes.

2.10.1 GNSS

The last time NGS published a substantial manual on the use of GNSS was with the paired documents by Zilkoski, D'Onofrio, and Frakes (1997) and Zilkoski, Carlson, and Smith (2008). This pair of documents has come to be called colloquially "NGS 58" and "NGS 59," based on their numbers within the NOAA Technical Memorandum (TM) publication series. Significant improvements in the availability and processing of GNSS data have occurred since 1997, making NGS 58 nearly obsolete. In addition, NAPGD2022 orthometric heights will be directly relatable to ellipsoid heights, thus making the methodology in NGS 59 entirely obsolete.

NGS has recognized this situation, and in 2019 we will publish a replacement document for NGS 58. It will address such issues as:

- The quality of a stand-alone GNSS occupation,
- Using RTK/RTN data,
- Best survey practices of RTK/RTN and static GNSS for best determination of geometric coordinates, and
- The need for redundancy.

Users who follow these specifications should be able to quantify the confidence level of GNSS-derived geometric coordinates. In addition, that document will discuss the interaction of those best survey practices with the future version of OPUS, particularly in the two-step adjustments which will yield preliminary and reference epoch coordinates to users. Of particular note is that GNSS occupations which users wish to process as "simultaneous" must occur within specific four-week periods referred to as “GPS months” in the first adjustment step (of a possible two). See section 2.13.

2.10.2 Leveling

Our feeling is that nothing in the immediate future will replace geodetic leveling for determining the most accurate local orthometric height differences, and a new leveling manual will be written explicitly to work in the modernized NSRS. That document will be quite extensive, so only a summary of its primary findings are found in the paragraphs below.

First, the determination of *absolute* heights (as starting control for a leveling project) will, for the time being, come from GNSS. That could mean some short RTK/RTN occupations, but reliance upon previously-determined “Final Discrete” (see earlier) orthometric heights from the NSRS database will not be supported in OPUS at the first introduction of the modernized NSRS.

Further, leveling surveys are known to be time consuming, so time-dependency must be considered when defining the maximum time one leveling survey should be processed as “simultaneous.” For now, the new leveling specifications will limit the processing and submitting of geodetic leveling surveys to a span of one calendar year for the leveling observations.

As GNSS occupations are required for geodetic leveling, the rules for how many and how frequently will be:

- For a leveling project to be processed using NGS software and/or submitted to NGS for inclusion into the NSRS database, its field observations should not span more than one year. Longer projects should be broken into sub-projects of less than one year.
- A minimum of three “primary control marks” must be in the level network for every project.
- More primary control marks should be added so there is never more than a 30- kilometer linear distance between marks in the entire network.
- Each primary control mark must have the following GNSS occupations (details on using GNSS occupations to work in the NSRS will be found in the 2019 update to NGS 58):

    A minimum of two occupations within +/- 14 days of the **beginning** of leveling, but also falling within the same GPS month and whose local start times are separated by between 3 and 21 hours.

        It is preferable, but not required, that all occupations on *any* primary control mark occur within the same GPS month as those of all *other* primary control marks.

    A minimum of two occupations within +/- 14 days of the **end** of leveling, but also falling within the same GPS month and whose local start times are separated by between 3 and 21 hours.

It is preferable, but not required, that all occupations on *any* primary control mark occur within the same GPS month as those of all *other* primary control marks.

- All projects exceeding six months must have a third set of GNSS occupations on all primary control marks some time near the middle of the project, without a rigorous rule as to when. They must follow the "minimum of two occupations" rule as per above, and each mark's occupation is required to fall in the same GPS month, with a preference that all primary control marks are occupied in the same GPS month.
- All GNSS data will first be processed in their respective GPS months. Afterwards, an averaging process, reliant upon those GPS month-based orthometric heights, the IFVM and GEOID2022 will provide orthometric heights at the primary control marks as stochastic constraints on the leveling adjustment. These will be at some representative survey epoch (TBD: most likely the midpoint date), based on the GNSS occupations.
- The final adjustment of leveling data will yield "Final Discrete" orthometric heights at the above-mentioned "representative survey epoch," as well as predicted differential heights between directly connected marks in the survey.

While new gravity measurements can be used in any leveling project, they are not required. NGS will offer the "GRAV2022" tool as a way for users to interpolate surface gravity to their points of interest.

2.10.3 Others

As necessary, NGS will be writing further manuals to cover other surveying techniques specifically as they relate to the modernized NSRS.

2.11 OPUS—How *NGS* Will Use It ("Loading Final Coordinates into the NSRS Ddatabase")

NGS will not be putting the same sort of data into the NSRS database as was put into the NGS IDB. The specific change in approach can be summed up in two words: *time dependency*. As mentioned in the first Blueprint for 2022 document (NGS, 2017a):

> *The use of the IFVM will allow NGS to provide, as a primary service, time-dependent coordinates at the highest levels of accuracy, while subsequently providing a secondary service of comparing those time-dependent coordinates across time at lower levels of accuracy.*

NGS will define very specific rules regarding how data are processed into time-dependent coordinates for loading into the NSRS database. For those NSRS customers either unwilling or unable to make the leap to time-dependent geodetic control by 2022, we will provide that secondary service mentioned above through OPUS. See section 2.13 on "OPUS—How *YOU* will use it"). However, note that the initial data processing steps required in OPUS will be to generate time-dependent coordinates under the very specific rules outlined below, and after that, comparing/adjusting coordinates across epochs will be allowed. The remainder of this section will draw upon previous sections and will outline exactly how NGS will use OPUS to process submitted projects into definitive time-dependent coordinates on passive marks.

2.11.1 Passive Marks—General Approach

The first rule for NGS to put any coordinate on any point in the modernized NSRS is to associate that coordinate with the time the data was collected at that point. This epoch, chosen as the **representative time** data were collected will be called the "survey epoch." Of course, data are rarely collected instantaneously (and geodetic data even less so), therefore, for data collections spanning various lengths of time, choices must be made regarding what the actual survey epoch is.

Second, all *geometric* coordinates will be computed in the ITRF2014 system first and only converted to NSRS coordinates afterwards.

Third, NGS is building the modernized NSRS with an eye toward the eventual achievement of millimeter accuracy in all spatial coordinates. That means any systematic signals exceeding half a millimeter will need to be considered when choosing survey epochs.

Fourth, NGS needs to make certain that any data you collect and submit can fulfill both your own needs as well as the broader needs of the NSRS. This is why the use of OPUS by NGS directly, and by NSRS customers, has been broken into separate sections.

Fifth, the metadata needed to support passive marks is being carefully parsed at NGS. On the one hand, the simplicity of the (currently named) OPUS-S process to use just an antenna type and antenna height as the entirety of metadata allows for ease of use. On the other hand, meticulous descriptions of marks currently in the database have great historic value in locating and identifying the exact mark sought. Could a photograph and accurate position be a replacement for the current descriptions? The answers to these types of questions remain TBD.

Finally, aside from the coordinates of points loaded into the NSRS database at their survey epoch, we will also attempt to estimate coordinates on points at reference epochs, currently scheduled to be five years apart, beginning with 2020.0 (Smith, 2018). The exact data and methods used to perform these reference epoch estimates are TBD, but will, at a minimum, rely on the actual observational data on passive marks, the IFVM, and GEOID2022. See section 2.12.

With these rules in mind, each type of data collection on passive marks will be addressed below.

2.11.2 Multi-Technique Processing

OPUS (currently referred to as OPUS-Projects) is being re-built with a variety of surveying techniques in mind. While originally a GPS-only (and two-plus-hour occupation-specific) tool, it is being expanded to include all the following:

- Multiple constellations (Galileo, GLONASS, and Beidou, as a start),

- Shorter sessions for static occupations (down to 15 minutes as a target),
- RTN/RTK vectors,
- Geodetic leveling,
- Classical surveying (trilateration, triangulation, trigonometric leveling, etc.),
- Relative gravity (in all varieties, including vertical gradient determination), and
- Absolute gravity.

The overarching project to make all of this work is known in NGS as "OPUS for Everything." Not all of these will be ready by 2022; however, we are committed to expanding OPUS to all survey techniques. Each of these techniques will be processed independently, yet all within one "project." Assuming you have a project that includes gravity, leveling, classical, and GNSS, each of those respective data files can be loaded as part of a single project, and OPUS will allow each technique to be processed. Combined adjustments ("integrated geodesy") of data will not be performed, and GNSS-based Cartesian vectors will always need to be processed first, so as to establish any passive control within the NSRS using purely geometric information uninfluenced by other information. After processing GNSS data in a project, other techniques will be adjusted to such GNSS-established control. The mathematical approach being built into OPUS to combine multiple techniques under one project is outlined in Smith, *et al* (2018).

2.11.3 GNSS on Passive Marks

Choosing a survey epoch for one or more GPS occupations on a passive mark is tricky, but not at all impossible. For decades, OPUS and most other GNSS processing software, would report the "representative" epoch of data collection for a single occupation, with each piece of software having its own mechanism for computing what was the "representative" epoch.

In (the currently named) OPUS-Projects, multiple occupations are grouped into sessions, and those sessions are then grouped into a single adjustment. At the end of the adjustment, the representative time (TBD) of all occupations for a given point is the reported epoch.

We will continue this approach, but with some very specific rules.

First, any GNSS data collection over a single passive mark, with the intent to determine a constant "instantaneous" position of that mark, should fall within a practical definition of "instantaneous." Details of how this definition was reached are found in Section 3.7 (Appendix G).

After a series of discussions, we came to a decision on the initial roll-out of the modernized NSRS. Like all decisions, this is, of course, subject to change. For now, however, we have decided, for GNSS occupations, Final Discrete coordinates will be computed as:

One or more GNSS occupation(s) over a single passive mark will be processed into one 'Final Discrete' coordinate triad,[23] if all occupations take place within one GPS month.

With the new term "GPS month" being defined as:

GPS month: *Four consecutive GPS weeks, with the first week in the GPS month having a GPS week number that is a multiple of 4.*

In this fashion, NGS defines:

- GPS month 0 = GPS weeks 0, 1, 2, and 3 (1/6/1980 through 2/2/1980)
- GPS month 1 = GPS weeks 4, 5, 6, and 7 (2/3/1980 through 3/1/1980)
- GPS month 2 = GPS weeks 8, 9, 10, and 11 (3/2/1980 through 3/29/1980)
- …
- GPS month 513 = GPS weeks 2052, 2053, 2054, and 2055 (5/5/2019 through 6/1/2019)
- etc.

What this will mean to the user (see section 2.11.3) is that all GNSS occupations within any given project will be processed by GPS month within OPUS as a first and **required** step in processing any GNSS project. After these time-dependent ("preliminary") coordinates are generated, other refinements will be available to users, but we will not accept GNSS processing which goes beyond, or fails to follow, the "within a GPS month" scheme. This includes projects processed entirely outside of OPUS and submitted to NGS.

One new tool NGS is considering building is a "countdown clock" running on the NGS web page. With such a clock, users would more easily be able to plan semi-redundant observations on marks so they fall within one GPS month. Although only in the planning stages, such a clock might look like the following (though actually running down, second by second):

NGS processes submitted GNSS data on geodetic control points every GPS month (4 GPS weeks). The current GPS month has been ongoing for the last 10 days 09 hours 22 minutes 53 seconds

If you have recently occupied a geodetic control point with GNSS and wish to have another occupation on that same point within the same GPS month, you have this much time to complete that occupation: 17 day s14 hours 37 minutes 07 seconds

Figure 5: Example of what a possible GPS month-based clock might look like on the NGS web page

Further details on why this decision was reached can be found in Appendix C.

[23] A "geometric coordinate triad" simply means XYZ coordinates in a Cartesian frame. These will be the basic coordinate set used when dealing with purely geometric data. Such things as Lat/Lon/Eht, UTM, USNG, and State Plane will flow from computations off the XYZ values.

2.11.4 Final Coordinates

Following the above rules will not, in and of themselves, generate "Final Discrete coordinates" for any point. There are two primary reasons for this, as follows:

1) NGS will always generate Final Discrete coordinates based on final IGS orbits. These orbits are released once a week, with an approximate two-week lag time.
2) NGS will always combine all GNSS data submitted from any source into a single project spanning one GPS month. That is, if three projects happen to have data in the same GPS month, we will combine them, process them together in sessions, and perform a final adjustment.[24] Because this sort of joint processing is only done at NGS, NSRS users can never be guaranteed the coordinates they compute—without access to data from other projects in the NSRS on the same day—will be identical to NGS-computed "final coordinates."

The workflow outlined in the number two, above, will occur once every GPS month, looking back a certain amount of time. The question is, "how far back?" This is a tricky question and one we only resolved through significant discussion. On the one hand, to allow for the availability of the IGS final orbits, at least three weeks must have passed for NGS to compute "final coordinates." On the other hand, NSRS users tend to turn data in quickly (as a rule), but there are numerous examples of data turned in months or even years after a project is complete. And yet, for us to process (and load "Final Discrete" coordinates from) submitted data *too* quickly could have the disadvantage that any blunders, particularly in metadata, might not be detected by a submitter until weeks after the Final Discrete coordinates have already been available to the public.

We will therefore adopt a processing cycle based on a twelve-week (three-GPS-months) waiting period. Once every GPS month, all data turned into NGS, from four-GPS-months prior (that is, from 13 to 16 weeks in the past) will be processed into Final Discrete coordinates and loaded into the NSRS database for public distribution. Data turned in after a particular GPS month's processing is complete—as time allows, but **no less often than once per year—**will be added to an already-processed GPS month project. We will re-process that GPS month, holding fixed all the coordinates from points with data that were already processed. It will be up to the submitter to determine if a possible year delay in receiving Final Discrete coordinates is acceptable. If such a delay were to create hardship, it is advisable to adopt a 12-week turnaround from project collection to submission. The figure below helps exemplify the situation.

[24] This could mean three projects in Florida, Colorado, and Hawaii processed together, or three projects all in the same county. Each type of combination has its own advantages and challenges.

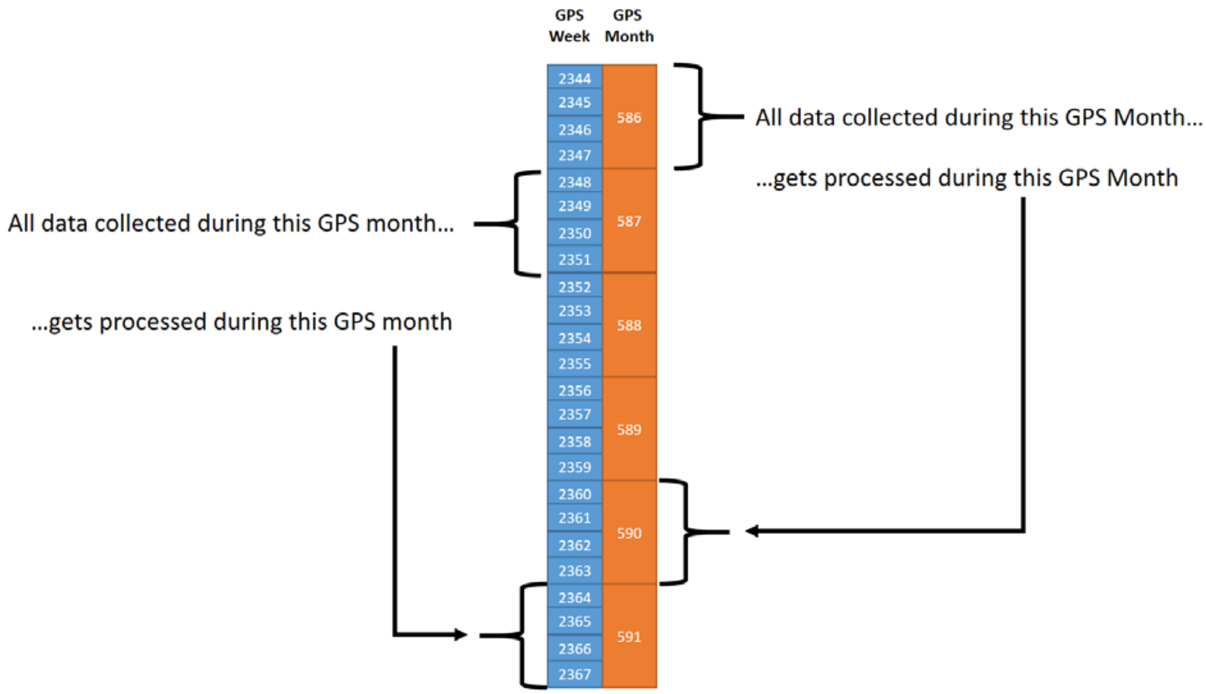

Figure 6: Timeline of GPS month-based processing with a 12-week (3-GPS-month) lag time

This should, it is assumed, raise the further question of, "What about projects that take longer than twelve weeks?" The question is valid, and the answer requires yet another change in the OPUS standard operating procedure. Specifically, as an NSRS user loads data into their project, they will have the opportunity to **"submit data to NGS as it gets uploaded."** This will give NGS access to your ongoing project's raw data (and metadata), and, on a GPS month-by-GPS-month basis, we can process any of your data that took place four GPS months past into the NGS in-house GPS month-based processing. Any data you find "questionable" can be thus tagged, and will be passed over during the by-GPS month processing until you tell us it is ready to go (but again, if it does not make the 12-week cut off, it may sit, unprocessed by NGS, for up to one year).

While the above logic will be applied to GNSS occupations, such a decision regarding being "simultaneous" was not as easy when considering leveling. More information concerning that is in the next section.

Further details about this twelve-week decision can be found in Appendix C.

2.11.5 Leveling on Passive Marks

As mentioned in an earlier section, with the modernized NSRS, all leveling projects will initially be required to have GNSS occupations as part of the project. We hope that, in time, this restriction can be loosened, so that heights on existing passive marks in the NSRS database might serve as geodetic control for leveling surveys, but that cannot be the case at the outset.

However, as leveling is a significantly more time-consuming practice than GNSS surveying, certain allowances for "temporal simultaneity" must be made. First, from a mathematical standpoint, it is impossible to solve for time-dependent orthometric heights within a single simultaneously adjusted leveling network. For that, substantial, non-leveling information (such as GNSS observations) would have to be taken on a vast majority of marks, or additional leveling over common lines not in the same network adjustment. Therefore, from a practical standpoint, the idea of designing a leveling survey for a single network, with the intent of solving for time-dependent coordinates is, for now, a non-starter. Consequently, the question on the table was one of how long a single leveling network could be allowed to build up, with the intent to solve for static heights that are at some "representative epoch" of the entire leveling project. That question was debated in a working group for months at NGS, with many ideas considered, and discarded. Finally, the working group arrived at the decisions listed in the previous section (New Surveying Specifications—Leveling). To summarize the key points are:

> ***Leveling projects are required to include at least three "primary control" marks, with GNSS "observations" occuring, at a minimum, within plus-or-minus two calendar weeks of the beginning and plus-or-minus two calendar weeks of the end of the leveling, provided each mark's observations: (a) consist of a minimum of two independent occupations, and (b) all occupations fall in the same GPS month.[25] Each mark's occupations will first be processed by their GPS month (see earlier and then weight-averaged into a single ellipsoid height, and thus a single orthometric height in NAPGD2022 will serve as stochastic control for the leveling network.[26]***
>
> ***Leveling projects spanning less than one calendar year will be adjusted in one simultaneous adjustment using the above GNSS-based stochastic control. Projects spanning greater than one calendar year must be broken into sub-projects, each of less than one calendar-year duration.***

This allowance for an adjustment to span an entire year is a compromise between knowledge that fast-moving subsidence can, and does, occur and the simple practicalities of leveling and GNSS surveying practices. We reserve the right to analyze every project so submitted to consider alternative adjustment strategies as the data warrants.

[25] Yes, two different four-week periods here are unlikely to align. Consider, for example, if the beginning of leveling starts on Wednesday, January 9, 2019. Each primary control mark must have all of its GNSS occupations fulfill two different criteria. The first is they must all fall within plus-or-minus two weeks of January 9—between December 26 and January 23. However, they must **also** all fall in the same GPS month. The GPS months of interest are GPS month 508, ending on Saturday, January 12, and GPS month 509, beginning on Sunday, January 13. Thus, it is required for the beginning of the leveling that all GPS occupations on primary control marks must occur in one of these two time-frames: either December 26 to January 12 (an 18-day span falling in GPS month 508) or January 13 to January 23 (an 11-day span falling in GPS month 509).

[26] Further details using example data can be found in section 3.5 (Appendix E).

2.11.6 Classical Surveying

The treatment of classical surveying techniques will be similar to the treatment of geodetic leveling. First, some GNSS occupations must be performed to establish initial control within the NSRS at survey epoch. From there, classical surveying measurements will be used to disseminate coordinates through the project network.

NGS policy was changed in 2013 to cease accepting Bluebooked projects containing classical data. This decision was made in recognition of the fact that such projects had slowed to "effectively none," whereas most projects being turned in were using GPS. The maintenance of "classical" processing software, when no such projects were being turned in, was also a consideration.

While substantial expansion of the NSRS is not expected to come from classical surveying techniques, two sources of critically important NSRS information will be derived from the technique: river crossings as part of a leveling network and "site surveys" performed as a service to the IERS. In consideration of this, OPUS will be built with the capacity for adding classical survey measurements as part of an overall project (leveling, GNSS, or both) and adjusted using the process found in NOAA TM 74 (Smith *et al*, 2018.) Of course, we are always investigating new and innovative techniques, and as future research warrants, OPUS options may expand.

We have not discussed the question of "simultaneity" in classical surveys, although we expect most of these projects to span a a maximum of a few weeks. Thus time-dependency within classical surveys should fit well within the proposed "one GPS-month" limit for multiple GNSS occupations and the "one-year" limit for leveling surveys. Further details will be discussed and drafted after OPUS' GNSS and leveling portions have been built.

2.11.7 Relative Gravity

Similar to leveling, relative gravity surveys are differential. And like leveling in the modernized NSRS (see above), our processing of relative gravity surveys will likely begin with restrictions.

Whereas leveling can begin with easily obtained GNSS-based orthometric heights, the "starting values" of gravity tied to relative gravity are not easily obtained. This is due to the rare availability of absolute gravimeters in the NSRS community. However, it should be noted that not every relative gravity survey requires absolute values; for instance, the use of a relative gravimeter in a multi-level platform instrument for determining vertical gravity gradients requires no absolute gravity whatsoever.

Therefore, aside from those surveys not naturally requiring absolute gravity, NGS has a few choices for the processing of relative gravity surveys for loading into the NSRS database:

1) Reject relative gravity surveys without timely absolute gravity,
2) Accept relative gravity surveys and only load time-dependent *differential* gravity values, or

3) Accept relative gravity surveys, and use the SGRAV2022 interpolation tool for starting absolute values.

None of these choices are perfect. If there were a way for relative gravity surveyors to contact the owners and operators of absolute gravimeters in some sort of collaborative partnership, none of these options would need to be chosen, but for now, the complexity of such a partnership makes this choice difficult.

Therefore, until a better option exists, we are leaning towards option number two above, so some useful time-dependent information could be entered into the database. As further discussion occurs at NGS, this will be less TBD.

One final case of relative gravity surveys we are interested in is airborne gravity surveys. However, NGS currently has an ongoing airborne gravity processing strategy, and the need to build a specific OPUS module for processing that data and storing it in the database is not critical. Nonetheless, we are considering this on our to-do list, as the airborne gravity campaign will continue post-2022 for a variety of purposes (re-flights, earthquake patches, improvement of geoid in neighboring regions impacting the United States, etc.).

2.11.8 Absolute Gravity

Rarely do we accept an absolute gravity survey into the NSRS that we did not directly observe and process. However, once the relative gravity version of OPUS (above) is built, it is conceivable an absolute gravity companion version of OPUS will also be built. There are several difficulties with this concept, not the least being that the overwhelming majority of absolute gravimeters in use rely on proprietary software ("g" by Micro-g LaCoste, Inc.).

Yet, absolute gravity is as important for relative gravity "getting into the NSRS" as GNSS is for leveling. Therefore, we intend to use OPUS as a method for processing absolute gravity, even if it relies on external software. However, completion of such a module is not likely to occur for several years.

2.11.9 Other Survey Types within OPUS

We expect almost no other survey types to be submitted for processing and loading into the NSRS Database. Rare exceptions may include GNSS/camera equipment for Deflection of the Vertical surveys and classical astronomic surveys for determining astronomic latitude and longitude.

NGS has much work ahead of us in the immediate future! Once OPUS is built and expanded for GNSS, leveling, classical, and gravity, discussions concerning the building of modules for more rare survey types will ensue. Such conversations, however, are years away from debate.

2.12 Reference Epochs

NGS made a commitment to estimate NSRS coordinates at reference epochs (spaced every five years, beginning in 2020.0.) Only by sheer happenstance would a survey take place on January 1, 2020 (or 2025, or 2030, etc.) Therefore, these Reference Epoch coordinates will consist of Final Discrete coordinates and/or Final Running coordinates in combination with the Intra-frame Velocity Model.

To execute such a plan requires answers to at least the following questions:

1) When will the coordinates be computed? Before the Reference Epoch? After the Reference Epoch?
2) What data will be used?
3) If, after you have computed the Reference Epoch coordinates, you acquire new data that influences your last Reference Epoch estimate, will you update the coordinates? If so, does that not destroy the entire purpose of those coordinates?
4) What about points with substantially "old" data (for example, 20 years or more)? Will NGS continue to estimate Reference Epoch coordinates every five years? Would that not add exponential uncertainty and therefore uselessness of the estimated coordinate?

The following plan for Reference Epoch Coordinates is tentative, but it answers the above questions and reflects the current direction we are heading.

First, for every Reference Epoch, there will be a unique project: the "**Reference Epoch Computation Project**." We will compute the vast majority of Reference Epoch Coordinates for the most recently passed reference epoch during the Reference Epoch Computation Project. Each reference epoch computation project will begin two years after the most recently passed reference epoch and will end no more than three years after the most recently passed reference epoch.

> **Example:** The "**2020 Reference Epoch Computation Project**" will begin on January 1, 2022 and end no later than December 31, 2022 and produce the vast majority of 2020.0 Reference Epoch Coordinates NGS will provide to the public. It will use data submitted to NGS through December 31, 2021.

It will be our policy that, for a given point and a given reference epoch, the **Reference Epoch Coordinates** will ***never be changed***, with one exception: to correct a blunder. This does not prevent us from *adding* new points to a Reference Epoch later (especially true considering the massive amount of work to process all historic data in 2022 for the 2020.0 reference epoch). But once computed, a Reference Epoch coordinate will stand in perpetuity.

The above details were laid out to make a few things clear:

1) We recognize the strong reliance our NSRS users have on Reference Epoch coordinates in the immediate future,

2) We recognize frequent changes of Reference Epoch coordinates can cause confusion and job difficulties for NSRS users,
3) We recognize tools, such as NADCON, require definitive Reference Epoch coordinates as input to their creation, and frequently changed Reference Epoch coordinates mean a large pool, rather than a definitive set, will be available.

Therefore, the above workflow means marks will never (blunders aside) have more than one set of Reference Epoch coordinates for any given Reference Epoch.

From a practical standpoint this means NGS is expecting (and in fact encouraging) a five-year cycle of re-surveying activity at any marks users find particularly useful, in order to keep their Reference Epoch Coordinate uncertainty perpetually small. Without such re-surveys, the Reference Epoch coordinates on points will still be computed, but will gradually become dominated by the propagation of uncertainty in the IFVM throughout the years.

2.13 OPUS—How *You* Will Use It ("Re-invented Bluebooking")

The Online Positioning User Service (OPUS), will be the name of the ***suite*** of products NGS provides to the public.[27] Everything from simple mark recoveries by hikers to complicated survey campaigns comprised of many years and involving GPS, Leveling, Gravity, and Classical observations will be handled by OPUS.

We will build significant flexibility into OPUS for you to process *your* data in *your* way. For geometric data, you will be allowed to choose any of five reference frames (ITRF2014, NATRF2022, PATRF2022, CATRF2022, and MATRF2022) to output your data, though adjustments will be limited (for now) to the ITRF2014, with Euler Pole Parameters (EPPs) used to convert to the other four frames. You will be allowed to estimate coordinates at a Reference Epoch of your choosing, or you may choose one of the NGS-supported five-year Reference Epochs. You will also be able to adjust a year's worth of GPS data in the ITRF2014 frame at the midpoint epoch and refer to it as "simultaneous" if you like (though this steps firmly on the toes of "best practice").

In summary, OPUS should serve your needs, but only within the bounds of our providing NSRS coordinates. Generally speaking, there will not be a function to "work in WGS 84," for example.[28]

When you have performed a survey (whether it be simply finding a mark while hiking or performing that aforementioned 'super' survey), NGS hopes you will submit your data to us for the expansion and improvement of the NSRS. **We are only interested, however, in high-quality surveys on geodetic control marks (points) of a permanent nature. Positions of mailboxes,**

[27] NGS is moving toward the removal of the various terms "OPUS-S," "OPUS-Projects," "OPUS-RS," "OPUS-Share," "LOCUS," etc. If you have data to share or process, in the future it is likely we will simply have you use "OPUS."

[28] NGS and the National Geospatial-Intelligence Agency (NGA) have engaged in discussions concerning 'co-defining' the new reference frames with WGS 84. If these talks finalize into a plan, a transformation between the NSRS and WGS 84 may be possible within OPUS.

manhole covers, wooden stakes, PK nails, or any other object which might possibly be part of a survey are not of interest to us. Submissions containing data on things that are non-permanent and/or not points are generally not going to be processed and loaded into the NSRS database.

It is worth mentioning the following before getting in details: How you process your data is your business. Your choices, within the NSRS, are for your reasons. But your choices may not coincide with ours when it comes to processing your data, checking it against other data in our holdings, and ultimately, using your data to compute and provide coordinates on passive marks. However, no matter whether you choose to process data at survey epoch or process it at some other epoch (either one of the five-year official Reference Epochs of the NSRS or some other epoch of your choosing), the type of coordinates OPUS will provide to you will always be labeled **Preliminary**.

One final note regarding coordinate types (see section 2.5) is worth mentioning. There are only three types of coordinates that will come from NGS: **Reference Epoch**, Final **Discrete** and **Final Running**. These coordinate types are the official NSRS locations for points either at an official Reference Epoch, at survey epochs, or running through time, and they will be reported through the future data delivery system (previously referred to as "datasheets"). Coordinates you compute in OPUS will be labeled **Preliminary**. Whereas it is possible your Preliminary coordinates could perfectly match the **Reference Epoch** or **Final Discrete** coordinates on a point, we only use those data you turned into **Preliminary** coordinates to make **Reference Epoch** or **Final Discrete** coordinates after we have taken certain steps. Those steps will at least include (a) quality-controlling your data and (b) merging your data with other data from other submitted projects.

Because so much of the modernized NSRS relies on GNSS, it will be the second topic discussed. But since reconnaissance is the first step in most projects, we will discuss it next.

2.13.1 OPUS for Reconnaissance

If you are familiar with reconnaissance of a survey project, it is possible you have considered that any modern smartphone contains all the components necessary to make it the most efficient recon' tool you own. With a photograph and a few meters of accuracy from the GPS chip, a mark recovery (or new mark installation) can quickly be reported to NGS using the internet connection in the smartphone. All that is missing is for NGS to exploit this power by developing a tool to allow for easy reporting.

Fortunately, in 2018 we took the first steps in developing such a mobile-friendly mark-recovery tool. Once completed, such a tool will not be restricted to professional surveyors. Hobbyists, such as geocachers, will be able to benefit the NSRS by simply reporting marks, without any intention of using them for a professional survey project.

OPUS will therefore allow a variety of ways to report marks. A photo and position will be the 'lowest bar' for recovering existing marks. But the tool will also be used to describe conditions of marks, to describe entirely new marks, and to add these reports to a survey project within OPUS.

The recovery tool, while built to work with smartphones, will have the same functionality on the NGS website using any standard browser.

2.13.2 OPUS for GNSS (Including RTN/RTK, Independent Vector Uploads, etc.)

As of the writing of this document, NGS has a variety of plans to expand our support for all GNSS constellations. Specifically, the PAGES workhorse (the GPS-only software we developed and maintain, and the 'guts' of the currently named "OPUS-S" software) is being re-built from scratch, with an eye toward supporting every current and future GNSS constellation.

However, that project is many years from completion, and users are not likely to see it fully implemented in OPUS before 2022.

However, one OPUS expansion likely to be ready (both for OPUS to use and to load the new NSRS database) is the support for GNSS-based vectors. This means two new related functionalities will be opened up:

1) **RTK/RTN surveys,** where the vectors between rover-occupied points and base stations are available, and
2) Static surveys of any (finite) duration, where the vectors have been **pre-computed outside of NGS software** (such as in a commercial software package) can also be uploaded and used in OPUS.

Aside from this and other longer-term planned changes, the overall use of OPUS by the user community will change as follows.

First, for the sake of simplicity in the following sections, ***the term "redundant" GNSS observation*** will mean "a second (or more) GNSS observation, taken on the same point, at a different time, as an independent equipment setup, but within the same GPS month."

Second, time dependency will be key. Each GNSS occupation of finite duration will yield an estimated coordinate triad in the ITRF2014 at survey epoch (think of this like the current OPUS-S service in that one file yields one coordinate), labeled **Preliminary** (see definition in section 2.5). A redundant observation will also yield **Preliminary** coordinates. An adjustment of the two observations, either into a coordinate at the midpoint ("survey epoch") or at some other (reference) epoch of your choosing, will also be labeled **Preliminary.**

However, once your data are submitted to NGS for quality control and loading, the coordinates we compute from your data (and possibly the simultaneous data of other NSRS users) will become **Final Discrete** coordinates. Final Discrete coordinates will be available through the NGS Data Delivery System (formerly called "Datasheets").

Note that, when you submit your project, **we will ask for your data files for any GNSS occupation of at least 15 minutes duration. You are strongly encouraged to submit those files**. These data will be stored and used in the NSRS database and used by NGS to verify any of your pre-computed vectors, as well as to allow for rapid re-derivation of all vectors when significant software changes occur (such as updates to PAGES or when a new ITRF is released.)

All computations and adjustments will be done in the ITRF2014 frame. However, immediately available from those coordinates will be the coordinates in all four frames of the modernized NSRS, through EPP2022.

As mentioned earlier, every four weeks, we will harvest all GNSS data from all submitted projects that occurred 3 GPS months (12-15 weeks) prior. Therefore, if your project will last longer than 12 weeks, or if you suspect it will take you longer than 12 weeks to process your project and hit the "submit" button, we will provide an option to allow us to harvest your data "on the fly." That is, while your project is ongoing, if you agree, we will (every four weeks) query your project for new data and "harvest it." Those data files will be pulled into the processing of Final Discrete coordinates for the 4-week (GPS month) span of 12-15 weeks prior.

2.13.3 OPUS for Leveling

Support for leveling surveys will follow many of the best aspects of OPUS, including uploading and processing digital data files, using a web-based graphical interface, and submitting data to NGS.

Leveling is a differential measurement technique, and to the ability it can, it will perform adjustments without attempting to yield absolute heights. For those users who need absolute heights, however, OPUS will support a mix of GNSS and leveling in a single project. As mentioned earlier, NGS requires a GNSS survey to be performed at specific times before and after leveling surveys in order for the data to be submitted for inclusion in the NSRS.

In summary, the only way to get "into the datum" will be through a GNSS survey, though this can be as simple as RTK/RTN data collection. Users will collect GNSS data both at the beginning and at the end of a leveling survey. Leveling surveys longer than one year must be broken up into multiple projects. Leveling surveys between 6 and 12 months in duration require a third, intermediary GNSS data collection.

Once all the data are collected, you will process them in OPUS as follows:

1) GNSS data collections performed on **primary control marks** should be processed into Preliminary geometric coordinate triads at survey epoch (2 [minimum] for surveys under 6 months, 3 [minimum] for surveys of 6 to 12 months duration).

2) These coordinates will be combined with GEOID2022 to yield Preliminary orthometric heights at survey epoch.
3) These orthometric heights will then be combined into one single Preliminary orthometric height for each primary control mark, at a "leveling epoch" that is the midpoint of all the GNSS occupations.
4) Those orthometric heights will then be held as stochastic control for the adjustment of all leveling data, yielding Preliminary orthometric heights at the above "leveling epoch."
5) Once these data are submitted to NGS and they are quality controlled, they will be turned into Final Discrete coordinates (two or three sets for GNSS at survey epoch, one set for orthometric heights) at the "leveling epoch" used above.

2.13.4 OPUS for Classical, Gravity, Others

As these modules are only in the planning stages, it would be premature to present any details regarding how they will function. However, certain commonalities with previously outlined OPUS modules can be ascertained: users will be allowed to set up adjustments and manipulate data in ways suitable to them, always yielding Preliminary coordinates in the NSRS. When those data are submitted to NGS, quality controlled, and loaded into the NSRS database, they will yield Final Discrete coordinates.

2.14 RTN Alignment Service or RAS

Prior to 2022, NGS did not explicitly attempt to quantify the alignment of any Real Time Kinematic Networks (RTNs) to the NSRS, although the intent to do so has been a part of our policy since 2008 (NGS, 2008). The policy was re-emphasized, with explicit plans to offer an RTN "Validation" service in 2013 (NGS, 2013.)

By 2018, no such service existed, yet we never wavered from our position that this service was necessary, considering the vast number of RTN users. In 2019 the project began again, under the name "RTN Alignment Service" (RAS). The slight name change reflects our intention to not become a regulatory agency, only to quantify "alignment" of RTNs to the NSRS. Such a service will be in use by the 2022 NSRS modernization, though at the time of the writing of this document, the project has only a goal, and no actual functionality. Nonetheless, it is worthwhile explaining that goal, so NSRS users can prepare for how such an RAS will operate.

The primary goal of the RAS is to serve RTN *users*. Many RTNs purport to work "in the NSRS," yielding up NAD 83 and/or NAVD 88 coordinates to their users. An RAS would inform the user whether any biases exist between the actual NSRS coordinates of a point and the RTN-based NSRS coordinates delivered to the user at his/her RTN rover at that point.

We propose to offer an RAS, accessible and usable by the *operators* of the RTN, to allow them to perform their own checks on how well their RTNs are aligned to the NSRS, and then report that alignment to the *users* of their RTN. The service would have two components:

1) Determine alignment of the RTN base stations to the NSRS, and
2) Determine alignment of RTN-provided coordinates at rovers, to the NSRS.

The first component could be performed with a great deal of autonomy, as RTN base stations (whether in the NOAA CORS Network or not) function as CORSs and could be processed regularly within the daily processing of all data in the NOAA CORS Network. Biases and standard deviations so computed would tell whether the base stations are "aligned to" the NSRS, and to what accuracy.

While useful, base station alignment is only half the story. The real payoff is determining the alignment of the coordinates at the rover location, and this is where the second component would be implemented. The most likely solution to this is not easy to automate, however. It would likely require two back-to-back occupations of some fiducial set of passive marks within the RTN service range. Those occupations would be of two different types. The first type would be a long session of GNSS data collection using OPUS and relying on no parts of the RTN. The second occupation would be with a rover, using RTN-provided data and software. A comparison of the differences between the two coordinates at these fiducial points would yield a statistical look at the biases and standard deviations in the RTN. That is, it would provide a quantification of the alignment of the RTN to the NSRS.

How many fiducial points would be needed and how frequently they would be checked is a matter of much study at NGS and will form a key part of the final RAS design.

2.15 Transformations and Conversions

NGS will continue to provide coordinate conversion and transformation tools, but they will be significantly more integrated than in the past. The two primary tools available will be VDatum and the NGS Coordinate Conversion and Transformation Tool (NCAT). By 2022, the functionality of these two programs will overlap significantly, although VDatum will expand upon NCAT by also supporting tidal datum information.

These two programs will encompass sub-programs, each with specific functions. For instance, NADCON will reside within each and perform datum transformations in latitude, longitude, and ellipsoid height.

The following tools (among others) will eventually be available in both applications:

- NADCON
- VERTCON
- All hybrid geoid models

- All 14 parameter transformations currently supported in HTDP
- IFVM2022
- GEOID2022
- SPCS2022

Of particular note, once we begin publishing Reference Epoch coordinates at the 2020.00 epoch, NADCON and VERTCON will support the transformation from NAD 83(**11) and NAVD 88 into *TRF2022 (epoch 2020) and NAPGD2022 (epoch 2020). That transformation will represent the last time NADCON and VERTCON will stand alone as separate NCAT and VDatum tools. After that, the IFVM will serve the same purpose as NADCON, and the combination of the IFVM with GEOID2022 will serve the same purpose as VERTCON.

2.16 Summary

This document has attempted to describe how users of the NSRS do business today, and how things will work differently with the modernized NSRS, scheduled for release in 2022. It would be understandable if a reader of this document came away thinking "everything is going to change." Yet, many things will not change, and some of those are most important. Good surveying practices are not going to change. The purpose of the NSRS, as the foundation of nationwide geodetic control will not change. The reliance on your submissions to us for the upkeep of coordinates on passive control will not change.

Yet, it is worthwhile to summarize the key changes mentioned in this document.

Using the NSRS / Submitting Data to NGS

How it will stay the same: The coordinates of points in the NSRS will serve as geodetic control for surveyors and other geospatial professionals. We will offer a method to allow your survey data to be processed entirely by you, to determine coordinates of use to you, and (if you choose) to submit to NGS for quality control and eventual inclusion in the NSRS.

Today: Tying your survey to the NSRS can mean connecting to the NOAA CORS Network with GNSS and/or finding passive control marks with their datasheets and holding the published coordinates fixed. You must download PAGES and ADJUST (or rely on the recently released version of OPUS-Projects) to perform your adjustments. Your projects are adjusted and submitted to us via Bluebooking, and they are, for the most part, loaded as you submitted them.

Future: The NOAA CORS Network will be the primary access to the NSRS. This means leveling and classical surveys will require GNSS surveys as part of the mix. Coordinates on passive control will be available as time-dependent (Final Discrete) and also will be estimated at five-year epochs (Reference Epoch Coordinates). OPUS will be available for processing all types of surveys. Users will be able, within OPUS, to adjust their projects using any mix of CORS data and passive control, but such projects, on submission, will be deconstructed at NGS and reduced to the raw observations, then adjusted solely to the NOAA CORS Network to determine Final Discrete coordinates every GPS month.

Reference Frames and Datums

How it will stay the same: In an attempt to maintain (horizontal) coordinates semi-stable through time, the NSRS will contain multiple "plate-fixed" reference frames, one for each tectonic plate where significant populations of American citizens live. There will be a vertical datum for these same regions.

Today: Confusingly, the name "NAD 83" is applied across the board to three different frames (one for North America and the Caribbean, one for the Pacific, one for the Mariana), making the incorrect assumption that the Caribbean plate rotates similarly to the North American plate. There are leveling-based datums for each region, which rely on passive control as the primary method of disseminating heights.

Future: Four frames, with the names of their respective plates put directly in the frame names will exist, yet all work will be performed first in the ITRF2014, and then a mathematical relationship to all four NSRS frames will occur at the very end. A single geopotential datum, capable of functioning as not only a vertical datum, but also as a self-consistent gravity field model, will be directly related to the reference frames through one geoid model, so that, for example, orthometric heights in any area of the United States are consistent with any other area, even when they are separated by vast oceanic distances.

Coordinates

How it will stay the same: NGS publishes coordinates on points serving as our best estimate of where that point lies within the NSRS. NGS promotes the use of the best coordinates to serve as geodetic control.

Today: The coordinates on passive control in the NSRS are static, attempting to determine where points were at 2010.0 (if possible.) Coordinates on CORSs are piecewise linear functions in the ITRF (currently ITRF2008.) Unless a user is expressly trying to acquire time-dependent coordinates in the ITRF, NGS generally promotes CORS coordinates and passive control coordinates as equally important parts of geodetic control in a survey.

Future: The NSRS becomes time-dependent across the board, so that GPS surveys done on, for example, February 17, 2005 will be used to compute coordinates (called "Final Discrete") in the GPS Month containing February 17, 2005. These Final Discrete coordinates will be used, with a model of crustal motion to estimate "Reference Epoch" coordinates every five years, beginning with 2020.0. Points which are not re-surveyed will be subject to progressively larger uncertainty estimates at each future Reference

Epoch. The coordinates at each CORS will continue to be time-dependent, but may (and most likely will) contain more than simple linear functions between discontinuities, to reflect actual motion at each CORS, so that such motion does not propagate into your surveys which tie to those CORSs.

2.17 In Closing

NGS (under various names throughout the decades) has stood on the line between being a science agency and a customer-service agency for hundreds of years. Unlike a purely scientific agency with the luxury of adopting the latest scientific advances as they come along, we have always had to weigh the effects of scientific progress against the impact such progress has on our valued customers.

For the last few decades, our concern for our customers has put our focus for certain scientific facts on the back burner. The non-geocentricity of the NAD 83 frames, the dynamic movements of geodetic control marks, and the rise of sea level, were once viewed as less critical than maintaining the status quo. But the preponderance of centimeter positioning has made these issues glaringly obvious. NGS has therefore concluded the time is ripe to collect all of the long-delayed improvements to the NSRS and modernize. We are scientists and civil servants both. It is the express hope of everyone at NGS that these changes, while intimidating at first, will eventually be embraced by our customers. We invite you along for the ride and hope you will help us continue to improve the NSRS.

3 Supporting Information

3.1 Appendix A: Geodetic Control Primer

Consider a situation where the following problem appears on a high-school math test:

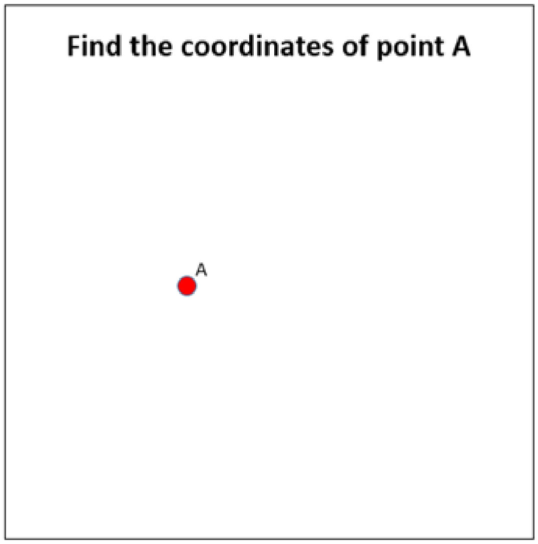

Figure 7: Positioning without enough information

With absolutely no additional information, the problem is unsolvable. Obviously, it would be helpful if there were some sort of useable (two-dimensional) coordinate axis. The problem would seem more solvable if it were presented something like this:

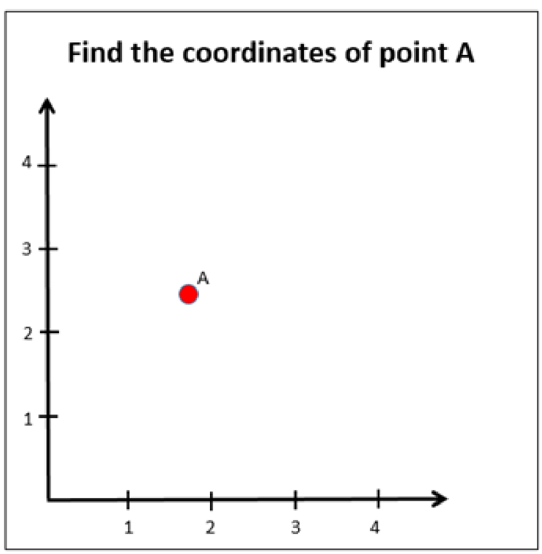

Figure 8: Positioning with axes

However, imagine you were not provided a coordinate system, but rather you were given the coordinates of a few nearby points, and you were allowed to measure angles and distances between them. That is, the problem is presented to you this way:

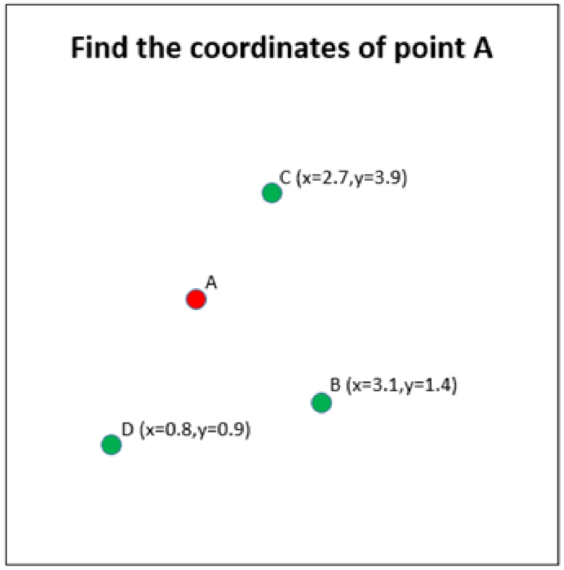

Figure 9: Positioning with geodetic control

Could you solve it? Sure! With only the measured distances from A to the three other given points (B, C, and D), the coordinates of point A can be determined. You do not even need to measure any angles to solve this problem!

The point is this: The need for coordinates is fundamental to many things, but *the Earth does not come with coordinate axes*. Anyone who makes a map, navigates a car, or builds a road needs coordinates. Anyone who asks, "Am I in a floodplain?" or "When is high tide?" needs coordinates. But unlike a globe, or a map, or *Google Earth*, all which have nice, neat lines drawn on them, the Earth offers no pre-drawn lines for our easy reference.

Sometimes the needed coordinates are latitude or longitude. Sometimes they are some type of height. Sometimes they are something more complicated. But, they all have the same problem: the Earth does not have convenient, visible, easy-to-use coordinate axes. Geodesists therefore provide something we call "geodetic control" to accomplish the next best thing. Geodetic control provides an *implied* coordinate system. The reason the third version of the above problem is solvable is because the points B, C, and D have been given a set of mutually consistent coordinates that *imply* some coordinate system you did not actually see.

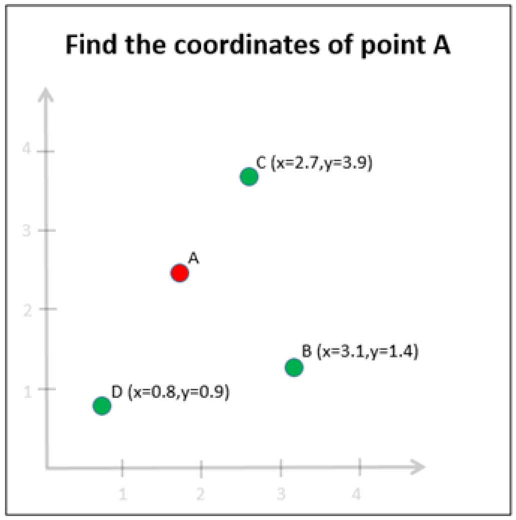

Figure 10: Geodetic Control implies coordinate axes

So, whereas those coordinate axes are not visible, their location and scale are *implied* by the given coordinates of the points B, C, and D.

In that problem, those three points would be called **geodetic control**. And, of course, the Earth is three-dimensional, implying elevations and surface curvature are to be considered in real applications.

One final word regarding the term "geodetic control." In the example provided above, no attempt to quantify the accuracy of the given coordinates was made. In the real world, the coordinates of points B, C, and D will also come with some estimate of their accuracy. The term geodetic control, as used throughout this document, will mean:

Geodetic Control are a set of unique, physical, zero-dimensional points existing on or near the (rotating) Earth; with coordinates assigned to them; at a specific time determined through rigorous data collection methodologies; often involving specific types of equipment built for high-accuracy, measurement redundancy, and the proper treatment of all error sources. While traditionally treated as unmoving and unchanging, geodetic control in the modernized NSRS will have acknowledged time-dependent movements.

Note that under this definition, no specific accuracy is attached, and this is intentional. Whereas NGS strives for increasingly greater accuracy with geodetic control, such accuracy is a sliding scale with time and requires all of the equipment and redundancy mentioned.

3.2 Appendix B: Accuracy

3.2.1 Digits as a (Poor) Way to Describe Accuracy

For most of the history of the NSRS, NGS did not place a numerical value on the accuracy of the coordinates of a point. Rather, marks were given an order, or an order and a class (FGCC, 1984). Such categorization by order was truly a statement of the quality of the survey which established the coordinates, and not a quantifiable magnitude of the absolute accuracy of the points.

In the late 1990s, the Federal Geographic Data Committee (FGDC) published standards for geospatial data accuracy (FGDC, 1998), and in response, NGS studied whether a one-to-one correspondence between order and coordinate accuracy could be established. Those attempts were generally unsuccessful (Dennis, 2019.) Rather than pursue this further, NGS modified our 2007 national adjustment of GPS vectors (yielding the NAD 83[NSRS2007] realization) so that local and network accuracies were reported. Those values were put on datasheets for NGS' first attempt to officially comply with the FGDC standards. However, this did not address issues of accuracy in orthometric heights or other quantities.

For orthometric height accuracy, as well as for accuracy of other quantities not included in the national adjustment, NGS frequently adopted the policy of publishing coordinates to a limited number of digits to reflect accuracy. That is, if an orthometric height was thought to have an accuracy (standard deviation) of about 1 decimeter, NGS would publish that height to only 1 decimeter (1 decimal place). If a scaled latitude or longitude were known only to 1 arcsecond, it would be published to the nearest arcsecond. That policy was a useful rule of thumb when formal standard deviations were not computed. However, in the modernized NSRS, formal standard deviations will be computed whenever data supports them. However, digits will *not* be rounded as a method of expressing that standard deviation. An example of the dangers of this follows:

Consider that NGS would like to report the mean and standard deviation for some quantity that is measured repeatedly. Consider the following five measurements were taken, all independent of one another, and each one reported their measurement accuracy (in meters) as follows:

6.641 +/- 0.143

6.544 +/- 0.206

6.839 +/- 0.086

6.540 +/- 0.158

6.746 +/- 0.191

A least squares adjustment of these five measurements yields the following estimate:

6.72575 +/- 0.062194

Note, however, how large the initial estimates of standard deviation are for each of the five measurements. At about 15 centimeters on average, we might (historically) have felt this point was “good to a decimeter” and reported the value as “6.7.” However, this ignores two key issues. The first is that failing to provide more digits will introduce a bias into the expected neighborhood of the measured value. The second is that five measurements, good to “about 15 centimeters each” can (and did, in this case) yield a significantly smaller standard deviation—in this case 6 centimeters.

The first issue, the bias, can be seen if one looks at the true standard deviation applied to the truncated, versus non-truncated, versions of the estimate:

6.7 +/- 0.062 yields a span of 6.638 to 6.762 (at 68 percent confidence)

6.726 +/- 0.062 yields a span of 6.664 to 6.788 (at 68 percent confidence)

These two neighborhoods are obviously offset from one another by 2.6 centimeters, a non-negligible bias.

Secondly, if NGS had simply reported the value as “6.7,” without a standard deviation, then one interpretation of the implied neighborhood could have been:

6.7 +/- 0.1 = 6.6 to 6.8 (at 68 percent confidence)

which is 6.4 centimeters too small on the left and 1.2 centimeters too small on the right, with both being non-negligible.

For this reason, NGS will compute and report all statistical quantities to an appropriate level (e.g., at least millimeters for those quantities with length scales) to avoid undesirable biases in the data.

3.2.2 Standard Deviation, the +/- Symbol, and Reported Accuracy

From a mathematical symbol standpoint, the use of “±” has a variety of meanings. In statistics it is used most often to reflect the univariate standard deviation surrounding some mean value, although that is not its exclusive meaning. NGS felt it necessary to expressly state how we will report accuracies, including the use of the ± sign. On one hand, the dominant use of ± is to reflect **one** standard deviation. On the other hand, a single standard deviation corresponds to only approximately 68.27 percent statistical confidence in a value. Different confidence levels require multiplying the standard deviation by a scale factor. For example, univariate (one-dimensional) quantities, scalars of 0.6745, 1.9600, and 2.5758 result in confidence levels of 50 percent, 95 percent, and 99 percent, respectively. Different scalars are required for 2D (e.g., horizontal) and 3D quantities when the components are correlated (as is usually the case). Scalars are called “bivariate” and “trivariate,” respectively, for correlated 2D and 3D data. Scalars corresponding to various confidence levels are given in Table 1. Note that confidence level based on unscaled standard deviations decreases as dimensionality increases (68.27 percent for 1D, 39.35 percent for 2D, and 19.87 percent for 3D data)

Table 1: Percentage spans of Univariate, Bivariate, and Trivariate statistics as a function of scaled standard deviations

Univariate		Bivariate		Trivariate	
Scalar	**Confidence level**	**Scalar**	**Confidence level**	**Scalar**	**Confidence level**
0.6745	50.00%	1.0000	39.35%	1.0000	19.87%
1.0000	68.27%	1.1774	50.00%	1.5382	50.00%
1.6449	90.00%	2.0000	86.47%	2.0000	73.85%
1.9600	95.00%	2.1460	90.00%	2.5003	90.00%
2.0000	95.45%	2.4477	95.00%	2.7955	95.00%
2.5758	99.00%	3.0000	98.89%	3.0000	97.07%
3.0000	99.73%	3.0349	99.00%	3.3682	99.00%
3.2905	99.90%	3.7169	99.90%	4.0331	99.90%

Some NGS products and services have reported unscaled standard deviations, while others have reported scale factors corresponding to 95 percent confidence. Moving forward in the modernized NSRS, NGS will adopt a single consistent reporting strategy for all products and services. While the FGDC has an accuracy standard (FGDC, 1998), that standard is, in the view of many at NGS, in desperate need of revision and update. Furthermore, it was not adhered to by the majority of geospatial agencies that were supposed to use it. Conflated against that fact is the recent passage of the Geospatial Data Act (https://www.congress.gov/bill/115th-congress/senate-bill/2128) which has, in some ways, fundamentally altered the FGDC and its interaction with NGS. Experts in the geospatial community are working diligently to parse the new law and provide guidance to those affected agencies, including NGS. Such guidance, and the likely update to the FGDC accuracy standards (FGDC, 1998) mean it is unknown what the future accuracy standard will look like, nor whether it will even be ready by 2022.

For these reasons, NGS will choose a single reporting accuracy standard that is logical and clear, and that reflects the method we will advocate for in any revised FGDC standard. While there remains some uncertainty, the following policies are likely to be included:

1) **Standard deviation will be the basis for all estimated accuracies, with the appropriate scalar applied for the reported confidence level.**
2) **The use of "±" *without any additional information* will mean "1 standard deviation" (i.e., unscaled). The confidence level will always be given if a scalar other than 1 is applied.**
3) **The standard deviation will always be available for every accuracy, along with the component correlations for bivariate and trivariate accuracies.**

Thus, one might see the following for a height of 5.403 meters that has a standard deviation of 0.035 meters:

At 1 standard deviation (i.e., unscaled): 5.403 ±0.035 m

or

Scaled to 95% confidence: 5.403 ±0.069 m (95% confidence)

or

Scaled to 99% confidence: 5.403 ±0.090 m (99% confidence)

For non-univariate quantities, there are some alternatives for how the accuracy can be reported. As an example, consider horizontal (bivariate) accuracy. It is fully represented using the length and orientation of the semi-major and minor axes of its uncertainty ellipse. This requires three values (two axes, one orientation). Alternatively, the same ellipse could be approximated by a circle which, for example, might encompass the same statistical confidence interval as the ellipse as a whole.) This alternative requires only one value (radius of the circle), but comes with a resulting loss of information. As computer space restrictions are not generally prohibitive, the likeliest scenario is that NGS would store the three-value ellipse and, if requested, perform on-the-fly conversions to less accurate representations if requested, such as the above-mentioned circle.

3.3 Appendix C: The Four-week / Twelve-week Decision

NGS uses collected GNSS data in a variety of ways. Primary among them are the determination of accurate orbits and coordinate functions for each CORS. Such processing is performed on a regular basis due to the nature of the continuous data collection.

In contrast, users perform finite-length GNSS occupations as part of a survey, at a variety of geographic locations, and then turn that data in to NGS at a variety of lag times. At NGS, we discussed the mixing of such sporadic ("episodic") field data collection into this production cycle at length and in great detail. The question was "is it still the best practice to process the network of stations and orbits independent of user-submitted surveys?"

That discussion ensued for more than a year, primarily because there was no clear and obvious answer. What was extracted from the debate was—as with any good compromise—both mildly satisfying and mildly dissatisfying to nearly every participant. Through the process, we feel we have likely hit on the best solution for the immediate future.

Listing every issue we debated would be tedious, but it would illuminate why the debate took so long and why the final methodology looks as it does. However, for the sake of some illumination, a very limited list of issues we needed to resolve is presented below.

On the one hand:	**On the other hand:**
Good survey practice should continue to ***require redundancy*** of GNSS occupations, under differing orbital geometry.	The modernized NSRS will work in time-dependent coordinates so, pedantically speaking, ***redundancy is impossible,*** since any surveyed point moves within an ideal coordinate frame (at least some very small amount) between one occupation time and another, even if separated by a single day.
Data from the CORS network comes in ***regularly, with delays of rarely more than a few days*****.** NGS is responsible to produce orbits on a weekly basis for the IGS.	Users contribute their data to NGS ***sporadically, with delays that frequently exceed years*** before a project is Bluebooked and turned in.
The greatest consistency and computational efficiency would be gained if ***the exact same software*** processing the CORS network data were to process episodic GNSS data.	Users expect the NSRS to be a framework they differentially position themselves to, necessitating that ***the NSRS be processed independently*** of their surveys.

As mentioned, in the end a negotiated compromise was reached, attempting to take both scientific validity and practical usefulness of the NSRS into account. That compromise was the four-week/twelve-week rule as outlined in 2.11.3. Occupations within one GPS month (four consecutive GPS weeks; see earlier definition) will be processed into a single midpoint-time coordinate. Such occupations turned in within three GPS months will be quality controlled, turned into “Final Discrete Coordinates,” stored in the NSRS database, and presented onto datasheets immediately thereafter.

Probably the single most important fact that broke the logjam was this: the great majority (about three quarters) of GPS projects turned in to NGS span a total of about four weeks. That means that users (already using good survey practice of, so-called, “redundancy”) are generally capable of performing two independent occupations on a point within four weeks of one another. Asking for such occupations to specifically fall inside of one GPS month (a specific four-week period) seemed to be no undue hardship. Finally, we felt that 13 possible coordinates in a single year is sufficient “time-dependent” information for any passive mark.

3.4 Appendix D: Persistent Disagreement

As mentioned in Section 2.1, NGS will have a daily check on the agreement between daily coordinates at each CORS and the coordinate function assigned to that CORS. The daily check will determine whether or not the daily coordinates exhibit a "persistent disagreement" with the current coordinate function assigned to that CORS. This section will detail exactly what that means and how it will be resolved.

3.4.1 Allowable Coordinate Functions

The first question to be answered is: "what algebraic terms will and will not be allowed to represent a CORS coordinate function?" This is critical, since a polynomial of degree "n-1" can be fit perfectly to a data set of "n" daily coordinates. Such a function would be neither beneficial (needing to be updated daily as "n" increases), nor scientifically justifiable. However, the current methodology, of using piecewise linear functions only can be criticized as being too limiting. While the exact nature of future CORS coordinate functions has not been determined in time for this document, for the purposes of the following discussions, it will be assumed that something more than piecewise linear, but less than polynomials of unlimited degree will be used. Therefore, this appendix will allow the following for example purposes only, as the coordinate function for any given CORS (after Bevis and Brown, 2014):

Across the entire data span:

- One polynomial up to degree four
- One set of annual and semi-annual sine and cosine terms
- Unlimited discontinuities[29]

Between discontinuities:

A logarithmic function representing post-earthquake transient motion

Not all of these terms will be part of every coordinate function, but they are all allowable pieces. One might ask "how will NGS know which terms to allow and which terms to disallow?" The answer is the crux of this appendix: by performing some statistical check of the daily coordinates against the assigned coordinate function. By building up the function's complexity one term at a time, we will eventually reach a point where the statistical test is passed day after day, and the function stands unchanged for some period of time. That is, on a day-by-day basis, each day's data is added to the check, and as long as the residuals between the daily coordinates and the coordinate function continue to pass the statistical test, that function will continue to be the official coordinate function for that CORS.

[29] Earthquakes are an obvious cause of discontinuities. A more disturbing source is antenna changes. This is "disturbing" because modern thinking is that GNSS antennae from the same product line tend to behave similarly to one another, and therefore calibrating one such antenna yields field-usable information about all antennae in that line. Yet if this were the case, switching a "properly calibrated" antenna of any product line for a new "properly calibrated" antenna of any product line should yield NO discontinuity. The sad truth, however, is that there is verifiable evidence that discontinuities are being caused by antenna changes without a clear and singular explanation as to exactly why.

3.4.2 How Much Data Will Be Checked?

The purpose of the coordinate function at any CORS is to accurately represent the entire positional history of that CORS. However, when coordinates are available only for a few days, a substantial number of significantly different functions might be used to fit those data and still yield acceptable results from a statistical standpoint.[30] It is anticipated that the number of terms needed to be in the coordinate function will approach stability through time if the CORS continues to behave in the same way as it has historically. Whether that stability is achieved with 6 months of data, 3 years of data, or 10 years of data has not yet been tested, but it will be before 2022.

Nonetheless, the approach NGS will take is that the **entire daily history of each CORS will be checked, daily, against the coordinate function of that CORS**. The statistical test for "persistent disagreement" is defined in the next section.

3.4.3 Definition of "Persistent Disagreement"

With full acceptance that the TBDs below must be finalized, the term "Persistent Disagreement" is defined as the following target:

> **A CORS exhibits persistent disagreement with its coordinate function if some set of statistical criteria (TBD) applied to the residual between daily solutions at that CORS and the coordinate function for some TBD time span exceeds 5 millimeters in latitude, 5 millimeters in longitude, or 10 millimeters in ellipsoid height.**

[30] Consider, for instance, having only a few dozen daily solutions. One could easily fit a line or a parabola through those points, and the statistics of the residuals would both likely be "small enough" to pass a statistical test.

3.5 Appendix E: Details of Leveling as Processed in OPUS

Geodetic leveling surveys are, in general, much longer projects than GNSS projects. Additionally, while each GNSS survey can be broken down into constituent, effectively independent occupations over a single point for a finite period of time, the observations in leveling surveys are significantly more complicated. This fact, combined with the complications new coordinates and time-dependency bring to the NSRS modernization, means a meticulous strategy for processing GNSS and leveling data together, as well as properly labeling each type of coordinate, will be paramount. Those details are too long for the main body of this report but are presented here for the sake of completeness.

Using the rules from section 2.13.3 regarding leveling and GNSS observations, let us set up a simple example and discuss how it would be observed and processed.

Consider a geodetic leveling survey designed to determine orthometric heights at 200 passive marks, with work scheduled to last six months. The marks span an area 50 kilometers by 80 kilometers.

With such a configuration, let us assume the number of primary control marks turns out to be ten. [*Remember: they are required to be no more than 30 kilometers from one another.*]

Next, a plan is made for GNSS occupations on these primary control marks. With a six-month work plan, the need for an *intermediary* set of GNSS observations is not necessary (that is only necessary for projects lasting 6 to 12 months; see section 2.13.3). Leveling is planned to begin on Monday, January 27, 2025. That is day 1 of GPS week 2351.[31] All GNSS observations should take place between these dates, inclusive: Monday, January 13, 2025 and Monday February 10, 2025. However, "redundant" observations must also fall in the same GPS month. The following graphic shows how the calendar days and GPS months line up:

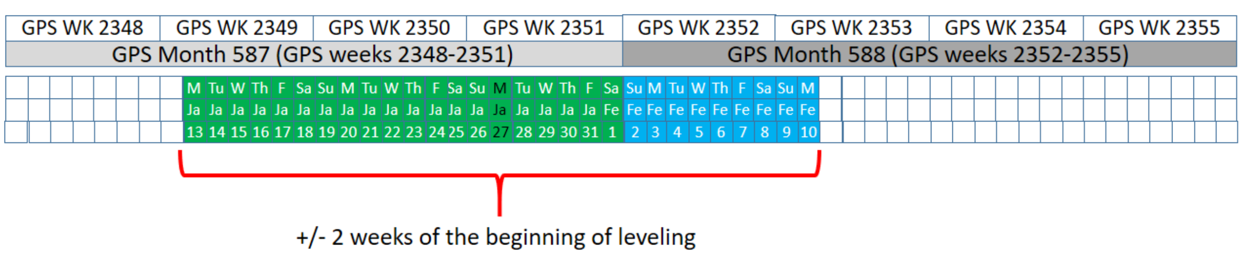

Figure 11: Determining timeframes for GNSS occupations at the beginning of a leveling survey

In the graphic, the leveling start date (Monday, January 27) is labeled in black. From that date, two requirements are shown. First, redundant GNSS occupations on any given point must fall in the same GPS month (seen as the gray bars on the above figure). Second, all GNSS occupations

[31] Note: GPS weeks "rollover" from 1023 to 0 every 1024 weeks due to the original 10-bit binary GPS week legacy numbering limitation. However, the number used here assumes no rollover and is a count of GPS weeks since the first GPS "week 0" in 1980. Counting GPS weeks without resetting for rollovers is consistent with the NGS GPS calendars and general use of GPS weeks as unique increments of GPS time. It is also consistent with GPS modernization plans to increase the number of bits available for GPS weeks.

must fall within the +/- 2-week span surrounding the start of leveling (seen as the red brace on the above figure). Taking *both* of these requirements into account, two spans of time to use for GNSS occupations can be seen. The green 20-day span, from January 13 through February 1, inclusive, and the 9-day blue span from February 2 to February 10, inclusive. There is both a requirement, and a recommendation, which now come into play:

Requirement: All GNSS occupations on *any given* primary control point must take place in either the green span or the blue span.

Recommendation: All GNSS occupations on *all* primary control points should take place in either the green span or the blue span.

It would be best if all the GNSS at the beginning of this project could be done in one GPS month, but if that does not happen, it is okay to use two GPS months for two different points.

Moving on, assume GNSS occupations go as planned, all in the green span. The user would then submit this data to OPUS and perform an adjustment of data. That adjustment would yield Final Discrete ("FD") coordinates (Cartesian and curvilinear) on all 10 primary control points, at some median epoch of observations. The user clicks the OPUS "submit" button on Monday, February 3.

Leveling commences on January 27 as scheduled. However, after five months of work, it becomes clear that leveling will not be finished at the six-month mark. The latest estimates place the project at an eight-month total completion time. Out of an abundance of caution, a plan for an *intermediary* set of GNSS occupations is put together, using the same rules as for the *initial* GNSS occupations. Similarly done and completed before the six-month deadline from the beginning of leveling, this yields a second set of FD coordinates on all primary control points with median dates around mid-June.

Finally, leveling ends on September 25 and again, a plan for GNSS occupations is developed and executed, yielding a third set of FD coordinates on primary control marks.

At this point, there are three time-dependent FD geometric coordinates from the three sets of GNSS occupations. However, as the definition of orthometric heights in NAPGD2022 is through the removal of GEOID2022, this also means there are also three sets of time dependent FD orthometric heights at the primary control points.

At this point, things become a bit complicated. All of the FD orthometric heights will be used, together with the IFVM, to compute something akin to an "average" orthometric height at the primary control points. The epoch of these "averages" will likely be the midpoint epoch of the GNSS observations and will be referred to as the "leveling adjustment epoch." These orthometric heights will not, however, be loaded into the NSRS Database; they are simply a stepping stone to Final Discrete orthometric heights.

These “average” orthometric heights at the primary control marks will then be held as stochastic control in an adjustment of the geodetic leveling observations, using the process outlined in Smith et al (2018.) When that adjustment is complete, there will be a set of adjusted orthometric heights at both the primary control points[32] and the leveled marks. These adjusted orthometric heights will be loaded as Final Discrete (FD) orthometric heights, both at the primary control points, as well as all other points at the “leveling adjustment epoch.” As before, since the ellipsoid heights and orthometric heights are tied definitionally through GEOID2022, there will also be Final Discrete ellipsoid heights at the leveling adjustment epoch. Note however, that there will be no Final Discrete latitudes nor longitudes at the leveling adjustment epoch, as they are not part of the leveling adjustment.

In summary, the GNSS/leveling survey above will get the following values loaded into the NSRS database:

1) Three sets of Final Discrete lat/lon/eht/oht coordinates at the three GNSS epochs at the ***primary*** control points
2) One set of Final Discrete eht/oht coordinates at the “leveling adjustment epoch” at ***all*** control points in the survey

[32] Because the “average” orthometric heights are held as stochastic control in the leveling adjustment, their final adjusted orthometric heights are subject to change from the input “average” orthometric heights.

3.6 Appendix F: Definitional Constants and Models

3.6.1 Definitional Constants

It was mentioned in the introduction to Section I that the core components to the modernized NSRS will be four terrestrial reference frames and one geopotential datum. In order to build those components, certain constants must be defined and held fixed:[33]

- A set of the three "Euler Pole Parameters" (EPPs) for each of the four frames in the modernized NSRS. These values are the three micro-rotations about the three ITRF2014[34] axes defining the relationship between Cartesian coordinates in ITRF2014 and those in the modernized NSRS frame. For simplicity, this set of four constants will be named EPP2022.

  Values currently TBD
- The value of W_0, being the gravity potential of the geoid at 2020.00

  62,636,856.0 m^2/s^2
- The four defining parameters of the chosen reference ellipsoid (GRS 80), per Moritz (2000): The Earth's equatorial radius (*a*), geocentric gravitational constant (*GM*), dynamical form factor (J_2), and angular velocity (*w*). All of these values are taken as exact:

  a=6378137 m

  GM=398,600,500,000,000 m^3/s^2

  J2=0.00108263

  ω=0.00007292115 rad/s

3.6.2 Definitional Models

In addition to the constants in the previous section, some models must exist for NGS to operate the modernized NSRS. The list is extensive, but the key data elements are listed below.[35] Some are more fully explained in later sections of this report, (sections, 2.7, 2.9) but all of them were first introduced in the prior two Blueprint documents (NGS, 2017a; NGS, 2017b).

- A functional Intra-frame Velocity Model in the ITRF2014 frame, called IFVM2022
- Grids for SGEOID2022, SDEFLEC2022, SGRAV2022, and SDEM2022
- A functional set of dynamic models: DGM2022, DGEOID2022, DDEFLEC2022, DGRAV2022, DDEM2022

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[33] Nothing in this world is known perfectly, but the values presented in the "definitional constants" section of this paper will be used in nearly all NGS products and services as if they are error-free. This will prevent, by way of example, the relatively large uncertainty of the rotation of the Mariana plate from propagating into uncertainties in MATRF2022 coordinates in such a way as to make them unusable.

[34] While NGS (2017a) stated that the EPPs would define a relationship between NATRF2022 (et al) and the IGS 14 frame, we have since updated that official policy so that the relationship will now be with the ITRF2014 frame. A pending update (to NGS, 2017a) will reflect this new language.

[35] Note that many of these items have two components: one that begins with an S and one that begins with a D, such as "SGEOID2022" or "DGEOID2022." In such cases the "S" refers to "Static" and the "D" refers to "Dynamic" (or, if preferred, "time invariant" and "time dependent"). The combination of the S and D components form the entirety of the model, so SGEOID2022 and DGEOID2022 together make "GEOID2022."

3.7 Appendix G: Defining "Instantaneous" GNSS Occupations

It is NGS' intent to process multiple GNSS occupations on the same point into a single "Final Discrete" coordinate and assign a "survey epoch" to that Final Discrete coordinate. As all processing occurs in the ITRF2014 frame, and because there are motions on all points in the ITRF2014 frame, it was necessary to define how long a time span would be referred to as "Instantaneous," based on the millimeter-accuracy goal stated earlier:

1) Before 0.5 millimeters of horizontal or vertical motion builds up (in the ITRF2014 frame)
2) After 0.5 millimeters of horizontal or vertical motion builds up (in the ITRF2014 frame), but by acknowledging and accounting for that motion.

In the **first approach,** NGS needn't worry about actual motion, and the point can be considered to have a "constant coordinate." This has the advantage of being scientifically correct (as far as considering a position "instantaneous"), but it comes with a disadvantage. Such an assumption severely limits the time span in which all observations need to be made under the umbrella of "instantaneous."

In order to bound the time-span of such an assumption, it is useful to consider the fastest moving locations in the United States. Horizontally, the drift of Hawaii and most Pacific territories is the fastest in the entire nation, with a maximum known velocity within the NSRS of 7.57 centimeters per year (or just over 0.2 millimeters per day) at CORS WQSL on Wake Island. Thus, in 2.5 days, that CORS has moved horizontally 0.5 millimeters. Thus, at least horizontally, a catch-all definition for "simultaneity" (which NGS will also call "coordinate stability," being that time span through which a point's coordinate could be considered "stable" or "constant," at least to 0.5 millimeters) should (in theory) be 2.5 days.

A similar computation can be done for other areas, and also for vertical motion. Unlike horizontal motion, vertical motion is significantly more local, though its magnitudes are similar. As mentioned earlier, an extreme example of vertical subsidence of 17.5 centimeters per year (just under 0.5 millimeters per day) was historically observed in California. So, vertically, a catch-all definition for "simultaneity" should (in theory) be 1.0 days.

Why the emphasis on a "catch all" definition? Because NGS has debated, and rejected, the idea of building software to address motion but that operates on a region-by-region basis. Such software would need to already know what motion is occurring, and where, and adapt every vector so-processed based on that knowledge. An approach of this nature is highly complex and comes with very little scientific gain. By building software that works in the *worst* scenarios, we are assured it works in *all* scenarios and with minimal software complexity.

Under this first approach, we would need to process GNSS observations daily to cover the worst possible known (vertical) motions. At the very least, one might stretch the limits of scientific accuracy and consider three days, or even a week-long stretch, as "simultaneous," but that is already past the one-day (vertical) and three-day (horizontal) limits points in the NSRS are moving.

In the **second approach,** NGS should account for the motion, but still attempt to find a single coordinate triad associated with a specific survey epoch. While this approach no longer assumes a point to be unmoving over a stretch of time, surveyors will have the advantage of more readily scheduling repeat observations on points which will influence a single "Final Discrete" coordinate. This allows greater semi-redundancy,[36] but has the disadvantage that one cannot simply average the positions of all occupations over a longer span, but must instead allow the IFVM to inform the Final Discrete coordinate.[37]

If one accepts this second approach, then some time span, both acceptably large and at the same time acceptably small, should be used. It should be "acceptably large" so multiple semi-redundant observations can inform a single coordinate triad. It should be "acceptably small" so the goal of such an approach (that is, "time-dependent coordinates") is met. To wit: what use are time-*dependent* coordinates when they are from a long time span, and they become only time-*averaged* coordinates? What this means in practicality is that the coordinates computed have a minimal (but not negligible) dependence on the IFVM across the time span.

NGS considered both the first and second approach (with various time spans) and decided on the second approach, using a four-week time span we are calling a "GPS Month."

This immediately raises one important question: What will happen if an occupation spans the midnight between one GPS month and the next? The answer is we are investigating the situation, and there are three possible solutions:

- The occupation is split into two different occupations, each one processed in its own GPS month,
- The occupation is processed, with all data, in the GPS month wherein the midpoint time falls, or
- The occupation is processed, with only the in-GPS month data, in the GPS month wherein the midpoint time falls.

The obvious answer is yet unclear, however, what NSRS users should take away from this is that redundant observations on a mark should be made within one GPS month if possible, and it is probably best if users avoided situations where single occupations cross over from one GPS month to another.

For this reason, the new GNSS height manual (see earlier) expressly states that users who wish to occupy a point two or more times during a project for the sake of redundancy should attempt to do such occupations within one GPS month when possible.

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[36] It is not true redundancy, as we now acknowledge it, that the point has the potential to have moved systematically by an amount greater than 0.5 millimeters between occupations.

[37] A simple, or even weighted, average of all occupations comes with the implicit assumption that the IFVM has a linear velocity between these occupations, which is by no means a foregone conclusion. Also, note that the IFVM in ITRF2014 **includes** the Euler Pole Rotations of all plates! To get the IFVM in any of the four TRFs of the modernized NSRS, the Euler Pole Rotations are simply removed. Thus, the IFVM-implied horizontal movements are much smaller in each of the four NSRS frames than in the ITRF2014. Since all GNSS processing and adjustments will be done in the ITRF2014, these larger motions are the ones being considered for decision-making purposes.

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4 Case Studies

An effectively unlimited number of examples might be invented to describe how someone might access and use the NSRS in the future. In the near future, NGS will provide Case Studies which apply the information contained in Section 2 to real world examples. A short list of proposed case studies follows. The list is not an attempt to be exhaustive, and extrapolation to other examples would be reasonable. Users interested in seeing their explicit Case Study examined and documented in a future update to this document are encouraged to submit their ideas to NGS.

4.1 Case 1: An RTK survey of existing passive marks along a roadway

4.2 Case 2: Laying out passive marks as geodetic control for a highway project spanning 10 years (GPS and Leveling)

4.3 Case 3: Annual terrestrial lidar surveys for the purpose of detecting deformation of a dam

4.4 Case 4: Floodplain mapping using LIDAR and comparing contours or digital elevation models when surveys were performed years apart from one another.