NOAA Technical Report NOS NGS 67

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

April 2019
Revised February 2021
Silver Spring, MD

Versions

Date	Changes
April 25, 2019	Original Draft Release
February 26, 2021	The following terms were changed: - **Final discrete coordinates** are now **survey epoch coordinates** - **Final running coordinates** are now **active coordinates** - **Preliminary coordinates** are now **OPUS coordinates** - **GPS Month** is now **geometric adjustment window** The official spelling for current data submissions to the NGS IDB was agreed to be "Bluebooking" An overarching tone change occurred as to what NGS will and will not allow OPUS to compute. In general, the restrictions were loosened, so that OPUS carries greater flexibility to users. It is now planned that OPUS will provide recommendations to users. Those who follow those recommendations will see their OPUS coordinates accompanied by the descriptor "tied to the NSRS." Certain decisions have been changed from "known" to "will be tested," such as the exact number of weeks of data which will go into the geometric adjustment window, the time span between reference epochs (5 vs 10 years) and exactly how long users will have to get their data into NGS for it to participate in an SEC or REC adjustment. A number of appendices were excised as being extraneous. The Case Studies section was completed. Additionally, the term "case studies" was replaced with "use cases."

Contents

Notes

Intended Audience: This document was written primarily for current users of the National Spatial Reference System (NSRS). Its goal is to highlight the differences between the current use of the existing NSRS and how the modernized NSRS will be used. Readers who are only moderately familiar with the NSRS, and its role as "geodetic control" in general, are directed to review Appendix A, "Geodetic Control Primer."

Best practices: The NGS mission (to define, maintain and provide access to the NSRS) requires that only high-quality geodetic survey data be used. However, within this document readers will occasionally see references to flexibility that is being built into NGS tools. These are not mutually exclusive topics, as the flexibility is mostly regarding how NSRS users *process* their survey data, not how that data is *collected*. Because NGS will (as seen in this document) process submitted data *independently* of how the collectors of that data process it, NGS still requires good survey practice in the collection of data if it is submitted to NGS for inclusion in the NSRS.

On the use of "TBD": This updated version of the document remains a draft of policies and procedures that the National Geodetic Survey (NGS) is refining as we prepare to define the modernized National Spatial Reference System (NSRS). The intent of releasing this document in advance is to provide the NSRS user community with insight and as many details as are currently available. This will allow for these details to be studied and understood, and for users to provide feedback to NGS. The release of this document, therefore, naturally comes with certain unresolved decisions. Rather than delay the entire document, the abbreviation 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 document we will define these terms in this way: the modernized 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" and "we" and "us": This document provides 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," NGS 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. Similarly, "we" or "us" will refer to NGS.

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 that 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 Continuously Operating Reference Stations." We have abandoned this confusing language, and now refer to that network as "the NOAA CORS Network" (NCN). Furthermore, "CORS" can be pluralized, and according to the AP style guide, Chicago Manual of Style, and the New York 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 are part of 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.***

Acknowledgments for the 2019 Version

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

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Delayed Release of the Modernized NSRS

(This message was publicly announced on June 22, 2020)

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

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

In 2013, NGS revised its 2008 plan, and targeted 2022 as the date of the release of the modernized NSRS. This date was reinforced with a 2018 Strategic Plan revision. By 2017, confidence in hitting the 2022 target was high enough to reach final agreement with Canada and Mexico on a naming convention for certain components, to include "2022" in their names.

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

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

Executive Summary

NOAA Technical Report NOS NGS 67

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

Sometime after 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, NGS will embrace time-dependency. Two types of coordinates will reflect this. Survey epoch coordinates (SECs) will estimate a mark's location on the dates when it was surveyed; active coordinates (ACs) will estimate a mark's location continuously, for example at a Continuously Operating Reference Station (CORS).

To transition users into a time-dependent NSRS, NGS will also be estimating, and providing to the public, coordinates on marks at reference epochs, likely every five or ten years. These will be called reference epoch coordinates (RECs) and will mimic the current status quo [the 2010.00 epoch of NAD 83(2011), for example].

OPUS will be expanded to support leveling, relative gravity and classical (angles and distances) measurements, as well as reconnaissance and project submission (previously called "Bluebooking").

NGS will treat the NOAA CORS Network (NCN) as having the definitive, up-to-date coordinates within the NSRS. The NCN will be modernized, and its reliability, usefulness, and accuracy will be improved. A NCN (CORS) data quality assessment system will exist. The improved NCN will be the definitive geodetic control, though recently surveyed passive control could be recommended in some circumstances.

Users who follow OPUS recommendations will receive OPUS coordinates with the descriptor "tied to the NSRS." While these OPUS coordinates will not go into the NSRS, the data behind them will, and will be used by NGS to compute RECs and SECs.

Finally, users will be able to query the new NSRS database in ways not possible with the existing NGS integrated database (NGS IDB). Instead of providing "datasheets," a future data delivery system (DDS) will allow users to access vastly more information about the NSRS than ever before, and have it displayed in a variety of dynamic ways.

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

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 with respect to their *geodetic* usage, not their *broader* usage within the English language. Terms in **bold** in the definitions are defined in this terminology guide.

Active Coordinates: See **Coordinate**.

Adjustment Window: The span of time in which **observations** will be adjusted in the creation of **survey epoch coordinates (SECs)**. Each of the three types of **SEC** adjustment projects (Geometric, Orthometric, and Gravimetric) will have its own **adjustment window**[1].

Antenna Reference Point (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 the aforementioned horizontal surface of the antenna; or it may be the center of a mounting axis, and thus coplanar 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 described the **coordinates** at a **CORS** as referring to the **ARP**, and not the **GRP**, which is not quite accurate. In 2019, that practice started being corrected. 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**.[2]

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 publication that had been distributed with a blue cover.

Classical Surveying: The measuring of angles and/or distances, as with theodolites, chains, tapes, electronic distance measuring instruments (EDMI), and total stations.

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[1] The exact lengths of time of each type of adjustment window have not been finalized as of the writing of this document. However, some initial values have been determined, from which experiments will begin, in an attempt to make a final decision. NGS will begin experimenting with a geometric adjustment window of four-weeks duration, and an orthometric adjustment window of one- year duration. No initial value of a gravimetric adjustment window has yet been established.

[2] NGS is working on a document (working title: "Anatomy of a CORS") that will identify all parts of a CORS and is expected to be released in 2021.

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, along with power and communications equipment. The purpose of a **CORS** is to continuously collect GNSS data 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**. See also **Active Control**.

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

Control, Geodetic: **Points** with known **coordinates**, used to assign new **coordinates** to other **points** through **observations** between the **geodetic control** and those other **points**. Usually comes in two varieties:

Active Control: A geodetic control **point** at a **station** occupied by equipment intended for and capable of continuously collecting geodetic quality data for multiple years and with **active coordinates** (see Section 2.5) defined by or adopted by NGS.

Passive Control: Any geodetic control **point** that is not **active control**. Common examples include a metal disk set in concrete or stone, or a stainless steel rod driven into the ground.

Also called: Geodetic Control Point(s), Active Control Point(s), Active Control Station(s), Passive Control Point(s), Passive Control Mark(s), Control Point(s), Control Mark(s)

Coordinate: One of a set of *N* numbers designating the location of a **point** in *N*-dimensional space[3]. Specific to the modernized NSRS, five types of **coordinates** will be supported (see Section 2.4 for more detail):

Reported coordinates: **Coordinates** directly reported to NGS without the data necessary for NGS to replicate or evaluate them. These coordinates are neither "part of the NSRS" nor "tied to the NSRS."

OPUS coordinates: **Coordinates** computed by OPUS that have not been evaluated by anyone at NGS. As these coordinates are not computed by NGS they are not considered "part of the NSRS." However, if NGS-provided OPUS recommendations are followed, they may be "tied to the NSRS."

Reference epoch coordinates (RECs): **Coordinates** estimated by NGS for one of the official **reference epochs** NGS will define (every five or ten years, as currently planned). As these coordinates are computed by NGS they are considered "part of the NSRS."

[3] "Space" can be broadly interpreted, so that a coordinate need not be "geometric" or "Cartesian." The acceleration of gravity, geopotential, dynamic height, deflection of the vertical and other geodetic quantities are all coordinates.

Survey epoch coordinates (SECs): **Coordinates** computed by NGS for one **survey epoch**. As these coordinates are computed by NGS they are considered "part of the NSRS."

Active coordinates (ACs): **Coordinate functions** in time, generated by NGS, and not associated with a specific **epoch**. As these coordinates are computed by NGS (or adopted by NGS) they are considered "part of the NSRS."

(CORS) Coordinate Function: A set of three piecewise (continuous or discontinuous) 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**[4]. Specific to **CORSs** only, the **coordinate function** is identical to **active coordinates** (see Section 2.5). As these coordinates are either computed by NGS (from the NCN) or adopted by NGS (from the IGS Network), they are considered "part of the NSRS."

Epoch: A particular instant of time from which an event or a series of events is calculated; a starting time to which events are referred. For astronomy and geodesy applications, an **epoch** is typically expressed as a decimal year (e.g., 2020.2418 = March 29, 2020, at approximately noon). Specific to the modernized NSRS, two types of **epochs** will see common usage:

Reference Epoch: Those **epochs** which fall exactly on five or ten year intervals, starting at 2020.00, and to which **reference epoch coordinates** will be estimated.

Survey Epoch: The **epoch** at the midpoint of an **adjustment window**, and to which **survey epoch coordinates** will be estimated.

Geometric Reference Point (GRP): A unique **point** that is part of a particular **station**. The **GRP** is the **point** to which any "**coordinates** of the **station**" refer, including but not limited to the **coordinate function** of a CORS. The operator of each **station** identifies the **GRP** of that **station**. The **GRP** is sometimes independent of equipment, such as 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**.

[4] As of 2020, NGS has not defined 100% of all GRPs at all CORSs. This is partly due to the vast number of partners and configurations of stations within the NOAA CORS Network and the IGS network. NGS is committed to identifying the GRP at all NGS owned CORSs, NOAA Foundation CORS Network (NFCN; see https://www.ngs.noaa.gov/CORS/foundation-cors.shtml) stations, all newly entering stations, all stations co-located with other space geodetic techniques and all IGS stations prior to the roll-out of the modernized NSRS. Nonetheless, that leaves many stations with a *potentially* ill-defined GRP. NGS will address this issue through the forthcoming CORS data quality assessment system (see Section 2.12), in which the user will be able to select proper identification of a GRP as an evaluation criterion.

Mark (or Marker): A physical structure of varying size or construction, attached to the Earth's surface in some way that is presumed to be stable[5] for years (or decades) and whose function is to contain a single, unique, identifiable **point** in a stable location[6]. Such **points** are often a small divot or cross on the top of the **mark.** Even the smallest divot is not zero-dimensional, so for highest accuracy, one must clearly identify which part of the divot is the **point** (e.g. the **point** on the **mark** might be the bottom of such a conical divot). Common forms of a **mark** include:

1) A metal (often brass or aluminum) disk (often about 3 inches in diameter but varying from 0.5 inch to more than 12) with a stem underneath which keeps it mounted in stone, masonry or concrete.
2) A metal rod (usually 1–2 centimeters in diameter) driven into the ground ("to refusal" or "substantial resistance") 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**."[7]

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

See Figure 1.

Measurement: A single value, measured or collected by some geodetic or surveying instrument and typically used to determine other quantities of interest (such as **coordinates**, distances, directions) or combined to perform various analyses and integrated computations (such as least-squares adjustments). Examples include:

1) The phase count of one GPS frequency of one GPS satellite at one **epoch**[8] (for example as one among many thousands of **measurements** within one RINEX file).

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[5] That presumption of stability was originally extended to both horizontal and vertical motion. Today, it is widely known that this stability can be different in the horizontal and vertical directions. Most marks do not move horizontally unless the crust in which they are mounted also moves horizontally. Vertically, however, the type of mark structure will dictate whether the mark moves as its underlying crust or segments of the underlying geologic profile moves.

[6] At least relative to the local surface of the Earth, though stability relative to a continent or even the planet would be preferable.

[7] 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 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 divot" 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 divot (or cross mark).

[8] Single instances of time when GNSS data are logged by a receiver are often called epochs. For example, "my GNSS receiver logs data at 5 second epochs" (i.e., a 5-second sample rate). This is not in conflict with the definition of

2) A horizontal circle reading using a theodolite sighting a single target.
3) The reading of a level rod by a single sighting through a geodetic level.

In most cases, raw **measurements** (as acquired by an instrument) are not used directly for computations. Instead, they are almost always first modified to make them more convenient and practical to use for calculating other quantities. Such modified **measurements** will be called **observations** within this document.

See also **Observation.**

NGS IDB (or IDB): The National Geodetic Survey Integrated Database. Until the modernized NSRS is released, the NGS IDB is the definitive storage place for all NSRS data. Currently, datasheets are generated only from this database. It is referred to as "integrated," because two separate databases (one for horizontal and one for vertical) were combined into the **NGS IDB** in the 1990s.

NOAA CORS Network (NCN): The name of the collection of **CORSs** that meet the NGS acceptance criteria and whose data are collected, processed, and distributed 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 (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** or **observations** using the modernized NSRS as their foundation.

Observation: One or more **measurements**, generally collected during a single **occupation**. If an **observation** consists of multiple **measurements**, it is often computed through averaging, "reducing," processing, or other ways of removing systematic effects (such as instrument offsets, biases, or known non-random errors) or obtaining an alternate representation (such as GNSS vectors from processed GNSS measurements). Sometimes such averaged, reduced, processed, or otherwise combined **measurements** will be referred to by other terms, such as "pseudo-observation" or "reduced observation." Within this document, such distinctions will be avoided, unless they are absolutely necessary for clarity. As such, **observation** should be taken in the general, vernacular sense without specific mention of what reductions were performed on the **measurements** that make up the **observation**.

Occupation*:* The static set-up of a geodetic instrument over a **mark** for the purpose of making measurements.

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epoch found in this terminology guide (since the instant of data collection is at an exact epoch), but the most frequent use of epoch in this document will be in the context of reference epochs or survey epochs.

Examples include

1) Holding an RTK rover plumb on a **mark** for six seconds while collecting GNSS measurements.
2) Setting up a GPS antenna on a tripod over a **mark** for 24 hours of data collection.
3) Setting up a total station on a tripod over a **mark** for collecting angles and distances.
4) Placing a zenith camera over a **mark** for collecting celestial image and GPS data simultaneously for Deflection of Vertical (DoV) determinations.
5) Standing a level rod plumb on a **mark** or turning pin long enough for foresights and backsights to be collected.

OPUS Coordinates: See **Coordinate**.

PID: Abbreviation for 'Permanent Identifier,' the unique six-character alphanumeric code assigned to each **point** residing on a **mark**[9,10] included in the **NGS IDB** or **NSRS DB**.

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 or a **CORS GRP** located within a bolt as part of its antenna mount or even the intersecting altitude/azimuth axes of a VLBI telescope). *See Figure 1.*

Also called: *Datum Point, Reference Point*

Propagate: The application of systematic information to either an observation or an uncertainty to compute a related observation or uncertainty.

Redundancy: Making the same **observation** more than once, where each **observation** is taken separately and independently of the other (e.g., separate tripod setups, separate instrument setups and separate height determinations from one **occupation** to the next). In the context of this document and within the field of surveying and specific to the NSRS, **redundancy** will generally mean "collecting **observations** at a **point** during two different **occupations** within the same **adjustment window**."

Reference Epoch: See **Epoch**.

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[9] Some points will 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. Such points without marks will not receive a PID. On the other hand, when a mark does contain a point, it is fair to equate the PID of the mark as the same thing as the PID of the point on that mark.

[10] Some marks exist in the NGS IDB that do not have a point. This was a common enough practice in two cases at least: (1) objects that were sighted in horizontal surveys (such as church steeples, water towers, or the hand of a statue) and (2) certain geodetic control marks that did not have a definable point (divot, etc.) on the mark itself. In these cases, the PID should be thought of as referring only to the mark, and not a point on the mark. While this has the potential for difficulty (two or more points on a single mark raise the question of whether there should be two PIDs), NGS will address this issue as the NGS IDB is replaced with the NSRS DB.

Reference Epoch Coordinates: See **Coordinate**.

Reported Coordinates: See **Coordinate**.

Site: The location name of the smallest area where (one or more) **stations** are located, usually with an associated legal or official definition (e.g., by deed; national- or state-recognized city, town, village, or hamlet; or geographic feature). Multiple **stations** can be on one **site**. (Example: "U.S. Naval Observatory" is a **site**, and it happens to contain two **stations**, which are the **CORSs** known as USNO and USN8). *See Figure 1.*

Station: A collection of equipment located at one **site** to collect one specific type of data (i.e., **measurements**) for a particular geodetic purpose. Within the geodetic community there are many types of **stations**. The 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.*

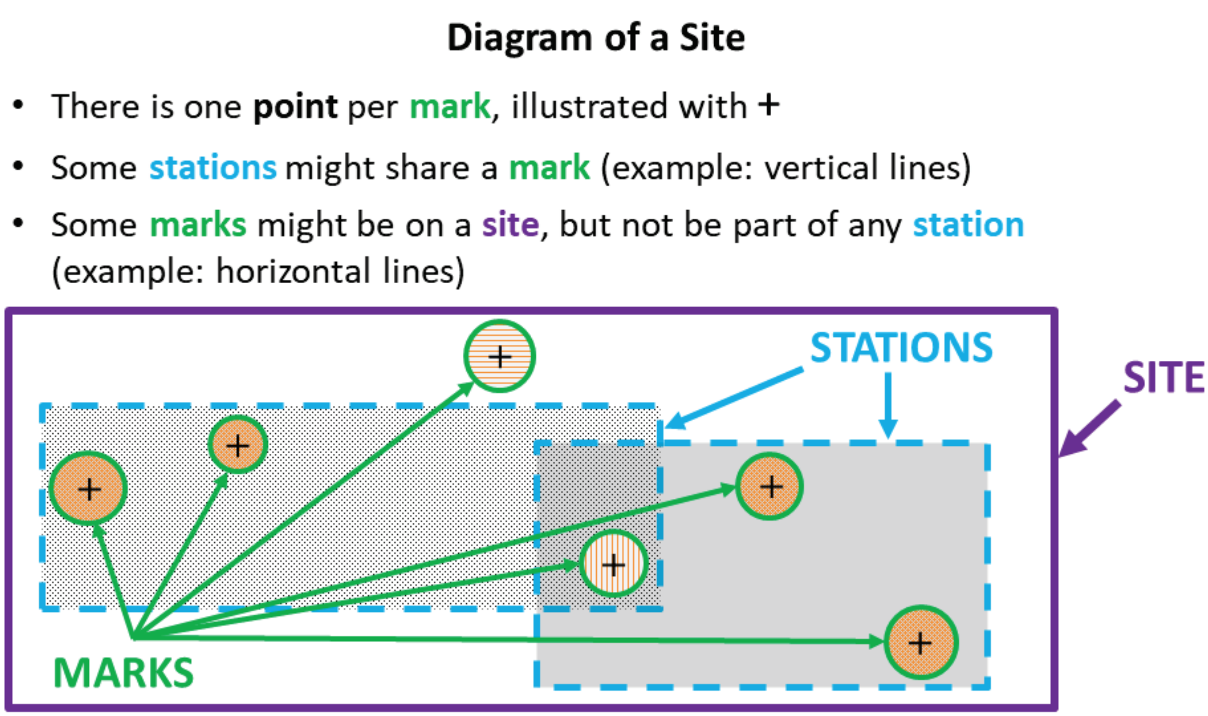

Figure 1: Site, Station, Mark, Site Marker, and Point Hierarchy

Survey Epoch: See **Epoch**.

Survey Epoch Coordinates: See **Coordinate**.

List of Abbreviations, Acronyms, and Initialisms

AC	**Active Coordinate (NGS); Analysis Center (IGS)**
ARP	**Antenna Reference Point**
ASVD 02	**American Samoa Vertical Datum of 2002**
CATRF2022	**Caribbean Terrestrial Reference Frame of 2022**
CORS	**Continuously Operating (GNSS) Reference Station**
DoV	**Deflection of Vertical**
ECEF	**Earth-Centered, Earth-Fixed (Cartesian coordinates)**
EPP	**Euler Pole Parameter**
FGDC	**Federal Geographic Data Committee**
FGCS	**Federal Geodetic Control Subcommittee**
GDA	**Geospatial Data Act of 2018**
GNSS	**Global Navigation Satellite System**
GPS	**Global Positioning System**
GRP	**Geometric Reference Point**
GRS 80	**Geodetic Reference System of 1980**
GUVD 04	**Guam Vertical Datum of 2004**
HTDP	**Horizontal Time Dependent Positioning *(NGS software)***
IDB	***See NGS IDB***
IERS	**International Earth Rotation and Reference Systems Service**
IFVM	**Intra-frame Velocity Model**
IGS	**International GNSS Service**
ITRF	**International Terrestrial Reference Frame**
LSA	**Least Squares Adjustment**
MATRF2022	**Mariana Terrestrial Reference Frame of 2022**
NAD 83	**North American Datum of 1983**
NADCON	**North American Datum CONversion *(NGS software)***
NAPGD2022	**North American-Pacific Geopotential Datum of 2022**
NATRF2022	**North American Terrestrial Reference Frame of 2022**
NAVD 88	**North American Vertical Datum of 1988**
NCAT	**NGS Coordinate Conversion and Transformation Tool *(NGS software)***
NCN	**NOAA CORS Network**

NFCN	**NOAA Foundation CORS Network**
NGS	**National Geodetic Survey**
NGS IDB	**National Geodetic Survey Integrated Database (alternatively *NGSIDB*)**
NMVD 03	**Northern Mariana Vertical Datum of 2003**
NOAA	**National Oceanic and Atmospheric Administration**
NSRS	**National Spatial Reference System**
NSRS DB	**National Spatial Reference System Database**
OPUS	**Online Positioning User Service *(NGS software)***
PAGES	**Program for the Adjustment of GPS Ephemerides *(NGS software)***
PATRF2022	**Pacific Terrestrial Reference Frame of 2022**
PRVD 02	**Puerto Rico Vertical Datum of 2002**
RAS	**RTN Alignment Service**
REC	**Reference Epoch Coordinate**
RINEX	**Receiver INdependent EXchange**
RTK	**Real-Time Kinematic**
RTN	**Real-Time Network**
SEC	**Survey Epoch Coordinate**
SPCS2022	**State Plane Coordinate System of 2022**
TRF	**Terrestrial Reference Frame**
VERTCON	**VERTical datum CONversion *(NGS software)***
VIVD 09	**Virgin Islands Vertical Datum of 2009**
WGS 84	**World Geodetic System of 1984**

1 The Past and Present

1.1 Introduction

In the near future, 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[11]. Whereas the NGS mission is to perform 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) within the Federal Geographic Data Committee (FGDC). The FGCS issues decisions in Federal Register Notices (FRN).[12]

The ***geometric*** component (latitude, longitude, ellipsoidal height, etc.) of the modernized NSRS is defined in *Blueprint for the Modernized NSRS, Part 1: Geometric Coordinates and Terrestrial Reference Frames* (NGS, 2021a). The ***geopotential*** component (heights, gravity, etc.) is defined in *Blueprint for the Modernized NSRS, Part 2: Geopotential Coordinates and the Geopotential Datum* (NGS, 2021b). With these two documents, four terrestrial 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. Those documents also include 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.

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

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[11] This is often due to project requirements, state laws, or dependency on federal data usage.

[12] 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 have not fully been analyzed, though it is not expected to have significant impact.

been included in the 1991 nationwide adjustment for the North American Vertical Datum of 1988 (NAVD 88). That adjustment consisted of decades of leveling data, with systematic errors that were only partially accounted for, with heights computed in 1991 and kept as-is to the present day.

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. Historic classical and leveling survey techniques can achieve high relative accuracy between nearby marks. But since such techniques are very local, they cannot detect changes over regional or continental scales. 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) but is completely invisible when using classical methods. Historic, local, classical, and leveling 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 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 a mark 24 hours a day, seven days a week. The exceptions to this rule are marks at tide gauges, continuously operating relative gravimeters, and continuously operating GPS/GNSS reference stations (CORSs). Without installed equipment to monitor their position, the majority of infrequently surveyed geodetic control marks—historically known as the workhorse of the geodetic control community—will be treated as a secondary (less trustworthy) source of NSRS coordinates.

Thus, in the modernized NSRS, the primary (most trustworthy) source of NSRS coordinates will be through the NOAA CORS Network (NCN).

NGS has made the decision to adopt up-to-date scientific practices and methods to fully utilize the modern tools and technology. One of the best reasons to implement the decision is 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. Moreover, those differences change with time. By switching to a more geocentric (and time-dependent) 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 to alleviate the impact of coordinate changes over time. The two primary components are:

1. Plate-fixed frames
2. Reference epoch coordinates

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 terrestrial reference frames (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 for those parts of the plate that are effectively rigid (not undergoing significant active deformation).

Reference epoch coordinates (RECs) are intended to provide a static, mutually-consistent set of coordinates at one fixed epoch, every five or ten years. The creation of RECs will require a number of assumptions and models, such as an intra-frame velocity model (IFVM[13]) whose job is to describe the motions of geodetic control points between the times those points were observed and the reference epochs. In effect, the job of the IFVM is to capture all *residual* changes in latitude and longitude, when dealing with the plate-fixed frames (above), as well as *all* vertical motion.[14]

Further details on plate-fixed frames and the IFVM are presented in NGS (2021a).

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[13] The term IFVM is tentative, as the model intends to capture all motions of all geodetic control marks, not just simple velocities. However, the global geodetic and geophysics communities as a whole are split on what term is best suited to be used. Replacement candidates for "velocity" include "deformation" (primarily because the model would likely be derived from crustal deformation) and "motion" (primarily because the model will include all motions of marks). When a final term is decided, NGS will update this and other documentation.
[14] 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.

1.2 Types of Geodetic Control and Their Relationships to the NSRS

At the most basic level, there are currently four types of geodetic control that may allow a user to access the NSRS (which can be used independently or collectively):[15]

Table 1: Four types of geodetic control and their access to the NSRS

	Type of geodetic control	Access to the NSRS?
1	GNSS Satellites	Generally not, but maybe through a PPP service
2	the NOAA CORS Network	Yes, in a variety of ways
3	other continuous GNSS stations	Possibly, but without quantification of alignment
4	passive control[16]	Yes, but coordinates could be outdated

Each of these types of control can be considered to have some zero-dimensional point, from which other points of interest can be located using direct or indirect observations.

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 2 of this document.

1.2.1 GNSS Satellites

The GNSS satellites themselves serve as "marks in the sky," and the geodetic control point is the center of mass of each satellite. Knowing the location of the satellites[17], 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 is by using only the broadcast signal, for example, via the GPS antenna and 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 autonomous GPS is used). As none of the constellation frames are

[15] 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."

[16] The term "passive control" could more accurately be expanded to be "infrequently surveyed geodetic control marks".

[17] 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.

part of the NSRS[18] **this form of using the GNSS satellites does not allow direct access to the NSRS.** Although the current version of WGS 84 (G1762) was nominally aligned with ITRF2008 to an accuracy of about 1 cm at an epoch of 2005.00 (NGA, 2014), that does not provide direct access to the NSRS, for a number of reasons. Among those are some ambiguities, including in the alignment itself, handling of velocities, and the time-dependent relationship between the NSRS and ITRF2008. But more importantly, an autonomous GNSS position is typically accurate to only a few meters, so cm-level alignment is largely moot in this context.

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.[19] 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.

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 accuracy. The same can be said of various satellite-based augmentation systems, such as the Wide Area Augmentation System (WAAS), which may or may not have a well-defined relationship to the NSRS.***

1.2.2 The NOAA CORS Network (NCN)

The NOAA Continuously Operating Reference Station (CORS) Network (or NCN) is an NGS-managed network of CORSs, with each station consisting of a static continuous GNSS antenna and related equipment. At each station is a permanent, unique point that is independent of the antenna,[20] called the Geometric Reference Point (GRP)[21], although NGS has not yet defined the GRP for every station in the NCN. NGS regularly collects data from each CORS and uses these

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[18] NGS will establish a strict mathematical relationship between the NSRS frames and the ITRF2020 frame, and this is what will allow 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, but those relationships are not currently known for all constellations.

[19] 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.

[20] 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.

[21] 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 to be identified for EVERY CORS. Relationships between this term and MON or ARP will be clarified in a separate document.

data to perform many functions, including GNSS orbit determination, as well as to keep track of the location of each CORS (meaning the coordinate functions of each GRP).

Because the NCN is managed by NGS, the station coordinate functions 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. Software is used to process received data in coordination with the CORS data, which then yields a differential vector between the CORS GRP and their point.[22] Knowing the coordinate function of the CORS GRP (provided by NGS) allows the software to compute the coordinates of the user's point of interest at the time of data collection. Though not required to arrive at an NSRS coordinate, NGS offers software to accomplish this task. ***However, currently, NGS does not provide a service to quantify the alignment of coordinates labeled as "NSRS" that are computed from non-NGS software.***

The second method—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 either directly or indirectly (using tangent sightings and circle fitting, for example) 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 geodetic control mark (see section 1.2.4). By this we mean, a level rod might be placed on the GRP to perform leveling, or a total station or reflector 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 CORSs (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. 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).

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

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

1.2.3 Other Continuous GNSS Stations

The NCN represents a large proportion of the available continuous GNSS stations in and near the United States, but they are by no means *the total sum of all* such stations.[23] 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 coordinate functions of these stations, ***the veracity of their coordinate functions is outside of our control***. This means that, despite the fact that coordinates derived from services that rely upon such stations may be listed as being "NSRS coordinates," we cannot judge or comment on the accuracy of those coordinates relative to the NSRS. Within that caveat, they can be used in one of the three ways mentioned in Section 1.2.2.

There is a *fourth* way to access and use other continuous GNSS stations as geodetic control that is *not* available through the NCN: if such stations are part of a Real-time Network (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 do more than just compute the coordinates of their own cGNSS stations ("base stations"). The coordinate functions, and other network data, are then transmitted to an RTN user's GNSS receiver ("rover") via some form of internet connection. The RTN user's hardware and software will then use the network data to determine a rover coordinate with respect to whatever coordinate frame the RTN operator has chosen for their network. In many cases in the United States, the RTN operator will state that they are operating in some frame of the NSRS, ostensibly ***allowing users of the RTN access to the NSRS***. However, as NGS neither computes nor tracks the coordinate functions of these stations, ***we cannot (currently) comment on the accuracy of RTN-derived coordinate functions (at base stations) nor coordinates (at rovers) within the NSRS.*** 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 2 for details.

1.2.4 Passive Control

The term "passive control" refers to a geodetic control mark that does not have semi-permanent[24] equipment installed for monitoring it. Passive control comes 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 design, they all have one thing in common: unlike the previous three types of geodetic control, up-to-date, time-dependent coordinates on passive control are generally not available.

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

[24] Nothing in this world is "permanent," but certain geodetic control marks have equipment that runs continuously at that mark, often for years. The most common are CORSs and continuously operating relative gravimeters. Since these pieces of equipment occasionally break down and/or need replacing, the term "semi-permanent" is used here without attempting to be specific about how long such equipment is actually in place.

Currently, NGS delivers the NSRS through passive control by "publishing" the official coordinates on each mark[25]. In the case of latitude, longitude, and ellipsoidal height, marks with the most up-to-date coordinates come from a single adjustment of all GNSS vector data spanning more than three decades to yield an estimate of coordinates at epoch 2010.00.[26] In the case of orthometric heights, the situation is generally one of publishing a height based on one or more observations of the point, whether that be from a single or multiple surveys 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 for most published orthometric heights.

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

As the Earth deforms (relatively) slowly, the coordinates computed for passive control might be "usable" for "long stretches of time,"[27] 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 control from having *one* official coordinate set to having *multiple sets* 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 control might be considered "stable": At the moment, the NAD 83 frame is *nominally* referenced to the North American tectonic plate but does not seem to actually be rotating at the exact speed as that plate. However, if it were, it would be a "plate-fixed" frame, and the latitudes and longitudes in NAD 83 would not change over time for much of the plate. Properly computing the plate's actual rotation and assigning that same rotation to

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[25] Over the years, the term "publishing" has come to mean, within the NSRS community, that a coordinate existed in the NGS IDB and appeared on a datasheet.

[26] In the current NSRS, adjusted coordinates are 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 many 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.

[27] These two terms are left purposefully vague. If observations at a certain epoch are turned into coordinates at that same epoch, then only the uncertainty in constraints and observations will impact the computed coordinate. 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 CORSs or from radar-mapped changes to the local topography, or some combination of these methods). 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."

the frame (which will be a cornerstone of the modernized NSRS) stabilizes coordinates, so trusting an "old" coordinate on passive control would be justified.

Why coordinates of passive control might be considered "unstable": Aside from plate rotation, many things can move passive control 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 and the subduction of the Juan de Fuca plate. These deformations can cause residual (non-rotational) horizontal velocities that approach a few centimeters per year. At a smaller magnitude, Glacial Isostatic Adjustment (GIA)[28] 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 mark 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 mathematical removal of the tectonic rotation does not attempt to remove any vertical motion. Some vertical motion impacting heights can be attributed to marks set in concrete posts or on structures that can settle into the local soil over time or be subject to frost heave. Other phenomena that impact a height include 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. For example, in the San Joaquin Valley in California, subsidence in the middle 20th century was recorded as 17.5 centimeters per year. This can be seen in Figure 2 (Graham, 2017). Unfortunately, subsidence does not necessarily manifest at a constant rate nor is it spatially consistent.

[28] A geologic process whereby a tectonic plate, long pressed down by glaciers during an ice age rebounds vertically.

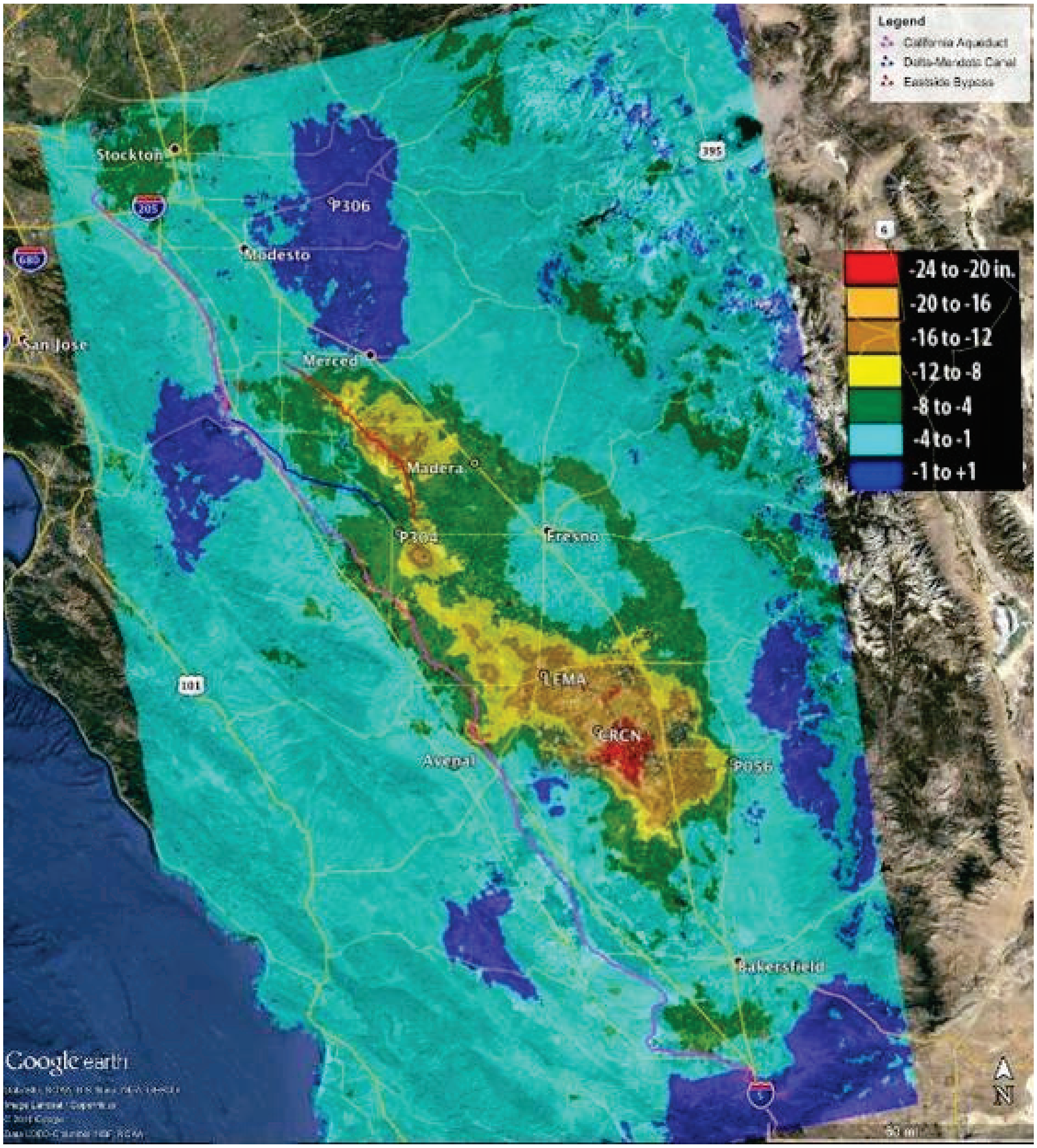

Figure 2. Total subsidence in California's San Joaquin Valley between May 7, 2015 and Sept. 10, 2016, as observed by ESA's Sentinel-1A and processed at JPL.

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

1.3 NGS Operations Today

Currently, NGS defines, maintains, and provides access to the NSRS 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 NOAA CORS Network (NCN)[29] 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 (initially referred to as the High-Precision Geodetic Network, or HPGN). This concept eventually blossomed into a global tracking network and morphed into the International GNSS Service (IGS), though within the USA the network grew and became the NCN. However, it wasn't until 1994 that a second function, to "enhance" the passive control network known as the NSRS, was proposed (Strange, 1994; Strange and Weston, 1995).

The NCN has now grown to more than 2,700 stations (with more than 1,800 of them currently active), including 200 partners in 25 countries. A number of challenges emerged as the number of stations increased in the NCN. Managing data feeds from disparate sources and attempting to maintain useful coordinate functions (see section 2.7) for the stations has slowly introduced problems. It is not difficult to find examples of CORSs with daily coordinates showing regular and systematic deviation from their current coordinate functions. 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 other challenges associated with maintaining an up-to-date record of the equipment actively in use at every station. For this reason, when users rely on the NCN as geodetic control for their GNSS surveys, they have found that the choice of which CORSs 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 GNSS data in the NCN. As an example, NGS's latest effort to reprocess all historic data—called "MYCS2" (for Multi-Year CORS Solution 2)—was an effort to support the IERS's transition to ITRF2014 (and the IGS's transition to IGS14) and it required two years[30] to complete. The effort yielded, for each CORS in the NCN, a triad of piecewise (continuous or discontinuous) 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

[29] Called simply "CORS" or sometimes "the CORS" or "the CORS network", prior to 2017.

[30] Thankfully, NGS is participating early in the transition to ITRF2020, and the workload is expected to be significantly less than our transition to ITRF2014.

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. Similarly, when a CORS experiences a real movement, such as from an earthquake or when a change of equipment causes apparent movement, it can take weeks[31] before the coordinate function is updated.

Despite these difficulties, the potential power has always existed for the NCN to serve as a mutually self-consistent and highly accurate foundation for the NSRS. Major changes in construction standards, data delivery, and data processing are expected to unleash that potential as part of 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, OPUS-RS (RS for Rapid-Static), became available. Other OPUS tools were subsequently developed. OPUS-DB (DB for Database, which later 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.[32]

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 sessions with a minimum 2-hour duration.
- OPUS-Share requires sessions with a minimum 4-hour duration.
- OPUS-RS will process sessions as short as 15 minutes, but it does not consistently agree with OPUS-S due to different processing engines.
- Position estimates provided to the user can be highly sensitive to which CORSs are selected as reference stations.
- OPUS-Share has only a weak relationship to the NGS IDB.

Whereas these issues are discouraging, NGS is building the future data submission process (currently called Bluebooking) around OPUS, and we will not only be correcting each of these

[31] Before late 2019, it used to take years, so things are improving.

[32] This changed in 2018 with the completion of the "OP2IDB" project, with a beta release of a version of OPUS-Projects that 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.

deficiencies, but we will be addressing much more, as well. Describing how we intend to do that is the overarching aim of this document.

1.3.3 Crustal Dynamics

In 1992, NGS released version 1.0 of the Horizontal Time-Dependent Positioning (HTDP) software (Snay, 1996; Snay, 1999; Pearson and Snay, 2013). Although HTDP is *capable* of modeling *surface* motion, the intent of that software was to provide users with the ability to access models of horizontal *mark*[33] motion across epochs. 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.

HTDP's ability to model *surface* motion stands in as a proxy for *mark* motion, which seems to have worked well since HTDP almost exclusively deals with horizontal motions. No doubt a major part of that success is due to the use of CORS velocities to constrain predictive models of surface motions. Nonetheless, even though velocity estimates for stations in the NCN are used to constrain these models, the models themselves must be relied upon to predict crustal motion for regions between stations.

1.3.4 Passive Control

NGS relies on passive control and the NCN as effectively being equal in providing users access to the NSRS. Viewing passive control and the NCN as equals is 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 estimate the change-over-time of vectors, which were observed 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

[33] NGS will try to be meticulous in the proper use of "crust," "surface," and "mark" when discussing things like HTDP and the IFVM. The ***crust*** being the entire 3-dimensional structure of the outer lithosphere surrounding the Earth, while the ***surface*** can be thought of as the crust/atmosphere boundary. Further, there is a difference between the velocities of marks set in the crust, and the movement of the crust itself, particularly in the vertical.

median ellipsoidal height residual magnitude was 0.51 centimeters (Dennis, 2020). This result speaks well to both the quality of GPS work in the NSRS user community, the viability of HTDP (including the presumption that horizontal *surface* motion and horizontal *mark* motion are identical) and/or the generally well-modeled 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 in most areas (along the Gulf Coast or California's Central Valley) by generally treating such *systematic* changes to the ellipsoidal height of a point as part of the *random* measurement errors, which is mathematically incorrect. Although various attempts other than HTDP were also made to appropriately account for subsidence in the northern Gulf Coast region, in general such vertical change was not handled rigorously or consistently throughout the NSRS.

An additional difficulty with passive control is that it remains 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 (Zilkoski, Carlson, and Smith, 2008) using GNSS technology suffer, as they do not observe 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, for example due to subsidence).

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 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 IDB, the repository for passive control information concerning the NSRS prior to its modernization. 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* (FGCS, 2016), which was revised and updated many times over 30-plus years. Because the first versions of that document were distributed in a 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 submit data 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 NSRS passive control network via the Bluebooking standard.

The time-dependency of passive control coordinates was originally solved primarily through the process of superseding coordinates. Significant human analysis was required to get new observations to fit to old coordinates. Sometimes the new observations would lead to a new coordinate that superseded the old. Sometimes the new observation would be rejected as an outlier. Such decisions happened regularly as projects were submitted; 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 NAD 83), and second, to provide access to models of crustal dynamics in order to estimate mark movement through time. The second function became a standard tool in Bluebooking in the early 2000s (Prusky, 2018). Initially, HTDP was only used in areas of known active crustal motion (such as California), but after the national adjustment of 2011, HTDP was used for all Bluebooked GNSS projects. In this way, prior information about horizontal mark movement was added to the project's analysis, and decisions concerning superseding older coordinates could be better informed.

Bluebooking performed its one task, 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 declined). Yet, its continued reliance upon antiquated 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 tends to focus on so-called "pseudo-observations" (see "observations" in the Terminology Guide). That is, each individual angle turned by a total station is not stored in a Bluebook file. Rather, the average of multiple angles is stored. Similarly, this is true for distances, azimuths, and differential vectors between two points each occupied by GPS. While those GPS files are often sent to NGS with the Bluebook submission, they were archived and (until the 2010s) effectively forgotten. The vectors derived from the GPS data (whether from NGS software—PAGES, for example—or commercially available software) were submitted and stored in the NGS IDB. This, of course, led to inconsistencies depending on both the age and source of the software. Fortunately, such inconsistencies tended to be small (Dennis, 2020), but they do exist and furthermore, without the ability to quickly re-process the raw observables, they 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 has for various statistical and least-squares computations. Others still in use are **GPSCOM**, used within OPUS-Projects; **NETSTAT**, used exclusively for national adjustments such as those completed in 2007 (Pursell and Potterfield, 2008) and 2011 (Dennis, 2020); and **CALIBRATE** used in the adjustment of observations at EDMI 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's standard operating procedure (SOP) regarding the NSRS prior to modernization. The initial 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 observing techniques improved to the point where this deformation could be more accurately observed), 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 (among other things) incorporate snapshots of geodetic control computed by NGS on a five or ten year basis, at reference epochs beginning with epoch 2020.00 (see section 2.11). These snapshots will consist of positions called ***reference epoch coordinates***. As before, the NCN will continue to operate with coordinate functions computed by NGS (called ***active coordinates***) through time, though the coordinate functions will be more readily available to users. However, an additional component, not previously available in the NSRS, will be coordinates computed by NGS at (or very near) the actual epoch when the data was collected, called ***survey epoch coordinates***. In this way, for example, a mark that has been occupied by a GNSS receiver seven times over 20 years would have seven different sets of survey epoch coordinates, each associated with some representative epoch at or very near when the observations occurred[34]. This sort of information will allow users to understand mark motion and underlying survey variations in a way previously not available. See section 2.11 for more detail.

Further, the current NSRS treats stations in the NCN as having purely linear velocities, rarely corrected when a CORS shows data that deviates regularly from its linear velocity. Post-modernization, the NCN will serve up coordinate functions at each CORS that may be non-linear (if appropriate), and that will be monitored daily for any persistent (or extreme episodic) 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.

[34] An epoch is instantaneous, while observations span some finite period of time. When coordinates are "associated with some *representative epoch* at or very near when the observations occurred", this really means that a *representative epoch* will be chosen (such as the midpoint time of the observations) for the coordinates computed from all those observations.

2.2 Definitional Constants, Models, and Data

The modernized NSRS will begin with definitional constants and models (such as the choice of ellipsoid, and the gravity potential value of the geoid). As these are extensively discussed in the previous two Blueprint documents (NGS 2021a, NGS 2021b), they are not further outlined here.

As for definitional data, the primary source will be the modernized NCN, and explicitly the coordinate functions NGS assigns to each CORS. In other words, access to the geometric component of the NSRS will effectively be defined by the CORS coordinate functions (AKA active coordinates) in the ITRF2020.

Further information is found in Section 2.7.

2.3 A New Database

One of the main contributors to 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 current database (the "NGS IDB").

One might think of the current NSRS as "whatever is in the NGS IDB," and that would have been reasonable based on NGS's own public information. As of 2019, OPUS-Share is the online database for users to share their OPUS-S solutions, but it is stored outside of the IDB. Although these solutions are checked against the IDB when an OPUS-Share mark already exists in the IDB, since they are not in the IDB they are not considered "**part of** the NSRS," but rather "**tied to** the NSRS.[35]" And whereas parts of CORS coordinate functions are stored in the IDB, they are derived from a richer data stream containing much more information than is in the IDB.

In the modernized NSRS, 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.

2.4 New Types of Coordinates

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 reference 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

[35] The connection is not completely missing between OPUS-Share and the NGS IDB however. Users who submit an OPUS-Share solution to NGS which disagrees by more than 7 cm from the NGS IDB are informed. Sometimes errors are found in the OPUS solution, sometimes not. But those OPUS-Share solutions are not currently being used to update the NGS IDB coordinates.

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 section 3.2. However, it will be instructive to first define the five types of coordinates which will be supported in the modernized NSRS.

1. ***Reported coordinates***. These are coordinates directly reported to NGS without the data necessary for us to replicate or evaluate them. Examples include coordinates scaled off a map, coordinates reported from a smartphone, or even coordinates reported directly from an RTN rover without supporting vectors. As NGS cannot compute these coordinates, they are not "part of the NSRS." 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. Such coordinates are useful for locating marks in the field, or plotting them on a map, but should not be used in high-accuracy computations or applications.[36]

2. ***OPUS coordinates***. These are coordinates computed by OPUS[37] that have not been evaluated by anyone at NGS. If a user restricts OPUS to only use the constraints that OPUS recommends (specifically coordinates, weights, and other metadata pulled directly from the NSRS Database) then OPUS coordinates will have an additional label of "tied to the NSRS," but they are never "part of the NSRS." ***Only coordinates computed by NGS and stored in the NSRS database are "part of the NSRS."*** If a user modifies any of the OPUS-recommended constraints, they will still be able to use OPUS for computations and receive OPUS coordinates, but such coordinates will not carry the moniker "tied to the NSRS." Users can quickly determine coordinates with OPUS and may (at their own risk) use them as geodetic control. As users of the NSRS perform geodetic surveys and process the data from those surveys in OPUS, NGS will always encourage users to submit their data for quality control, and for use in the creation of NSRS coordinates (SECs and RECs; see later).

3. ***Reference epoch coordinates (RECs).*** These are coordinates computed by NGS in an adjustment project to estimate the coordinates at one of the official (every five or ten years, as currently planned) reference epochs NGS will define (NGS 2021a). Thus, they

[36] 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" (from a topographic map) or "HAND HELD" (from a low-accuracy GPS device).

[37] OPUS will compute coordinates based upon whatever data a user uploads, whatever constraints the user requests, at whatever epoch they request and in whatever frame they desire. In all such cases, the output coordinates will always be labeled OPUS coordinates, reflecting that NGS has in no way evaluated the computations.

are “part of the NSRS.” As (generally) all such coordinates come from observations that did not take place *at* the reference epoch, such coordinates require the introduction of an intra-frame velocity model (IFVM) into the adjustment, and thus the coordinates so computed are subject to all uncertainties and assumptions in the IFVM.[38] See Section 2.11, and Figure 3.

4. ***Survey epoch coordinates (SECs).*** These are coordinates computed by NGS using submitted data and its metadata, then checked, adjusted and *defined at one “survey epoch*.” Thus, they are “part of the NSRS.” These represent the best estimates we have of the coordinates at any mark at some specific point in time. See section 2.11, and Figure 3.

5. ***Active coordinates (ACs).*** Unlike all other coordinates, active coordinates are actually coordinate *functions in time*, and not associated with a specific epoch. They will only be generated by NGS at stations with active control, such as a continuous GNSS receiver or a continuous gravimeter. Thus, they are “part of the NSRS”. At a CORS, they will be identical to the CORS coordinate function (see Terminology Guide). They will not exist on passive control. See Figure 4.

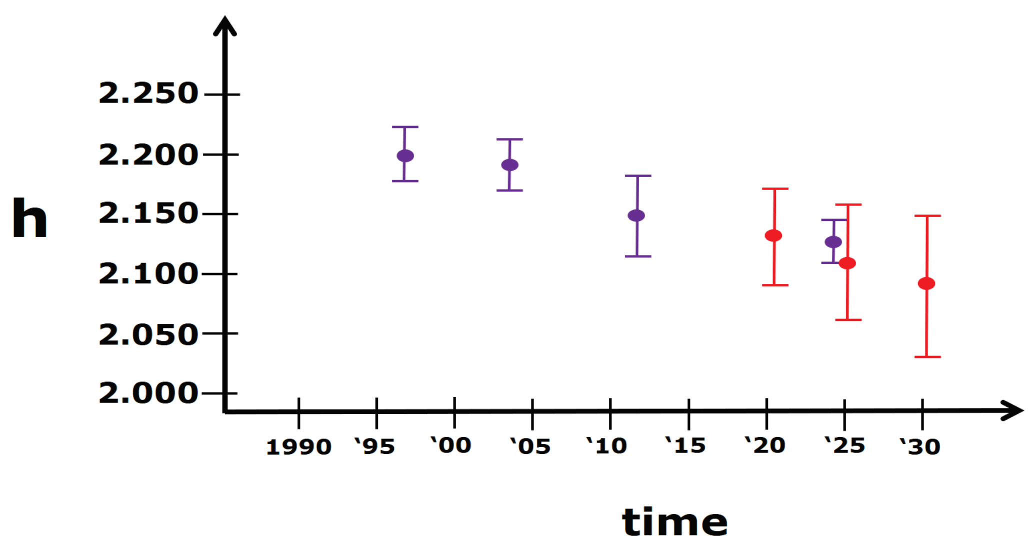

Figure 3: Ellipsoidal height SECs (purple) and RECs (red) for a fictitious point. Note that RECs are computed on a regular and repeating schedule, but SECs are computed specifically for when data is collected. As such, note the growing error bars for RECs going forward in time as no new data is being collected on this point.

[38] 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.

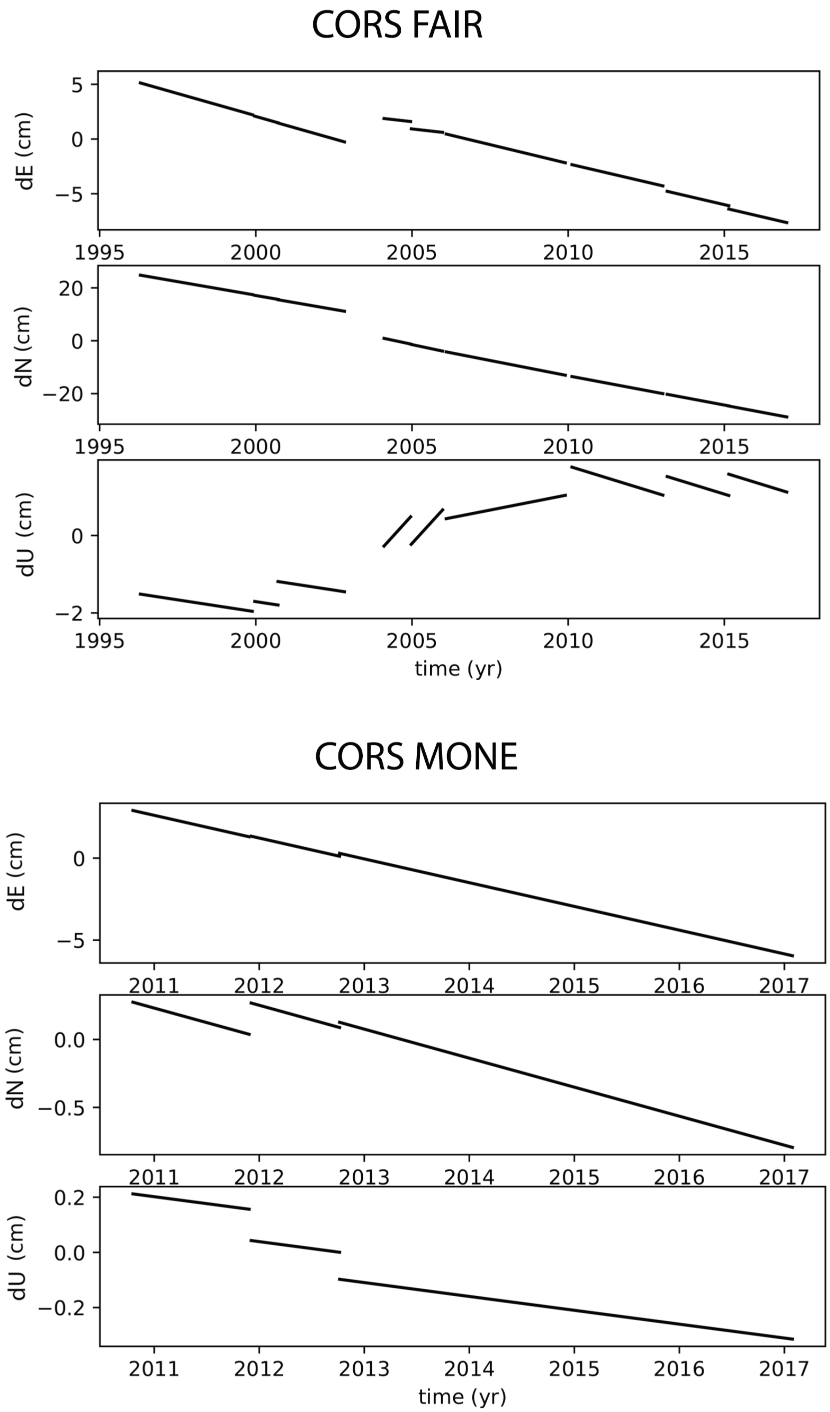

Figure 4: <u>Active Coordinates</u> on CORS FAIR (top) and MONE (bottom) as computed at NGS for the Multi-Year CORS Solution 2. Note the use of linear velocities and discontinuities only. Though active coordinates will be stored in X,Y,Z values (in the ITRF), they have been displayed here as changes in E, N, and U directions to emphasize the complex horizontal and vertical signals. Note the nearly constant velocities for MONE and inconsistent ones for FAIR.

Note that each type of coordinate (except active coordinates) listed above will also be identified with some epoch, if possible. Reported coordinates may or may not have a reliable date on which they were created, but if they do, it will be associated with them. OPUS coordinates will be computed and reported to users of OPUS at one or more epochs, depending upon the user's choices. Survey epoch coordinates will be tagged to a representative epoch (see Section 2.11.2) of the observations(s) used to determine the coordinates and will correspond to NGS's most accurate estimates of those coordinates. Reference epoch coordinates will always be reported at one of the reference epochs (currently scheduled to be every five or ten years, starting at 2020.00).

2.5 New Types of Non-Coordinate Information

Geodesy and surveying are, by their very nature, frequently concerned with differential, not absolute, observations. 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 or across time). Such differential observations are usually used in an adjustment to determine the best coordinates of marks (and their uncertainties), as long as some minimum number of absolute coordinates are known, a-priori. However, the coordinates are derived from the adjusted differential observations ("vectors") connecting them. An available output that can (and will in the future) be provided for adjustments is the best value for the differential vector connecting adjusted marks. This gives additional and useful information about the relationship between marks, rather than just at the marks themselves.

In the past, we have stored the differential observations, but rarely has NGS stored all the information of the a-posteriori (predicted) differential vectors. Neither the observed 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[39]. The individual observations inform how the coordinate can be determined in the absence of redundancy. In contrast, the a-posteriori differences reflect NGS's best estimate of the coordinate differences between points based on the adjustment of redundant observations, as well as the uncertainty of that coordinate difference. Such information cannot readily be obtained simply by differencing the absolute coordinates of two points or considering their uncertainties without accounting for correlation. The intent is to provide complete information about the relationship between marks, which is important in relative positioning.

[39] NGS has presented so-called "local accuracies" on datasheets. While this gives the uncertainty of the adjusted observation (differential vectors) between marks, it does not report the adjusted (best estimate) of the coordinate differences between the two marks.

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 differences between points.
   Including ΔX, ΔY, ΔZ and Δϕ, Δλ, Δh
2. Geopotential differences between points.
   Including differential orthometric heights and differential gravity

These values will come from adjustments performed that compute reference epoch coordinates (RECs), and survey epoch coordinates (SECs). When possible, such values will come with uncertainty estimates, as well.

2.6 The NOAA CORS Network

NGS will continue to process the collective data from the NOAA CORS Network (NCN) into CORS coordinate functions, one for each CORS. Whereas we do many other things with those data, it is the coordinate function that allows a CORS to serve as geodetic control. That coordinate function is ***a function, in time, of the ITRF 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.

Each CORS coordinate function spans the lifetime of that CORS and is a set of other shorter-duration functions, each of which is *continuous*. These shorter-duration functions do not necessarily abut one another in time, but they may. They do not, however, overlap one another in time. When they do not abut one another in time, there is a gap wherein the CORS coordinate function is not defined, therefore any given CORS coordinate function is either piecewise continuous or piecewise discontinuous.

Examples of more complicated (non-linear) CORS coordinate functions are shown below (from Bevis & Brown, 2014). While NGS does not currently compute nonlinear functions, these graphs provide inspiration and proof that some non-linear trajectories are real and will be considered in the future.

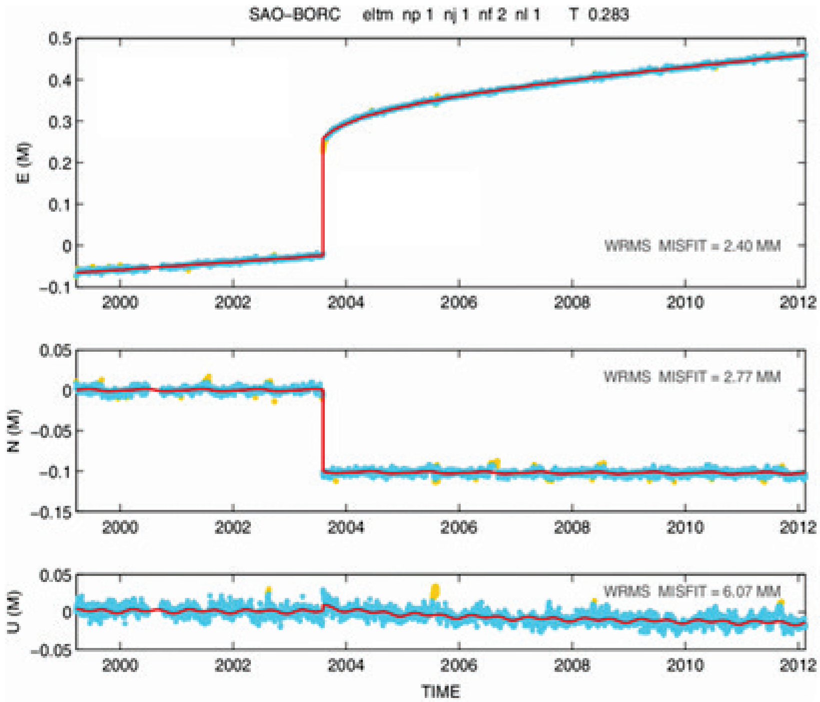

Figure 5: Example of non-linear coordinate functions

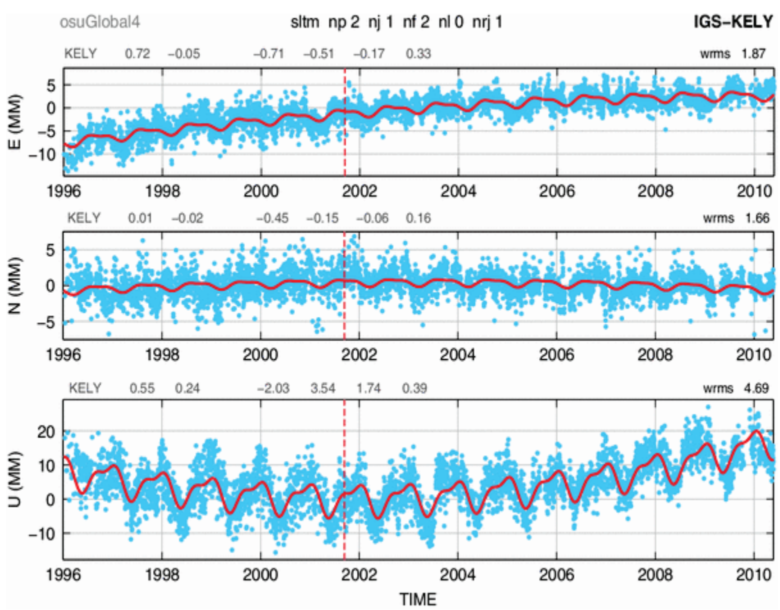

Figure 6: Example of non-linear coordinate functions

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.

2.7 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, 2021a) and a geopotential datum (NGS, 2021b). Because those documents already contain substantial detail, the following sections only briefly re-iterate the key points necessary for this document.

2.7.1 Terrestrial Reference Frames

First, NGS will perform most geometric computations in time-dependent Earth-Centered, Earth-Fixed (ECEF) Cartesian coordinates in the ITRF2020. All coordinates (and other information, such as accuracies, correlations, etc.) will be served up to users in that frame.

From the time-dependent ECEF Cartesian coordinates in the ITRF2020, the four sets of Euler pole parameters (EPPs) in EPP2022 will yield the same information in four NSRS terrestrial reference frames (TRFs) in addition to ITRF2020:

- 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 ECEF Cartesian coordinates (and related information) will be derived five sets of geodetic coordinates (geodetic latitude, geodetic longitude, and ellipsoidal 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.

2.7.2 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 NCN and the use of GNSS and OPUS. That means, access to absolute *orthometric* heights initially comes from ellipsoidal heights, minus GEOID2022. However, for the highest accuracy *differential* orthometric heights, leveling will remain the primary tool. Later sections will delve into the method by which GNSS and leveling should 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 tied to NAPGD2022. 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 OPUS coordinates (such as the current OPUS-S and OPUS-RS). That means an OPUS solution will yield not only geometric coordinates (both Cartesian and geodetic), but also the following:[40]

- 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 values on grids defined at the surface of the Earth.

2.8 Intra-frame Velocity Model

NGS is committed to providing an intra-frame velocity model (IFVM) to capture the residual horizontal motions and complete ellipsoidal height motions of geodetic control points within all four terrestrial reference frames of the modernized NSRS (NGS, 2021a). The exact nature of the IFVM is under development, but its use inside of the modernized NSRS is already clear.

The IFVM will be used in the following ways:

1) It will serve as stochastic prior information in NGS software when coordinates are estimated at an epoch that is different from the epoch when the data were collected. Examples include:
    a) Someone requesting an OPUS coordinate at an epoch besides the epoch at which their data were collected
    b) Someone requesting that OPUS compare two different surveys performed at different times
    c) NGS's reference epoch adjustment projects (geometric, orthometric and gravimetric)
    d) NGS's survey epoch adjustment projects (geometric, orthometric and gravimetric)
2) 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 or ten years. Pre-modernized NSRS geometric coordinates (NAD 83(2011/PA11/MA11) epoch 2010.00) will be connected to NATRF2022/PATRF2022/CATRF2022/MATRF2022 at epoch 2020.00 by *NADCON*. However, to connect the 2020.00 RECs to 2025.00 RECs, *IFVM2022* will be used, as it will

[40] 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 (NGS 2021b). 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 DEFLEC2022 (ibid), NGS can provide improved estimates of the listed quantities.

be used for connecting 2025.00 to 2030.00, etc. Thus, from 2020.00 forward, NADCON and IFVM2022 will be identical. However, this subtlety will be invisible to 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 coordinates to be transformed into NATRF2022 coordinates at epoch 2035.00, and NCAT or VDatum will do so without the user realizing that NADCON did part of the work (until 2020.00) and IFVM2022 did another part (after 2020.00). 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.

2.9 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 plan to produce in support of these changes. For now, only the GNSS and leveling specifications are discussed, though NGS is considering new specifications for gravimetry and other surveying techniques.

2.9.1 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 ellipsoidal heights, thus making the methodology in NGS 59 entirely obsolete.

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

- The need for redundancy,
- The quality of a stand-alone GNSS occupation (i.e., connected only to the NCN but no other passive marks),
- Using RTK/RTN data,
- Best survey practices of RTK/RTN and static GNSS for best determination of geometric coordinates

Users who follow these specifications should be able to achieve the desired level of accuracy for GNSS-derived geometric coordinates. In addition, the document will discuss the interaction of those best survey practices with the future version of OPUS.

2.9.2 Leveling

It is unlikely that anything 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 likely be quite extensive, so a brief summary of its expected contents is found in the paragraphs below.

First, the determination of some reliable *absolute* heights (as starting control for a leveling project) must occur, if the survey is to yield heights and not height differences alone. The most reliable source would be a new GNSS survey near the time and space of the leveling survey. That could mean some short RTK/RTN occupations (following the methodology in the document to replace NGS 58). Reliance on previously determined heights from the NSRS database on passive control comes with risk, which NGS will address in the manual. Further, leveling surveys are known to be time consuming, so time-dependency must be considered when defining the maximum permissible time span for which a leveling survey should be processed so that the heights (or height differences) can justifiably be assigned to a single representative epoch. For now, the new leveling specifications will recommend the processing and submitting of geodetic leveling surveys where the leveling observations span no more than any twelve month period.

If GNSS occupations are used to establish reliable absolute heights as control for geodetic leveling, the recommendations for how many and how frequently are tentatively looking like this:

- Leveling field observations should be processed in time spans of not more than one year. Longer projects should be broken into sub-projects of one year or less.
- A minimum of three "primary control marks" should be in the level network for every project, whose purpose is to provide access to NAPGD2022 orthometric heights.
- 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 should have the following GNSS occupations (details on using GNSS occupations to work in the NSRS will be found in the update to NGS 58):

  A minimum of two occupations within +/- half the size of a geometric adjustment window of the **beginning** of leveling, but also falling within one geometric adjustment window and whose local start times are separated by between 3 and 21 hours.

    It is preferable that all occupations on *any* primary control mark occur within the same geometric adjustment window as those of all *other* primary control marks.

  A minimum of two occupations within +/- half the size of a geometric adjustment window of the **end** of leveling, but also falling within one geometric adjustment window and whose local start times are separated by between 3 and 21 hours.

    It is preferable that all occupations on *any* primary control mark occur within the same geometric adjustment window as those of all *other* primary control marks.

To better visualize the complexity of this rule, consider Figure 7, below.

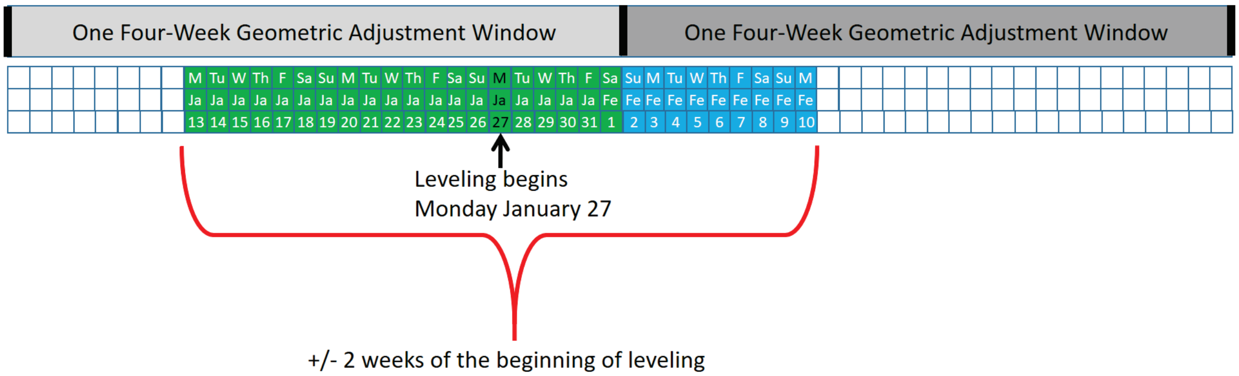

FIGURE 7: Visualizing how leveling and redundant GNSS fit on the calendar

In the Figure 7 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 should fall in the same geometric adjustment window (seen as the gray bars on the above figure). Second, all GNSS occupations should fall within the +/- 2-week span (the half-size of a geometric adjustment window) 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. It would be best practice either to do (at least) two redundant occupations of GNSS on all primary control marks in the green days, or to do so in the blue days. All projects exceeding six months should 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 should follow the "minimum of two occupations" rule as per above, and each mark's occupation should fall in the same geometric adjustment window, with a preference that all primary control marks are occupied in the same geometric adjustment window.

- All GNSS data should first be processed and adjusted (relying upon the IFVM) to yield absolute ellipsoidal heights (at some representative epoch of all the GNSS occupations, likely near the middle of the leveling project timespan). These ellipsoidal heights will be combined with GEOID2022 to yield absolute orthometric heights at that same representative epoch. These GNSS-based orthometric heights at the representative epoch will then serve as stochastic control for the leveling adjustment (i.e., control weighted based on the estimated ellipsoidal height and geoid accuracy).
- The final adjustment of leveling data (relying upon the IFVM and GEOID2022) will yield orthometric heights at the representative epoch as well as predicted differential heights between marks in the survey.

- Additional guidance (TBD) will be given to users interested in more than adjusted orthometric heights (such as adjusted latitudes, longitudes, or ellipsoidal heights) in such mixed GNSS/leveling projects.

All leveling processed through OPUS will automatically interpolate the GRAV2022 surface gravity model as part of the corrections applied to leveling observations. However, users who make their own gravity observations can use them instead for any leveling project processed in OPUS. As with other OPUS processing, such leveling will be "tied to the NSRS" if the gravity observations follow OPUS recommendations to ensure consistency with NAPDG2022.

2.10 Survey Epoch Coordinates

In the modernized NSRS, NGS will be computing two different types of coordinates on passive control and making them available to the public through the NSRS database. The first, which is a best attempt at true time-dependent coordinates are survey epoch coordinates (SECs). NGS will define very specific rules regarding how data are processed into SECs for loading into the NSRS database. The remainder of this section will draw on previous sections and will outline exactly how NGS will process submitted projects into definitive time-dependent coordinates on passive marks.

The second type of computed coordinate for passive control, reference epoch coordinates (RECs), will be addressed in section 2.12.

2.10.1 Time-Dependency: Basic Approach

The most accurate way for NGS to put a coordinate on a point in the modernized NSRS is to associate that coordinate with the actual time (or very close to the actual time) the data was collected at that point. This is because nearly no assumptions about mark movement through time (which would come from the IFVM) need be made for this approach. This will be the approach for survey epoch coordinates (SECs).

Of course, data are rarely collected instantaneously (and most geodetic data even less so), therefore, for data collections spanning various lengths of time, *choices* must be made regarding what epoch will be used in an adjustment for SECs. Some initial decisions have been made at NGS for a few different data types. While reasonable, each of these decisions will be carefully tested before being finalized. The different techniques will be discussed in sections 2.11.2 through 2.11.4.

One last note, on naming. The creation of SECs as discussed in the next three sections will occur in <u>adjustment projects</u> (to distinguish them from <u>survey projects</u>). Until or unless NGS decides on a different naming scheme, these adjustment projects will follow this naming scheme:

SEC.Adjustment.Project.TYPE.Start Date.Start Time.End Date.End Time.Iteration

Where:

- TYPE = Geometric, Orthometric, or Gravimetric[41]
- The start & stop dates and times[42] reflect the adjustment window (see Terminology guide) for data and observations that go into the project (with the midpoint epoch of a data file determining if a data file does or does not go into the project). This use of specific dates and times in the adjustment project name allows for substantial flexibility, not only to use different lengths of time (such as four weeks for geometric adjustments versus one year for orthometric) but also to allow breaking up regularly divided adjustment projects into sub-projects. An example is splitting a single geometric adjustment project spanning a four-week adjustment window into two adjustment projects (each with its own adjustment window) if a massive earthquake happens to occur within the original geometric adjustment window. Otherwise the assumption that the coordinates of all points can be assumed constant within an adjustment project is not valid.
- Iteration will begin with 001 for the first computation. Later, if new data comes along or a blunder needs to be corrected, iteration numbers will be ramped up.

2.10.2 Geometric Survey Epoch Coordinates (SECs) from GNSS and Classical Surveying Techniques

The processing of GNSS data into coordinates will, for the time being, continue to rely upon a step called "simultaneous processing," a technique built into (among other software) the NGS program PAGES (and its currently unnamed replacement, due to be complete in early 2022). Simultaneous processing co-processes all GNSS data from common satellites collected by multiple receivers at the same time into a single solution. This solution is represented as a set of correlated vectors equal to the number of receivers minus one, with no dependent ("trivial") vectors.

These vectors are of a geometrically similar nature to vectors that come from RTK/RTN techniques and most commercial baseline post-processing software, but they may differ somewhat stochastically. The main source of this difference is that such RTK/RTN vectors are sequentially processed, between a single pair of receivers, and so correlations between simultaneous observations are not determined. For sequentially post-processed solutions, trivial vectors (a source of false redundancy) are possible, but if they occur, OPUS will be able to identify and have a variety of means to handle them.

Finally, such vectors are of a similar geometric nature to angles and distances collected in classical survey techniques.

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[41] NGS neither performs nor receives other survey types on any sort of regular basis. Nonetheless, it is conceivable that some small SEC projects may be created to cover uncommon surveys, such as astronomic and/or DoV surveys. But these would be created and executed only on an ad hoc basis, and only for those rare epochs when such survey data were actually collected.

[42] The time system used in these adjustment project names has not been decided. Top candidates are UTC and GPS time.

Therefore, NGS is considering the creation of geometric SECs through a combined adjustment of simultaneously and sequentially post-processed GNSS vectors, RTK/RTN vectors, and classical data.

Choosing a survey epoch for one or more occupations on passive control is tricky. For decades, OPUS, 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 coordinates are reported at the weighted mean time of all occupations.

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

First, all GNSS (including RTK/RTN) or classical occupations over marks, must fall within the same geometric adjustment window, in order to be processed within a single geometric SEC adjustment project. NGS decided on the following for the initial tests of the modernized NSRS. Like all decisions, this is, of course, subject to change. For now, however, we have decided, for GNSS occupations and classical data, survey epoch coordinates will be computed as:

> ***One or more GNSS occupation(s) with or without classic survey occupations over a single mark will be processed into one survey epoch coordinate triad,[43] if all occupations take place within one geometric adjustment window[44]***

The set of four consecutive GPS weeks is pre-defined and based on the first window consisting of GPS weeks 0 through 3, the second of weeks 4 through 7, etc. (GPS week 0 begins on Sunday, January 6, 1980). This type of scheme will almost certainly be employed regardless of the actual number of weeks used to define the geometric adjustment window.

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 redundant observations on marks so they fall within a single geometric adjustment window.

It is worth asking *why* a user would care whether they collect data within a geometric adjustment window, especially since OPUS will continue to process their data no matter how it is collected. The answer really isn't about the user's processing of OPUS, but about whether they care what happens to their data after submission to NGS.

If a user submits two occupations on one mark, but they happen to fall in two consecutive geometric adjustment windows, NGS will use them to create two distinct survey epoch

[43] 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.
[44] Initial plan is for the geometric adjustment window to span four consecutive GPS weeks.

coordinates (in consecutive geometric SEC adjustment projects), each one being based upon just one occupation. Having two SECs without redundant occupations back-to-back in the database certainly seems less useful than having a single SEC built from redundant occupations. So, while NGS will encourage GNSS data to be collected in a single geometric adjustment window for the sake of redundancy, we have plans to work with data that does not strictly follow this scheme.

In addition to the decision to work within a geometric adjustment window for adjusting geometric SECs, a few other plans are in place:

1) Any GNSS data used in computing geometric survey epoch coordinates will always be processed with final IGS orbits. Currently, these orbits are released once a week, with an approximate two-week lag time.
2) NGS will always combine all GNSS and classical data submitted from any source into a single geometric SEC adjustment project spanning one geometric adjustment window. That is, if three survey projects happen to have GNSS and/or classical data in the same geometric adjustment window, we will combine them, simultaneously process the GNSS data together in sessions (with no regard for their having come from different survey projects), combine these simultaneous session-generated vectors with any RTN/RTK or third-party post-processed vectors and classical observations and perform a final adjustment.[45] Because this sort of joint processing is only done at NGS using very specific adjustment rules, NSRS users can never be guaranteed that the OPUS coordinates they get will be identical to the NGS-computed survey epoch coordinates.

The workflow outlined above, will occur once for every geometric adjustment window, performed some period of time after the window. The question is, "how far after the window?" This is a tricky question and one which will not be resolved until NGS performs more experiments. 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 survey epoch coordinates. On the other hand, NSRS users tend to submit data quickly (as a rule), but there are numerous examples of data submitted months or even years after a survey project is complete. However, for us to process (and load survey epoch 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 SECs have already been available to the public.

We therefore have proposed, as an initial plan based on a 4-GPS week geometric adjustment window, to adopt a processing cycle based on a twelve-week waiting period (See Figure 8). Thus, each geometric SEC adjustment project will begin twelve weeks after the end of the geometric adjustment window itself, and will use data submitted to NGS within that geometric adjustment window. Data submitted *after* a particular geometric SEC adjustment project has been processed will be placed in a holding bin. Then, as time allows, but **no less often than once per year**, NGS will stand up a new (2nd iteration) geometric SEC adjustment project for that

[45] 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.

particular geometric adjustment window, only with some new rules. Notably, we intend to re-process that geometric SEC adjustment project, holding *fixed* all the coordinates from points with data that were already processed.

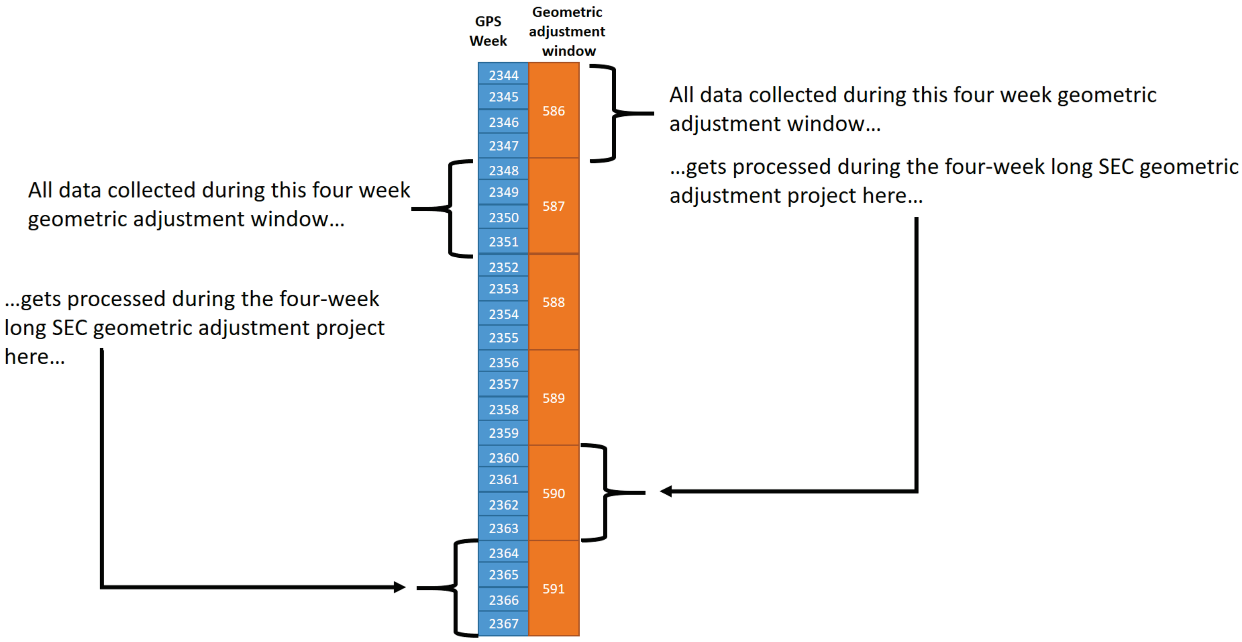

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Figure 8: Timeline of geometric adjustment window-based processing with a 12-week lag time

If it so happens that a user wishes for their data to be used by NGS to compute SECs, then that data will need to be submitted to NGS within 12–16 weeks of collection (again, assuming the four-week size of a geometric adjustment window holds.) -This should, it is assumed, raise the further question of, "What about survey projects that take longer than twelve weeks?" The question is valid, but has a simple answer. Specifically, as you load data into your survey project in OPUS, you 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 geometric adjustment window-by-geometric adjustment window basis, we can process any of your data that took place 12–16 weeks in the past into the appropriate SEC geometric adjustment project. Any data you find questionable can be thus tagged, and will be passed over by the NGS 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 and classical observations, the 4 week decision regarding data being considered simultaneous could not be justified when considering leveling. More information concerning that is in the next section.

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

2.10.3 Orthometric Survey Epoch Coordinates (SECs) from Leveling

As mentioned in an earlier section, with the modernized NSRS, NGS will recommend new GNSS observations for all leveling projects, rather than relying on pre-computed heights at passive control. We hope that, in time, the use of GNSS will be so pervasive that the idea of relying on some "old" height becomes anathema to good surveying practice.

However, as leveling is a significantly more time-consuming practice than GNSS surveying, certain allowances must be made when NGS considers how they will adjust orthometric survey epoch coordinates. 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. Finally, the working group tentatively decided that an orthometric adjustment window of 1 year was an appropriate amount of time to both allow for large amounts of leveling data to be collected and submitted, while at the same time not allowing for substantial height changes to impact the result. As experience grows, this decision on a 1 year window may be revisited.

This allowance for the orthometric SEC adjustment project 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.

Further, in order for NGS to maintain a semblance of order to orthometric SECs, a preliminary decision was made to set the orthometric adjustment window to one *calendar* year (Jan 1 through Dec 31). See section 3.3 for more information.

What will NGS do if there is submitted leveling data, but no associated GNSS data? Such a situation will occur if either (a) users submit leveling data but no GNSS data or (b) NGS begins computing SECs out of leveling that predates GPS. In such cases, NGS will need to consider one of two approaches. Either the adjustment will be done purely in a differential sense or else some approximate absolute control will need to be introduced. In either case the adjusted differential heights will be computed and made available, and will be associated with some representative epoch for that orthometric adjustment window (such as the midpoint of the calendar year, e.g. 2027.50 for calendar year 2027).

In anticipation of each orthometric SEC adjustment project, NGS derived a math model that could be used, and codified it as the use of stochastic constraints within the variance component model (Smith et al, 2020). However, even that model must be expanded to properly account for the uncertainties in the geoid and uncertainties in the IFVM.

2.10.4 Gravimetric Survey Epoch Coordinates (SECs) from Relative and Absolute Gravimetry

Similar to leveling, relative gravity surveys are differential, while absolute gravimetry provides absolute values at points.

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 user community. In a parallel vein as discussed above for leveling, NGS will certainly have some gravimetric SEC adjustment projects that have no absolute gravity control. In such situations, like leveling, the differential values themselves can and will still be adjusted, made available, and will be associated with some representative epoch for the entire adjustment window. Whether NGS uses some approximate absolute control or not remains an open research question.

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.

2.11 Reference Epoch Coordinates

In contrast to SECs, which are the coordinates of points loaded into the NSRS database at a survey epoch (some time at or very near when the data were collected), NGS will also attempt to estimate coordinates on points at reference epochs, currently scheduled to be five or ten years apart, beginning with 2020.00 (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 control, coordinate functions at the NCN and IGS network stations, the IFVM, GEOID2022 and DEFLEC2022.

It should be noted that there is no fixed adjustment window for REC projects, per se[46]. Rather, all possible data from all time will be considered for each REC project[47]. Such data will be thinned based upon age, geography, quality, and (in particular) upon the viability of the IFVM to accurately account for the full 3-D motions of marks (and associated observations) across the years. Every five or ten years, therefore, NGS will perform the first iteration of three reference epoch coordinate adjustment projects: geometric, orthometric, and gravimetric. Only by sheer happenstance would a survey take place on January 1, 2020 (or 2025, or 2030, etc.). Therefore, certain assumptions must be made when performing the REC computations, which will be addressed in each of the following sections.

To execute the first iteration of each REC adjustment project requires answers to at least the following questions:

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46 There will be a cutoff date for the last data to go in. For the 2020.00 projects, that cutoff date is December 31, 2021. But the cutoff for the earliest data cannot be determined without significant experimentation and will undoubtedly be geographically dependent at the least.

47 However, the first iteration of each REC adjustment project will likely be of a much larger scale than subsequent iterations. The first iteration will be "nationwide," encompassing all data available to NGS. Subsequent iterations will likely be smaller projects stood up with the intent of adding RECs to newly surveyed points which do not yet have RECs.

1) When will the first iteration of the REC adjustment project take place? Before the reference epoch? After the reference epoch?
2) What data will be used?
3) If, after NGS has computed the RECs, they acquire new data on a mark that might influence the recently computed RECs, will NGS update the RECs? If so, doesn't that 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 RECs every five or ten years on such points? Wouldn't that add exponential uncertainty and therefore uselessness of the estimated coordinates?
5) If, after the first iteration, NGS acquires new data on marks that do not have an REC, should NGS stand up latter iterations, and compute RECs, thus expanding the pool of points with RECs? If so, how big should such an adjustment be? Nationwide? Only a sub-network? And how often should these latter iterations be performed?
6) How much support for older reference epochs should NGS provide?

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

For every reference epoch, there will be an initial iteration of three unique adjustment projects; like the SEC adjustment projects, these will have a formal naming convention, which will (tentatively) look like this:

2020.REC.Adjustment.Project.TYPE.Iteration

Where:

- 2020 means the epoch of the adjustment (2020.00)
- TYPE = Geometric, Orthometric, or Gravimetric
- Iteration = 001 will be the main project itself. Any expansions to the REC data set (by the acquisition of new data or the correction of blunders) would ratchet up the iteration count.

In the first iteration of these three adjustment projects we will compute the vast majority of RECs for the most recently passed reference epoch. The first iteration of each REC adjustment 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[48].

> **Example:** The "**2020.REC.Adjustment.Project.Geometric.001**" will begin on January 1, 2022, and should end no later than December 31, 2022, and produce the vast majority of

[48] These are planned schedules only. Obviously the first REC adjustment projects will be the most complicated as entirely new ways of doing business are attempted and may take longer than 1 year. Future REC adjustment projects should be able to rely upon previous ones, reducing total calendar time for their completion.

2020.00 geometric RECs NGS will provide to the public. **<u>It will use data submitted to NGS through December 31, 2021.</u>**

It will be our policy that, for a given point and a given reference epoch, the RECs will ***never be changed***, with one exception: to correct a blunder[49]. This does not prevent us from *adding* new RECs (on points with new data that have not yet had an REC computed). But once computed, a REC should stand in perpetuity. With this in mind, if NGS receives observations on points that do not have an REC in the most recently passed reference epoch, then a new iteration of the appropriate REC adjustment project will be stood up, and the new RECs computed and added to the NSRS. For simplicity, this is likely to happen on the same schedule as SECs.

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

1) NSRS users are expected to have a strong reliance on RECs in the immediate future.
2) Frequent changes of RECs can cause confusion and job difficulties for NSRS users.
3) Tools, such as NADCON, require definitive RECs as input to their creation, and frequently changed RECs prevent a definitive set from being available.
4) NSRS users expect their good survey work to be reflected as coordinates in the NSRS on a timely basis.
5) NGS defines NSRS coordinates on passive control for a reason: for them to be used as geodetic control.

Therefore, the above workflow means marks will never (blunders aside) have more than one set of RECs for any given reference epoch, and that all data that support the creation of RECs will be turned into RECs on a timely basis.

From a practical standpoint this means NGS is expecting (and in fact encouraging) a regular[50] cycle of re-surveying activity at any marks users find particularly useful, in order to keep their REC 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.

As to the question of what data to use and/or what to do about substantially "old" data, that question can only be fully answered while performing tests in the actual REC adjustment projects. However, certain factors can be stated which will influence this decision:

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[49] Examples would include user-reported blunders that could not have been caught by NGS (say for an incorrectly reported fixed height pole), NGS software bugs, and other difficult to identify issues at the time of the original adjustment project.

[50] The best way to keep RECs current would be a re-survey cycle that matches the REC cycle, namely 5 or 10 years. However, as mentioned earlier, NGS will consider ***all*** historic data in its archives for each REC adjustment project. But as the age of data grows, so too does the chance that said data will be dropped from an REC adjustment project. Therefore NGS cannot guarantee that a mark will get an REC every five or ten years, unless NGS receives updated data on that mark "often enough" so that the data can be trusted, though how often (past 5 or 10 years) cannot be answered except on a mark-by-mark basis.

1) The further in time that an observation is from the reference epoch, the more NGS will have to rely on the IFVM to estimate mark movement through the years
2) The IFVM should reflect mark motion, but many existing data sources that might go into the IFVM (geodynamic models, InSAR) are actually models of surface motion.
    a. Horizontally, surface motion is expected to have a very high correlation with mark motion
    b. Vertically, surface motion would only correlate with mark motion for certain mark settings. For others, particularly deep driven rods, their very reason for existing is to separate mark motion from surface motion, leaving a weak correlation, if any.
3) The movement of marks through time is geographically dependent. Subsidence that might be seen in the Gulf coast might be missing in the great plains. Non-rotational horizontal tectonic movement might be seen in California, but not in the Atlantic coast.
4) The ITRF2020 coordinate functions at NCN and IGS Network will serve as prior information to the geometric REC adjustment projects. The geometric RECs will generate orthometric heights which will serve as prior information to the orthometric REC adjustment projects. The NCN and IGS Network only have coordinate functions back to 1994 in ITRF2014. It is a reasonable assumption that when coordinate functions for ITRF2020 are created they will similarly go back only to 1994.

With all of these factors, it is impossible to state exactly what data will and will not go into each REC adjustment project. A discussion of possible data limits is provided in each of the sections below.

2.11.1 Geometric Reference Epoch Coordinates (RECs) from GNSS and Classical Surveying Techniques

For reference epoch 2020.00, the first iteration of this adjustment will probably be built mostly from pre-existing GPS vectors at NGS. The historic workflow at NGS ("Bluebooking") did not prepare us for the possibility of re-processing all historic raw GPS data, and a scoping study within NGS estimated a total of 40 person years would be needed to properly associate each raw GPS file in NGS archives with the right PID, antenna height, and antenna type for it to be properly re-processed. Going forward, with OPUS pre-organizing raw GNSS data, this is not an issue, but for most GNSS data before about 2007[51], NGS is likely to rely upon existing vectors.

Very little classical surveying data exists in NGS archives after about 2010, which reflects how the surveying community relied on GPS. However, what is available will also be part of this adjustment project.

Finally, a few years of RTN and RTK vectors are also expected to participate, if NGS gets the RTK/RTN expansion to OPUS-Projects live in 2021, which is the current plan.

[51] The approximate date when the current "OPUS-Share" service was stood up, at which time raw data was organized during submission and therefore lends itself well to easy batch reprocessing.

As mentioned earlier, it is not clear what the age limit will be for data to participate in the iterations of this adjustment project. However, in anticipation that an age limit might exist, NGS issued a Federal Register Notice (FRN)[52] on this topic in 2020, encouraging the NSRS user community to submit what data they have, with a special focus on new observations since 2010.

The latest observation date for data to enter the first iteration of the REC adjustment projects is December 31, 2021. Beginning in 2022, all three REC adjustment projects should begin in earnest. Adjusted XYZ values at 2020.00 in ITRF2020 will be the primary output value of the 2020 geometric REC adjustment project, from which a number of subsidiary values will be created:

- XYZ values in the four NSRS terrestrial reference frames, at 2020.00
- φλh values in ITRF2020 and the four NSRS terrestrial reference frames, at 2020.00
- H values in NAPGD2022, at 2020.00[53]
- Differential coordinates between some points[54]
- Uncertainty estimates for all of the above

The first iteration will be a massive effort, particularly for the 2020 project. However, once that is successful, the organization of data should carry over well to latter iterations of the 2020 adjustment project, as well as subsequent REC adjustment projects.

2.11.2 Orthometric Reference Epoch Coordinates (RECs) from Leveling

Most leveling data in NGS archives comes from the mid-20th century, in support of the NAVD 88 project. Because that data pre-dates GPS and is exclusively about height information, and because the least reliable portion of the IFVM is expected to be in the vertical, it is not obvious that such leveling data will participate in the 2020 orthometric REC adjustment projects.

On the other hand, if NGS restricts itself to, say, post-1994 leveling data only (so as to rely on the orthometric heights derived from the geometric REC adjustment projects), then it will probably contain very inconsistently distributed leveling-based RECs around the nation, and a quantitatively much smaller sample of points.

[52] https://www.federalregister.gov/documents/2020/07/24/2020-16084/consideration-of-potential-age-limiting-observations-to-be-used-to-compute-202000-reference-epoch

[53] If there is no leveling to a mark, then its orthometric height, based on the geometric REC adjustment project, will be loaded as an orthometric REC. However, for all marks that do have leveling, these geometric-based orthometric heights will instead serve as stochastic prior information to the 2020 orthometric REC adjustment project, from which orthometric RECs will be computed.

[54] Adjusted differential values are simple to compute for points that are "directly connected" (e.g. a GNSS vector between two points was one of the input pseudo-observations to the adjustment). Computing differential coordinates between other pairs of points is more complicated and less likely to be an output of the adjustment project.

The real question, therefore, is how well the IFVM can actually model, mark by mark, the vertical movements throughout the decades. As of right now, that question is open.

Because the idea of excluding hundreds of thousands of kilometers of historic leveling from the 2020 adjustments is such a serious consideration, it is worth expanding a few words about why the IFVM vertical component is such a problem. First, it must actually be a model of *mark* motion, not *surface* motion. That means, mark-by-mark, it would need to model each mark's vertical motion. Even if NGS had a reliable vertical *surface* motion model, and NGS could believe the *setting* metadata for each mark, certain assumptions would have to be made. For example, concrete bells might be assumed to move like the surface, but marks set into buildings with deep foundations might be slightly decorrelated from surrounding surface motion, and perhaps rods driven to refusal would need to be substantially decorrelated from surface motion. But deep driven rods are susceptible to uplift of deep bedrock structures, even if they are decorrelated from soil compaction. And sometimes rods are not driven to refusal, but to a "slow driving rate" like 60 seconds per foot. These rods, having failed to hit bedrock may move differently in the vertical than the "driven-to-refusal" ones.

The point is, unless NGS has actual re-observations on every mark or NGS has a comprehensive study on every setting type, to determine how it moves in relationship to the surface, the IFVM is not likely to have mark-by-mark vertical motion information of any significant years-long reliability.

Now, let us say we accept this situation and nonetheless want to use the IFVM to propagate some 1950's leveling observations to 2020.00 for the first iteration of the 2020 orthometric REC adjustment project. Let us say that we attempt to recognize the failure of the IFVM to properly capture mark-by-mark vertical motion by giving the IFVM-based vertical velocities some large uncertainties. If NGS had the data, we might be able to come up with a correlation function to help. For instance, we might learn that two marks with the same setting that are on either end of a single leveling section might have vertical movements that correlate near 1.0. Or we might learn that they correlate at 0.85. But these tests haven't been done in any formal way yet, and without substantial re-survey data, they can't easily be done. Assuming they are not done, NGS would have to make some assumptions about correlation of vertical movement at a distance and assign some reasonable values. Let's take a worst case scenario, where NGS makes no assumption about mark correlation over distances, and assigns something like +/- 1 cm/year uncertainties on each mark. That means the adjustment would have a hypothetical a-priori standard deviation of +/- 70 cm on each mark's height from the 1950s. Now this may get reduced to a more reasonable value in the a-posteriori uncertainties, especially if the math model is set up properly to yield the right variances of unit weight, but the simple fact is that we don't know.

All of the last few paragraphs say the same thing—it will be a lot of work, possibly more than can reasonably be expected, for NGS to do scientific justice to the use of decades-old leveling data, but we will certainly examine the situation.

2.11.3 Gravimetric Reference Epoch Coordinates (RECs) from Absolute and Relative Gravimetry

The least cohesive adjustment for 2020 RECs will be in gravimetry. This is because of a few factors:

1) Gravity changes significantly based on local environmental factors, and therefore the potential for large uncertainties in 2020 gravimetric RECs is high.
2) There is very little relative gravity data in NGS archives that are both recent and on geodetic control marks.
3) Many absolute and relative gravity surveys are disconnected from one another.

With these concerns in place, it is not obvious that NGS must compute 2020.00 gravimetric RECs. Nonetheless, the prospect is on the table and will be investigated. No significant details beyond this are available at this time.

2.12 OPUS ("Re-invented Bluebooking")

The Online Positioning User Service (OPUS), will be the name of the ***suite*** of products NGS provides to the public. 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. Everything from simple mark recoveries by the public to complicated survey campaigns comprised of many years and involving GNSS, 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 (or all) of five reference frames (ITRF2020, NATRF2022, PATRF2022, CATRF2022, and MATRF2022) to output your data, though geometric adjustments will be limited to the ITRF2020, with Euler pole parameters (EPPs) used to convert to the other four frames. You will be allowed to estimate coordinates at any epoch of your choosing.

However, just because OPUS can process your data in a variety of ways, does not mean every choice is the right one. NGS plans to support users by guiding them down the paths of "best practice". Examples of this guidance will include the following:

1) For leveling surveys, OPUS will allow users 3 options of a-priori absolute height control: (a) collect your own GNSS-based orthometric heights within your survey, (b) rely on previously computed heights on passive control from the NSRS database or (c) provide no absolute height control. But the NGS guidance will be toward option a, and users who go with option c will only be provided with adjusted *differential* heights. No matter the source (or lack thereof) of absolute control, OPUS will require that every mark in a leveling survey have some horizontal coordinates for the purposes of data reduction.

Horizontal coordinates collected from, and with the accuracy of, current cell phone technology is acceptable for this purpose.

2) For GNSS surveys, OPUS will provide a CORS data quality assessment system that will auto-select stations based upon data quality and availability. OPUS will recommend the use of certain stations but will allow users the flexibility to ignore them.
3) For classical surveys, OPUS will require some GNSS data on at least three control points. This is due to the nature of classical data, where each occupation allows data to be collected relative to a local horizon system. In order for this data to be processed into a system that NGS can use for maintaining the NSRS, it must be related to a global ECEF frame, and this will be accomplished through those GNSS occupations.
4) For most surveys in general, OPUS will recommend computing coordinates at one of two (possibly three) epochs. The first would be a representative epoch that is at or very near when the observations were collected (to have little to no reliance upon the IFVM). The second would be the most recently passed of NGS's official reference epochs. Optionally, if NGS chooses to produce RECs on a five, rather than ten, year basis, then a third epoch will be supported: the reference epoch before the most recently passed reference epoch. (That is, if RECs for 2020.00, 2025.00 and 2030.00 exist, and 2030.00 is the most recent, then OPUS will recommend adjusting to either 2030.00 or 2025.00, but not 2020.00. No matter which epoch OPUS recommends, users will be able to estimate coordinates at any epoch (or epochs) they choose (within reason[55]).
5) For most surveys in general, NGS will recommend using NSRS control from the NSRS database (including both active and passive control). For users who follow these recommendations, their OPUS coordinates will also be labeled "tied to the NSRS." But for users who choose to change any OPUS-provided control coordinates (or weights or other recommendations) two things will happen:

   a) OPUS will warn them that they are deviating from OPUS-provided recommendations, and their results will be "not tied to the NSRS."

   b) Their OPUS solution will explicitly state that their OPUS coordinates are "*not* tied to the NSRS."

   In both cases, OPUS will provide an explanation as to why the coordinates are not tied to the NSRS.

   No matter which choices are made, OPUS will always label the output coordinates as OPUS coordinates to reflect that these coordinates did not come from the NSRS database. In neither case will OPUS coordinates be considered "part of the NSRS."

[55] For the initial roll-out of the modernized NSRS, reasonable epochs which OPUS will allow users to choose, will range from the day the user is actually using OPUS back to January 1, 1994. Choosing dates before then will not initially be possible, as that is the earliest expected date that CORS coordinate functions in ITRF2020 will be available, and choosing dates in the future would be dangerous, due to the impossibility of predicting things like earthquakes, and would yield coordinates not tied to the NSRS.

In summary, OPUS should serve your needs, and within reasonable limits can provide you coordinates that are tied to the NSRS at the epoch of your choosing.

When you have performed a survey, NGS hopes you will submit your data to us for the expansion and improvement of the NSRS. However, because NGS is expanding OPUS to work with a variety of survey instruments, and because such instruments can output data in different formats (depending on manufacturer and other variables), NGS will build the modernized OPUS suite to work with ***only one*** format for ***each*** type of instrument. Such decisions on format will be coordinated both with industry partners as well as the International Association of Geodesy. As each data format choice is finalized, it will be documented and a Federal Register Notice (FRN) issued. While the exact names and contents of each format have not yet been determined, a few things are known, and are listed below:

Table 2: Current status of NGS's "standard file format" project

Instrument / Data type	**Format**
GNSS / raw data	RINEX version 3 or higher[56]
GNSS / processed vectors	GVX (currently under development)
Total Station	TBD
Digital Level	TBD
Relative gravimeter	TBD

Simple mark recoveries or new mark reports are always welcome (submitting, say, a photograph and a location using cell phone location accuracy). However, for survey projects, **we are only interested in surveys on geodetic control marks each with a uniquely defined point of a permanent nature. Positions of mailboxes, manhole covers, wooden stakes, nails, or any other object that might possibly be part of a survey are not of interest to us. We recognized that sometimes a survey contains observations to a mix of "high quality geodetic control marks" and "other things" like nails or temporary bench marks. Submissions containing data on things that are non-permanent and/or not points will still be accepted, but only NGS-computed SEC and REC coordinates on high quality geodetic control marks will be made available to the public from the NSRS database.**

How you process your data is your business. Your choices, using or not using 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, how we will use your data to compute and provide coordinates (SECs or RECs) on passive control. However, no matter

[56] For archival and historical purposes, RINEX 2 will continue to be supported, but going forward, when RINEX 3 is possible, it will be required.

whether you choose to process data at the OPUS-recommended representative epoch or process it at some other epoch of your choosing, the type of coordinates OPUS will provide to you will always be labeled OPUS coordinates.

One final note regarding coordinate types (see section 2.5): there are only three types of coordinates that will come from computations performed at NGS and stored in the NSRS database: reference epoch coordinates (RECs), survey epoch coordinates (SECs) and active coordinates (ACs). 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 OPUS coordinates. Whereas it is possible your OPUS coordinates could perfectly match the reference epoch coordinates or survey epoch coordinates on a point, we only use those data you submit to NGS to make reference epoch coordinates or survey epoch 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 OPUS coordinates do not have the same rigid creation rules as NGS-generated coordinates, they will not be loaded into the NSRS database, and therefore will not be available through the data delivery system. However, NGS recognizes that users may have a desire, or even a contractual obligation, to share their OPUS coordinates with others. As such, as NGS builds the modernized version of OPUS, a new element will be added, sharing. Specifically, if an OPUS user has performed a survey, and processed their data into OPUS coordinates, those coordinates will be available to the public through a shareable URL provided to the OPUS user. See Figure 9. In this way, OPUS coordinates and a reported coordinate PID can be immediately made available to anyone with the right URL. If, however, a user requires that their survey be used to create NSRS coordinates (either SECs or RECs), then NGS will require that survey to be submitted, quality controlled and NGS will then take the required time to stand up the right iterations of SEC and REC adjustment projects.

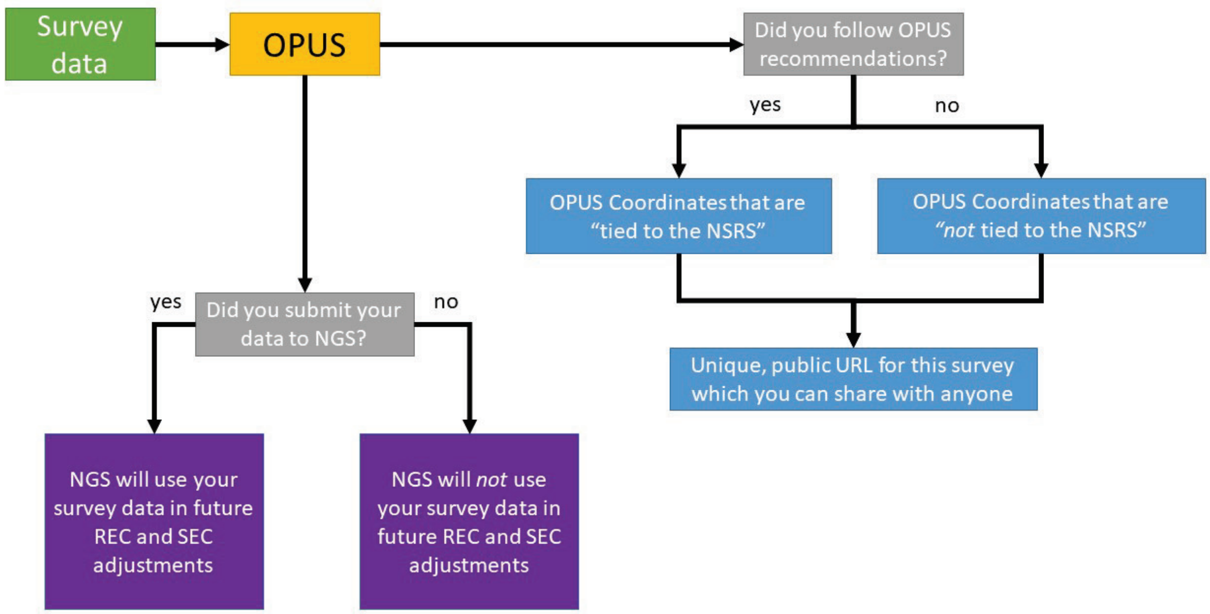

Figure 9: The two paths data are used in OPUS – to create OPUS coordinates and/or to create SECs and RECs

Since reconnaissance is the first step in most projects, we will discuss its use within OPUS first.

2.12.1 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 reconnaissance 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. In 2020, NGS developed (and continues to improve) a mobile-friendly web page for finding and reporting marks. It is available at: https://geodesy.noaa.gov/cgi-bin/mark_recovery_form.prl

This tool is accessible on both desktop and mobile environments. This tool is not restricted to professional surveyors. The general public are 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 coarse 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, has the same functionality using any standard computer browser.

2.12.2 OPUS for GNSS (Including RTN/RTK, Independent Vector Uploads, etc.) *and* Classical Surveying

Because there are commonalities between differential vectors between pairs of GNSS receivers and classical survey data (angles and distances), NGS is currently planning for OPUS to have the capability to upload, process, adjust, and submit data from these two different survey types within the same module. However, as they are different topics, three subsections follow, describing the two different survey types, and then the changes expected within OPUS.

2.12.3 GNSS

NGS is expanding our support for all GNSS constellations. Specifically, PAGES (the GPS-only software we developed and maintain, and which is the engine of the currently named OPUS-S software) is being re-built from scratch, with an eye toward supporting every current and future GNSS constellation. That project is currently scheduled for completion in early 2022 and will be fully integrated into tools built for the modernized NSRS.

Additionally, one OPUS expansion likely to be ready (both for OPUS to use and to load the new NSRS database) soon 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
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

As NGS opens up OPUS (currently OPUS-Projects) to accommodate GNSS vectors that are not computed within OPUS, it seems appropriate to paraphrase the "best practices" note from earlier. That is, the NSRS requires high-quality geodetic survey data. Users who bring exo-OPUS vectors to OPUS have a responsibility to make sure that such vectors have been meticulously checked for accuracy, since NGS will not necessarily be able to do so (particularly with RTK/RTN vectors). Providing redundant observations will help tremendously in assessing quality, and it is required for establishing marks that qualify as geodetic control in the modernized NSRS.

2.12.3.1 Classical Surveying

Although the use of classical angle and distance observations was the cornerstone of the original NAD 83 project, its use in the geodetic community has dropped precipitously for 40 years with the rise of GNSS. However, there are very specific uses and applications of this data that cannot be replaced by GNSS, including many of which NGS regularly executes (IERS co-location site surveys; special projects such as the 2013 Washington Monument survey; river crossings).

2.12.3.2 Changes to OPUS

Firstly, NGS is committed to the dual purposes of OPUS to be both (a) highly flexible to the NSRS user community and (b) a portal to NGS for the submission of high-quality survey data collected using best practices.

To those ends, OPUS will allow users to use whatever data they upload, whatever constraints they wish, and choose whatever epoch or epochs of interest they like for their final processed coordinates. All such coordinates will always be labeled as OPUS coordinates.

However, if the user restricts their choice of constraints, epochs and other metadata to the OPUS recommendations, then these OPUS coordinates will also be labeled as “tied to the NSRS.”

While NGS is not particularly interested in the finer details of your own survey contracts, we are quite interested in both the quality and redundancy of any data you submit. As such, NGS will encourage that, within your own survey project requirements that you consider the following as best surveying practices:

1) Occupy any given point at least twice within the same geometric adjustment window. (See section 2.11.)
2) Take photographs of all marks whenever found, both with and without equipment occupying them.
3) Submit everything to NGS.

Once your data are submitted to NGS, they will be checked for quality and eventually used in the creation of both survey epoch coordinates as well as reference epoch coordinates. These will both be available through the NGS data delivery system (formerly called “Datasheets”).

All geometric computations and adjustments will be done in the ITRF2020 frame. However, immediately available from those coordinates will be the coordinates in all four frames of the modernized NSRS, through EPP2022, as well as a variety of geopotential coordinates in NAPGD2022.

As mentioned earlier, the initial plan is that a geometric adjustment window will last four weeks. If that plan holds, then NGS will harvest all GNSS and classical data from all submitted projects that occurred 12–15 weeks prior, during one four-week long geometric adjustment window. 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 survey epoch coordinates for the 4-week (geometric adjustment window) span of 12–15 weeks prior.

2.12.4 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 observing technique, and to the ability it can, OPUS will perform adjustments without attempting to yield absolute heights. For those users who need absolute heights, however, OPUS will support three options: (1) collect your own GNSS to provide orthometric heights on select points, (2) pull heights from the NSRS database, or (3) provide no absolute heights. NGS prefers a GNSS survey to be performed at specific times before and after leveling surveys to support accurate creation of both SEC and REC orthometric heights from your leveling data. In the absence of timely GNSS data being submitted with a leveling project, NGS may only be able to provide adjusted differential RECs and SECs from leveling-only projects.

In summary, the most accurate way for your leveling survey to produce absolute NSRS orthometric heights will be through a GNSS survey, though this can be as simple as RTK/RTN data collection. Users should collect GNSS data both at the beginning and at the end of a leveling survey whenever possible, unless the leveling project is shorter than four weeks in duration, in which case one set of redundant GNSS occupations on all primary control marks should be sufficient. Leveling surveys between 6 and 12 months in duration should acquire a third, intermediary GNSS data collection. Leveling surveys longer than one year should be broken up into multiple projects.

Furthermore, current plans call for NGS to process submitted leveling projects into survey epoch coordinates every calendar year. (See Appendix C.) As such, if your leveling project extends across two calendar years, NGS will request that additional GNSS occupations on primary control marks be performed in December and January of the two subsequent years, with each set of redundant occupations falling into a geometric adjustment window.

Presuming GNSS data were collected as suggested, you should process them in OPUS as follows:

1) GNSS data collections performed on primary control marks should be processed into a single geometric coordinate triad at the representative epoch of the survey (such as the midpoint of all GNSS and leveling observations).
2) These coordinates will be combined with GEOID2022 to yield orthometric heights at the representative epoch.
3) Those orthometric heights will then be held as stochastic control for the adjustment of all leveling data, yielding OPUS orthometric heights for all points in the entire project at the representative epoch.

Additionally, you should submit all of your data through OPUS to NGS so that it can be used in the creation of RECs and SECs.

2.12.5 OPUS for Gravity, Others

As these expansions to OPUS 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, yielding OPUS coordinates (including being tied to the NSRS, provided they follow OPUS-recommended constraints). When those data are submitted to NGS, quality controlled, and used to create either SECs or RECs, those SECs and RECs will become part of the NSRS by being loaded into the NSRS database.

2.12.6 Support for Non-NSRS Information in OPUS

NGS frequently receives requests for our tools to support non-NSRS geodetic information, such as WGS 84 or EGM2008. Unfortunately, as these are the creations of the National Geospatial-Intelligence Agency (NGA), and are neither part of nor tied to the NSRS, it is not a simple matter to support them. It is safe to say that generally speaking, there will not be a function to "work in WGS 84"[57] within OPUS unless there were a formally defined transformation between WGS 84 and the modernized NSRS frames (or ITRF2020).

2.13 RTN Alignment Service or RAS

NGS has never explicitly attempted 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 NSRS modernization, though as of 2020, 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 provide NSRS coordinates 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-labeled coordinates delivered to the user at his/her RTN rover at that point.

[57] NGS and the National Geospatial-Intelligence Agency (NGA) have engaged in discussions concerning either 'co-defining' the new reference frames with WGS 84, or having NGA define a formal 14 parameter Helmert transformation between ITRF2020 and the next release of WGS 84. If these talks finalize into a plan, a transformation between the NSRS and WGS 84 may be possible within OPUS.

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
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 NCN or not) function as CORSs and could be processed regularly within the daily processing of all data in the NCN. 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 a 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 control within the RTN service range. Those occupations would be of two different types. The first type would be a long session of static 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, at these fiducial marks.

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

2.14 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). As NGS modernizes our tools, the functionality of these tools will overlap significantly, although VDatum will expand on NCAT by also supporting tidal datum information.

These tools will include various components each with specific functions. For instance, NADCON (which was once a stand-alone tool, but now is a component of the larger NCAT and VDatum tools) will reside within each and perform datum transformations in latitude, longitude, and ellipsoidal height.

The following components (among other historic tools already integrated) 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 RECs at the 2020.00 epoch, NADCON and VERTCON will support the transformation from NAD 83(2011/PA11/MA11) epoch 2010.00 and NAVD 88, without epochs (as well as all other vertical datums of the NSRS) into *TRF2022 (epoch 2020.00) and NAPGD2022 (epoch 2020.00). Those transformations will represent the last time NADCON and VERTCON will stand alone as separate NCAT and VDatum components. After that, IFVM2022 will serve the same purpose as NADCON, and the combination of IFVM2022 with GEOID2022 will serve the same purpose as VERTCON.

Additional information about how NGS will support the transformation of data from the current NSRS to the modernized NSRS can be found in Section 3.3 (Use Case 3: Transitioning Data to the Modernized NSRS).

2.15 Transitioning from the Current NSRS to the Modernized NSRS

When NGS has completed all aspect of the modernized NSRS, they will be released simultaneously. This will include ITRF2020 coordinates on the NCN and IGS Network stations, EPP2022, IFVM2022, and all components to support NATRF2022, PATRF2022, CATRF2022, MATRF2022 and NAPGD2022. There will also be a complete OPUS suite supporting multiple survey types, and transformation tools fully integrated into NCAT and VDatum that will allow users to transform their current NSRS archives into the modernized NSRS.

While all of this is being prepared, certain aspects of the current NSRS will be disappearing and/or ramping down. For instance, NGS will likely transition from ITRF2014 to ITRF2020 within the next few years. However, this switch will not trigger a national re-adjustment of passive control in NAD 83. It will also not trigger the creation of a new hybrid geoid model. However, OPUS will continue to support GNSS users and NAD 83, to the best of its ability, without updating passive control coordinates.

When the entire modernized package is ready, it will be released on the NGS Beta website (beta.ngs.noaa.gov) for user feedback. During this time, the somewhat slimmed-down current NSRS (NAD 83, NAVD 88, etc.) will continue to be supported on the main NGS website (www.ngs.noaa.gov). There will likely be a short overlap period, but the maintenance of any extended overlap period cannot be sustained. As such, NGS does not anticipate more than 3 months of support for the current NSRS once the modernized NSRS is available. After that period, OPUS will not adjust data in earlier frames and datums.

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. 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 will remain 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 NGS 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: Having your survey "tied to" the NSRS can mean connecting to the NCN with GNSS and/or finding passive control 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. Once loaded, they become "part of" the NSRS.

Future: The NCN will be the primary access to the NSRS. This means OPUS will expect GNSS data as part of leveling surveys and will require it as part of classical surveys in order for users to process their projects. Coordinates on passive control will be available in two forms: survey epoch coordinates (SECs) will represent best estimates of coordinates at (or very near) the time data was collected while reference epoch coordinates (RECs) will represent best estimates of coordinates at five or ten year reference epochs. 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 and any reasonable epoch. Provided users do not change any OPUS-recommended NSRS coordinates or constraints on the control, OPUS will yield OPUS coordinates that will be labeled "tied to the NSRS." However, such projects, on submission, will be deconstructed at NGS and reduced to the raw observations, then used in the separate creation of SECs and RECs. These NGS-computed SECs and RECs are "part of" the NSRS.

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, often with each island having its own independent datum, 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 ITRF2020, 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 2010.00 (if possible). Coordinate functions on CORSs are piecewise (continuous or discontinuous) linear functions in the ITRF (currently ITRF2014). Unless a user is expressly trying to acquire time-dependent coordinates in the ITRF, NGS generally promotes CORS coordinate functions 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 survey epoch coordinates in the geometric adjustment window containing February 17, 2005. By themselves, these individual survey epoch coordinates reflect the best estimate NGS has of the coordinates of the mark at (or very near) the time data was collected at that mark. The same data that goes into these SECs will also be used to estimate reference epoch coordinates every five or ten years, beginning with 2020.00. Points that 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 some may 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.

For more details see Use Cases in Section 3

2.17 In Closing

NGS (under various names) has stood on the line between being a science agency and a customer-service agency for more than 200 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 changes 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 Use Cases

An effectively unlimited number of examples might be invented to describe how someone might access and use the NSRS in the future. A short list of use cases follows. The list is not an attempt to be exhaustive, and extrapolation to other examples would be reasonable.

3.1 Use Case 1: Flood Mapping

3.1.1 Introduction to Flood Mapping Use Case

Flood mapping has been long recognized as one of the applied geospatial activities that will benefit significantly from NSRS modernization (see Leveson, 2009 and Youngman et al. 2011). For the purposes of exploring the benefits of a time-dependent and nationally-consistent geopotential datum in more detail, this use case explores use of the NSRS within the context of mapping associated with the Federal Emergency Management Agency's (FEMA's) National Flood Insurance Program (NFIP). As a result, the content of this section will be of direct interest to professional land surveyors, engineers, or architects authorized by law to certify NFIP Elevation Certificates (ECs), NFIP Mapping Partners, and FEMA Cooperating Technical Partners. More broadly, however, flood mapping provides an illustration of modernized NSRS considerations that are pertinent to any geospatial product that relies on accurate hydraulic modelling or on the successful compilation of multiple data sets from disparate sources, methods, and points in time.

This use case's examples are set in an imaginary flood-prone coastal community experiencing non-uniform ground subsidence at the watershed scale (see Figure 10). Although many areas are not subject to this level of vertical motion, the full benefits of NSRS modernization are most apparent in this context. We illustrate differences in the use of the NSRS of today and the modernized NSRS with two common NFIP workflows. First, we consider steps anticipated in the certification of NAPGD2022 elevations for a NFIP Elevation Certificate. Second, we step into the shoes of a FEMA Mapping Partner to examine the ways future NSRS tools support more accurate mapping in Flood Insurance Rate Map (FIRM) and Flood Information Study (FIS) updates.

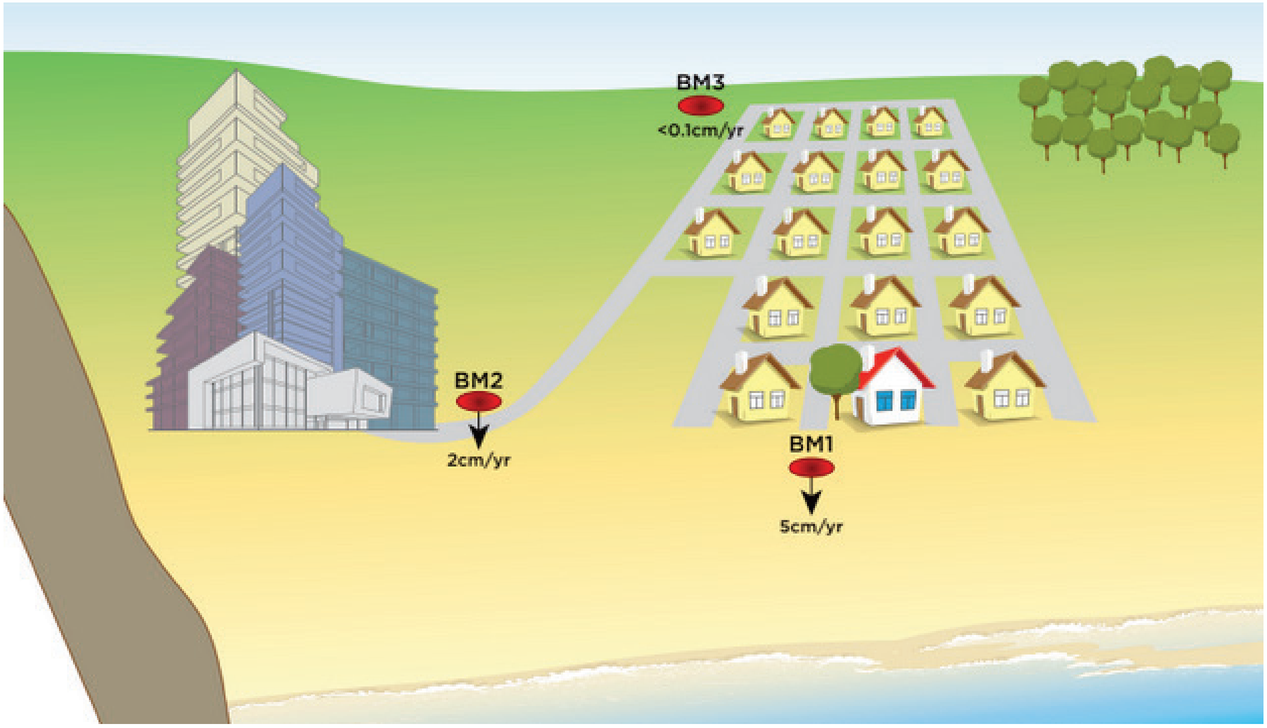

Figure 10. Diagram of fictional case study location. The arrows correspond to hypothetical rates of ground subsidence

As the NFIP is structured today, NFIP products will primarily utilize the official NSRS reference epochs. Additionally, some NFIP products such as the EC form itself, as well as guidance, and technical references for FIRM and FIS preparation would benefit from updates that reflect changes to the NSRS. While the time-dependency and incorporation of a gravimetric geoid model will manifest as improved risk assessment reliability in inundation map products, we notably anticipate that NSRS modernization will have a limited impact on the basic structure of most recommended workflows associated with the NFIP of today. The most significant development is therefore the opportunity for FEMA's National Flood Mapping Program (NFMP) to increasingly leverage the new capabilities of the NSRS to ensure that current, accurate ground elevation data is used, and to better incorporate relevant flood control structure and future conditions mapping data to support decision-making beyond the NFIP. Details of how the modernized NSRS can help FEMA achieve broader NFMP objectives and opportunities for data-driven case studies to explore this are described at the end of the use case.

3.1.2 Elevation Certificate Example

Elevation Certificates (ECs) are an administrative tool of the NFIP. An EC, signed by an authorized professional provides the building elevation information necessary to ensure compliance with community floodplain management ordinances, determine proper insurance premium rates, and support necessary Flood Insurance Rate Map (FIRM) amendments[58]. Since the intent of the EC is to accurately determine the building elevation relative to the Base Flood Elevation (BFE) on the published FIRM, the datum used for building elevations *must be the same* as that used in defining the BFE.

The current version of the EC form relies on the NSRS in three sections (see Table 3), and a field survey is required to populate section C2. In the past, the BFE datum in B11 often varied by location but NAVD 88, where available, has become the vertical datum of choice for new FIRM production since the mid-1990s. The EC form is routinely updated by FEMA, and it presently includes instructions for populating section C2 from a GPS survey with use of OPUS.

Table 3. Sections of the 2019 EC Form that employ the NSRS.

2019 EC Section	Purpose	Accuracy Requirement
A5. Latitude/Longitude: Lat. ________ Long. ________ Horizontal Datum: ☐ NAD 1927 ☐ NAD 1983		
A5	defines approximate location of the center front of building	within 66 feet
B11. Indicate elevation datum used for BFE in Item B9: ☐ NGVD 1929 ☐ NAVD 1988 ☐ Other/Source: ________		
B11	defines the BFE reference datum used on the FIRM	n/a
C2. Elevations – Zones A1–A30, AE, AH, A (with BFE), VE, V1–V30, V (with BFE), AR, AR/A, AR/AE, AR/A1–A30, AR/AH, AR/AO. Complete Items C2.a–h below according to the building diagram specified in Item A7. In Puerto Rico only, enter meters. Benchmark Utilized: ________ Vertical Datum: ________ Indicate elevation datum used for the elevations in items a) through h) below. ☐ NGVD 1929 ☐ NAVD 1988 ☐ Other/Source: ________ Datum used for building elevations must be the same as that used for the BFE.		
C2	defines passive control used as the basis for building elevations	nearest tenth of a foot (3 cm) for most of US

Based on the EC directions, the basic workflow used to populate Section C2 can be reduced to the following steps:

[58] Note: The content of this use case addresses basic EC data collation and associated accuracy requirements. The use of resulting building elevation values for NFIP rate-setting and other purposes often rely on different requirements that are beyond the scope of the use case.

1. Identify a bench mark with a unique identifier such as an NGS PID as the basis for field control.
2. Transform the survey datum to the same vertical datum used for the BFE (if necessary).
3. Populate the Comments space with metadata for the methods used, including name and version number of any transformation software (e.g. VDatum or NCAT).

Today, professionals employ their training, expertise, and knowledge of local conditions in conjunction with local laws and guidance to determine the most appropriate methods and tools for accomplishing the above steps. In establishing a height on a controlling bench mark, this often involves leveling from a mark with a NAVD 88 height published in the IDB, and/or re-leveling to additional marks to verify the vertical stability of this control (See Figure 11). For GNSS-based survey control, EC instructions require indication of the (1) bench mark used for the base station, (2) the CORSs used for an OPUS solution (see Figure 11), or (3) the name of the Real Time Network used.

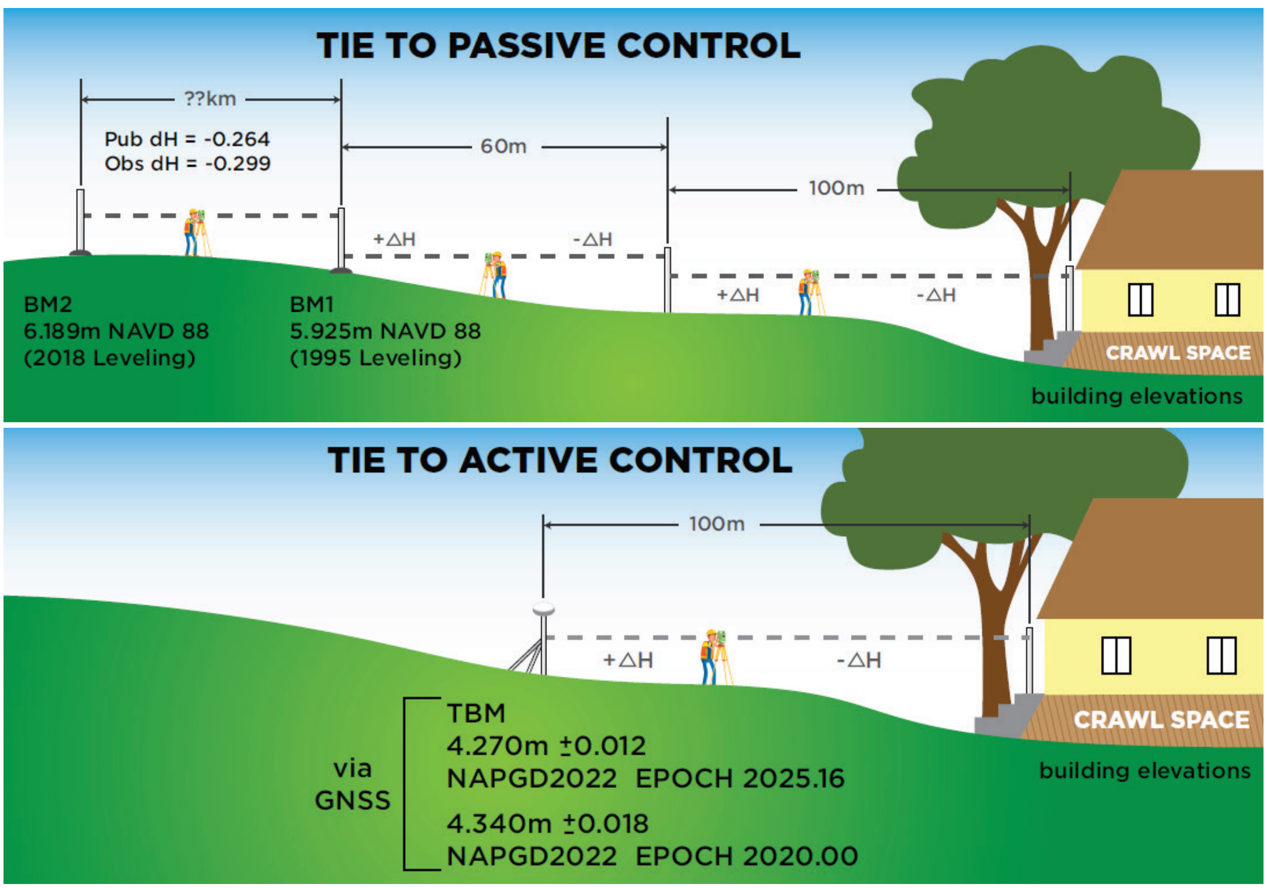

Figure 11. Cartoon of Elevation Certificate field surveys based on establishing a tie to the NSRS via passive control leveling (top panel) and via active control with GNSS (lower panel).

In the context of our subsiding coast example, the shortcomings of today's NAVD 88 datum for accurate flood control become apparent in preparing an EC for the highlighted house. We might pull an official NAVD 88 height for nearby mark BM1 from the IDB and use that as the basis of control for conventional or digital leveling—not realizing that this mark has subsided more than 3 cm from the Height Modernization survey that was used to define the active BFE; this would result in all reported building elevations being more than 3 cm higher than their actual values. Perhaps we happen to suspect that BM1 has subsided substantially relative to the surrounding area (or maybe BM1 was visibly disturbed by construction), we might then find ourselves in a very expensive and time-consuming leveling survey transferring NAVD 88 heights from a mark known to be used as BFE control in the FIS (BM2) or from a stable mark several miles away (BM3, in Figure 10 only). Alternatively, we could attempt to account for subsidence by using OPUS (or other GNSS methods) to determine ellipsoidal heights consistent with the BFE. By tying to a stable BM, these ellipsoidal heights could be used along with the slope of a hybrid geoid model to re-establish an NAVD 88 height on BM1 or on a Temporary Bench Mark (TBM) adjacent to the house. However, this might still result in different values from the NAVD 88 definition used by the BFE since the NAVD 88 datum itself is lacking in epoch information, and the hybrid geoid model is created in part from NAVD 88 BMs. If the hybrid geoid model included stable BMs as well as BMs that have subsided, then even its slope might not match current conditions (for additional information on inconsistencies in accessing orthometric height values via leveling and the hybrid geoid model, see Blueprint Part for the Modernized NSRS (NGS 2021b), Section 5).

The greatest benefits of the modernized NSRS to these EC workflows are therefore the epoch definitions and tools that provide professionals with the confidence to make more informed decisions about the basis of their field surveys. In stable areas, this may still mean retrieving a published REC from the NSRS database and transferring that NAPGD2022 height via leveling to the area of interest. Where stability is uncertain, a pre-evaluation of the mark could be conducted by looking at the REC or SEC history in the Data Delivery System (DDS) or at the ACs of nearby CORSs. Additionally, the IFVM will allow for OPUS coordinates on an existing mark or TBM to be computed at *the same* reference epoch used by the BFE, or transformed to the BFE reference epoch with a transformation tool such as VDatum or NCAT. Last, for those using a Real Time Network in their EC workflow, or trying to decide if one can be used, the planned RAS will give RTN operators a means of supporting professionals in their decision to select an RTN that will meet the requirements of an EC.

3.1.3 Flood Insurance Rate Map and Flood Insurance Study Example

A Flood Insurance Rate Map (FIRM) is the geospatial depiction of regulatory flood hazard information such as BFEs and is the official jurisdiction-specific product of the NFIP. Each FIRM is accompanied by a corresponding FIRM Database and a Flood Insurance Study (FIS) report that includes the FIRM's study methodology, data, and results. In the NFIP as it operates today, local FIRMs are updated on a rolling basis by FEMA's Mapping and Cooperating Technical Partners;

according to the NFIP Community Status Book, the average age of a FIRM in the more than 22,000 NFIP-participating communities in 2020 is 11 years.

Wherever practicable, FEMA presently requires the use of the NAD 83 and NAVD 88 in FIS and FIRM production. However, the rolling nature of NFIP restudies in combination with the limited capabilities of past NSRS transformation tools has resulted in very gradual and incomplete adoption of the NSRS or NSRS updates. Additionally, limited or lack of access to NAVD 88 geodetic control in some parts of the United States has necessitated the continued use of local datums that are not always well documented and often lack supporting transformation tools. Whatever the basis for NFIP control today, these choices are currently described in *FIS Section 6.1 - Vertical and Horizontal Control*, in the *Notes to Users* section of the FIRM legend, and in more detail in survey notes included within the *Category 3 FIS backup data*.

In the future, FEMA will continue to require use of the NSRS in the NFIP, but the NSRS will now be accessible nationwide. Additionally, tools that support time-dependent transformations will enable more accurate alignment of data than ever before by allowing for the removal of positional uncertainty in areas undergoing motion. Together, these improvements are expected to alleviate localized jurisdiction-to-jurisdiction vertical datum discrepancies that have plagued the NFIP at FIRM boundaries. Like with past updates to the NSRS, this modernization is expected to be phased into NFIP products over the course of the regular restudy cycle. As per standing FEMA guidance, each FIS and FIRM update will adopt the most recently passed of NGS's official reference epochs for horizontal and vertical control. The enhanced ability to link component data to a date of collection is a natural fit for NFIP products, which already encourage extensive metadata documentation of the date that the information corresponds to the ground condition.

The production or update of a FIS and FIRM can be generally categorized as having three phases: a flood hydrology analysis phase, a hydraulic modeling phase, and a hazard zone mapping phase. All three parts of this production process rely heavily on the NSRS's capability to enable the consistent and accurate alignment of geospatial data from many sources. This is particularly true for the flood hydraulics and hazard zone mapping components of the FIS, which require accurate elevation information in data acquisition and combined use for successful interpolation across the entire study area (see NRC, 2007). In addition, orthometric heights based on a gravimetric geoid revised with new GRAV-D data are more conducive to accurate hydraulic modeling then heights derived from a hybrid geoid model, particularly in places where passive control was historically limited (Youngman et al. 2011).

New field survey data collection for flood mapping is primarily conducted for one of two reasons: establishing hydraulic obstruction heights (e.g. toe, crest or deck elevations on coastal structures and levees) and surveying stream cross sections for hydrograph calculations. For all new surveys, FEMA presently specifies that Mapping Partners must use ≤5 cm GPS procedures or Third-Order (or better) differential leveling (see Youngman et al. 2011). For detail on the many ways various types of field surveys can use the NSRS, see the use cases in sections 3.2 and 3.4, and stay tuned for the replacement document for NGS 58 ("Guidelines for Establishing GPS-Derived ellipsoidal heights").

During a typical FIS discovery phase, it is not uncommon that numerous datasets with different sources, formats, native spatial reference systems, varying metadata quality, and collections times are found, evaluated, and used (Figure 12). This is because FEMA Mapping Partners are strongly encouraged to leverage existing geospatial data with valid FGDC-compliant metadata. These datasets may include a mix of different terrain datasets, orthoimagery, and field survey data that must all eventually be transformed into the NSRS for the storage in the FIRM Database, and like EC professionals, NFIP Mapping Partners rely on their training, expertise, and knowledge of local requirements to decide how and when these transformations are conducted in their individual workflow process (see FEMA, 2016c). In the future, new capabilities of the modernized NSRS within familiar tools such as NCAT, VDatum, and in commercial software will enable consistent transformations and will also sustain transformations to and from tidal datums for the production of seamless topobathy surfaces at the coast.

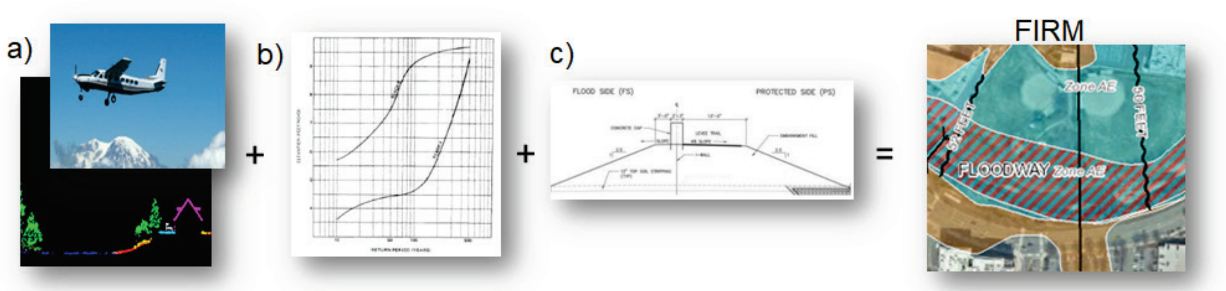

Figure 12. Many disparate data sets are combined in the production of a FIRM. As illustrated above. The FIS discovery process and FIRM production may involve the collection of (a) new lidar where contemporary Digital Surface Models are lacking, (b) incorporation of existing hydrographs showing cf/s flow of water during peak rain events, and (c) use of engineering drawings for any new construction that could impact hydrology and hydraulic modeling.

Limitations in past NSRS transformation tools, both provided directly by NGS and as incorporated into commercial software, led to FEMA issuing transformation guidance that routinely degrades the accuracy of the component datasets for the sake of simplicity (see FEMA 2014). For example, standing guidance for "converting" all data to a common vertical datum urges a fixed average vertical shift on a study-wide basis if differences between the two datums exhibit more than a 0.25 foot (7.6 cm) variance at any location. Where local variance between two datums exceeds this variance, a stream-based vertical datum "conversion" is recommended. Where the average calculated difference between vertical datums is less than 0.1 ft (3 cm), a "conversion" is considered "passive" and the datum can be renamed with a note in the metadata.

Today and looking toward the future, the data management challenges that gave rise to this type of simplified vertical datum transformation guidance out of necessity are no longer an issue. FEMA Mapping Partners will have access to NCAT and VDatum, not only for tidal to geodetic transformations, but also for transformations from one reference epoch to the next. This will not only help to transform legacy geospatial data to a consistent NSRS reference epoch (see the transitioning data use case in section 3.3) but can also simplify FIRM updates in restudies. For example, in areas like our imaginary subsiding coastal community, having this level of control to align critical vertical data such as levee crest heights and stillwater levels across different points in time will result in direct improvements to the ability to update the vertical datum such that risk calculations are more accurate.

At a minimum the following NFIP publications would benefit from a re-versioning or supplemental guidance to reflect the modernized NSRS:

- Elevation Certificate Form and Instructions
- Guidance for Flood Risk Analysis and Mapping, Metadata
- Guidance for Flood Risk Analysis and Mapping, Projections and Coordinate Systems
- Guidance for Flood Risk Analysis and Mapping, Vertical Datum Conversion

3.1.4 Applicability beyond National Flood Insurance Program of Today

Beyond use of the modernized NSRS to improve the geospatial components of the NFIP as we know it today, NGS is looking to the future and is committed to providing technical assistance to FEMA and other partners to further explore how the time-dependent features of the modernized NSRS can be leveraged to fundamentally inform new and improved approaches to flood mapping, flood risk determination, and related inundation map products such as sea level rise viewers.

For example, close coordination with FEMA's Technical Mapping Advisory Council (TMAC) and the United States Geological Survey National Map program will ensure more hydraulically correct elevation surfaces are employed in Risk MAP and the graduated risk products associated with Risk Rating 2.0 NFIP modernization efforts. Also, NGS intends to provide technical assistance to partners such as the North Carolina Floodplain Mapping Program or any others seeking to examine how all aspects of the modernized NSRS could potentially enhance flood mapping, from the initial definition of more accurate flood zones, to the use of the IFVM to prioritize FIRM restudies, or even the ability to dynamically update Base Flood Elevation values in regions actively undergoing local relative sea level change.

3.2 Use Case 2: Passive Control for a Multi-year Corridor Project

3.2.1 Project Requirements and Scoping

a. Scenario

Consider a hypothetical scenario where a new road is going to be built over the course of 10 years (from 2025 to 2035). Although real projects of this type can be considerably more complex than this use case suggests, the goal here is to provide a somewhat general scenario on using the modernized NSRS. Attempting to go into greater depth would likely detract from this goal. In addition, many specific details of the modernized NSRS are not yet known.

b. Contract requirements

The project must be tied to the National Spatial Reference System and will make use of a real-time network (RTN) aligned with the NSRS at epoch 2020.00. The intent is to use that epoch for the duration of the project, even if the RTN switches to another epoch during the project. Clearly defined criteria will be used to determine whether the 2020.00 epoch can be maintained for the entire project duration, as described later in this use case.

c. Coordinate system/datum

Geometric (latitude, longitude, and ellipsoidal height) control will be referenced to the North American Terrestrial Reference Frame of 2022 (NATRF2022[59]) at epoch 2020.00.

The State Plane Coordinate System of 2022 (SPCS2022) will be used for projected horizontal coordinates (northing and easting), based on NATRF2022. The SPCS2022 zone used for this project will have only minor linear distortion at the topographic surface. That is, the difference between "grid" and "ground" distances will be small enough to ignore.

Vertical (orthometric height) control will be tied to and reported relative to North American-Pacific Geopotential Datum of 2022 (NAPGD2022) at epoch 2020.00.

This use case is based on the assumption that reference epoch coordinates will be re-computed every 5 years (however, a decision has not yet been made by NGS as to whether this interval will be 5 or 10 years).

d. Parties involved

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[59] NATRF2022 is selected here because it is assumed the use case is in North America. For projects located elsewhere, one of the three other frames would likely be used: the Caribbean, Pacific, and Mariana Terrestrial Reference Frames of 2022.

A state Department of Transportation (DOT) and project contractors (surveyors, engineers, construction professionals, etc.)

e. Survey data used

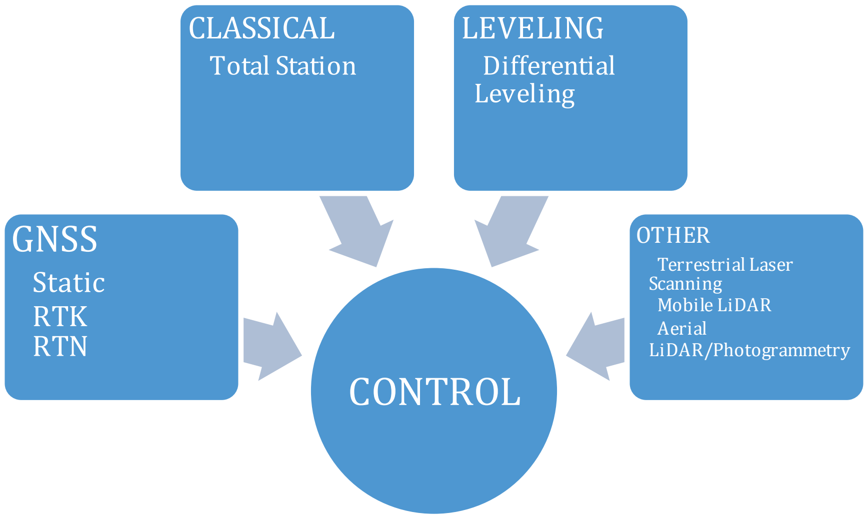

Figure 13: Diagram of survey data used in a multi-year corridor project

3.2.2 Control Surveys

a. Introduction

This surveying phase starts by establishing geometric and vertical control for the project. Surveying teams will investigate the existing geodetic control in the area of the future-proposed highway project. Once the published passive geodetic control with geometric (NATRF2022 Epoch 2020.00) and vertical (NAPGD2022 Epoch 2020.00) coordinates are identified using the NGS Data Delivery System (DDS), reconnaissance is completed to recover those marks. Existing control will be occupied and assessed for suitability, and it will be augmented with new control marks as necessary.

Depending on the size of the proposed highway project and the locations of the recovered geodetic control marks, the locations for future primary and secondary control marks can be identified. Certain distance and inter-visibility criteria are to be followed to maintain proper spacing between the primary (and secondary) control markers.

It is important to note that the same survey control will be used throughout all of the phases of the project. That means that the entire project will be referenced to one common epoch of 2020.00 for NATRF2022 and NAPGD2022, and originally determined coordinates will be maintained for the duration of the project, if possible. Change of coordinates with respect to the frame is important and will be monitored, and if it occurs, it might affect the project coordinates.

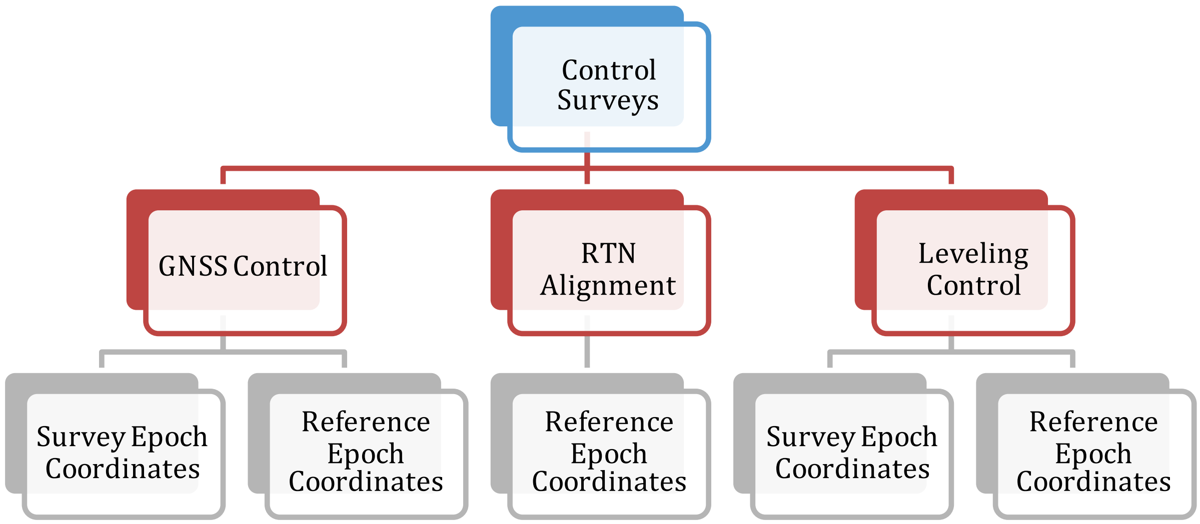

Figure 14: Hierarchy of survey types and coordinate types (chart breaks down the types of control surveys by GNSS control, RTN alignment, and leveling control).

b. GNSS Control

Survey control should be tied to a common reference epoch. The idea is to use one set of coordinates (assuming they have not changed). This will allow for a proper QA/QC (ensuring that projects are being built as designed) throughout all of the phases of the project.

Generally speaking, in the future OPUS will compute coordinates at any epoch a user wishes to use, and therefore, this will require that they adjust their survey to epoch 2020.00 (which will be different from when the data were collected).

Reference epoch coordinates will be re-computed every 5 or 10 years, and this will create a long stable platform while allowing surveyors to conduct their daily checks through OPUS.

The benefit of using reference epoch coordinates is that users are familiar with them as they work in a similar way to currently used NAD 83(2011) coordinates. NATRF2022 coordinates have been estimated by NGS, from time-dependent age-limited historic survey data, CORS coordinate functions, and an intra-frame velocity model, at an official NSRS reference epoch (initially at 2020.00, and then at 5-year intervals, e.g., 2025.00, 2030.00, etc.).

On the other hand, survey epoch coordinates represent the best estimate NGS has of the time-dependent coordinates at any mark. They will be adjusted to a specific epoch near the survey, and they will show time dependency at marks. NGS will publish both reference and survey epoch coordinates.

The desire is to keep the entire project on the initial reference epoch of 2020.00 for the entire duration. But the coordinates may change too much over the life of the project to make that feasible, so it is important to establish a rule for how much change can be tolerated before an update is necessary, and then what actions must be taken because coordinates have changed. The coordinate change must be due to actual temporal change in the project area, not simply disturbance of a monument (e.g., damaged by a backhoe). The change can be assessed in part with the IFVM (Intra-Frame Velocity Model). The rule adopted for this project is applied if change occurs to at least 20% of the control marks and has two parts, both based on relative accuracy within the project itself (note that this is only an example, not an NGS recommendation; requirements for actual projects can vary considerably, based on criteria specific to projects and/or the organizations in responsible charge):

- A change of 5–10 cm horizontally and/or vertically will require an update of the epoch, but only if the change is so non-uniform that it cannot be adequately modeled by a best-fit coordinate transformation (e.g., "calibration" or "localization;" these terms are defined in the last section of this use case). Specifically, the epoch will be updated if the root mean square error (RMSE) of the horizontal or vertical calibration is greater than half the mean coordinate change and/or if the slope of the vertical correction surface exceeds 5 parts per million (ppm). All available undisturbed project control must be used in the calibration. (Note that calibration-like functionality will not be part of OPUS. It is only supported in vendor software, and varies between different vendors. Calibrations are only included here to allow continued use of an RTN even when its base coordinates are updated during the project.)
- A change of more than 10 cm horizontally and/or vertically will require an update of the epoch, regardless of how uniform the change is.

c. RTN Alignment

An RTN alignment service will be created for RTN operators to work with NGS, so that RTN base station coordinates can be updated every 5 or 10 years. These updates will ensure that RTN base stations are aligned with the most recent reference epoch coordinates.

An RTN is used for this project, and it transmits NATRF2022 epoch 2020.00 coordinates until sometime in 2027, when it switches to 2025.00 coordinates. The use of epoch 2020.00 coordinates continues, as planned. Use of the RTN coordinates can continue by calibrating to the previous control coordinate values. The change is small and uniform enough that the RMS of the calibration is <2 cm horizontally and vertically.

Sometime during or after 2032, the RTN begins broadcasting 2030.00 coordinates. Coordinates for about a quarter of the monuments change by 5–8 cm, but another quarter change by <2 cm. The change is so non-uniform that the calibration RMS is 4 cm. Because of this, along with corroborating information indicating actual relative movement, a decision is made to update the project coordinate epoch to 2030.00. This means that control coordinates and all spatial data must be updated to 2030.00.

d. Leveling Control

Geodetic leveling will be run through a control network to establish highly accurate differential heights.

Geodetic leveling surveys are, in general, much longer projects than GNSS projects. This fact, combined with the complications that new coordinates and time-dependency bring to the NSRS modernization, means a meticulous strategy for processing GNSS and leveling data together, as well as complete documentation (metadata) to properly describe the processes for deriving coordinates, will be paramount.

Consider a geodetic leveling survey designed to determine orthometric heights at passive marks, with work scheduled to last one year. GNSS occupations that will be used to constrain the leveling are done at a subset of all points, called “primary control points” near the beginning, middle, and end of the leveling. The general process is described below:

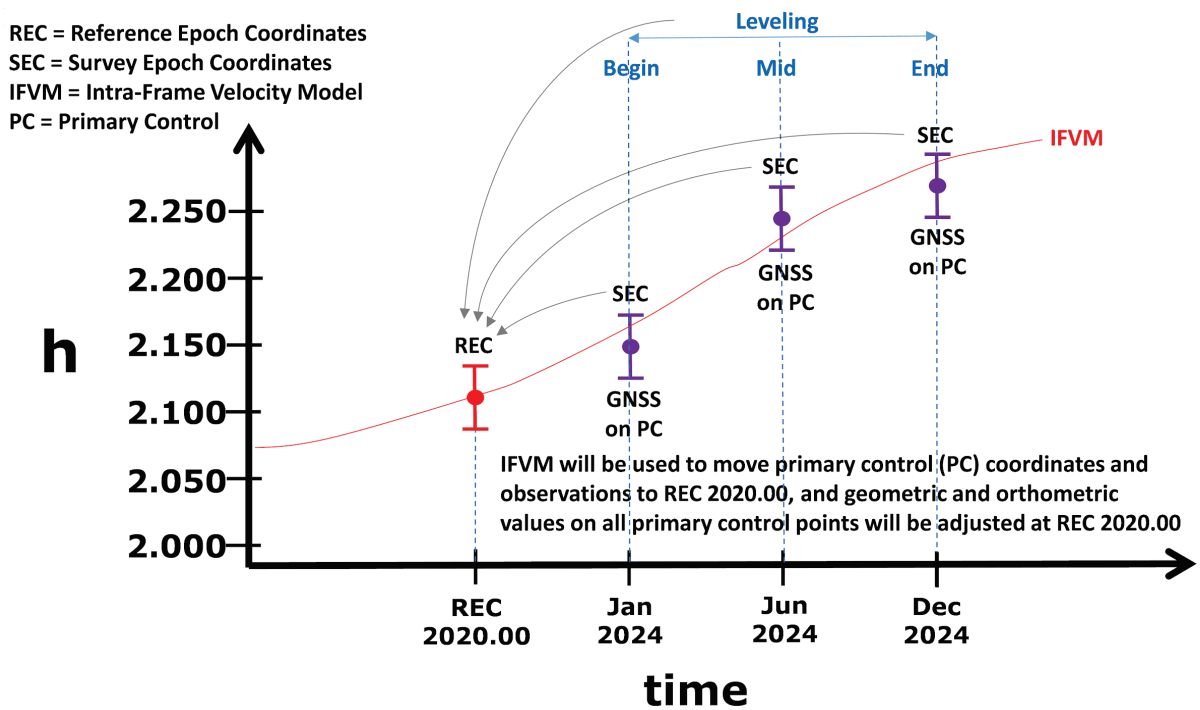

Figure 15: Relationship between RECs, SECs and the IFVM

1. Although the three GNSS surveys (Figure 15) could provide geometric coordinates (latitude, longitude, and ellipsoidal height) at the beginning, middle, and end of the leveling, they will not be used in this way. Rather, they will be combined in an adjustment, with the IFVM, to provide a single set of geometric coordinates at the epoch of interest to the user (in this case, 2020.00) Applying GEOID2022 will provide orthometric heights at that same epoch, as stochastic control to the leveling at the primary control points.
2. In the adjustment that combines GNSS and leveling, stochastic constraints are used for the GNSS-derived orthometric heights on all primary control marks at the reference epoch.
3. Adjusted orthometric heights on all marks will be generated as a result of the least square adjustment process, while preserving the accuracy of relative adjusted heights from leveling. That is, the difference of adjusted orthometric heights between any two marks will be consistent with that obtained from leveling, because the leveled height differences will have higher precision and thus greater weight in the adjustment.
4. GEOID2022 heights (N) will be applied to all adjusted orthometric heights (H) on all marks to obtain a set of ellipsoidal heights h on all marks, computed as h = H + N.

5. This will result in two sets of ellipsoidal heights on all primary control marks. The first one is from GNSS derived geometric values at the reference epoch, and the second one is from h = H + N in the previous step. Only the ellipsoidal heights from the second set will be used.
6. All primary control marks will have published latitude and longitude from GNSS, and ellipsoidal heights from h = H + N (based on the adjusted orthometric heights, H).
7. All marks will have published adjusted orthometric heights, H. Leveled-only marks will not have latitude, longitude, or ellipsoidal heights.

Later work performed for the project using GNSS-only will yield orthometric heights that are not adjusted to match the leveling. However, the vertical shift applied in that GNSS+leveling adjustment is smaller than the error of the GNSS-only orthometric heights (i.e., based only on the NATRF2022 ellipsoidal height and GEOID2022 geoid height). Because of this, there is no need to perform a vertical calibration to match the leveled heights, since they will match within the accuracy of the GNSS-only heights.

3.2.3 Preliminary/Planning Surveys

Selecting the right location for a new highway project is an important task that takes into consideration a number of different factors. Normally, the proposed alignment is determined based on topographic and geotechnical data. It may also be constrained by real estate. Design elements, such as horizontal and vertical alignments, are based on a design speed.

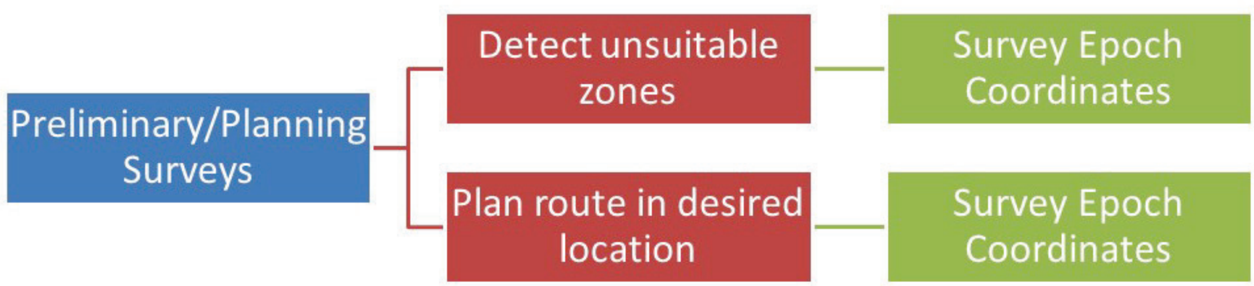

Figure 16: Relation between survey type, function and coordinate type

3.2.4 Design Surveys

Figure 17: Relation between design surveys, functions and coordinate types

In order to select a proposed route, it is necessary to obtain a recent topographic (existing condition) survey. Depending on the size of project, these existing condition surveys can be terrestrial (GPS, leveling, total station, static laser scanning, mobile LiDAR) or aerial (LiDAR and photogrammetry). All of those surveys will utilize the survey control for this project.

The end product of this survey phase is a digital terrain model (DTM), which will be used to sample alignment (based on design criteria).

3.2.5 Legal Surveys

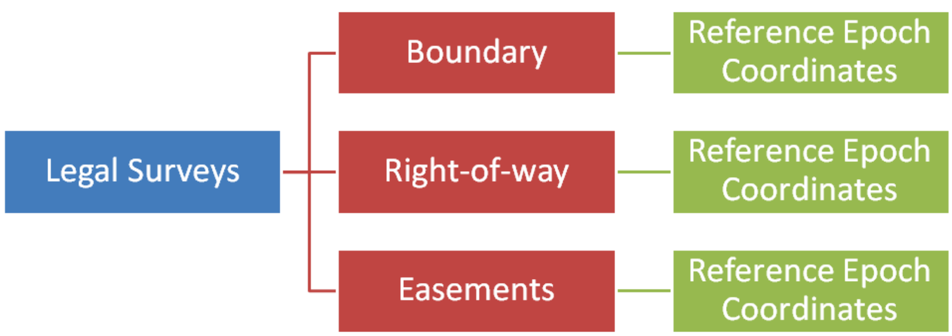

Figure 18: Relation between legal surveys, functions and coordinate types

The legal surveys (including boundaries, right-of-ways, and easements) are conducted to evaluate the property rights and obtain accurate boundary information. This phase includes the existing records research, field work to find evidence, and boundary analysis. The right-of-way acquisition process might need to be done to ascertain additional property rights. It is important to note that coordinates are at the bottom of the list as far as the location of the boundary is concerned. Other physical evidence, such as monuments and fences, are more important indicators and provide better evidence of the boundary location.

3.2.6 Construction Surveys

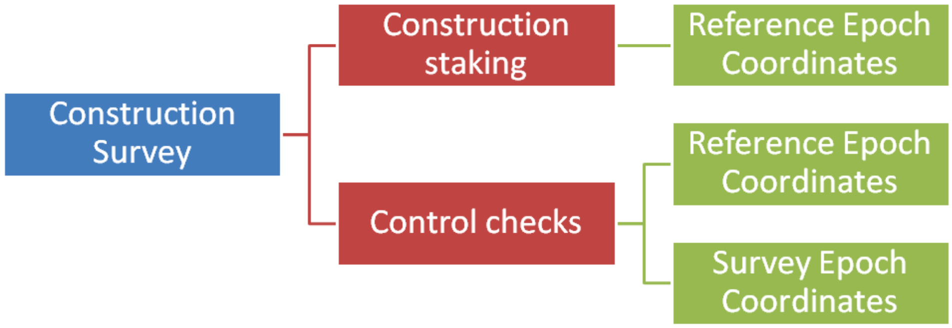

Figure 19: Relation between construction surveys, functions and coordinate types

The purpose of construction surveys is to establish control stakes for project construction. It is important to have project control laid out on both sides of a linear project with the right spacing between control stations to ensure a good geometry and strength of control network.

It is important to understand acceptable precision/tolerances for different types of stakes as far as proposed alignment and grades are concerned. For example, the required tolerance is not the same for cut/fill information provided on rough grade and curb stakes.

3.2.7 As-Built Survey Surveys

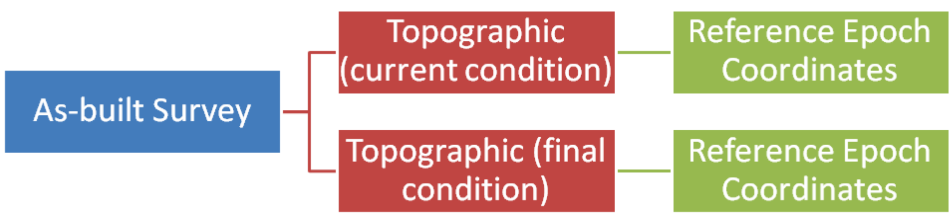

Figure 20: Relation between as-built surveys, functions, and coordinate types

The purpose of as-built surveys is to keep track of work progress by obtaining the up-to-date information during construction and documenting the final conditions after project completion. These surveys will capture the location of various improvements at any given point in time and confirm if they were built per design specifications.

A complete set of as-built survey plans is included in project documentation, and these drawings are valuable assets to planners, engineers, surveyors, and all contractors. The as-built plans are the official record of completed work as well as basis for any further construction change and project update, if needed.

3.2.8 Documentation

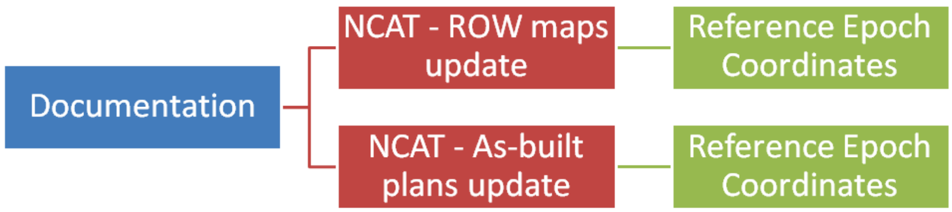

Figure 21: Relation between documentation, functions and coordinate types

The NCAT tool can be used to update right-of-way maps and as-built plans to the most recent NATRF2022 reference epoch coordinates and NAPGD2022 orthometric heights.

3.2.9 Supporting Information

1. **Metadata example.** This is an example of the type of information that should be included for engineering plans or surveying plats for the modernized NSRS. It defines all components of the coordinate system and gives a brief description of the methods used for determining the coordinate system.

   Basis of Bearings and Coordinates

   <u>Latitude, longitude, and ellipsoidal heights</u>: North American Terrestrial Reference Frame of 2022 (NATRF2022)

   <u>Orthometric heights</u>: North American-Pacific Geopotential Datum of 2022 (NAPGD2022)

   <u>Epoch</u>: 2020.0000

   <u>Linear unit</u>: International foot, ift (1 foot = 0.3048 meter)

   <u>Projected coordinate system</u>: State Plane Coordinate System of 2022 (SPCS2022), Kentucky North Central zone (KY NC, 211007)

   Projection type: Oblique Mercator
   Origin latitude: 38°30′N
   Origin longitude: 274°57′E (085°03′E)

Skew axis scale: 1.000 02 (exact)
Skew axis azimuth: +50°
False northing: 625,000 m (exact) = 2,050,524.934 ift (approximate)
False easting: 1,520,000 m (exact) = 4,986,876.640 ift (approximate)

All distances and bearings shown hereon are projected (grid) values based on the preceding projection definition. The projection was defined to minimize the difference between projected (grid) distances and horizontal ("ground") distances at the topographic surface within the projection zone.

The grid bearings shown hereon (or implied by grid coordinates) do not equal geodetic bearings due to meridian convergence.

Orthometric heights (elevations) were determined using GNSS with NGS geoid model GEOID2022 combined with differential and trigonometric leveling.

The survey was conducted using post-processed and real-time GNSS, leveling, and total station equipment and methods (not necessarily all inclusive). The resulting coordinates are referenced to the National Spatial Reference System. A partial list of point coordinates is given below (additional coordinates are available upon request). Accuracy estimates are at the 95% confidence level and are based on an appropriately constrained and weighted least-squares adjustment of redundant observations.

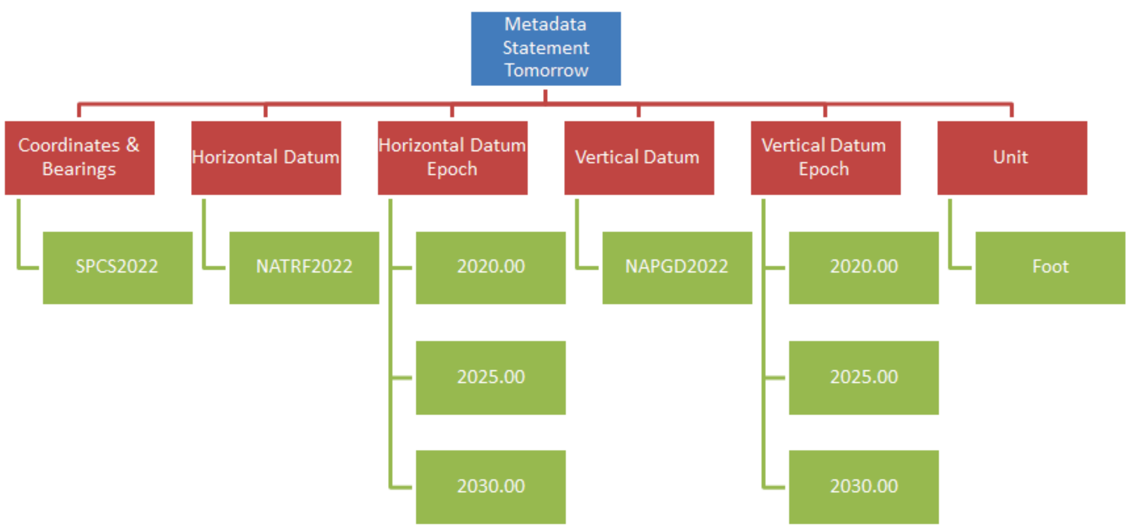

Figure 22: Metadata hierarchy

2. "Calibration" or "localization" of survey data derived using GNSS

“Calibration” and “localization” are terms (among others) used by various commercial software vendors for modifying surveying data obtained using GNSS. For this discussion they can be considered synonymous, and “calibration” will usually be used for both.

Site calibrations are commonly used for GNSS surveys, yet considerable confusion exists about their purpose, when they should be used, how they should be used, and even their mathematical form. On this latter point, calibrations are often generically described as a method for converting “WGS 84” to “local” coordinates. Sometimes these descriptions go so far as to describe a calibration as a 3D geodetic datum transformation. But in reality, a calibration instead decomposes into two separate (non-geodetic) horizontal and vertical operations, and either can be performed without the other.

GNSS is a strictly geodetic tool. Once the X, Y, Z Earth-Centered, Earth-Fixed (ECEF) Cartesian coordinates have been determined, the GNSS part of the process is done. All subsequent operations used to obtain the final coordinate values are coordinate conversions or transformations of some type. The general overall sequence is:

1. If the initial X, Y, Z ECEF coordinates are interpreted as being in the GNSS frame (e.g., WGS 84), they are transformed to the “local” frame (e.g., NAD 83). Note that in many cases the initial coordinates are actually already in the local frame, in which case a “null” transformation is used that does nothing (e.g., treats WGS 84 and NAD 83 as essentially the same).
2. Convert “local” X, Y, Z coordinates to latitude, longitude, and ellipsoidal height (ϕ, λ, h).
3. Compute N, E “grid” coordinates from ϕ, λ using a map projection (or local geodetic horizon).
4. Apply a geoid model to convert h to orthometric height (“elevation”) H.
5. Optional: Perform a “calibration/localization” to compute final coordinates.

Calibrations are transformations that generate final coordinates from GNSS devices after steps 1 through 4 have been completed. Although there is some minor variation in options and details among software vendors, all do essentially the same thing.

A horizontal calibration is a 2-D conformal (similarity) transformation from an initial set of projected N, E coordinates to a new set of N, E coordinates. The transformation parameters (translation, rotation, and scale) are computed from a least-squares best fit of the initial N, E coordinates to a common set of existing N, E coordinates obtained from another source (such as a previous survey).

A vertical calibration can be as simple as a vertical shift to match orthometric heights at one or more specific points, or a more complex inclined planar correction surface with its offset and slope computed by least squares best fit using orthometric heights at common points.

Although calibrations are commonly used by surveyors, there are numerous pitfalls in their application. For further details, see Appendix D, "On Determining Survey Project Coordinates and Heights" in the *User Guidelines for Single Base Real Time GNSS Positioning*, v2.1 (https://geodesy.noaa.gov/PUBS_LIB/NGSRealTimeUserGuidelines.v2.1.pdf). Note that the transformation process for calibrations may change in the future. Regardless of how it is used now or in the future, surveyors should have a complete understanding of how it works and when it should be used.

3.3 Use Case 3: Transitioning Data to the Modernized NSRS

This use case addresses the reality that many users of the NSRS have a lot of data referenced to the existing NSRS that may need to be transitioned into the modernized NSRS.

3.3.1 Background

The last major modernization of the National Spatial Reference System occurred in the late 1980s and early 1990s with the releases of NAD 83 and NAVD 88. At that time, personal computers had barely been around for a decade, awareness of the Internet was in its infancy and most geospatial data was stored in analog form.

For sixty years prior to the release of NAD 83 and NAVD 88, the country had been working within NAD 27 and NGVD 29, planning and building interstate highways, ports, airports, flood maps, tax maps, postal routes, the decadal Census, and thousands of other everyday activities that rely on accurate positions and the consistency of the NSRS to build communities across the Nation and the infrastructure that connects us. Some sixty years of data had built up on those old datums, primarily in analog form (paper maps, survey plats, datasheets, etc.) that needed to be transformed into the new system. Three primary problems faced users of the NSRS who needed their old data transformed to the new system:

1) Transformation tools were not released with the new datums. Specifically, NADCON (for transforming NAD 27 to NAD 83) was not released until 3 years after NAD 83 was released. Similarly, VERTCON (for transforming NGVD 29 to NAVD 88) came 3 years after the release of NAVD 88.
2) NGS policy was (and remains) to advise users of the NSRS that **re-surveying**, rather than transforming, is the most accurate way to establish coordinates in a new datum. Occasionally NGS would also advise users to **re-adjust** original observations to new control as a middle ground, but **transformation** tools were always viewed as the least accurate way to get into the new datums.
3) Analog data is expensive to re-create. For agencies and companies with geospatial data that might span decades in time, span the entire country spatially, or both, the re-printing of paper maps (etc.) could be a significant financial burden.

A number of work-arounds were developed at the time. One notable example is US Geological Survey (USGS) topographic maps. Despite the truth of #2 (above) it would have been impossible to expect that agency to perform an entirely new topographic re-survey of the entire United States using the new datums as control. Once NADCON and VERTCON were released, however, the USGS had to decide how to apply these tools to their flagship products—topographic quad sheets. In theory, each map layer that made up a quad sheet should have been transformed, on a point-by-point basis, into the new datums and then re-consolidated into a new quad sheet. Again, relying primarily on analog data, this was not a feasible option. Therefore, USGS hit on a work-around. For each quad sheet, they computed (from NADCON) the horizontal shift necessary to reflect the NAD 27 to NAD 83 change in coordinates:

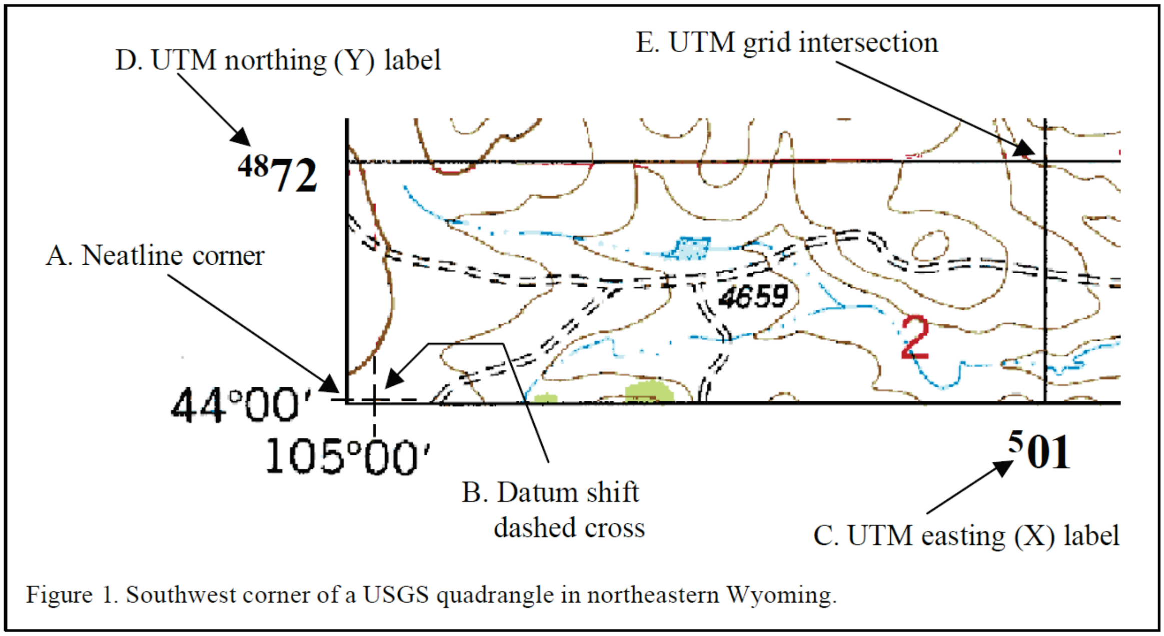

Figure 23: Historic datum shift information as presented on a USGS topographic quad sheet (From DATUM SHIFTS AND DIGITAL MAP COORDINATE DISPLAYS, Larry Moore, 2001 @ http://www.wvgis.wvu.edu/resources/standardsGuidelines/datum_shifts_v2.pdf)

Although printing horizontal datum shifts on paper maps came with a financial cost, that cost was less than the cost of re-surveying the country or even of computing transformations for each layer and re-building each quad sheet. Consider, for example, that the area spanned by each quad sheet is defined through the coordinates of their edges, being on exact multiples of 7.5 minutes of latitude and longitude. The coordinates of those edges all changed with the horizontal shifts from NAD 27 to NAD 83, and could, therefore, have meant a complete change to what actual area was contained within each quad sheet. Rather than adopt new coverage for each quad sheet, USGS did the more prudent thing, and kept the coverage the same, while showing an average horizontal shift for each quad sheet.

One final note on this topic is relevant: When NGS defined the official NAVD 88 height at the datum origin point (Father Point/Rimouski), it was done in consideration of the workload at USGS. Specifically, the defining height was chosen *not* to reflect NGS's best idea of what the true orthometric height (height above the geoid) was at that point. Rather a height was chosen that minimized the total height change from NGVD 29 to NAVD 88 in the eastern half of CONUS (which generally has less topographic relief and thus a smaller contour interval than the western half of CONUS). In this way, the need to re-draw contours on paper maps was minimized over half of CONUS. This decision, a compromise between good science and financial practicality, meant that NAVD 88 was defined with approximately 50 cm of bias between the best known location of the geoid and the adopted zero height surface of NAVD 88. In the future, since most large organizations have digital rather than analog archives, good geodetic science alone will be the driving force behind the definition of the new vertical datum.

3.3.2 Moving into the Future

Consider now the four decades that have passed since the release of NAD 83 and NAVD 88. The pervasive use of computers has meant that analog data has been replaced with digital data, and that trove of digital data has grown exponentially. The entire USGS mapping program is digital, and so solutions meant to resolve analog problems are no longer appropriate. This use case will discuss what has changed, what hasn't changed, and most importantly how forty years of digital geospatial data in the public sector, referenced to the current NSRS, can be efficiently and accurately transformed into the modernized NSRS.

<u>What will not change</u>: In order of decreasing accuracy, the best way for users of the NSRS to determine coordinates in a new datum is:

1. **Resurvey:** Return to the field and collect new observations, relying on geodetic control that has coordinates in the new datum
2. **Readjust:** Using existing observations, re-compute new coordinates based on geodetic control that has been defined in the new datum
3. **Transform:** Take finished products that have coordinates in the old datum and use transformation software to estimate coordinates in the new datum

NGS is committed to supporting NSRS users who wish to do any of the above three tasks. In general, here are the ways each one will be supported:

1) **Resurveying:** NGS will provide geodetic control in the modernized NSRS and will expand its flagship OPUS (Online Positioning User Service) to support a wider variety of surveying methods including RTK/RTN, Leveling, Classical (angles and distances), and gravity. Users will be able to re-survey points of interest using any of these techniques and upload those surveys for processing in OPUS. OPUS will then provide recommendations to users so that their surveys, once processed and adjusted, will be tied to the NSRS. NGS anticipates that this type of transition will be useful for municipalities looking to migrate a local datum into the NSRS or for ongoing project control in areas experiencing lots of vertical motion.

2) **Readjusting:** The OPUS tool will be available for users to upload existing observations of a variety of types and adjust those data to geodetic control in the modernized NSRS. NGS anticipates that this type of transition will be most appropriate for updating existing project control in stable regions.
3) **Transforming:** NGS will continue to offer two overlapping transformation tools: NCAT (NGS Coordinate Conversion and Transformation Tool) and VDatum. These tools currently contain certain identical components (such as NADCON and VERTCON), while work is ongoing to continue to align these two tools. In the future, these tools will both contain the same official transformations between the current NSRS (NAD 83, NAVD 88, etc.) and the modernized NSRS (NATRF2022, NAPGD2022, etc.). NGS anticipates that this type of transition will prevail for updates to legacy mapping data.

Because transformation of existing data is likely to be the primary solution for most NSRS users with legacy mapping data, NGS will specifically support those users in the following additional ways:

1) The source code for both NCAT and VDatum will be made available so that these tools (or their components, such as NADCON or VERTCON) may be more easily incorporated into non-NGS software.
2) The data sets (grids or otherwise) that are the defining parts of NCAT and VDatum will be available in a standardized format. At this time, NGS is planning to release all such grids in GeoTIFF, though NGS continues to participate in international discussions on developing a standard open source grid format.
3) The instructions for executing transformations will be documented. This includes, but is not limited to, providing equations for interpolation, and codifying the proper order of events when chaining together multiple transformations.
4) Sample data sets (both input and output) for NCAT and VDatum will be provided so that users may test other transformation software against NGS's definitive transformation software. These data sets will reflect a variety of transformations, including special cases (such as transforming near the edges of grids, transforming across multiple datums, transforming both geometrically and orthometrically, etc.).
5) Superseded historic transformation software (such as NADCON prior to NADCON 5.0 release 20160901 or VERTCON prior to VERTCON 3.0 release 20190601) will continue to be available on the NGS website, for those users who relied on them and are interested in the differences between older and newer versions of these tools.
6) NGS will not update older transformations. That is, the transformations that exist in NADCON 5.0 release 20160901 (up through and including a transformation to NAD 83(2011) epoch 2010.00) will stand unchanged. When a new transformation, such as

from NAD 83(2011) epoch 2010.00 to NATRF2022 epoch 2020.00 is created, that transformation will be added to the overall set of transformations which are part of NADCON (within NCAT and VDatum) and will remain unchanged once released.
7) Provide uncertainty estimates for transformations.

What will change: NGS has committed to releasing transformation tools NADCON and VERTCON concurrently with the modernized NSRS, and will make them accessible through NCAT and VDatum.

While "resurvey, readjust, and transform" are listed in decreasing order of accuracy they are also in decreasing order of cost and increasing order of simplicity. Users of the NSRS have therefore asked for transformation tools that are capable of handling their large datasets both efficiently and as accurately as such tools can allow. While NGS will provide such tools, there are steps which users can take to prepare themselves for this transition. For instance, LIDAR users would be well-served to make sure the heights in their point clouds are stored as ellipsoidal heights, not orthometric.

NGS has so far been able to handle all of the data that has been sent to NCAT, our current online transformation tool. NGS does not have an accurate estimate of the size of data archives that may require transformations, but even without that estimate it is clear that the current NGS servers and internet bandwidth alone could not possibly handle all of the work. This leaves a few other options:

1) NCAT and VDatum are both available for users to download and run locally on their own computers. As these two tools both draw on the same definitive NADCON and VERTCON source codes, users may be guaranteed that results will be correct, provided they have downloaded the most recent versions of NCAT or VDatum
2) Software developers of all types (private sector companies, other government agencies, open-source communities) may incorporate the NGS-provided NADCON and VERTCON tools into their own code, and make these tools available to their customers that require NSRS coordinates. NGS will always work with any software developer on technical issues surrounding the proper implementation of the transformations. Using such tools carries some risk that the definitive transformations might not be implemented properly, but that risk can be mitigated in a few ways. First, NGS will always have the definitive tools available online so that users can test small sample datasets to ensure agreement with the NGS tools. Secondly, users can run the NGS provided sample input coordinates through their third-party tools and check the results against the sample outputs.

While both fee-for-service and open-source communities may adopt NGS's authoritative tools, NGS is not planning to direct such efforts nor to directly fund them but remains ready to assist communities with any technical advice necessary to their efforts.

3.3.3 Feedback

A number of colleagues within the geospatial community, from local, state, and federal government as well as industry were queried about their data archives, and their need (or lack thereof) to bring those archives into the modernized NSRS.

One common thread that ran through these responses was this: nobody is planning to update their entire geospatial data archives in a single go, right at the release of the modernized NSRS. This was particularly true for those colleagues with LIDAR point clouds. This seems to be related to the size of those LIDAR data sets. What is fascinating about this particular response is that a single point (such as one point in a LIDAR point cloud) is the easiest thing to transform. Unlike a finished product (say a topographic map, consisting of multiple layers, each of which requires its own transformation and then a complicated process of re-integrating the layers into a new map and topology validation), a set of millions of points could be quickly and accurately transformed without much difficulty. However, it must be acknowledged that the raw point cloud is often not the final product, but instead the basis for derived products such as digital elevation models, which require significant processing.

Some further improvements that our colleagues have requested, and which NGS will definitely provide are the following:

1) There will be sample input/output data sets associated with the updated NADCON and VERTCON tools. These will be diverse, covering a variety of complicated issues (points near grid borders; multiple chains of obscure datums; etc.). This will allow users to validate exo-NGS software as fully replicating what the NGS tools are doing.
2) NGS will provide technical assistance to anyone attempting to use or incorporate our tools. We are committed to providing the above-listed sample data sets and also to provide very simple to understand documentation on the proper use and functionality of NGS's definitive transformation tools.
3) Although the U.S. survey foot will be officially deprecated on December 31, 2022, NGS will continue to support the U.S. Survey Foot in our software for historic applications, such as the State Plane Coordinate System of 1983.

Additional feedback from our colleagues indicate that NGS tools might not be suitable for large data sets. We agree. NGS does not have the bandwidth to accept massive quantities of data. Feedback was provided to NGS of other tools being significantly faster at datum transformations than VDatum. While difficult to explain, such speed differences (if true) are further evidence that, though NGS's tools are definitive, they may not be best suited for mass transformations.

3.4 Use Case 4: Leveraging the Modernized NSRS for Airport and Other Infrastructure Monitoring

3.4.1 Introduction: What Does NGS Mean by Infrastructure Monitoring?

Knowing the precise location and measurements of hard infrastructure can be essential for saving lives and reducing damage to private and public property. Broadly speaking, infrastructure monitoring is tracking any motion of a bridge, dam, navigation lock, water level station, power plant (hydropower and nuclear), airport or any other infrastructure relative to itself and/or the NSRS. This use case will focus on an airport example, since accurate positioning of airport infrastructure and maintaining a geospatial database is vital to the National Airspace System (NAS), but the methods discussed can be extrapolated to other types of infrastructure.

An airport's network of permanent geodetic control consists of a Primary Airport Control Station (PACS) and two or more Secondary Airport Control Stations (SACS) tied to the NSRS. Once these marks are established and included in the NSRS Database, they serve as survey control for all airport features and facilities and are available as permanent, recoverable marks on the ground to conduct future surveys tied to the NSRS. Imagine you are performing an AC 150/5300-16B Airport Survey. New Primary and Secondary Airport Geodetic Control Stations (PACS and SACS) have been requested at an airport. The scope of the project is to establish new geodetic control for inclusion in the NSRS. What steps are performed today? How will that change in the modernized NSRS?

3.4.2 Background

A national infrastructure program for establishing and maintaining geodetic control on more than 3,000 airports is identified in the National Plan of Integrated Airport Systems (NPIAS) and the Airports Capital Improvement Plan (ACIP) established by FAA Order 5090.5. NPIAS incorporates specific characteristics for all airports to support an intermodal transportation infrastructure. The ACIP, a subset of NPIAS, defines the characteristics of safety, efficiency, flexibility, and environmental sustainability. NPIAS also oversees federally funded installations of airport geodetic control in the form of PACS and SACS. Airport Geodetic Control submissions are reviewed by the National Geodetic Survey's Airport Survey Program (ASP) for inclusion in the NSRS.

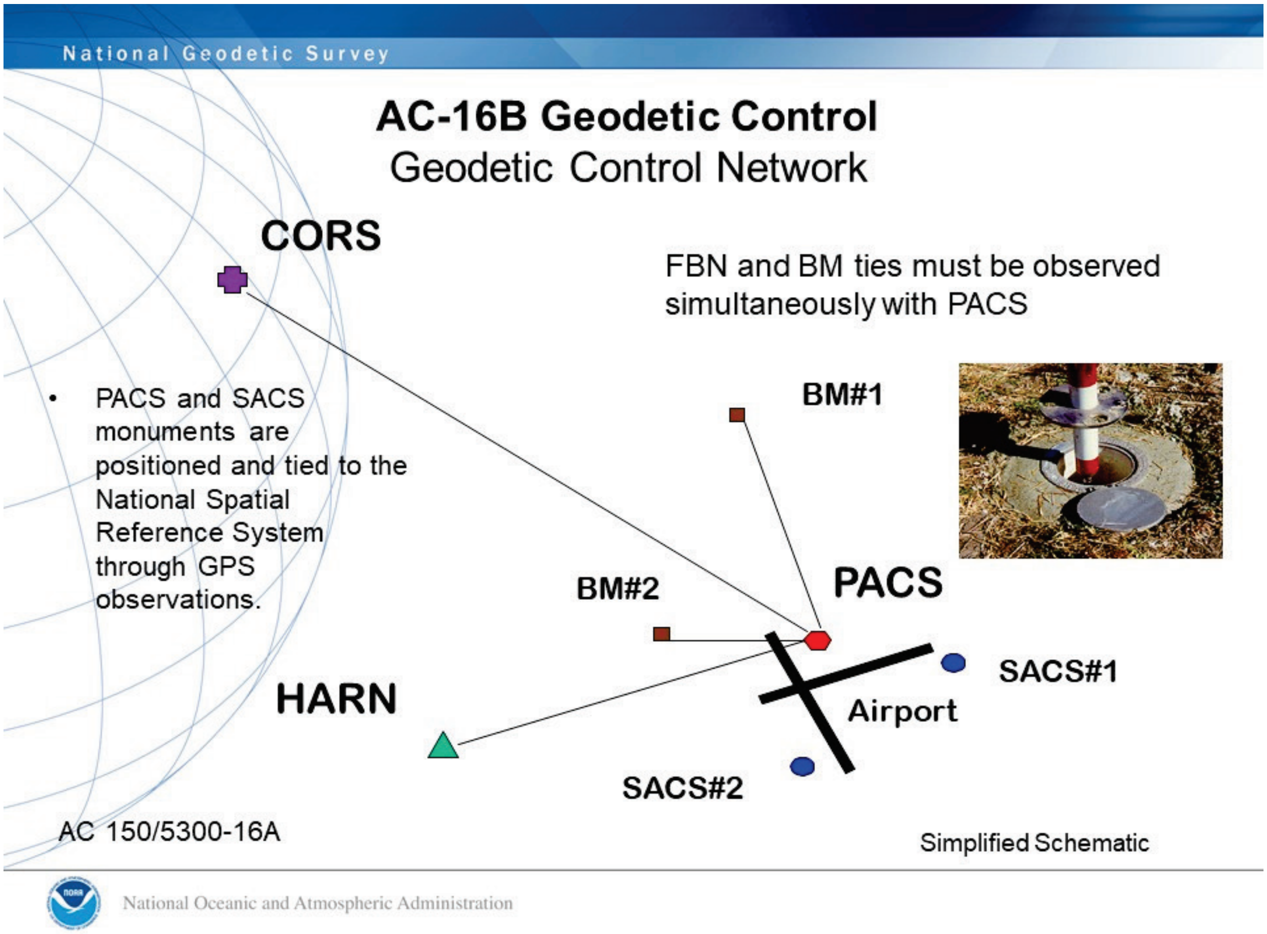

Figure 24. Current Geodetic Control Scheme (Pre-NSRS Modernization)

3.4.3 Establishing Geodetic Control at an Airport

3.4.3.1 Today

The FAA Regional Airports Division determines which airports require permanent geodetic control. Contracted surveyors provide a proposal to the FAA for the establishment of one Primary Airport Control Station (PACS) and two or more Secondary Airport Control Stations (SACS). The PACS and SACS must meet all minimum siting, construction, and intervisibility requirements defined in the FAA Advisory Circular AC 150/5300-16B. These proposed locations are documented in the form of field logs, sketches, and descriptions and are included in the proposal. In addition to the proposal, ties to existing NAD 83 and NAVD 88 passive control are also recovered and documented. Ties to CORSs are also included in the proposal, however, the selections may change at the time of processing due to availability and processing results.
The initial phases of a geodetic control plan requires a search of the NGS IDB using DSWorld or the NGS datasheet retrieval webpage to find at least two 1st or 2nd Order NAVD 88 bench marks within 25 km of the airport. These marks serve as the vertical control for the new PACS/SACS. No

differential leveling is required to meet the FAA requirement; GPS surveying and the latest geoid provide sufficient ties to the NSRS at the time of survey.

Historically, FAA Advisory Circulars have required ties to at least one High Accuracy Reference Network (HARN) horizontal control point within 50 km of the airport. Though today, the use of the HARN is obsolete for control, these marks are still used as a separate positional check when establishing PACS/SACS. Most importantly, users are encouraged to rely on quality metrics from the NOAA CORS Network (NCN) and evaluate processing results.

Once the proposed locations of the new monuments are added to the plan and reconnaissance information is provided for the use of existing passive control, the contracted surveyor also provides detailed information with regard to the GPS observing scheme. These schemes include the observation duration and number of occupations for each passive mark. GPS observations are required to meet a minimum simultaneous session duration. Multiple occupations are required to be independent (separate tripod setups, separate height determinations, and separate solutions). It should be noted that today, static GPS observations are the only approved method used to establish geodetic control at airports.

These geodetic control plans are provided to the FAA for review. Through an Inter-Agency agreement with the FAA, NGS retrieves these project submissions, performs a comprehensive review of all the proposed work, and provides review findings through the FAA Data and Information Portal. Following the approval of the geodetic control plan by NGS, the contractor may commence work.

3.4.3.2 Data Processing and Alignment to the NSRS

OPUS Projects is used today to process and adjust the data, so that it may be included in (or added to) the NGS IDB. Though the project can be created at any time, processing of the project occurs only after final ephemerides become available (12–18 days following the last observation[60]). This ensures the best possible alignment to the IGS realization of the ITRF. PACS, SACS, HARN, and bench mark observations are uploaded to the project while a selection of CORSs are automatically added to the project. The user has the option to add/delete CORSs to/from the project based on the data available at the time to produce favorable results. The initial processing of these simultaneous observations are grouped into sessions. Sessions are analyzed to meet project requirements, then a combined network solution is performed to align the project to the NSRS. For submission of the project to be included in the NGSIDB, a series of Horizontal adjustments are performed to produce latitude/longitude/ellipsoidal heights. In the horizontal constrained adjustment, the user has the option to constrain local passive control marks that are consistent with the NSRS. The current datum for horizontal coordinates is referenced to NAD 83. Vertical adjustments are performed by constraining leveled bench marks that are published in the NGSIDB (e.g., NAVD88, Local Tidal). In certain cases where NAVD88 is not available, NAD 83 ellipsoidal height minus geoid height is used to estimate the orthometric height of marks. The position/elevation that is computed by the user is referenced to

[60] The International GNSS Service (IGS) data products: http://www.igs.org/products

NAD 83(2011) epoch 2010.0. Orthometric heights are referenced to **NAVD 88**. These are coordinates that are **tied to the NSRS** and NGS will load them in the NGSIDB and publish them on datasheets.

Quality control measures ensure the data received has been performed using the latest guidance and remains consistent with the NGS Data Submission Policy. NGS performs a comprehensive analysis of the mark setting, stamping, and proximity to other airport features. GPS Observation Logs are checked for consistency with the submitted RINEX data, equipment listing, and observation scheme. IGS precise orbit data and NOAA CORS Network (NCN) data must be used in data processing. The current IGS/ITRF epoch must be used in computations. CORS constraints and passive control constrained in the adjustments must have a consistent NAD 83 reference frame (2011, PA11, or MA11) and epoch (2010.0) coordinates.

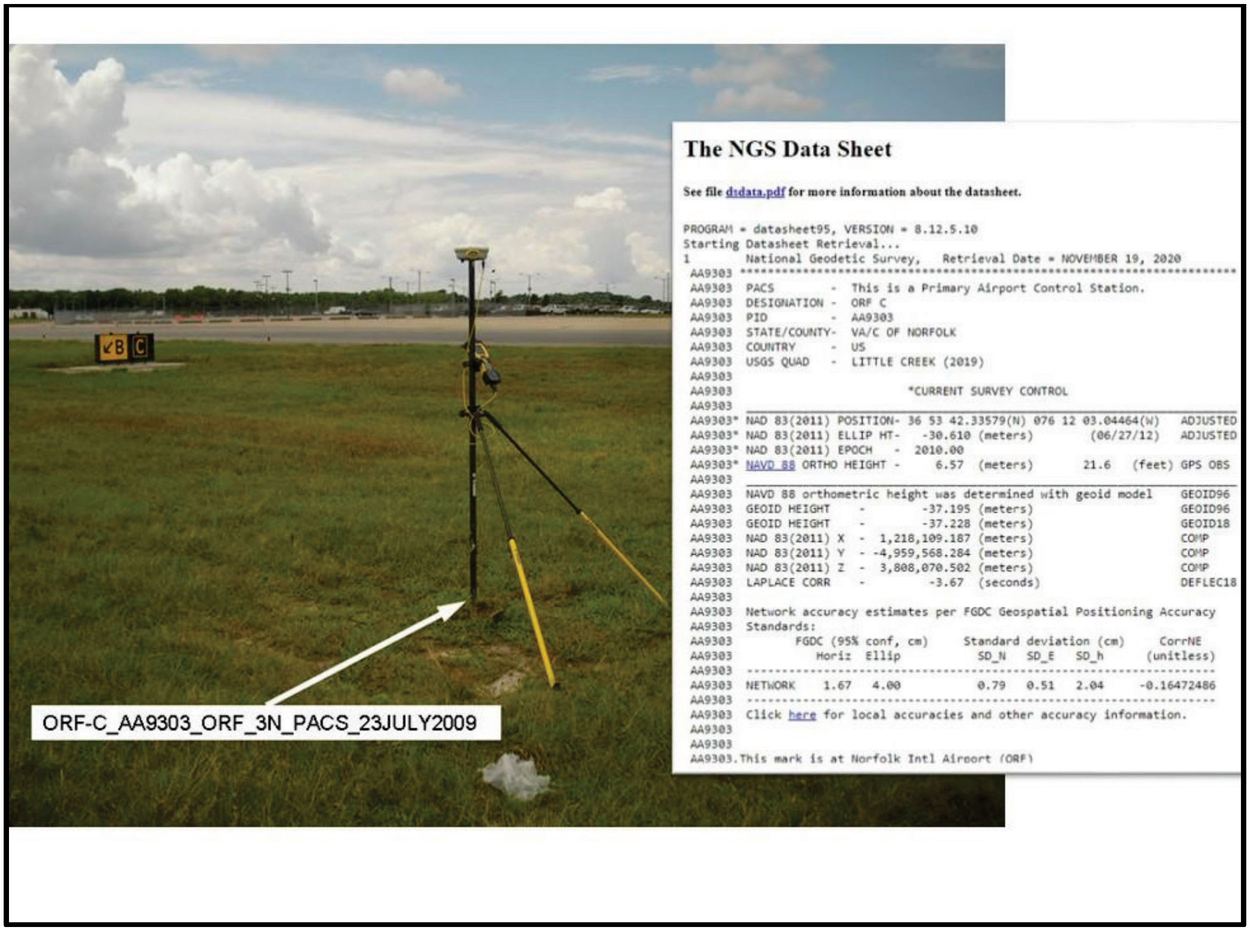

Figure 25. PACS example with NGS Datasheet

3.4.3.3 Survey control for airport infrastructure

Why is the NSRS important to airport infrastructure? Quite basically, what goes up, must come down. Geodetic ties to runway ends, NAVAIDS, obstructions and other airport features are all necessary to maintain the spatial integrity that connects the National Air Space to those features and infrastructure on the ground. Once the NSRS tie of PACS and SACS are in the NGSIDB, they serve as passive control for all supplemental surveying, engineering, and mapping work on an airport. In previous years, NGS has provided updated coordinates on PACS/SACS relative to the multi-year CORS solution of the NOAA CORS Network (NCN). NGS provides accuracy information for adjusted passive control relative to the NSRS in the form of local and network accuracies and included on datasheets for each published mark. If these monuments are damaged or destroyed, the link to the airport infrastructure is broken. New survey control must be established in order to maintain the geodetic tie to the NSRS.

3.4.3.4 Future

NSRS Modernization efforts to replace NAD 83 and NAVD 88 have been ongoing since 2007. In a modernized NSRS, users will tie to the NSRS using enhanced functionality of OPUS. A number of changes will happen with the modernization. OPUS tools will be expanded to allow for multi-constellation GNSS data, RTK/RTN data, as well as leveling, classical (total station) data and gravimetry. The reliance on passive control to assign coordinates in perpetuity on marks is an old way of doing business. The use of HTDP (2-D, assumed errorless mark movement model) will be replaced with IFVM2022 (3-D, with uncertainties). The four reference frames (NATRF2022, PATRF2022, CATRF2022, and MATRF2022) will replace the three NAD 83 frames. GEOID2022 combined with the geometric coordinates will produce orthometric heights in NAPGD2022. Vertical land motion will be accounted for using IFVM2022 resulting in time-dependent ellipsoidal heights, which (when combined with the time-dependent GEOID2022 model) will yield time-dependent orthometric heights in NAPGD2022, which will replace NAVD 88. All of these features of the modernized NSRS will provide more realistic coordinates relative to the dynamic earth.

PACS and SACS will still have a critical role for airport infrastructure monitoring, however, their usage will be redefined in the future. While the primary purpose of PACS/SACS is to monitor the airport's position within the NSRS, it can be used for the secondary purpose of monitoring the infrastructure relative to itself and its surrounding area (that is, to monitor deformation of the infrastructure). Depending upon accuracy and monitoring needs, other infrastructure may use similar passive control, but for swapped needs. That is, the primary purpose may be to monitor deformation of the infrastructure itself, with a secondary purpose of monitoring it within the NSRS. The following use case provides a theoretical example of a PACS/SACS survey performed in a modernized NSRS, but it is hoped readers can extrapolate this example to their own particular infrastructure monitoring needs. In this use case example, the Office of Airports and the Airport Manager have requested PACS and SACS be established on an airport in 2026.

3.4.3.5 Search

Prior to submission of a geodetic control plan, perform a search of the NSRS Database using the NGS Data Delivery System for any existing passive control on the airport property that meet the siting, proximity, and stability requirements to be established as PACS or SACS. The use of existing marks reduces the proliferation of marks on airports and reduces mark setting costs. In the event no suitable marks are found, three new marks will be established as performed in previous years. The proximity offsets from other airport features and stability requirements will not change. Perform reconnaissance of these locations and provide photos, sketches and preliminary descriptions of the proposed locations (Figure 26).

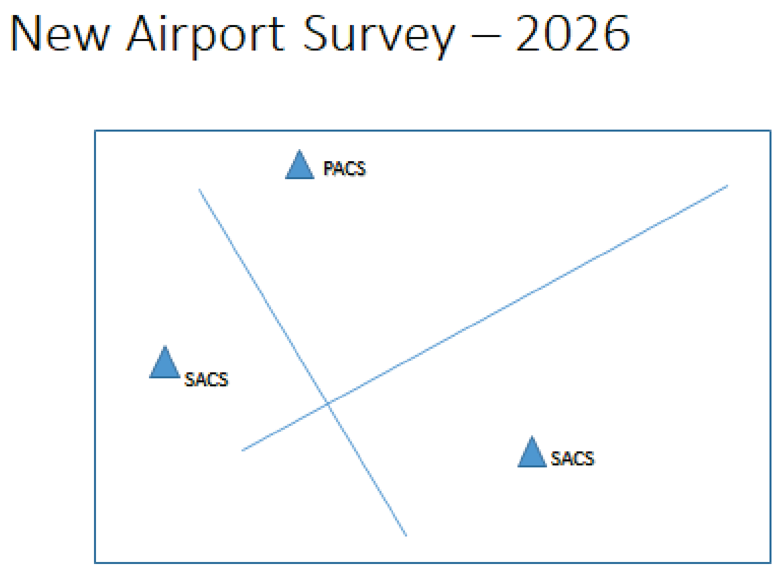

Figure 26. Simplified airport geodetic control schematic showing PACS/SACS (triangles)

The first step of the survey will be to **tie your control to the NSRS**. The primary source of NSRS coordinates for geodetic control in a modernized NSRS will be accessed through the NOAA CORS Network (NCN), assuming your survey contains GNSS. The reliance on existing passive geodetic control for positioning new marks is therefore not a requirement for future PACS/SACS surveys. Additionally, NAPGD2022 orthometric heights will be determined using the NCN and no bench marks are required to provide vertical control. The network configuration is simplified.

3.4.3.6 Observe

In the modernized NSRS, observations can be performed using static GNSS, RTK or RTN (as well as leveling, classical and gravity[61]) to tie to the NSRS. Though the specific methods recommended for GNSS observation time, collection interval, etc. will be addressed in the updated NGS 58 document (*Guidelines for Establishing GPS-Derived Ellipsoidal Heights*), survey best practices will remain consistent. These include the use of calibrated equipment, the need for redundant observations, unobstructed satellite visibility, avoiding multipath, collection of metadata, and avoiding data collection during elevated Dilution of Precision times (DOPs). In this sample scenario, observations are collected using static GNSS equipment and an assumed midpoint epoch date for the combined observations.

3.4.3.7 Processing and Adjustment

Active coordinates (ACs)[62] of each CORS in the NOAA CORS Network (NCN) will serve as geodetic control in the modernized NSRS. As users perform vector processing for projects today, OPUS will continue to provide computations of coordinates in the Earth-Centered, Earth-Fixed (ECEF)

[61] These aren't expected to be part of airport surveys, but they will be supported in the modernized OPUS
[62] Also called "coordinate functions"

ITRF. In the modernized NSRS, OPUS will also apply Euler pole parameters (EPPs) to produce ECEF coordinates in either NARTF2022, PATRF2022, CATRF2022, or MATRF2022. The GRS 80 Ellipsoid will be applied to produce geodetic latitude/longitude and ellipsoidal height. The NGS geoid model (GEOID2022) is then applied to the geometric adjustment to yield orthometric heights referenced to NAPGD2022. These coordinates produced by OPUS will be coordinates computed by the user and (assuming all OPUS recommendations are followed) will be labeled as "Tied to the NSRS" and will be suitable for geodetic control for positioning all other airport features. These coordinates will be known as "**OPUS Coordinates.**" This is the primary service of OPUS (Figure27).

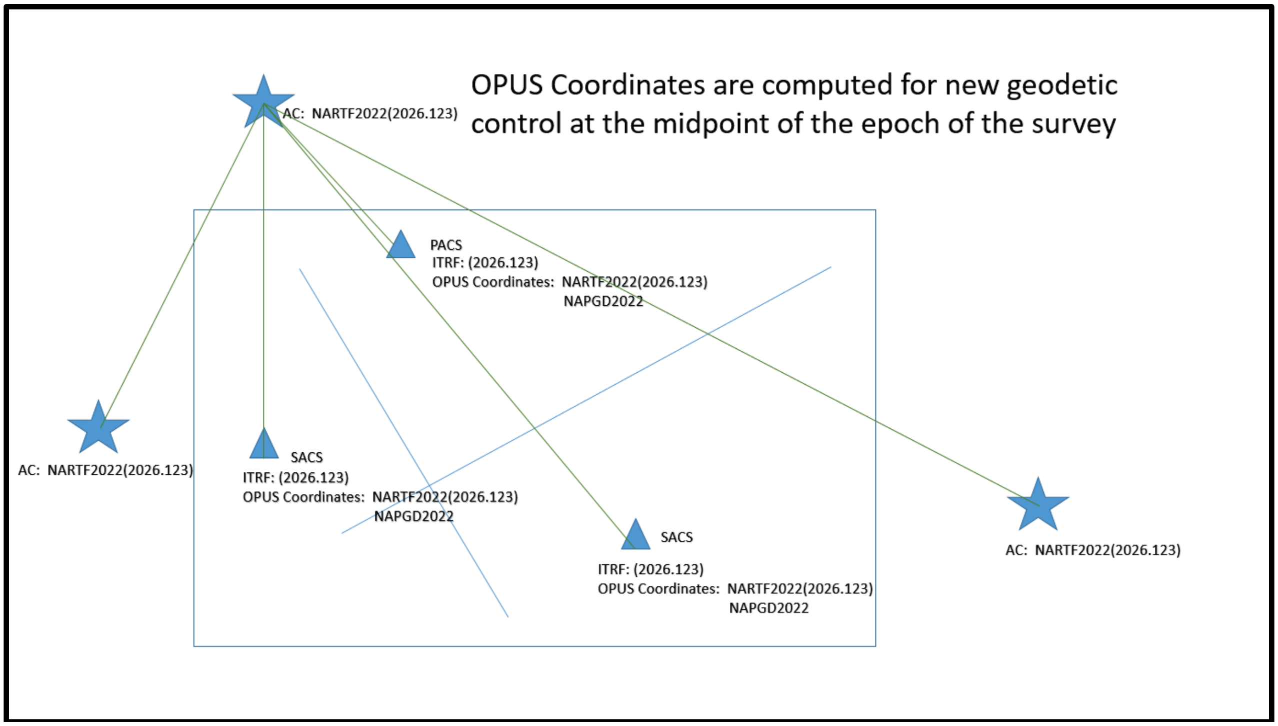

Figure 27. CORSs (stars) are added to the project with the epoch date of the observations (date is assumed)

In addition to OPUS Coordinates, users may choose to investigate and compare coordinates within reference frames to previous collected survey data. OPUS will provide additional tools to make these comparisons by allowing the user to produce coordinates at previous epochs. The initial plan is that if OPUS is used to adjust a project to a reference epoch no further than two reference epochs prior (and all other OPUS recommendations are followed), those OPUS coordinates will still be "tied to the NSRS." OPUS will use the EPPs to transform coordinates between frames, while also using the IFVM2022 to account for residual surface motion within each frame and to propagate the coordinates through time to other epochs. While this is a useful function of OPUS to produce coordinates in matching reference frames/epochs for inverse comparison to investigate mark stability through time, this function should be used for survey control with caution. These user-specified coordinates can still be labeled as OPUS Coordinates tied to the NSRS but cannot be retrieved at some later date through the NGS Data

Delivery System (DDS). Sourcing OPUS Coordinates from a previous survey is a valid case to provide comprehensive metadata for all geodetic control projects and publication of all airport survey data. At a minimum, each survey must include a Basis of Bearings and Coordinates to include the geodetic reference frame (NATRF2022, PATRF2022, CATRF2022, or MATRF2022), the epoch date of computed coordinates (2026.123 from Figure 28), and the geopotential datum (NAPGD2022). It is required that the CORSs used in vector processing also be tabulated.

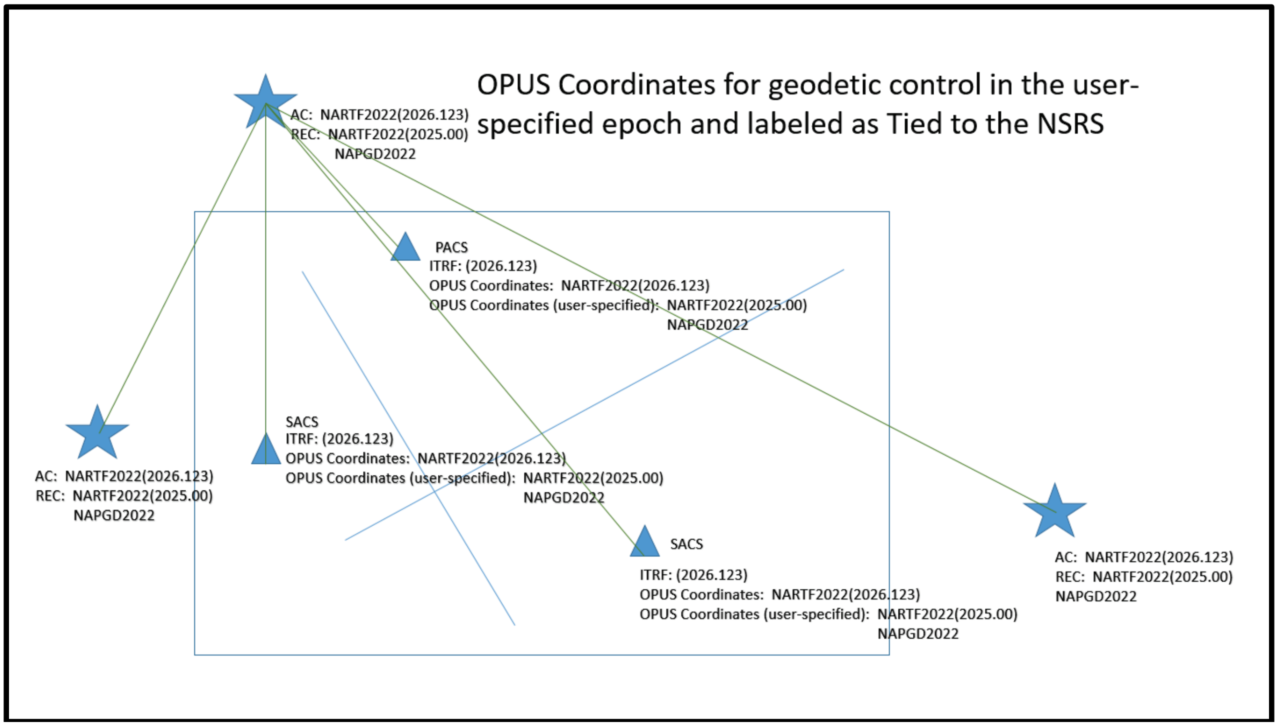

Figure 28. Example of User-Specified Epoch Coordinates

3.4.3.8 Review and Submit for Publication

Following the vector processing and adjustment of PACS and SACS, users will be encouraged to submit their survey data to NGS. For all projects submitted to NGS, NGS will perform quality checks, and then store the data, using it in their computations of survey epoch coordinates (SECs) and reference epoch coordinates (RECs) (Figure 29). Both of these types of coordinates will be computed by NGS using the submitted raw observations from all survey projects submitted to them. In the case of geometric coordinates, the submitted data will be processed into the SEC and REC adjustment projects with all other data that fall with it in an approximate 4-week window known as a Geometric Adjustment Window. The SECs represent NGS's best estimate of coordinates on a point at the epoch of data collection. In contrast, RECs represent NGS's best estimate of the coordinates on a point at the most recently passed reference epoch (likely on a 5 or 10 year basis). These published coordinates will be **part of the NSRS.** The NGS processing cycle for each geometric adjustment window is currently expected to be done every four weeks, with a delay of 12–16 weeks. This will allow enough time for data collected within an adjustment window to be submitted to NGS for the creation of SECs and RECs.

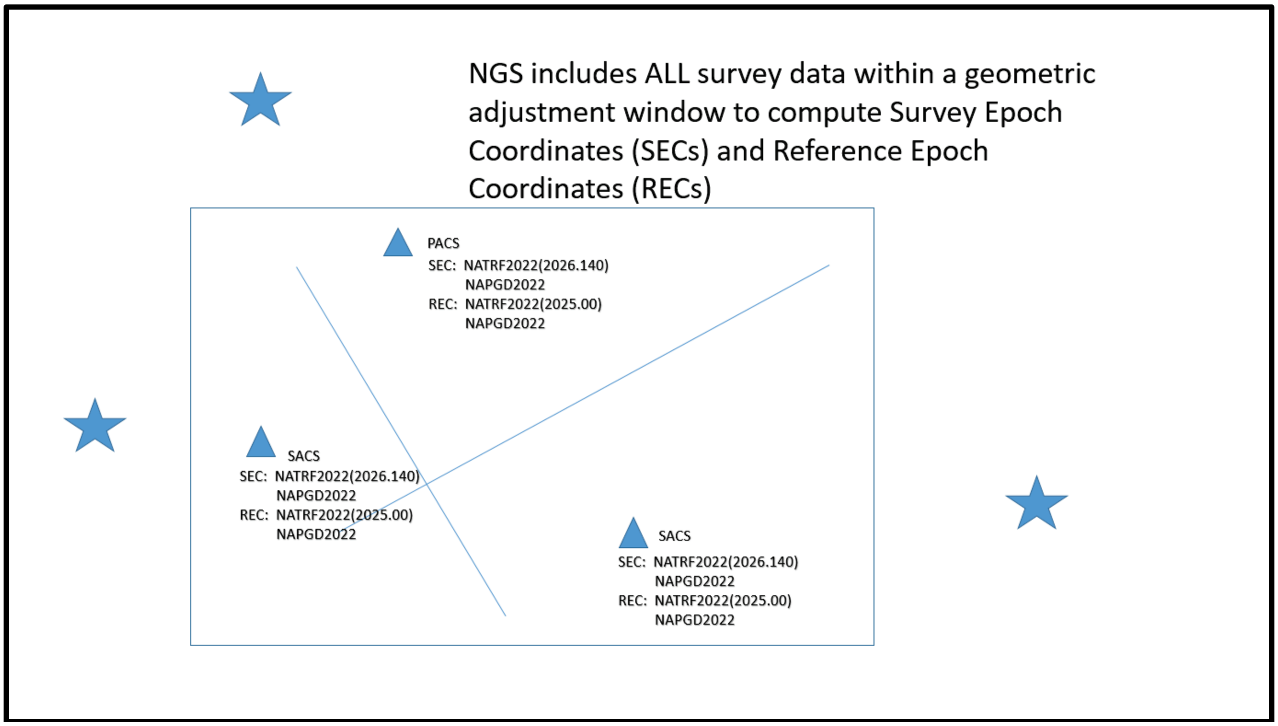

Figure 29. Example of NGS computed Survey Epoch Coordinates (SECs) and Reference Epoch Coordinates (RECs)

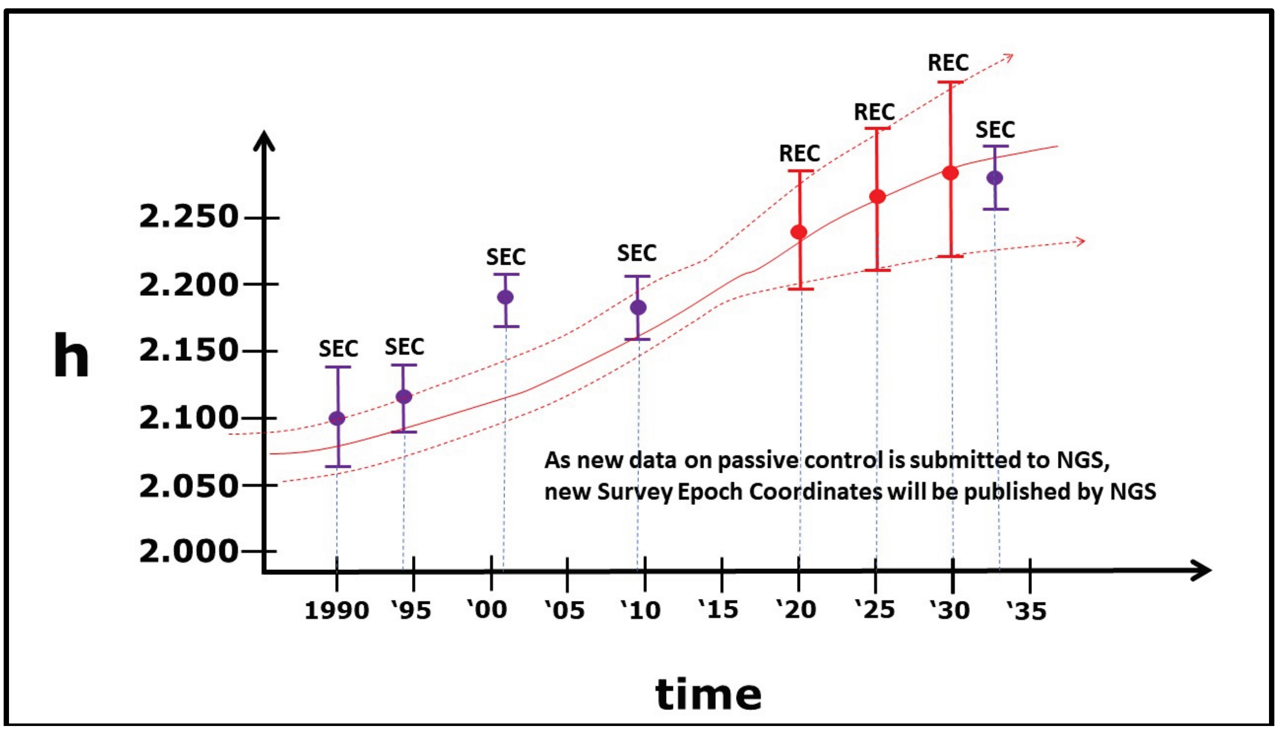

Figure 30. Example of SECs and RECs in a modernized NSRS

3.4.3.9 Benefits of a Modernized NSRS

For many years, FAA has used Ground Based Navigation Aids, specifically Instrument Landing Systems (ILS) to safely navigate aircraft and provide precision approach and landing procedures. These systems rely on radio beacons to provide vertical and horizontal navigation guidance during precision approach and landing. There are limitations to these systems. For example, an ILS composed of a localizer and glideslope used in precision approach and landing serves only one approach for one runway. Realizing the benefits of the accuracy and integrity of GPS, the FAA has begun incorporating advances of GPS they refer to as Performance Based Navigation (PBN). One system known as Wide Area Augmentation System (WAAS) utilizes a combination of ground-based reference stations and geostationary satellites to augment GPS and provides about 1–2 meters accuracy H/V. Since its implementation in 2003, WAAS has been used to safely navigate aircraft in all phases of flight. To further enhance precision approach and landing procedures, some public and private airport authorities known as Air Navigation Service Providers (ANSP) have begun to incorporate a Ground Based Augmentation System (GBAS) (Figure 31). A single GBAS at an airport can serve up to 48 approaches with a high-level of precision and integrity <1 meter H/V. GBAS technology uses an omni-directional VHF Data Broadcast Signal, four GPS Antennas/Receivers, and a processing computer for aircraft to receive differential GPS corrections for approach procedures. By incorporating this system and tying these systems to the NSRS, aircraft will be using the NSRS for precision approach procedures.

For airport infrastructure monitoring, NSRS time-dependent coordinates associated with NAVAIDS, runway ends and other airport features, the modernized NSRS will improve orthometric height accuracy and reliability relative to the local environment, especially in areas where NAVD 88 has become unreliable. Following the installation of PACS and SACS, future surveys can recover, observe and tie new surveys to the NSRS. Access and tying to the NSRS will remain as user-friendly as it has under OPUS-S and OPUS Projects, while enhancements to these tools within a modernized NSRS will include GNSS, RTK, and RTN (and others) to produce OPUS Coordinates tied to the NSRS. Labor-intensive and sometimes daunting efforts to "Bluebook" data in the NGS database will be replaced by user-friendly tools in OPUS. NGS will continue to publish user-provided survey data with the addition of publishing survey epoch coordinates (SECs) and future estimation of reference epoch coordinates (RECs) to capture the best estimation of how a mark moves through time. User-contributed repeat observations of PACS/SACS to NGS via OPUS following recovery and subsequent usage, and NGS's effort to use those observations to create SECs, is an effective way to monitor change of airport infrastructure relative to itself and the NSRS (Figure30). Repeat observations over time will also provide useful data in building a comprehensive IFVM.

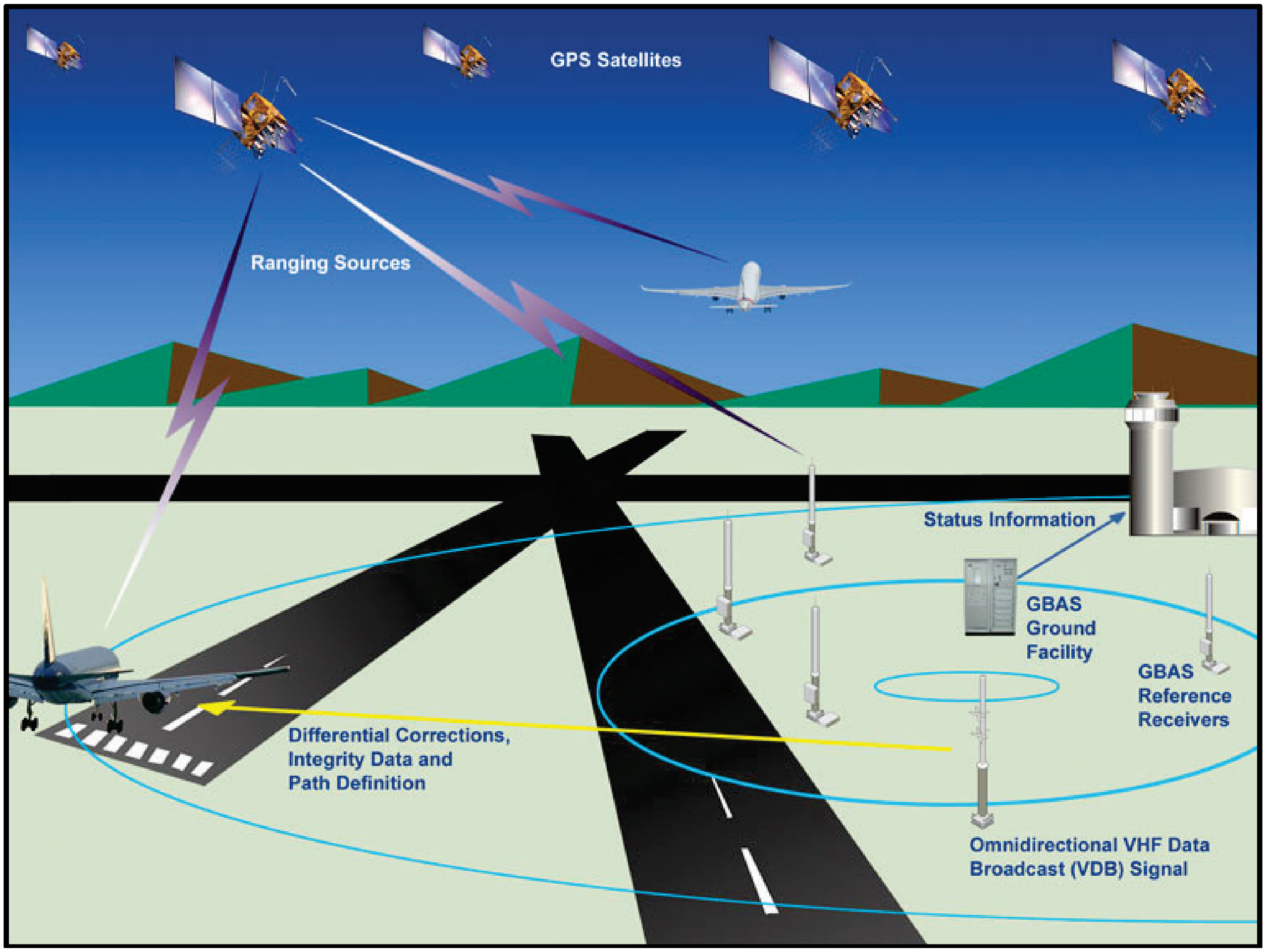

Figure 31. FAA example of GBAS (Source: https://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/laas/)

3.4.4 Recovery, Verification and Control of Future Surveys

Working in the modernized NSRS will require some adaptive changes to future workflow for verification of existing geodetic control. Many of the existing PACS and SACS residing in the NSRS will be carried forward to an epoch date of 2020.00 in the four TRFs as well as ITRF2020 using previously submitted GPS observations. These coordinates will likely have greater uncertainty in the new frames, so in the modernized NSRS, OPUS will provide tools for the verification of existing control.

As mentioned earlier, the NSRS Database will be accessed using the NGS Data Delivery System (DDS). Information for existing PACS and SACS can be retrieved from this source to aid in the physical recovery of these marks. Physical stability, photographs, and reference measurements should be recorded as metadata to be submitted to NGS as recovery information. Static GNSS, RTK, and RTN observations can be performed while also ensuring the minimum standards of observation frequency and duration are met or exceeded.

3.4.4.1 Comparison of OPUS Coordinates to Published RECs/SECs.

In the past, OPUS has provided ITRF coordinates for the epoch date of survey as well as transformed coordinates in the latest realization of NAD 83, back to its most current reference epoch of 2010.00. Additionally, OPUS computes orthometric heights using the latest hybrid geoid model. Users were able to compute 3D inverse computations of observed to published NAD 83(2011) epoch 2010.0 to verify PACS and SACS met the required accuracy of the AC 150/5300-16B shown in Table 4:

Table 4. AC 150/5300-16B PACS and SACS Accuracy Standards

ITEM	HORIZONTAL	VERTICAL	
		ORTHOMETRIC	ELLIPSOIDAL
Primary Airport Control Station (PACS) [1]	3 cm	5 cm	5 cm
Secondary Airport Control Station (PACS) [2]	2 cm	5 cm	4 cm
Wide Area Augmentation System (WAAS) Reference Station [1] (not an NGS CORS)	3 cm	5 cm	5 cm
Wide Area Augmentation System (WAAS) Reference Station [3] (not an NGS CORS)	1 cm	0.2 cm[4]	2 cm

Notes:
[1] Network accuracies (relative to NSRS stations used as constraints).
[2] Local accuracies relative to the PACS and other SACS at the airport
[3] Local accuracies relative to the other WAAS Reference Station at the site.
[4] For leveled height differences between WAAS Reference Stations.

In the future, OPUS will continue to provide ITRF coordinates for the epoch date of survey *(t)*. As mentioned above, OPUS will incorporate Euler pole parameters (EPPs) transformation to produce:

- XYZ (*t*, NATRF2022)
- XYZ (*t*, PATRF2022)
- XYZ (*t*, CATRF2022)
- XYZ (*t*, MATRF2022)

For any of these TRFs, use GRS-80 to produce:

- Lat/Lon/EHT (*t*, NATRF2022)
- Lat/Lon/EHT (*t*, PATRF2022)

- Lat/Lon/EHT (t, CATRF2022)
- Lat/Lon/EHT (t, MATRF2022)

These OPUS coordinates, however, will have an epoch date consistent with the midpoint date of the observations and cannot necessarily be used as a basis for comparison to published RECs or SECs. This is because the creation of SECs and RECs by NGS may include additional information or different choices not used in OPUS. Additional tools within OPUS will allow users to incorporate the Intra-Frame Velocity Model (IFVM) that accounts for residual motion to compute coordinates to an epoch that matches the latest published REC. This can be expressed as t_0:

- Lat/Lon/EHT (t_0, NATRF2022)
- Lat/Lon/EHT (t_0, PATRF2022)
- Lat/Lon/EHT (t_0, CATRF2022)
- Lat/Lon/EHT (t_0, MATRF2022)

The results of these OPUS coordinates propagated to an earlier epoch consistent with the published REC of each PACS and SACS will provide the user a basis for coordinate comparison. The results of this comparison can help the user ascertain the accuracy and integrity of the published marks. If the accuracy requirement is met, the user has the option of controlling the subsequent airport survey using the published RECs. If the accuracy requirement is not met, the user will need to consult the FAA Advisory Circulars for the next steps for establishing geodetic control at the airport. In any event, users are encouraged to submit all data and metadata from their observations to NGS through OPUS functions to update the status of these control marks. Additionally, NGS will harvest the data for these marks to process during an adjustment window to produce updated SECs and RECs. Only unless the physical condition of the mark shows disturbance or instability should these PACS and SACS be removed from publication. Every user-contributed recovery and observation tells a story and provides a history of passive marks. The modernized NSRS makes use of these recoveries and observations to provide a broader scope of the relationship of passive marks to the dynamic earth.

3.4.5 Extrapolation to Other Infrastructure

The installation and use of passive control at airports is done primarily to monitor that airport within the NSRS, for the purposes of developing and maintaining an airport layout plan. However, other infrastructure could be monitored with passive control for other reasons and at other accuracy requirements. For example, consider the situation of a levee. Installing passive control on the levee itself would allow for regular GNSS occupations (say at an annual basis) that would allow for uplift or subsidence of the levee to be monitored. While this monitoring is within the NSRS itself, it could further be tied to local mean sea level by performing additional GNSS surveys at a local tide gage. However, what if the needs were for internal deformation, rather than global positioning? For example, consider the need to monitor a dam for bulges or other deformations. In such a case, passive control on the dam wall itself may not be prudent or even possible. However, passive control surrounding the structure could be used to monitor both deformation and global position. A network of passive control could be installed and surveyed, forming an adjusted network whose relations between points are well known. This could be done using GNSS and OPUS. From these points a laser scanner or total station could be used to target points or create point clouds on the dam face itself. In future visits, rather than assuming the passive control network remained internally consistent, it should be re-surveyed and re-processed in OPUS. As OPUS will have access to prior surveys, you can determine the new relative positions. And then, a re-survey of the dam wall will yield new relations to the marks. Using OPUS to compare the old network to the new network, one can determine what changes have happened to the dam wall relative to the marks, but more importantly, one can determine how much of those changes are changes due to the mark movements and how much is due to actual changes to the dam itself (deformation).

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Appendix A: Geodetic Control Primer

For readers unfamiliar with the concept of geodetic control, this appendix attempts to clarify what it is and how it works.

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

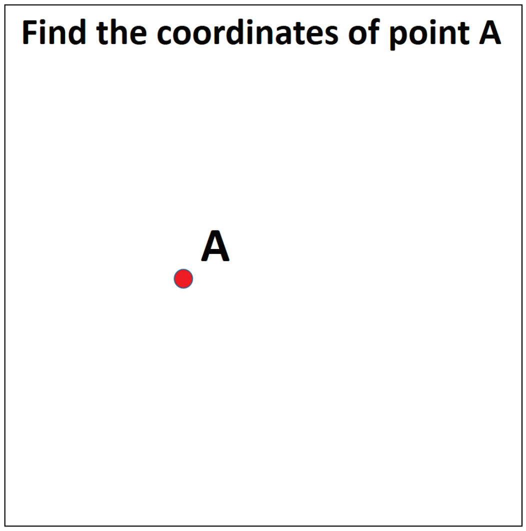

Figure 32: Positioning without enough information

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

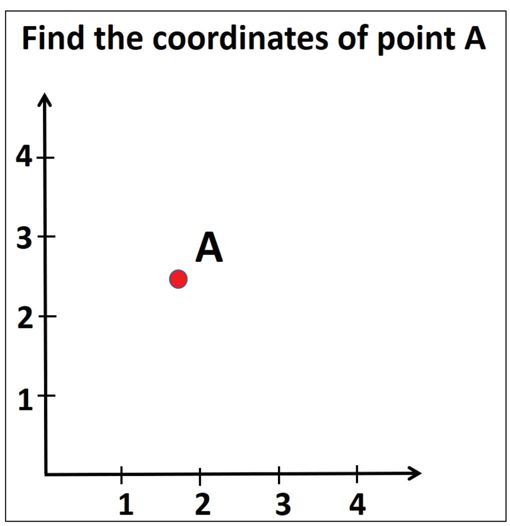

Figure 33: Positioning with axes

However, imagine you were not provided coordinate axes, 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:

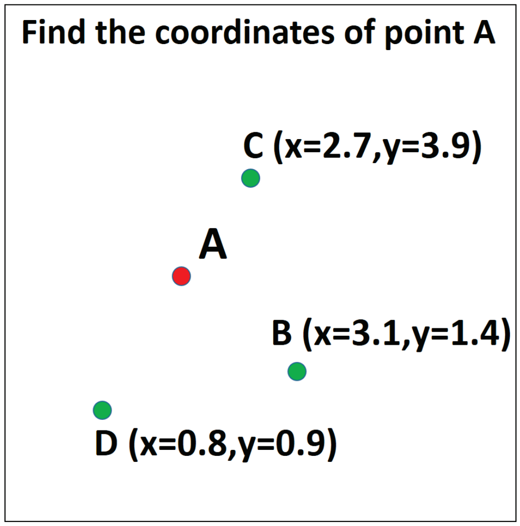

Figure 34: Positioning with geodetic control

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, "Is my house 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.

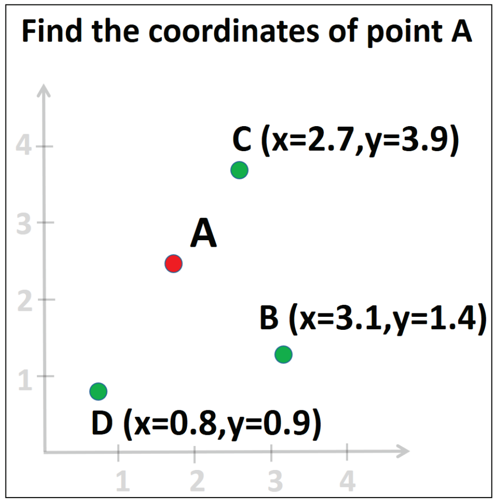

Figure 35: Geodetic Control implies coordinate axes

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, so elevations and surface curvature must 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 surface of 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, observational redundancy, and the proper treatment of all error sources.*

While the coordinates assigned to geodetic control are traditionally treated as unchanging, geodetic control in the modernized NSRS will have acknowledged time-dependencies, due to the dynamic nature of this planet on which they reside.

Note also 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.

Appendix B: Accuracy

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 to some extent quantified the relative accuracy to "nearby" marks. But it was not a quantifiable magnitude of the absolute accuracy of the *coordinates* 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, 2021). Rather than pursue this further, NGS modified our 2007 national adjustment of GPS vectors, yielding the NAD 83(NSRS2007) realization (Pursell and Potterfield, 2008) so that local and network accuracies were reported. Those values were included on datasheets for NGS's 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 2007 national GPS vector readjustment (ibid), 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.

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. Therefore, 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 with normally distributed errors, which may not be the most useful statistical confidence value for every user. 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. Historically, some NGS products and services have reported 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. Although NGS wrote the sections on geodetic control, NGS departed from some parts of that standard when publishing accuracies that were purportedly in compliance. 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 mean it is unknown what the future accuracy standard will look like, nor whether it will even be ready at the time the NSRS is modernized.

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), whereas 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.

Table 5: Multiple ways to report uncertainty in the modernized NSRS

What confidence level is being reported	**How it is reported**
1 standard deviation	5.403 ±0.035 m
Scaled to 95% confidence	5.403 ±0.069 m (95% confidence)
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). See Figure 36. 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. See Figure 37. As computer space restrictions are not generally prohibitive, the likeliest scenario is that NGS would store the complete 3 x 3 dispersion matrix, allowing computation of the three-value uncertainty ellipse and, if requested, perform on-the-fly conversions to less accurate representations if requested, such as the above-mentioned circle.

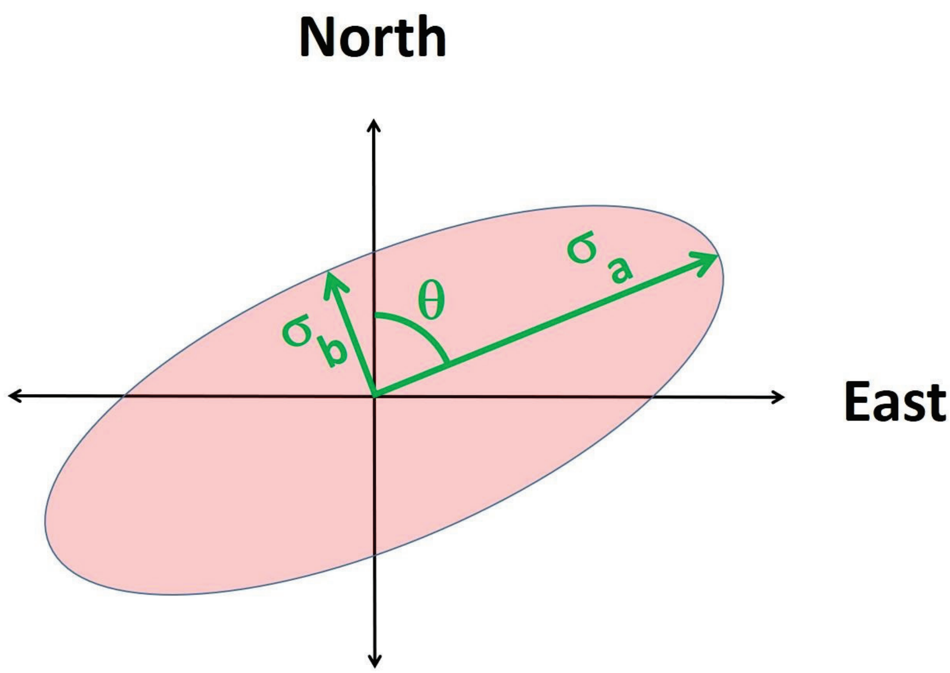

Figure 36: A generic error ellipse. Note that three elements are required to describe both the shape and orientation of the ellipse.

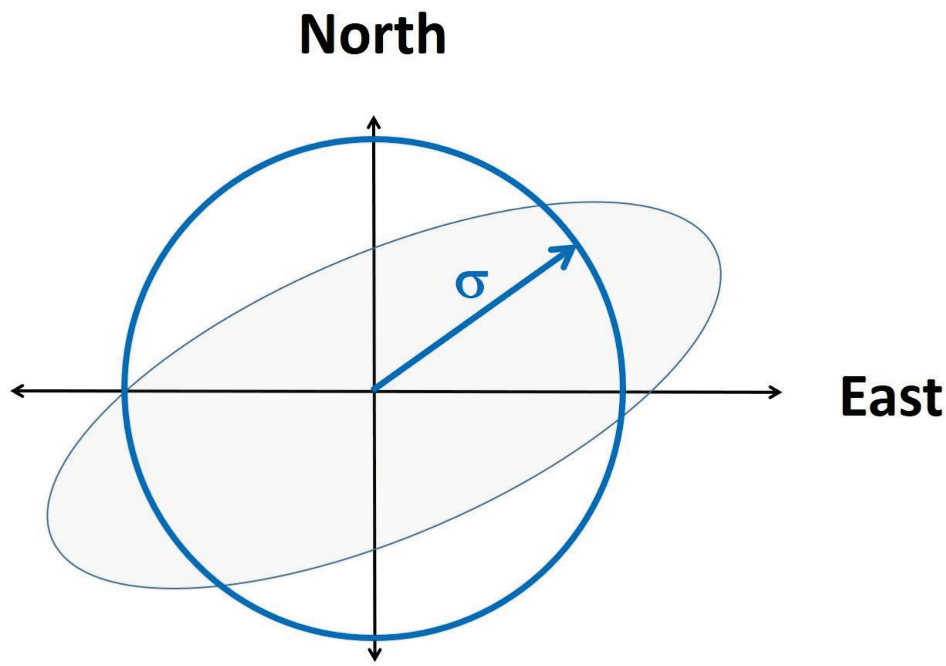

Figure 37: The approximation of an error ellipse by an error circle.

Appendix C: Choosing Adjustment Window Sizes and Lag Time for Processing SECs

Survey epoch coordinates (SECs) are designed to fulfill NGS's plan to provide time-dependent geodetic coordinates. While it would be wonderful if every occupation of every mark yielded a useful time-dependent coordinate that is neither possible nor advisable. First off, some form of redundancy should exist in the observations that underlie a coordinate computation. Second, the occupation of marks takes place throughout projects that span days, weeks, months or even years and it is often necessary to treat those occupations as semi-simultaneous for the sole purpose of making the mathematics of a network adjustment work.

Therefore, NGS had to choose some time span, in which observations would be processed together to yield SECs. These time spans, called "adjustment windows" needed to be short enough so that true time-dependent movements of marks didn't occur (or would be small enough that they could be easily accounted for or ignored) but also long enough to allow users the time to collect redundant observations and complete projects for submission to NGS[63].

While all of the decisions below are preliminary, they are based upon lengthy discussions within NGS as a result of decades of interactions with NSRS users. Final decisions on adjustment window sizes and processing dates remain open to experiment and testing in the next few years, but those final decisions are not likely to deviate radically from these initial ones.

Without regard to type of survey, the following rules were viewed as critical to picking both the adjustment window size and the lag time for creating SECs out of observations that fall in each adjustment window:

1) The window should be large enough to allow for redundant observations and for a standard project to be completed.
2) The window should be small enough to justifiably understand and account for all motions the marks experience.

To put some perspective on magnitudes, the drift (within the ITRF) of Hawaii and most Pacific territories is the fastest horizontal motion in the entire nation, with a maximum known velocity (relative to the ITRF) of 7.57 centimeters per year, or just about 0.5 millimeters in two and a half days, at CORS WQSL on Wake Islands.

Vertical motion is significantly more local and unpredictable, though its magnitudes are similar. An extreme example of vertical subsidence of 17.5 centimeters per year (just under 0.5 millimeters per day) was historically observed in California.

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[63] In fact, let's be clear: it is the submission of data by our constituency which has been the cornerstone of the NSRS for the past few decades, and will continue to be so into the future. SECs, RECs and even ACs, all to be computed by NGS, will come from data whose vast majority is, and will be, contributed from outside of NGS.

NGS is interested in keeping systematic errors below 0.5 mm in all of our tools, but the above known movements does not mean that adjustment windows should be in the 1–2 day range; rather it means that if they exceed that timespan, NGS must carefully account for them. Let us briefly then, consider the three possible adjustment windows: geometric, orthometric and gravimetric.

Geometric

Initial Decisions (subject to change):

Adjustment Window Size:	**4 weeks (every 4 GPS weeks)**
Frequency of adjustment:	**every 4 weeks**
Processing Lag Time:	**12 weeks**

The great majority (about three quarters) of GNSS projects submitted to NGS span a total survey time of about four weeks. That means that users (already using good survey practices, including redundancy) are generally capable of performing two independent occupations on a mark within four weeks of one another. Asking for (but not requiring) such occupations to specifically fall inside of one geometric adjustment window of four weeks 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 control.

Deciding when to process that data was a different story. Basing the lag time on actual historic data submissions is difficult, as users submit data with lag times from days to years. The only clear and obvious requirement was for the IGS final orbits to be available, which required at least a lag time of 2–3 weeks. In the end, a lag time of twelve weeks fulfilled the orbital requirement while allowing enough delay for a “substantial” number of surveys to be submitted to NGS.

Orthometric

Initial Decisions (subject to change):

Adjustment Window Size:	**1 calendar year**
Frequency of adjustment:	**every February**
Processing Lag Time:	**4 weeks**

Unlike GNSS and classical projects, leveling projects tend to span weeks to months. Yet even the most complex leveling network cannot be easily designed in a way to mathematically solve for vertical motions at marks that occur during that project. This means that every leveling network will need to be processed in a way that solves for one (constant) height per point, in general. Considering this, but also considering that these projects take months, NGS has initially decided that the size of the adjustment window for orthometric SEC computations should be 1 calendar year. This will certainly allow for more vertical motion in certain regions than others, but by recommending that NSRS users take GNSS occupations both at the beginning and at the end of their leveling projects (see section 2.9.2), NGS intends to control this situation.

Leveling projects that include observations in two different calendar years will be split up and put into two orthometric adjustment windows.

Because leveling projects are submitted to NGS more sporadically, and from many fewer sources than GNSS projects, NGS is likely to process them into SECs with very little lag time. If they are submitted with GNSS data (as recommended), then only enough time needed to wait for IGS final orbits to be available, which should be 4 weeks at most.

Gravimetric

Adjustment Window Size:	**TBD**
Frequency of adjustment:	**TBD**
Processing Lag Time:	**TBD**

Gravimetric projects have never been a steady submission to NGS, and the last time a Bluebooked gravity project was submitted was before 2000. Nonetheless, NGS performs their own gravity surveys and, once OPUS is expanded to support gravity processing, NGS anticipates an increase in submissions.

Like leveling, most gravity surveys are likely to be self-contained relative surveys, though of shorter duration. Even more so than heights, gravity is very sensitive to vertical motion of the marks over which it is collected as well as other environmental factors. As such, the adjustment window size for gravimetric SEC processing is probably not going exceed a few weeks, but without proper experimentation, such decisions cannot be stated with any definitiveness. Considering the rarity of such submissions at first, the lag time is likely to be short, with individual projects processed at first opportunity (unless mixed with GNSS data, in which case the requisite 3-week waiting period for final orbits will always be observed).