

**AUTOMATED METHODS FOR  
CORRECTING ODOT'S REAL-TIME  
GNSS NETWORK FOR SURVEY AND  
POST-DISASTER RECOVERY**

**Final Report**

**SPR 856**



Oregon Department of Transportation



# **AUTOMATED METHODS FOR CORRECTING ODOT'S REAL-TIME GNSS NETWORK FOR SURVEY AND POST-DISASTER RECOVERY**

## **Draft Final Report SPR856**

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16. Abstract The Oregon Real-Time GNSS Network (ORGN), managed by the Oregon Department of Transportation, serves as a critical backbone for high-precision positioning services across the state. However, the absence of a streamlined workflow for aligning ORGN station coordinates to the National Spatial Reference System (NSRS) has introduced challenges in consistency, traceability, and long-term network maintenance. This project developed and validated a semi-automated alignment tool, ORGN Align, that integrates baseline design, RINEX data management, OPUS Project adjustment, and time-series visualization into a unified platform. Unlike fully automated systems, ORGN Align emphasizes operator oversight and interpretability, empowering GNSS network managers to make informed decisions regarding coordinate adoption and network integrity. This report outlines technical implementation, system capabilities, and recommendations for integration into operational practice, offering a scalable model for GNSS network alignment applicable to other state and institutional networks.					
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**SI\* (Modern Metric) Conversion Factors**  
**Approximate Conversions to SI Units**

Physical Quantity	Symbol	When You Know	Multiply By	To Find	Symbol
Length	n	inches	25.4	millimeters	mm
Length	ft	feet	0.305	meters	m
Length	yd	yards	0.914	meters	m
Length	mi	miles	1.61	kilometers	km
Area	in <sup>2</sup>	square inches	645.2	square millimeters	mm <sup>2</sup>
Area	ft <sup>2</sup>	square feet	0.093	square meters	m <sup>2</sup>
Area	yd <sup>2</sup>	square yard	0.836	square meters	m <sup>2</sup>
Area	ac	acres	0.405	hectares	ha
Area	mi <sup>2</sup>	square miles	2.59	square kilometers	km <sup>2</sup>
Volume	fl oz	fluid ounces	29.57	milliliters	mL
Volume	gal	gallons	3.785	liters **	L
Volume	ft <sup>3</sup>	cubic feet	0.028	cubic meters	m <sup>3</sup>
Volume	yd <sup>3</sup>	cubic yards	0.765	cubic meters	m <sup>3</sup>
Mass	oz	ounces	28.35	grams	g
Mass	lb	pounds	0.454	kilograms	kg
Mass	T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
Temperature (exact degrees)	oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	oC
Illumination	fc	foot-candles	10.76	lux	lx
Illumination	fl	foot-Lamberts	3.426	candela/m <sup>2</sup>	cd/m <sup>2</sup>
Force and Pressure or Stress	lbf	poundforce	4.45	newtons	N
Force and Pressure or Stress	lbf/in <sup>2</sup>	poundforce per square inch	6.89	kilopascals	kPa

\*SI is the symbol for the International System of Measurement

\*\* Volumes greater than 1000 L shall be shown in m<sup>3</sup>

**SI\* (Modern Metric) Conversion Factors**  
**Approximate Conversions from SI Units**

Physical Quantity	Symbol	When You Know	Multiply By	To Find	Symbol
Length	mm	millimeters	0.039	inches	in
Length	m	meters	3.28	feet	ft
Length	m	meters	1.09	yards	yd
Length	km	kilometers	0.621	miles	mi
Area	mm <sup>2</sup>	square millimeters	0.0016	square inches	in <sup>2</sup>
Area	m <sup>2</sup>	square meters	10.764	square feet	ft <sup>2</sup>
Area	m <sup>2</sup>	square meters	1.195	square yards	yd <sup>2</sup>
Area	ha	hectares	2.47	acres	ac
Area	km <sup>2</sup>	square kilometers	0.386	square miles	mi <sup>2</sup>
Volume	mL	milliliters	0.034	fluid ounces	fl oz
Volume	L	liters	0.264	gallons	gal
Volume	m <sup>3</sup>	cubic meters	35.314	cubic feet	ft <sup>3</sup>
Volume	m <sup>3</sup>	cubic meters	1.307	cubic yards	yd <sup>3</sup>
Mass	g	grams	0.035	ounces	oz
Mass	kg	kilograms	2.202	pounds	lb
Mass	Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
Temperature (exact degrees)	oC	Celsius	1.8C+32	Fahrenheit	oF
Illumination	lx	lux	0.0929	foot-candles	fc
Illumination	cd/m <sup>2</sup>	candela/m <sup>2</sup>	0.2919	foot-Lamberts	fl
Force and Pressure or Stress	N	newtons	0.225	poundforce	lbf
Force and Pressure or Stress	kPa	kilopascals	0.145	poundforce per square inch	lbf/in <sup>2</sup>

For More Information see: <https://www.fhwa.dot.gov/publications/convtabl.cfm>

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This project was originally developed to support alignment and maintenance of the Oregon Real-Time GNSS Network (ORGN). The resulting tool and workflow prompted exploration of its applicability as a scalable, national real-time network (RTN) alignment service. In support of this ongoing effort, additional work related to national expansion is being conducted at the time of publication.

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# 1.0 INTRODUCTION

## 1.1 PROBLEM STATEMENT

The Oregon Real-Time GNSS Network (ORGN) plays a critical role in delivering high-precision positioning services to public and private users across the state. From transportation and construction to surveying, research, and emergency response, the accuracy of these services depends on maintaining consistent alignment with the National Spatial Reference System (NSRS). This alignment ensures that station coordinates remain traceable, stable, and interoperable with national geodetic frameworks and reference datums.

Historically, the process of managing this alignment has relied on a combination of manual tools, disjointed workflows, and time-consuming procedures. GNSS station operators, particularly those managing real-time correction services, have had to perform baseline design, RINEX file retrieval, OPUS submission, and network adjustment manually, often without access to standardized diagnostics or residual time-series visualizations. These limitations have made it difficult to detect subtle station movement, assess coordinate stability, or determine when re-publication of station coordinates is warranted.

These challenges are becoming increasingly consequential as GNSS networks grow in scale, as more users rely on real-time services, and as national reference systems evolve toward new datums such as NATRF2022. In this context, Oregon and other RTN operators face a growing need for consistent, semi-automated workflows that not only streamline GNSS data processing but also support operator-led decision-making. Maintaining alignment to the NSRS is no longer a one-time task, it is an ongoing responsibility that requires tools for monitoring, evaluating, and adjusting station coordinates in response to both gradual and abrupt changes.

This project addresses that need by designing, developing, and validating a software tool, ORGN Align, that enables GNSS network managers to align and evaluate their station networks with greater consistency, transparency, and control.

## 1.2 PROJECT OBJECTIVES

The primary objective of this project was to develop and validate a semi-automated workflow to support the ongoing alignment of the Oregon Real-Time GNSS Network (ORGN) with the National Spatial Reference System (NSRS). This alignment is essential for ensuring the long-term integrity, interoperability, and traceability of real-time and post-processed GNSS positioning services across Oregon. The ORGN Align tool was developed to address the inefficiencies and inconsistencies of legacy workflows, offering a unified platform that supports operator-guided decision-making and repeatable network evaluations.

To achieve this goal, the project focused on the following five technical and operational objectives:

1. **Develop a modular, GUI-based alignment tool** that consolidates key components of the alignment workflow, including baseline network design, RINEX file management, and OPUS Project submission, into a single, accessible application. The interface was structured to mirror the logical flow of GNSS adjustment procedures and support intuitive use by RTN operators.
2. **Automate routine processing tasks** such as RINEX download, conversion, and batch upload to OPUS Projects, while preserving user control over essential parameters. This design ensures that the system enhances efficiency without eliminating the expert oversight needed for high-confidence alignment decisions.
3. **Incorporate residual analysis and time-series visualization tools** to enable ongoing evaluation of coordinate stability at individual stations. By parsing OPUS Project outputs and producing daily residual plots, the system allows users to detect both gradual drift and abrupt displacement, supporting alignment decisions grounded in traceable, time-dependent evidence.
4. **Enable flexible configuration and regional customization**, including user-defined baseline strategies, CORS constraints, and the ability to isolate or group stations for targeted reprocessing. This flexibility is critical for responding to localized station movement, infrastructure changes, or operational needs without requiring full-network reprocessing.
5. **Demonstrate and evaluate the workflow through applied case studies**, including a three-month monitoring campaign to assess baseline network stability and a seismic case study following the December 2022 Ferndale earthquake. These examples highlight the tool's ability to detect centimeter-level displacement and support various response strategies, such as temporary coordinate adoption or regional network realignment.

While the ORGN Align system was developed around the specific infrastructure and geodetic framework of Oregon, its design and functionality are broadly transferable. The tool provides a model for how GNSS network alignment can be managed more consistently, with semi-automated support for both routine maintenance and event-driven response, across a wide range of organizational and geographic settings.

### 1.3 ORGANIZATION OF THE REPORT

The remainder of this report is organized into six chapters. Chapter 2 presents background context and a literature review, covering existing alignment tools, GNSS adjustment methods, and best practices for managing reference frame consistency in real-time networks. Chapter 3 introduces the architecture of the ORGN Align workflow and describes the software's core components. Chapter 4 outlines data sources, input formats, and key configuration parameters used in the system. Chapter 5 provides a detailed walkthrough of the user interface, supported by visuals, input/output examples, and step-by-step instructions. Chapter 6 presents two case studies that demonstrate the functionality and diagnostic value of the tool under different operating conditions. Finally, Chapter 7 concludes with a summary of key findings, recommendations for future practice, and a roadmap for continued development and operational integration.

## 2.0 BACKGROUND AND LITERATURE REVIEW

A reliable geospatial reference system is critical for ensuring that data from different sources can be accurately compared and integrated. In the United States, the National Spatial Reference System (NSRS) serves as the foundational geodetic reference maintained by the National Geodetic Survey (NGS). It underpins positioning, navigation, and geospatial data management for a wide array of stakeholders, including federal agencies, state and local governments, private industry, and academia.

This literature review covers the fundamentals of reference systems and frames, describes horizontal and vertical geodetic datums in the U.S., examines the modernization efforts of the NSRS, and explains the importance of aligning geospatial data to standardized datums. The review also outlines Real-Time Networks (RTNs), their role in high-accuracy GNSS positioning, and current best practices for their alignment to the NSRS. Finally, it discusses the significance of robust datum management, including strategies for handling post-disaster deformation scenarios based on lessons from New Zealand.

### *Reference Systems and Reference Frames*

Geodesy is the science that studies the measurement and representation of the Earth's shape, gravity field, and rotation, including their temporal variations (Torge & Müller, 2012). It establishes the spatial reference necessary for mapping, surveying, navigation, and Earth observation. The discipline is commonly divided into two major branches: geometric geodesy and physical geodesy. Geometric geodesy focuses on determining positions on or near the Earth's surface using spatial coordinate systems derived from satellite and terrestrial measurement techniques (Hofmann-Wellenhof & Moritz, 2006). Physical geodesy, by contrast, deals with the Earth's gravity field and the definition of height systems based on gravitational potential, such as orthometric heights (Rapp, 1991).

To assign coordinates meaningfully, a reference system must be defined (Jekeli, 2016). This system includes conventions specifying the origin, orientation, and scale of the coordinate axes. Historically, the celestial sphere served as the principal global reference, realized through star catalogs and astronomical observations. The current inertial reference is defined by the International Celestial Reference System (ICRS) and is realized through the International Celestial Reference Frame (ICRF), based on extragalactic radio sources observed with very long baseline interferometry (Petit & Luzum, 2010).

For Earth-fixed positioning, terrestrial reference systems are employed. These systems are defined in a geocentric, Earth-fixed frame that rotates with the Earth, allowing coordinates of fixed surface points to remain constant over time under the assumption of a rigid Earth model (Jekeli, 2016). The International Terrestrial Reference System (ITRS), maintained by the International Earth Rotation and Reference Systems Service (IERS), is the standard terrestrial system. It is defined with its origin at the Earth's center of mass and axes aligned with the Conventional International Origin and the Greenwich meridian (Petit & Luzum, 2010).

The operational realization of a reference system is called a reference frame. While the reference system is theoretical, the frame provides physical implementation through a network of reference

stations with precisely determined positions and velocities. These coordinates are derived by combining observations from several space geodetic techniques, including Global Navigation Satellite Systems (GNSS), satellite laser ranging (SLR), Doppler orbitography and radiopositioning integrated by satellite (DORIS), and very long baseline interferometry (VLBI). The International Terrestrial Reference Frame (ITRF) realizes the ITRS using these observations; the 2014 release, ITRF2014, incorporates models for seasonal and postseismic station motion, enhancing both spatial accuracy and temporal consistency (Altamimi et al., 2016).

The consistent application of reference systems and their realizations in the form of reference frames provides the foundation for accurate positioning, navigation, and geodetic analysis across a wide range of spatial and temporal scales.

### 2.1.1 Figure of the Earth

Early geodesists first modeled the Earth as a sphere for low-precision mapping. With progressively longer arc measurements in the seventeenth and eighteenth centuries and the development of gravitational theory, it became evident that the Earth is slightly flattened at the poles and is better represented by an oblate ellipsoid (Rapp, 1992). An ellipsoid used in geodesy is described by its semi-major axis ( $a$ ) and its flattening ( $f$ ), which together specify its size and shape for accurate coordinate computations.

However, the Earth does not conform exactly to an ellipsoid, and it is not perfectly rigid. Spatial variations in mass and gravity produce an irregular equipotential surface called the geoid, which can be regarded as the mean sea-level surface in the absence of winds, currents, and other oceanographic effects. Relative to a best-fit ellipsoid, the geoid deviates by amounts on the order of up to a hundred meters worldwide. Geodesists represent this separation by the geoid undulation ( $N$ ) and relate ellipsoidal height ( $h$ ) to orthometric height ( $H$ ) via the simple relationship:

$$H = h - N$$

2-1

as given in Jekeli (2016).

The geoid provides the physical foundation for vertical datums, whereas the ellipsoid serves as the mathematical surface for computing latitude and longitude in horizontal datums.

### 2.1.2 Geodetic Datums

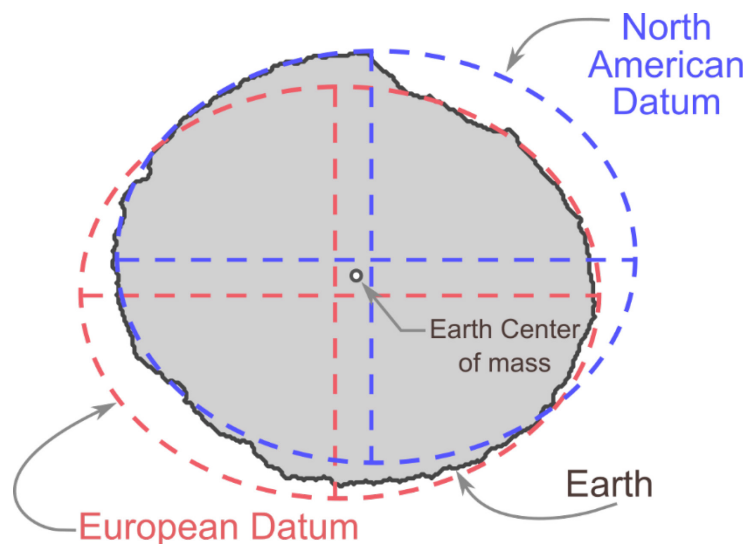
Geodetic datums establish the foundational spatial reference by specifying a conventional coordinate system with defined origin, orientation, and scale, together with the standards and models used for its realization, and by linking this definition to an accessible realization for users. In *practice*, realization is a terrestrial reference frame provided as a catalog of globally distributed sites with reference coordinates at a common epoch and time series that describe their temporal evolution, enabling consistent positioning and mapping (Plag & Pearlman, 2009). Modern realizations also model temporal station motion including seasonal signals and

postseismic deformation to strengthen the stability of the secular frame and the estimated site velocities (Altamimi et al, 2016). Datums support positioning and navigation and are commonly grouped as horizontal and vertical. Horizontal datums define positions in latitude and longitude on a chosen ellipsoid, and vertical datums provide elevations with respect to a reference surface.

### 2.1.2.1 Horizontal Geodetic Datums in General

A horizontal geodetic datum provides a reference for positions in latitude and longitude and is described by parameters that specify the ellipsoid's origin and orientation, together with its size and shape, typically through the semimajor axis and the flattening (Leick, 2004). In practice these can be grouped as three translations and three rotations for the origin and orientation plus two ellipsoid parameters, which together form an eight-parameter definition of the datum

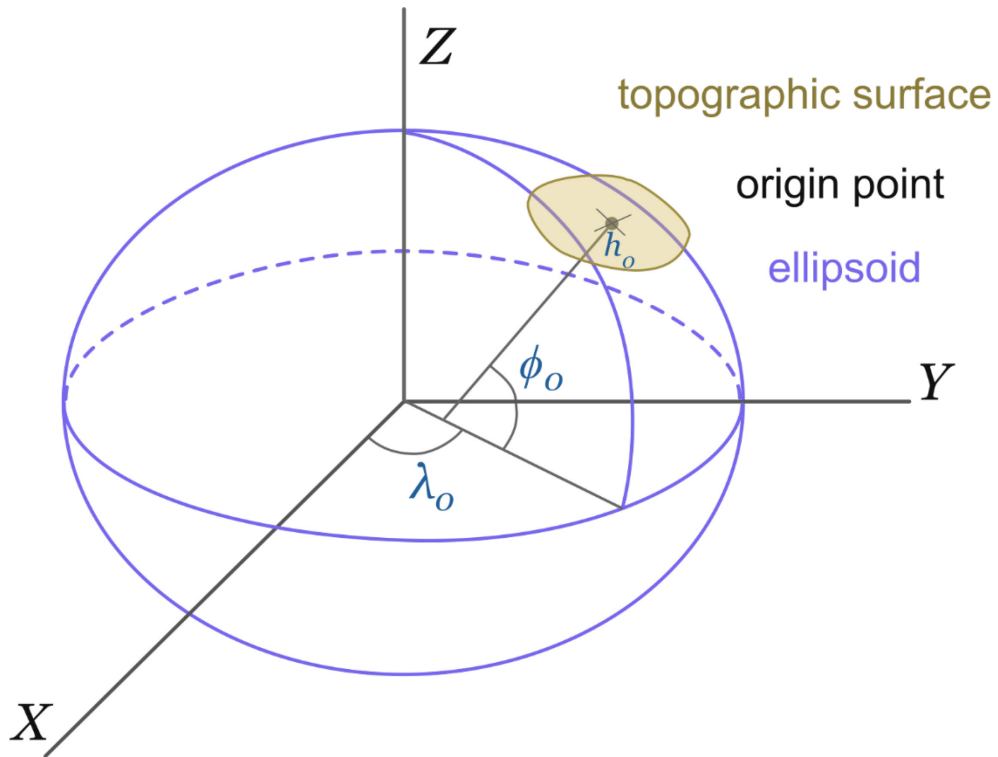
The origin could be defined by placing the center of the ellipsoid at the center of the Earth's mass. Determining the center of mass of the Earth has improved with time. The ellipsoid is usually placed relative to the Earth such that it has a good fit with the region in which the geodetic control is to be established. A good fit means that the surface of the ellipsoid should closely approximate the regional reference surface for heights (geoid) or mean sea level. Figure 2.1 is an example of two different reference ellipsoids for different geodetic datums, each with a different fit. From the figure, notice that the North American datum's reference ellipsoid aligns with the surface of the Earth near North America but does not align with the Earth in other regions. The same can be said for the reference ellipsoid of the European datum. Achieving a good regional fit defines a traditional geodetic datum, which may not be suitable for global positioning but is optimized within its region of fit. As a result, the geometric centers of the ellipsoid models typically do not coincide with the Earth's center of mass.



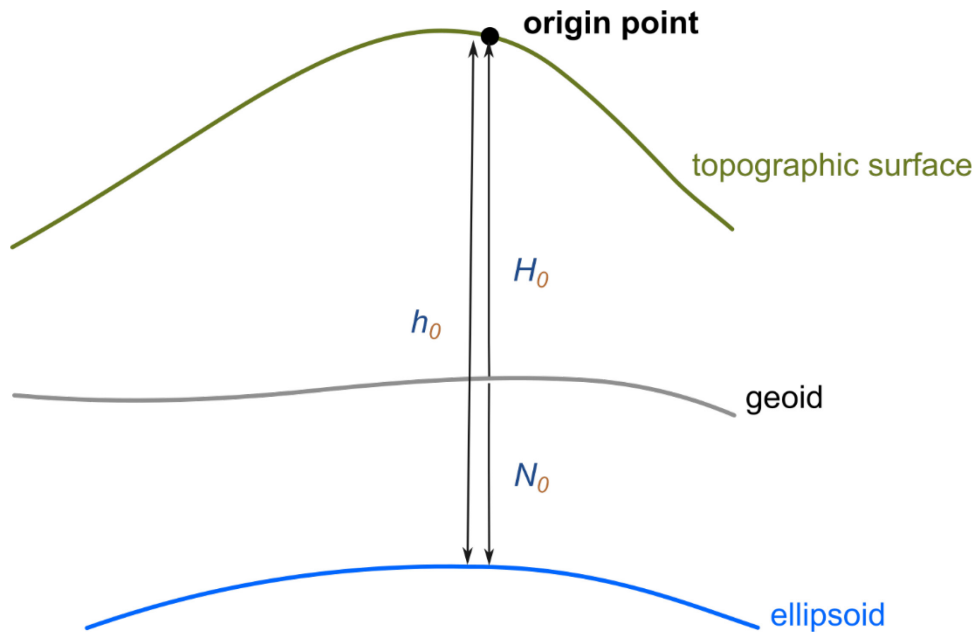
**Figure 2.1: Non-geocentric Datums.**

The origin point can be chosen arbitrarily but is usually selected under the condition that the separation between the geoid and the ellipsoid (geoid height or geoid separation) is

minimized (Figure 2.3). All coordinates for our points of interest within the datum is defined with respect to this origin point shown in Figure 2.2.



**Figure 2.2: Datum Origin Point.**



**Figure 2.3: Geoid Separation ( $N_0$ ) at the origin point.**

**The orientation** is defined as parallel to the astronomic system. This means that the three orientation angles between the ellipsoidal and astronomic system are zero. This relationship is made under the assumption that both systems are concentric, and that the placement of the origin was considered to have no effect. Astronomic and geodetic azimuths are related by Laplace’s condition (a condition imposed by the LaPlace equation on a geodetic longitude or azimuth), and hence a sufficient condition for parallelism (Jekeli, 2012). The LaPlace equation expresses the relationship between astronomic azimuth ( $\alpha_A$ ) and geodetic azimuth ( $\alpha_G$ ), in terms of astronomic longitude ( $\lambda_A$ ), geodetic longitude ( $\lambda_G$ ) and geodetic latitude ( $\phi_G$ ), and is defined mathematically as:

$$\alpha_A - \alpha_G = +(\lambda_A - \lambda_G) \sin \phi_G \text{ (Jekeli, 2016).}$$

2-2

The last two parameters that define the horizontal geodetic datum are those that define the geometric shape, defined by the flattening ratio,  $f$ , and size of the ellipsoid, defined by the semi major axis,  $a$ . Table 2.1 lists the most common ellipsoids models and their defining parameters.

**Table 2.1: Defining parameters for the various ellipsoids used to model the earth**

Ellipsoid Name (year computed)	Semi-Major Axis, $a$ , [m]	Inverse Flattening, $1/f$
Airy (1830)	6377563.396	299.324964
Everest (1830)	6377276.345	300.8017
Bessel (1841)	6377397.155	299.152813
Clarke (1866)	6378206.4	294.978698
Clarke (1880)	6378249.145	293.465
Modified Clarke (1880)	6378249.145	293.4663
Geodetic Reference System (1980), GRS80	6378137.	298.257222101
World Geodetic System (1984), WGS84	6378137.	298.257223563

In summary, the horizontal geodetic datum, as a reference system, is defined as a coordinate system referenced to an ellipsoid with specific parameters, whose origin is fixed relative to the Earth and whose orientation is defined to be parallel to the astronomic system. The reference system is realized by the coordinates of the origin point and indirectly through parameters derived from the astronomic and geodetic azimuths, which are related by Laplace’s condition.

### 2.1.2.2 History of Horizontal Geodetic Datums in the U.S.

The National Geodetic Survey (NGS) has carried the responsibility for the creation and maintenance of the National Spatial Reference System (NSRS) in the United States and

its territories. In 1879, the New England Datum used the Clarke 1866 ellipsoid with Station Principio in Maryland as its origin point. In 1909, Meades Ranch in Kansas was chosen as the datum's origin, following an adjustment of the coordinates. Mexico and Canada adopted the datum in 1913, and it was subsequently expanded to become the North American Datum. A major re-adjustment of the horizontal datum across the continent was undertaken in 1927, with the coordinates at Meades Ranch held fixed, and the new system was named the North American Datum of 1927 (NAD27). Numerous Laplace stations controlled the orientation of the datum throughout the network. Later, it was estimated with new satellite observations that the orientation was accurate to about 1 arcsec (Jekeli, 2012, Rapp, 1992, p.A-6). The Clarke Ellipsoid of 1866 was still retained despite the availability of a newer and more representative international ellipsoid at the time. The NAD27 ellipsoid is not geocentric. In the reduction of coordinates of points in NAD27, the geoid height was neglected, resulting in ellipsoidal distances with systematic errors, since all lengths were technically referred to the geoid rather than the ellipsoid. Similarly, most angles were not corrected for the deflection of the vertical and were reduced to the ellipsoid as if they were turned about the ellipsoid normal. New satellite data, extensive gravity observations, early satellite altimetry, and satellite perturbation analyses have yielded improved geoid models, more accurate deflection of the vertical values, and better estimates of Earth's size and flattening.

In the 1970s and 1980s, a major re-adjustment of the North American Datum was undertaken. The ellipsoid was changed to that of the Geodetic Reference System 1980 (GRS80), which was intended to be geocentric and oriented to the actual surface of the Earth. The result of this major re-adjustment and re-definition was the North American Datum of 1983 (NAD83). Improvements in the accuracy of the origin and orientation led to new realizations of NAD83, driven by advances in satellite techniques.

The NAD83(1986) realization was based on a transformation of Doppler station coordinates. High-Accuracy Regional Networks (HARNs), derived from GPS, continued this trend of improvement through subsequent realizations. The realizations NAD83(HARN) (1989–1997) changed the scale by  $-0.0871$  ppm but retained the known origin and orientation offsets of approximately 2.24 m from the geometric center, as determined through satellite and space-based observations.

New realizations of NAD83 made use of the Continuously Operating Reference Stations (CORS) throughout the United States, yielding NAD83(CORS93), NAD83(CORS94), and NAD83(CORS96) with each new adjustment. The origin and orientation of the NAD83(1986) frame were retained. Further realizations that re-adjusted the HARNs produced NAD83(NSRS2007). A subsequent reprocessing of all CORS station data from 1994 to 2011 resulted in the realization NAD83(2011), with published coordinates referenced to epoch 2010.0.

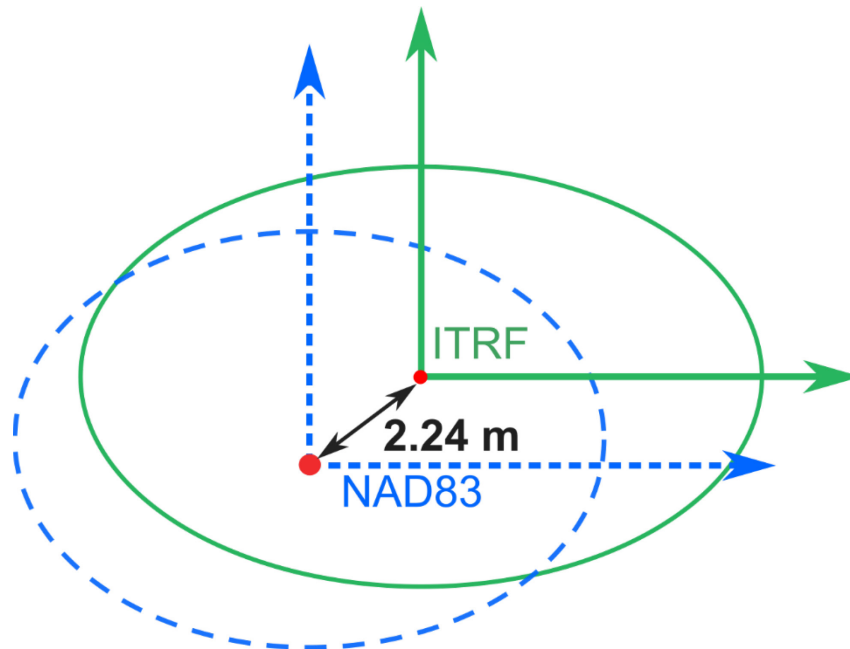
Table 2.2 is a summary of the horizontal geodetic datums for the NSRS and their approximate accuracies.

**Table 2.2: National Spatial Reference System (NSRS) Improvements in the Horizontal Datums**

Network	Time Span	Network Accuracy	Method of Reference
NAD 27	1927-1986	10 m	Traverse and Triangulation: Ground stations used for referencing the NSRS.
NAD83(86)	1986-1990	1 m	GPS and ground stations used for referencing.
NAD83(199x) *HARN	1990-2007	0.1 m	GPS and ground stations used for referencing.
NAD83(2007)	2007 - 2011	0.01 m	CORS stations are means of reference.
NAD83(2011)	2011-2022	0.01 m	CORS stations are means of reference.

The reference ellipsoid used to define the NSRS was intended to be geocentric, but it is now known to be offset by 2.24 meters from the true geometric center of the Earth. There is, however, a reference system known as the International Terrestrial Reference System (ITRS) that is fully geocentric.

Figure 2.4 The relationship between the origins of NAD83 and the ITRF is significant. The International Terrestrial Reference Frame (ITRF) is the realized frame of the International Terrestrial Reference System (ITRS). The ITRF is produced by the International Earth Rotation Service (IERS), an organization that also monitors Earth Orientation Parameters (EOP) through a global network of observing stations.



**Figure 2.4: NAD83 and ITRF reference ellipsoid origin.**

### 2.1.2.3 Vertical Datums in the U.S.

A vertical datum provides a one-dimensional reference for measuring elevations or depths relative to a surface that reflects Earth’s gravity field. This makes vertical datums fundamentally different from purely geometric systems (e.g., ellipsoidal heights), which do not account for gravity. Because water flows according to gravity potential, two points with the same ellipsoidal height may not exhibit the same water-flow characteristics. In contrast, a level surface is one where the gravity potential is constant. The geoid is a notable example, as it approximates mean sea level under the assumption that only gravity acts on an ocean imagined to cover the entire Earth.

Similar to a horizontal datum, a vertical datum requires an origin, which is a point on the Earth’s surface defined as having zero height. However, a vertical datum is one-dimensional and does not require an orientation. From this origin, surveyors establish relative heights using leveling. Each “traditional” datum remains tied to its specific origin rather than to a global or international reference point. Because gravity varies across the Earth, geopotential can be scaled to define several types of physical heights (e.g., normal, dynamic, orthometric, and Helmert orthometric). If a point’s geopotential is known, different physical heights can be computed by selecting the corresponding reference gravity. Table 2.3 highlights key properties of these gravity-based height definitions.

**Table 2.3: Heights based on Geopotential numbers.**

Physical Height	Gravity Source
Normal Height (NGVD 29)	Average normal gravity, equated around the equator and along lines of latitude
Dynamic Height (IGLD 55, 85)	Value of normal gravity determined at a 45° latitude.
Orthometric Height	Average gravity along the plumb line
Helmert Orthometric Height (NAVD 88)	Surface gravity measurement used to approximate gravity along the plumb line

By definition, **orthometric height** represents the distance along a curved plumb line from the geoid to a point on the Earth’s surface. Accurately measuring it would require knowing how gravity varies at every point along that line, which is impractical without drilling a borehole. Helmert orthometric height circumvents this issue by using only a surface gravity measurement to approximate the average gravity along the plumb line.

Historically, the National Geodetic Vertical Datum of 1929 (NGVD29) served as the United States’ principal vertical control network until the late 1980s. Its origin defined zero height at multiple coastal tide-gauge stations across the U.S. and Canada; however, because mean sea level is not truly a single level surface, these multiple origins led to systematic distortions of up to several decimeters, exacerbated by the non-parallel nature of level surfaces.

In 1988, the North American Vertical Datum of 1988 (NAVD88) was introduced to address these issues by defining a single origin at Pointe-au-Père (Father’s Point) in Rimouski, Québec, with a precisely established height. This simplified approach avoided

the inconsistencies associated with linking a level surface to multiple mean sea levels and incorporated more rigorous corrections for non-parallel level surfaces. The result was a more accurate, internally consistent vertical datum for North America.

### 2.1.3 State Plane Coordinate Systems of 1927 and 1983

The State Plane Coordinate System (SPCS) was developed in the early 1930s to provide a practical method for converting geodetic coordinates on the ellipsoid into plane coordinates suitable for surveying, engineering, and mapping. The initial planning and design were carried out by the U.S. Coast and Geodetic Survey in cooperation with state agencies. North Carolina requested a statewide plane system in 1933, and New Jersey served as an early test case. By early 1934, a first set of 110 zones had been designed on the North American Datum of 1927. Subsequent additions and revisions brought the final State Plane Coordinate System of 1927 to 131 zones (Dennis, 2018).

SPCS 1927 primarily used conformal map projections selected to match the shape and orientation of each state. The Lambert Conformal Conic projection was applied where states were elongated east–west, the Transverse Mercator projection where states were elongated north–south, and the Hotine Oblique Mercator projection in special cases. All SPCS 1927 zones were based on the Clarke 1866 ellipsoid, including cases where local datums were used for island territories. Michigan’s three zones were later redefined on a scaled form of Clarke 1866 to reduce distortion (Dennis, 2018).

There are two main conformal projections used to create State Plane zones nationwide:

1. **Lambert Conformal Conic (LCC):** Generally preferred for states elongated in an east–west direction.
2. **Transverse Mercator (TM):** Generally preferred for states elongated in a north–south direction.

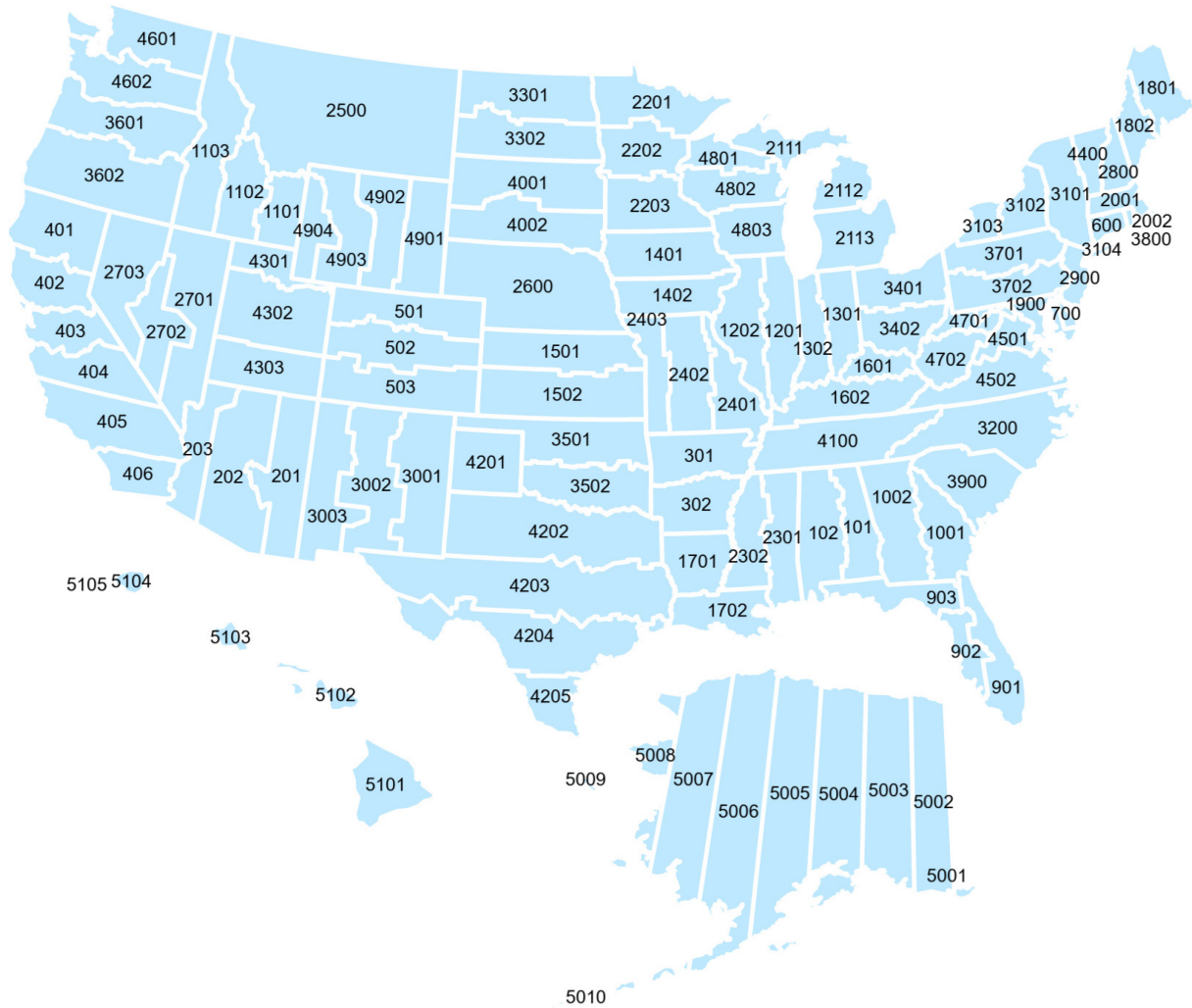
In Oregon’s case, both official SPCS 83 zones use Lambert Conformal Conic with different standard parallels. The fundamental conversion in SPCS is between:

1. **Geographic coordinates** (latitude and longitude), measured on the Earth’s ellipsoid, and
2. **Grid coordinates** (x and y), expressed in a planar Cartesian system.

With the adoption of the North American Datum of 1983, the system was redefined as SPCS 1983. SPCS 1983 consists of 125 zones and retains the same three conformal projection types. It is defined on the Geodetic Reference System of 1980, with specified ellipsoid parameters. SPCS 1983 also standardized grid origins in meters and, in some cases, changed the projection type or zone configuration relative to SPCS 1927. The SPCS 1983 manual by Stem provided the full computational framework and parameters for computer implementation to millimeter-level accuracy within each zone (Stem, 1990).

Figure 2.5 provides an overview of SPCS 1983 zones and their four-digit zone identifiers, often called FIPS codes in the literature. In SPCS 1983 usage, these identifiers are NGS zone codes.

They are commonly referred to as FIPS codes, although the state portion does not match the official federal FIPS state codes. The figure highlights how Oregon is divided into two zones (North and South), with each zone further defined by its particular central meridian, standard parallels, false origins, and scale factor choices.



**Figure 2.5: Overview map of State Plane Coordinate System 1983 (SPSC83)**

In both SPCS 1927 and SPCS 1983, the fundamental conversion is between geographic coordinates (latitude and longitude) on the reference ellipsoid and planar grid coordinates. SPCS 1983 specifies the mapping equations and computations for forward and inverse conversions, point and line scale factors, and other related quantities.

### ***2.1.3.1 The Oregon Coordinate Reference System (OCRS)***

In the OCRS Handbook and User Guide, Armstrong et al. (2017) describe the Oregon Coordinate Reference System (OCRS) as a statewide framework of coordinate reference systems built from low-distortion map projections, so that grid distances closely represent

distances measured on the ground within published tolerances. They report that the framework now covers Oregon with 39 zones and was produced through a collaborative technical process led by the Oregon Department of Transportation and its partners.

Armstrong et al. (2017) note that the legacy Oregon State Plane Coordinate System consists of a north zone and a south zone that use Lambert Conformal Conic projections. Its maximum scale error with respect to the ellipsoid is about  $\pm 105$  parts per million, and the distortion at the topographic surface is typically larger, increasing by about 4.8 parts per million per 100 feet of height. These characteristics can produce grid-to-ground differences that become significant for high-accuracy work.

As presented in the Handbook, the OCRS uses conformal projections selected to match regional geometry and relief, including Lambert Conformal Conic, Transverse Mercator, and Hotine Oblique Mercator in rectified skew orientation. The design objective was a distortion target on the order of 10 parts per million where feasible, with 20 parts per million adopted as a practical statewide goal during optimization.

The Handbook situates the OCRS within the National Spatial Reference System. Armstrong et al. (2017) instruct practitioners to reference zones to NAD 83 on the GRS 80 ellipsoid and to document the realization and epoch in project metadata. They also emphasize that the method avoids scaling the ellipsoid, that parameters are provided in metric units, and that horizontal positioning within a zone does not require site calibration when parameters are entered correctly.

For implementation, Armstrong et al. (2017) indicate that many software vendors distribute the zones through the EPSG registry, and that users can also load the published parameters directly. They provide guidance for verifying correct parameter entry through virtual checks supplied for each zone.

In practice, Armstrong et al. (2017) position the OCRS as a complement to the State Plane system. The State Plane system remains effective for statewide or coarse regional mapping. When survey, engineering, or geographic information system projects demand minimal distortion across a defined area, selecting the appropriate OCRS zone reduces computational effort and the risk of cumulative error, while maintaining compatibility with national datums and models.

## **2.2 NATIONAL SPATIAL REFERENCE SYSTEM (NSRS) MODERNIZATION**

The National Spatial Reference System (NSRS) is the positional framework used by United States federal agencies and widely relied upon by state, local, and private users to ensure the consistent alignment of maps, surveys, and related geospatial products (NGS, 2021c). The legacy system has been anchored to the North American Datum of 1983 and the North American Vertical Datum of 1988. Analyses by the National Geodetic Survey identified systematic issues that necessitate modernization. In particular, the NAD 83 reference frame is not geocentric, and NAVD 88 heights exhibit regional biases and tilt that stem from leveling networks and the use of a single tide-gauge control point (NGS, 2021b).

NGS’s modernization plan focuses on four major elements: the introduction of plate-fixed terrestrial reference frames aligned with ITRF2020; the definition of a unified geopotential datum based on geoid modeling; the redesign of workflows and data submission through OPUS; and the development of tools that handle time-dependent coordinates and transformations with full traceability (NGS, 2021c). The framework distinguishes between transformations among frames and propagation across epochs so that users can maintain consistency in both spatial and temporal dimensions (NGS, 2021a).

The modernization has four principal goals:

1. Replace NAD 83 realizations with plate-fixed terrestrial reference frames defined in relation to ITRF2020 (NGS, 2021c).
2. Establish a geopotential datum that derives orthometric heights from GNSS and GEOID2022 within the same integrated workflow (NGS, 2021b).
3. Re-invent submissions and quality control around OPUS using standardized coordinate types and epochs, including survey epoch coordinates and reference epoch coordinates (NGS, 2021c).
4. Integrate and expand transformation tools so users can relate coordinates across frames and epochs using documented models and grids (NGS, 2021c).

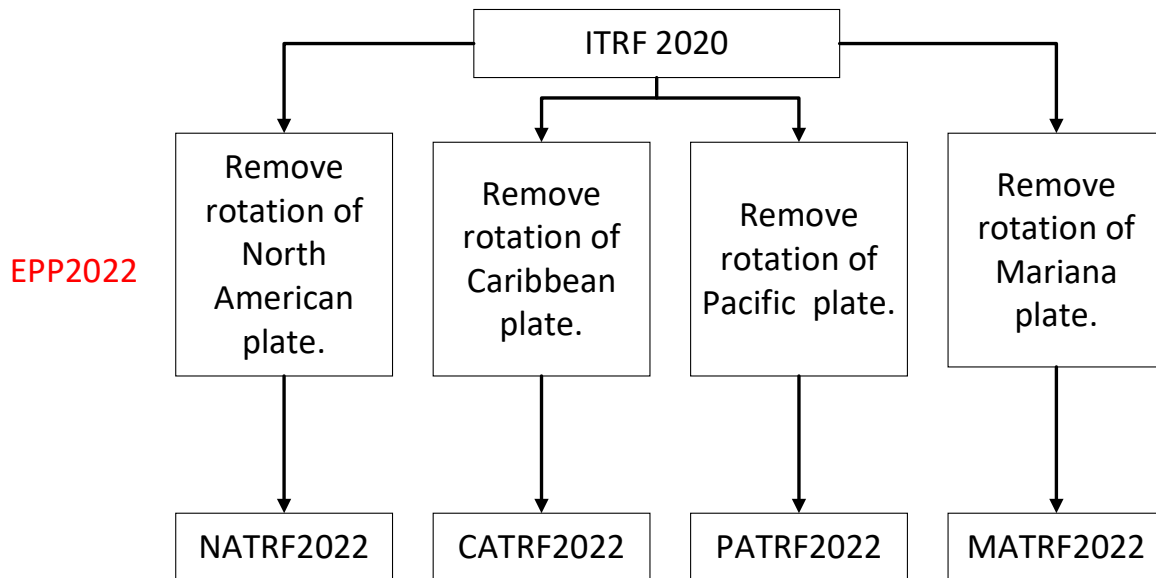
### **2.2.1 Replacing NAD83 with NATRF2022**

The North American Datum of 1983 has been refined through multiple realizations, yet a fundamental limitation persists. NAD 83 is offset from the geocenter, which produces meter-level discrepancies when compared to geocentric frames (NGS, 2021b). To resolve this issue, NGS will replace NAD 83 with four plate-fixed terrestrial reference frames that are defined relative to ITRF2020 through a rotation model (NGS, 2021c). These frames are:

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

In the modernized NSRS, geodetic coordinates will continue to use the GRS 80 reference ellipsoid to maintain computational continuity (NGS, 2021a). The roles of two core components are distinct. Euler Pole Parameters (EPP) define the relationship between each plate-fixed frame and ITRF2020, changing the coordinate frame without altering the epoch. The Intra-Frame Deformation Model (IFDM) represents residual motions within a frame and is used to change the epoch without modifying the frame (NGS, 2021a). Figure 2.6 shows this relationship schematically between ITRF2020 and the four plate-fixed frames at survey and reference epochs. Table 2.4 summarizes the operational roles of EPP2022 and IFDM2022 for frame changes and epoch propagation. Figure 2.7 and 2.8 illustrate horizontal differences encountered when moving

from NAD 83 to a geocentric frame on different tectonic plates. Figure 2.9 and 2.10 depict the separation of plate rotation from non-Eulerian deformation visible in regional velocity fields.



**Figure 2.6: Relationship between ITRF and the four new reference frames (adapted from NGS, 2021a).**

In practice, OPUS will continue to output ITRF coordinates at the survey epoch and will apply Euler pole parameters to provide plate-fixed coordinates, while IFDM2022 will be available to propagate coordinates to the latest reference epoch for comparison with published reference epoch coordinates (NGS, 2021c). The overall approach ensures that transformations between frames and propagation across time occur with explicit models tied to the modernized NSRS architecture (NGS, 2021a).

**Table 2.4: EP2022 and IFDM2022 NGS tools (adapted from NGS, 2021a).**

Aspect	EPP2022	IFDM 2022
Changes	Frame	Epoch
Motion captured	Plate rotation	Residual horizontal and vertical motions
Coordinates affected	Geocentric Cartesian coordinates	Geodetic coordinates
Use case	Transforming between ITRF and plate-fixed frames	Propagating coordinates across time within a plate-fixed frame

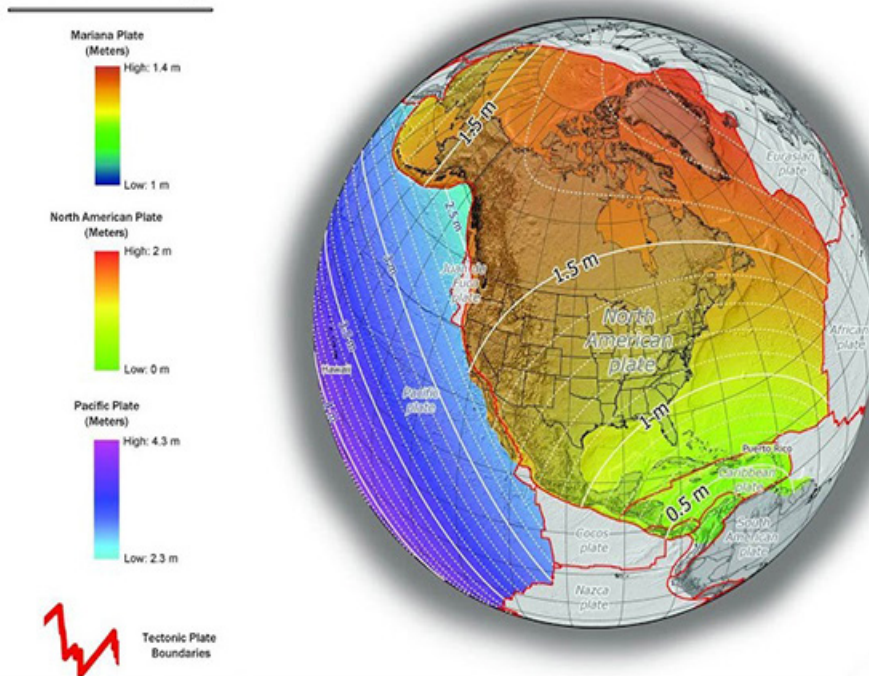


Figure 2.7: Approximate horizontal change for the North American Plate (NGS Website).

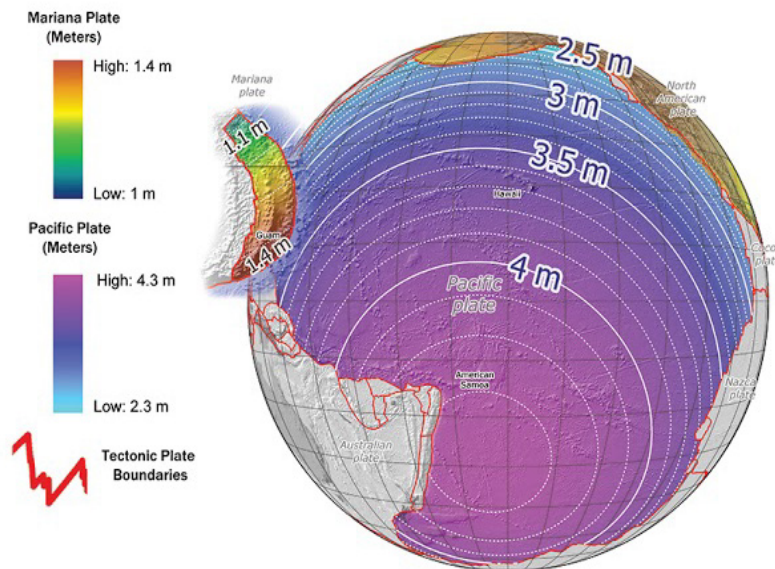
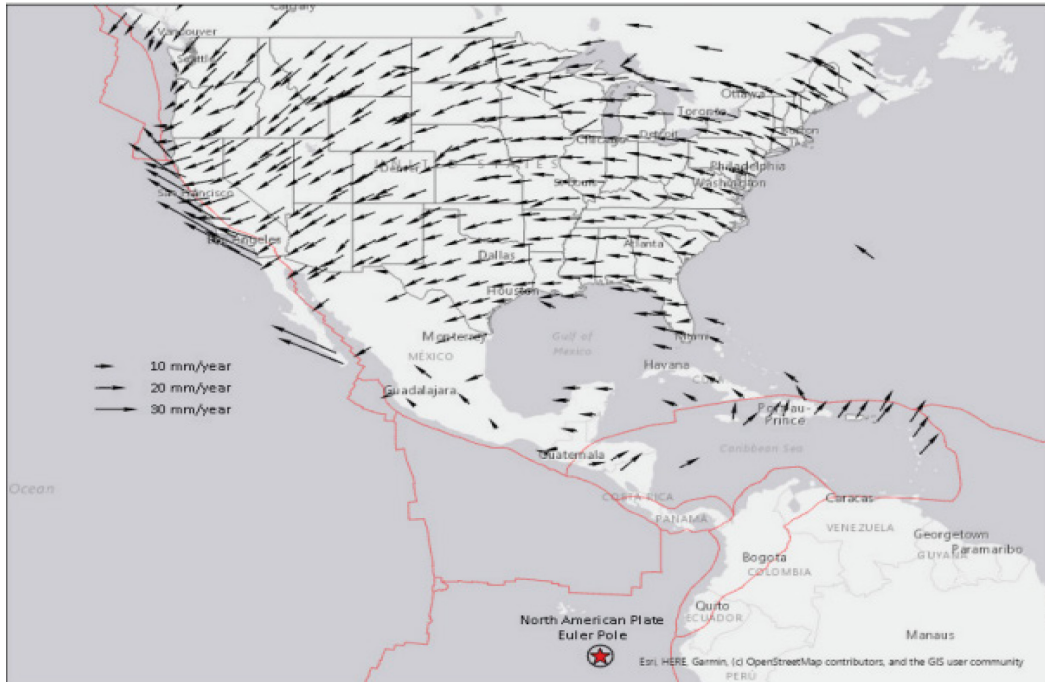
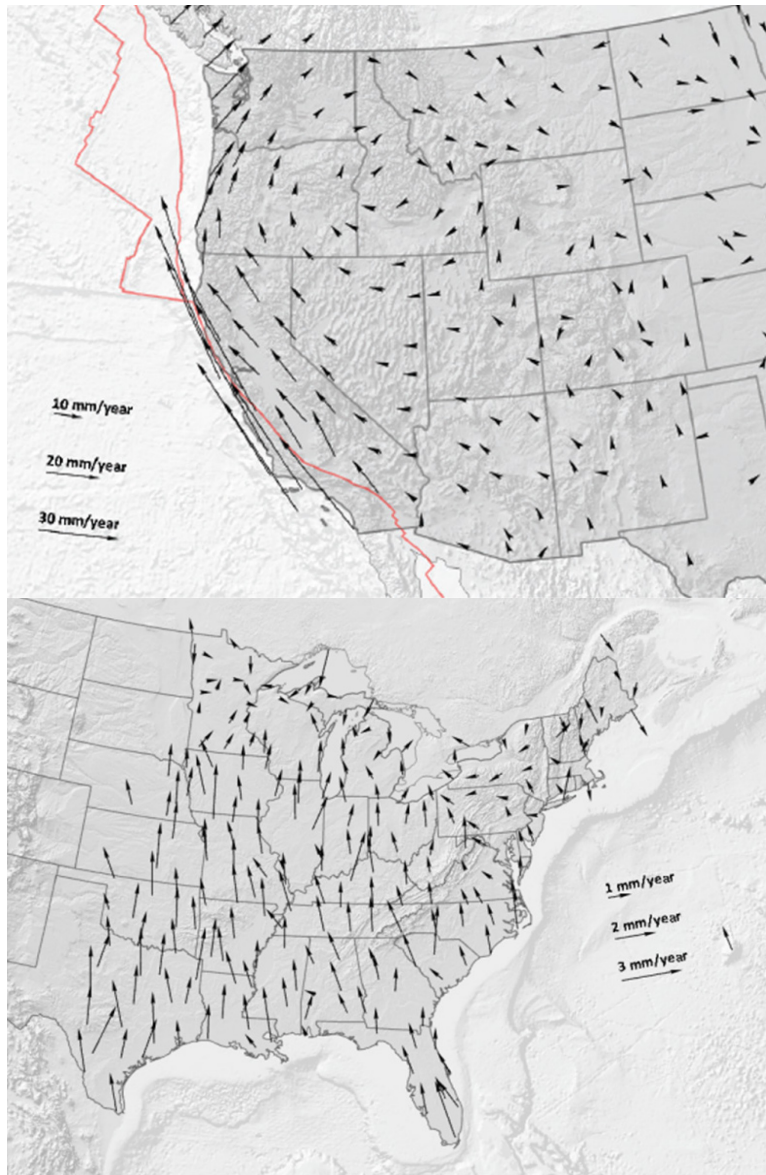


Figure 2.8: Approximate horizontal change for the Pacific Plate (NGS Website).



**Figure 2.9: Vectors of horizontal velocity of the North American tectonic plate (Source: NGS, 2021a)**



**Figure 2.10: Horizontal non-Eulerian velocities for the Western (top) and Eastern (bottom) Continental United States (Source: NGS, 2021a). Note the scales for the velocity arrows are different.**

## 2.2.2 Replacing NAVD88 with NAPGD2022

The North American Vertical Datum of 1988 (NAVD 88) was realized by fixing a single tide-gauge constraint at Rimouski, Québec, and propagating that reference through continent-scale spirit leveling, embedding datum characteristics tied to historical observational practice (NGS, 2021b). NAVD 88 is not aligned to a true geopotential equipotential, which produces a broad bias and a long-wavelength tilt when compared with a modern gravity-based geoid (NGS, 2021b). Figure 2.11 illustrates the large-scale inconsistency of the NAVD 88 zero surface, motivating its replacement with a geoid-based, time-aware geopotential reference (NGS, 2021b).

NOAA Technical Report NOS NGS 64 defines the North American–Pacific Geopotential Datum of 2022 (NAPGD 2022) as the geopotential datum that replaces NAVD 88, with an internally consistent set of models and grids that disseminate the datum (NGS, 2021b). NAPGD 2022 is designed to operate on ITRF2020 as well as on the four modern terrestrial reference frames of 2022, ensuring that height determination and frame realization remain compatible and epoch-aware (NGS, 2021b). In this structure, orthometric heights, gravity, and deflection fields are unified within a single geopotential framework explicitly tied to a reference epoch, with provisions for updates as warranted (NGS, 2021b).

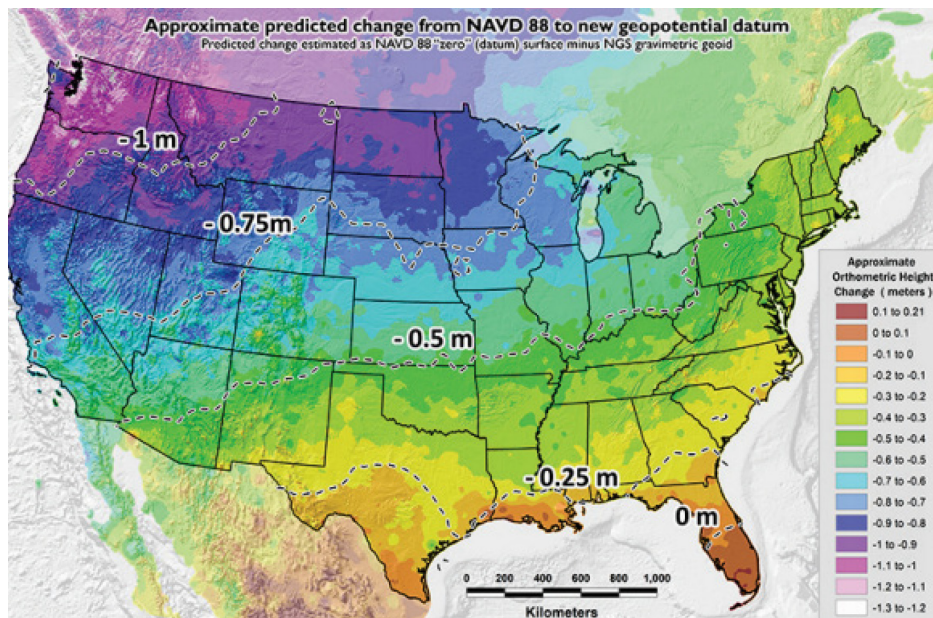
NAPGD 2022 disseminates four interrelated products for operational use: a global geopotential model (GM 2022), regional geoid undulation grids (GEOID 2022), regional deflection of the vertical grids (DEFLEC 2022), and regional surface gravity models (GRAV 2022) (NGS, 2021b). The gridded regional products are provided for three areas: North America, American Samoa, and Guam/Commonwealth of the Northern Mariana Islands, with OPUS and other NGS services delivering geoid undulation, deflection, and surface gravity values within these regions (NGS, 2021b). Within the National Spatial Reference System, GEOID 2022 serves as the zero-height surface for orthometric heights, establishing the vertical reference for mapping and surveying (NGS, 2021b).

In the modernized system, absolute orthometric height at epoch  $t$  is obtained by subtracting the geoid undulation at epoch  $t$  from the ellipsoid height at epoch  $t$  in an appropriate 2022 terrestrial reference frame (NGS, 2021b). This formulation is time-dependent because the geoid varies with mass redistribution and other processes, and NAPGD 2022 provides static and dynamic components to represent the geoid, deflection, and gravity fields through time (NGS, 2021b). The GM 2022 model enables global estimation of geopotential-related quantities, and NGS tools use the regional grids for higher-accuracy values within the three gridded regions (NGS, 2021b). OPUS provides orthometric height, geoid undulation, deflection of the vertical, and surface gravity values, computed from these grids at the Earth’s surface as part of the NSRS workflow (NGS, 2021c).

Modernization also consolidates legacy vertical references into one geopotential framework referenced to a common epoch, including territorial datums and Great Lakes dynamic heights, so that regional systems are consistently related to NAPGD 2022 (NGS, 2021b). Figure 2.11 emphasizes the physical basis for this transition from a leveling-only realization to a geoid-based, gravity-constrained datum maintained with versioned updates whenever new observations or theory justify changes (NGS, 2021b). Table 2.5 summarizes representative legacy vertical references and related models unified within NAPGD 2022.

**Table 2.5: Representative legacy vertical references and related models unified within NAPGD 2022**

Category	Examples	Purpose and modernization note
Continental orthometric datum	NAVD 88	Leveling-based national datum; biased and tilted; replaced
Territorial orthometric datums	PRVD 02; VIVD 09; ASVD 02; NMVD 03; GUVVD 04	Territorial references; transformed at the reference epoch
Great Lakes height system	IGLD 85 to IGLD 2020	Dynamic heights for the Great Lakes; kept consistent with NAPGD 2022
Pre 2022 geoid and gravity resources	Hybrid national geoid series, including GEOID18	Legacy hybrids; replaced by GEOID 2022 with uncertainties
Deflection of the vertical	Historical astro geodetic or hybrid grids	Legacy deflection grids; replaced by DEFLEC 2022



**Figure 2.11: Bias of the NAVD 88 surface across the conterminous United States inferred from modern gravity-based geoid modeling; the pattern motivates adoption of a single, time-dependent geopotential surface for national elevation control (NGS, 2021b).**

### 2.2.3 Replacing the State Plane Coordinate System (SPCS) of 1983

The State Plane Coordinate System provides a practical, large-scale projection framework used for surveying, engineering, and mapping within the National Spatial Reference System (NSRS) (Dennis, 2018). In its NAD 83 form (SPCS 83), the system consists of 125 zones that employ conformal Lambert Conformal Conic, Transverse Mercator, and Hotine Oblique Mercator projections (Dennis, 2018). Historically, SPCS 83 design guidance emphasized distortion

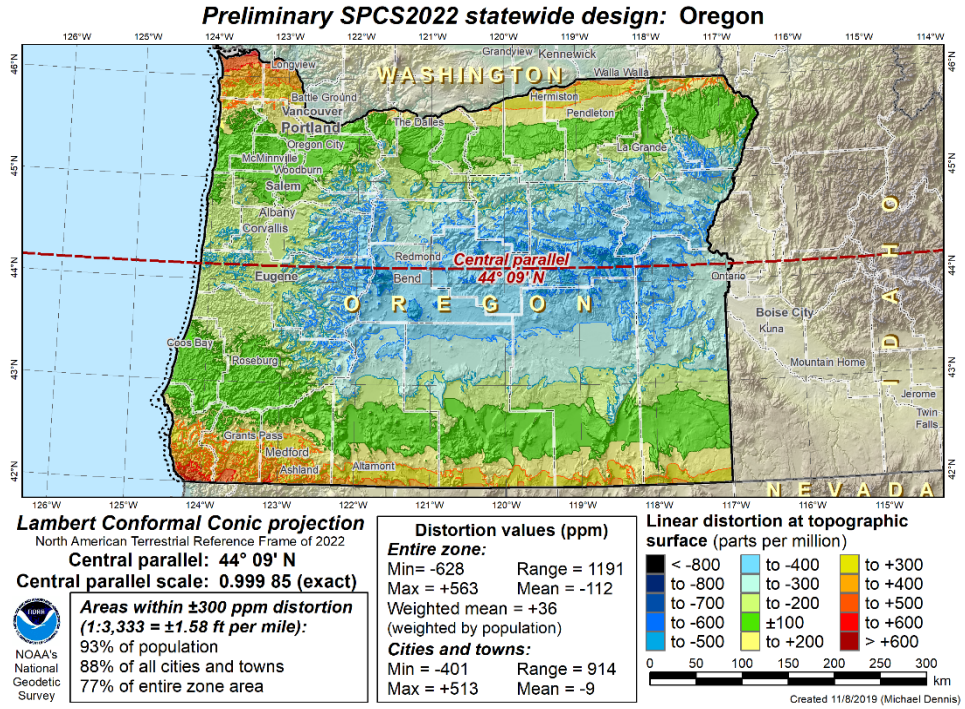
evaluation with respect to the reference ellipsoid rather than the topographic surface where measurements are applied (NGS, 2023a). As part of NSRS modernization, the National Geodetic Survey is replacing SPCS 83 with the State Plane Coordinate System of 2022 (SPCS2022) (Dennis, 2018).

SPCS2022 uses the same three conformal projection families and is based on the Geodetic Reference System 1980 ellipsoid without modification to any defining parameters or computations (NGS, 2023b). For computing SPCS2022 coordinates, the input geodetic latitude and longitude must be taken from one of the four 2022 terrestrial reference frames, and the specific frame must be identified for each zone (NGS, 2023a). The modernized NSRS defines four plate-fixed frames, named the North American, Pacific, Caribbean, and Mariana Terrestrial Reference Frames of 2022 (NATRF2022, PATRF2022, CATRF2022, MATRF2022) (NGS, 2021a).

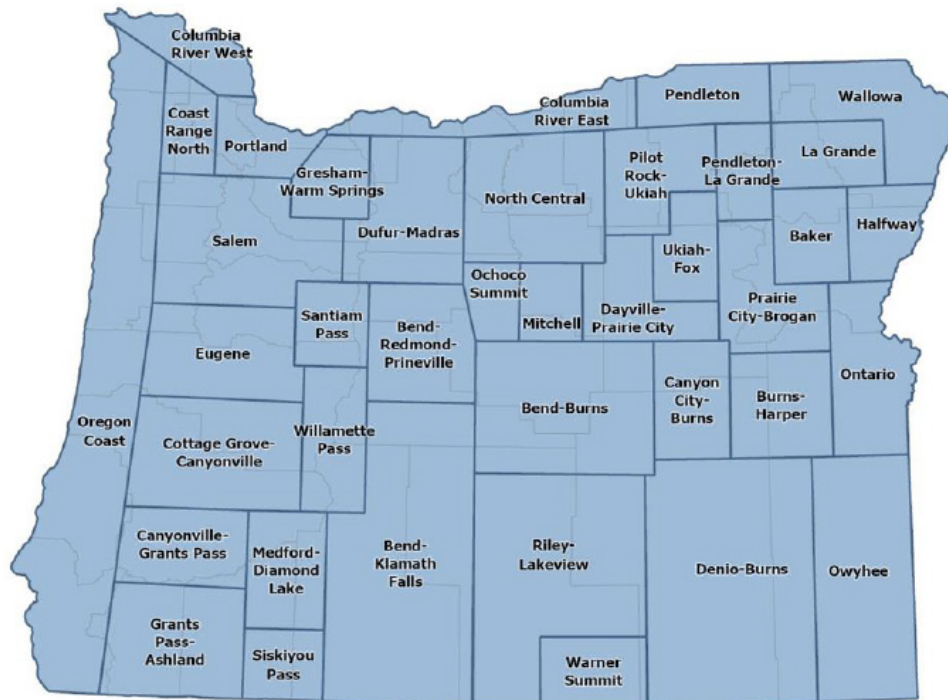
Key advancements to SPCS 83 include the following:

1. **Surface-based distortion design.** The criterion for maximum allowable linear distortion is specified and evaluated at the topographic surface rather than at the ellipsoid, aligning design performance with where data are used (NGS, 2023a).
2. **Layered zone configurations.** Every state has a single statewide SPCS2022 zone, and a state may have up to two additional multizone layers that are entirely contained within the statewide layer, with coverage rules that govern complete and partial coverage (NGS, 2023a).
3. **Standardized projection definitions.** Only one computational form of each conformal projection is used nationwide, specifically LCC limited to the one-parallel form, TM in the Gauss–Krüger form, and OM in the centered rectified (rectified skew orthomorphic) form with specified skew azimuth (NGS, 2023b).
4. **Distortion control and design guidance.** The procedures define discrete allowable ranges for the linear-distortion design criterion and provide quantitative guidance that relates zone width to an initial distortion estimate and minimum statewide coverage percentages for population, municipalities, and area (NGS, 2023b).
5. **Governance, documentation, and metadata.** NGS coordinates requests and proposals, reviews submittals, and publishes approved parameters and defining metadata, including naming, abbreviations, and units, to ensure national consistency (NGS, 2023b).

SPCS2022 computations use explicitly stated GRS 80 parameters, including the semi-major axis and the inverse flattening, to maintain uniformity across all implementations (NGS, 2023b). The policy requires that all zones be tied to the 2022 terrestrial reference frames for coordinate input to ensure consistency with the modern reference framework and associated NSRS services (NGS, 2023a). Figure 2.12 and 2.13 provide examples consistent with the SPCS2022 design framework. Figure 2.12 shows the preliminary statewide Oregon design, while Figure 2.13 illustrates the OCRS low-distortion projections.



**Figure 2.12: Preliminary SPCS2022 statewide zone design for the state of Oregon (NGS, 2023b).**



**Figure 2.13 SPCS2022 will incorporate the OCRS low distortion projections for the State of Oregon (Callahan, 2024).**

## 2.2.4 Importance of Aligning to the NSRS

Aligning projects and datasets to the National Spatial Reference System (NSRS) ensures that positions, heights, and derived measurements have the same meaning across agencies, jurisdictions, and applications. This alignment provides a shared foundation for engineering, mapping, and scientific work, allowing independently produced results to be combined without ambiguity.

A common reference frame is the basis for interoperability. When all participants use the NSRS, survey control, GNSS observations, photogrammetry, lidar, hydrography, and inertial measurements can be integrated without chains of ad hoc transformations. This reduces the risk of silent offsets between adjoining projects, minimizes rework during design and construction, and supports cross-boundary initiatives such as transportation corridors, river basin management, and coastal resilience planning.

Alignment strengthens quality assurance and the defensibility of reported accuracy. Positional accuracy testing is most meaningful when the dataset under evaluation can be compared to control that is external to the project and traceable to a national standard. Tying project control to the NSRS provides that traceability, allowing accuracy statements in reports and metadata to be supported by reproducible procedures and external references rather than solely by internal benchmarks. This improves auditability, supports regulatory submissions, and builds confidence among stakeholders who depend on geospatial information for decision-making.

NSRS alignment also improves integration across technologies and scales. Mobile mapping systems that combine GNSS and inertial sensors, aerial and bathymetric lidar, multibeam sonar, and terrestrial scanning all benefit when project control and processing are anchored to the same reference. Results from contractors, partner agencies, and internal teams can be merged with confidence, which shortens schedules and allows effort to shift from coordinate reconciliation to analysis and design.

Alignment enhances data lifecycle management. When datasets are tied to the NSRS with complete metadata, they remain relatable as the national reference system is maintained over time. Clear documentation of control, processing methods, height system, and any applied transformations makes it possible to reproduce results and to understand differences between editions of the same dataset. This protects investment in long-lived assets, supports longitudinal studies, and reduces the risk that legacy holdings become isolated on outdated datums.

In summary, aligning to the National Spatial Reference System delivers a reliable and traceable foundation for geospatial work. It enables seamless integration of independent datasets, supports rigorous accuracy evaluation, and ensures that both horizontal positions and heights can be used confidently across regions and disciplines. By embedding NSRS alignment into project planning, field operations, processing, and metadata, organizations reduce risk, increase efficiency, and improve the credibility and longevity of their spatial information.

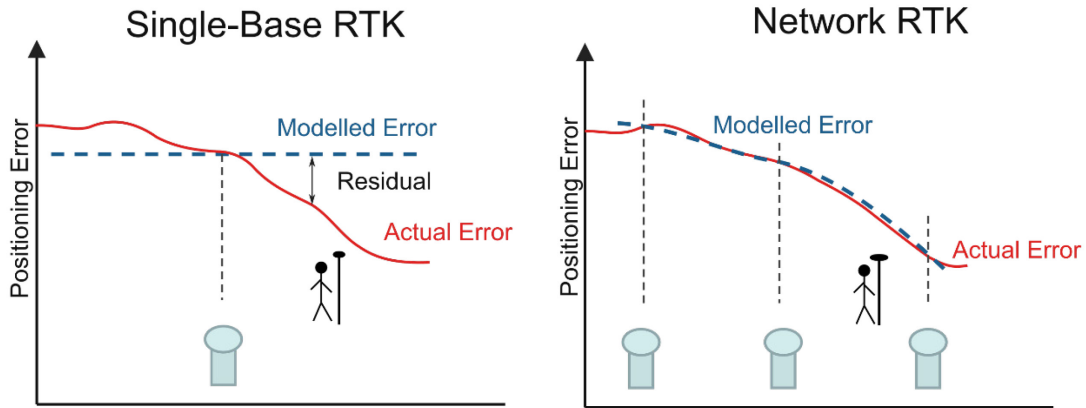
## 2.3 AN OVERVIEW OF REAL-TIME GNSS NETWORKS (RTN'S)

Precise relative positioning in GNSS can be achieved through two main methods: (1) single-baseline RTK (sRTK), which uses a single local base station, and (2) network-based RTK (NRTK), which relies on a network of Continuously Operating Reference Stations (CORS). In both cases, the objective is to determine the user's coordinates in real time, typically with centimeter-level accuracy.

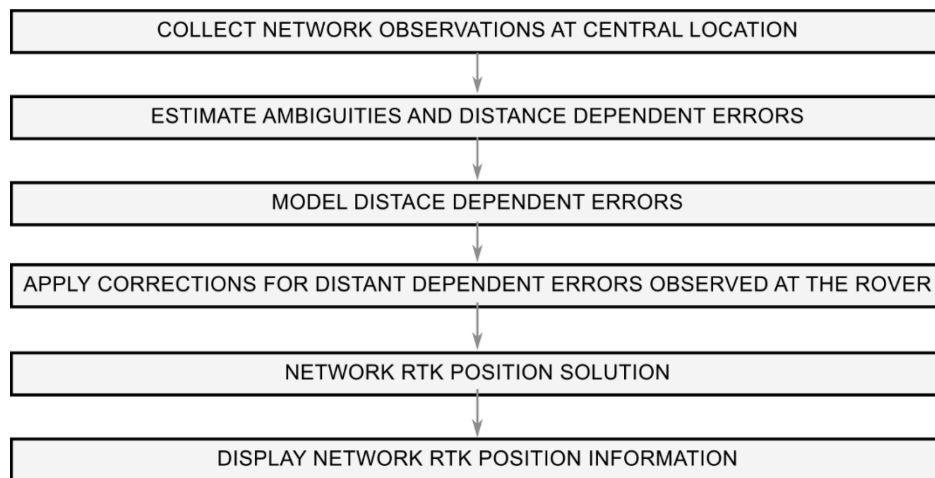
**Single-baseline RTK** involves at least one stationary receiver (the “base”) with precisely known coordinates and one or more rover receivers. Both the base and rover simultaneously track the same satellites (at least four) to form carrier-phase-based “double differences,” yielding a highly accurate relative position for the rover. Historically, single-baseline RTK was limited to distances of about 10–20 km (Janssen, 2009), primarily because the spatial correlation of ionospheric and tropospheric delays degrades with longer baselines (Janssen & Haasdyk, 2011). Although long-range RTK solutions can extend to about 50 km, accuracy and reliability often diminish as distance increases.

The concept of network-based RTK (NRTK) originated in the mid-1990s (Rizos, 2002) to mitigate the degradation of single-baseline RTK over longer distances. A CORS network is used to model distance-dependent errors, such as ionospheric delays, tropospheric delays, and satellite orbit errors. By simultaneously processing data from multiple reference stations, an NRTK solution provides corrections that more accurately represent the actual conditions at the rover's location. Figure 2.14 illustrates how single-baseline RTK differs from NRTK in modeling distance-dependent errors. In general, NRTK relies on the following core steps, as shown in Figure 2.15.

1. **Data Collection:** Each reference station simultaneously observes GNSS signals, along with supplementary information such as IONEX files, ephemerides, and Differential Code Bias (DCB) values.
2. **Network Processing:** Observations from all reference stations are combined and reduced to a common “ambiguity level,” effectively canceling satellite clock and orbit errors while modeling ionospheric and tropospheric effects.
3. **User-Specific Corrections:** A subset of network stations is selected, often the closest stations to the rover, to generate individualized corrections. The network center transmits these corrections to the rover in real time.
4. **Rover Positioning:** The rover applies these corrections, typically using interpolation algorithms (e.g., distance-based linear interpolation, low-order surface models, or least-squares collocation) to minimize spatially varying errors and compute a high-accuracy position solution (Brown et al., 2006; Gao et al., 1997).



**Figure 2.14: Single-baseline RTK versus NRTK – Modelling of distant dependent errors. (Adapted from Janssen & Haasdyk, 2011).**



**Figure 2.15: General steps in Network RTK (adapted from Takac & Zelzer, 2008).**

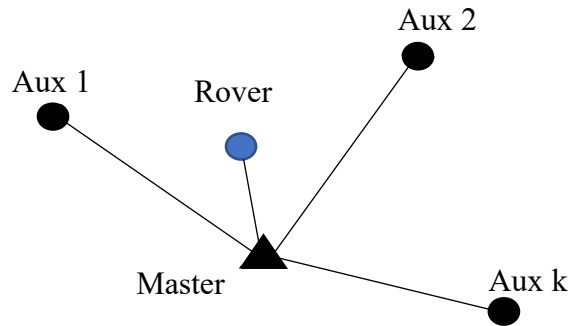
### 2.3.1.1 Different NRTK Techniques

Several NRTK techniques have emerged for conveying corrections to the rover. While they share commonalities, they differ in how corrections are generated, interpolated, and transmitted (Wang et al., 2010). Key methods are briefly summarized below, and Table 2.6 compares the advantages and disadvantages of three popular approaches, namely VRS, FKP, and MAC (Gümüř & Selbesođlu, 2019).

The **Master Auxiliary Concept (MAC)** was introduced to strike a balance between comprehensive error modeling and bandwidth efficiency. A typical MAC network designates one station as the “master,” broadcasting its complete GNSS observations and coordinates, while additional “auxiliary” stations provide only partial or differential observables (Euler et al., 2001; RTCM v3.1, 2007). Before transmissions begin, the network processing center synchronizes and reduces integer ambiguities for all reference stations, ensuring that observations share a common ambiguity level (Brown et al., 2006). At the rover, full data from the master station and partial differences from the auxiliary

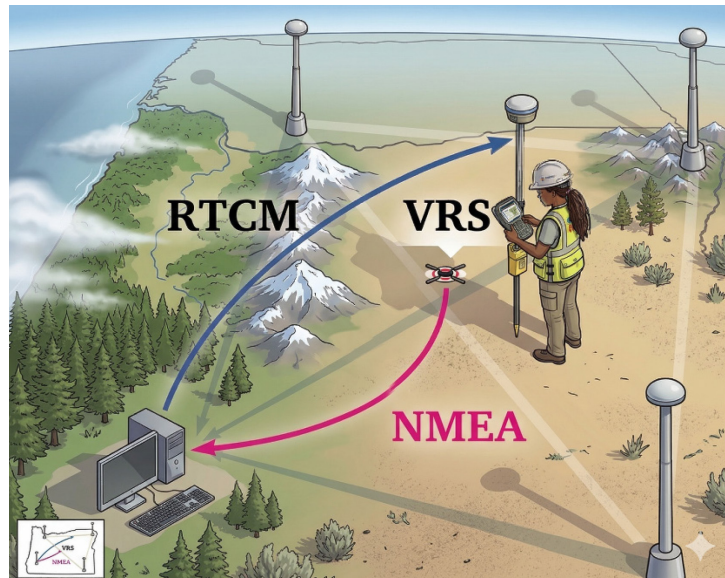
stations are combined to interpolate corrections for ionospheric, tropospheric, and orbit errors. By sending one complete data stream plus auxiliary differences, MAC efficiently minimizes bandwidth. This design is illustrated in Figure 2.16, with one master station and several auxiliary stations. Systems such as the Oregon Real-Time GNSS Network (ORGN) favor MAC because it efficiently disseminates precise corrections to numerous simultaneous users without requiring user position feedback.

Additional methods, such as MAX and i-MAX, are essentially refinements of the MAC concept. In these approaches, the network either transmits the entire network correction structure (MAX) or merges the information into a single “individualized” base-format stream (i-MAX) for rovers lacking advanced NRTK capabilities (Wang et al., 2010). While these variations differ in the amount of computation and interpolation performed at the rover versus the control center, they largely follow the master-auxiliary logic and maintain compatibility with RTCM messaging protocols.



**Figure 2.16: MAC network definition (master station  $m$  and auxiliary stations  $1\dots k$ , ( $k \geq 2$ )).**

In contrast, **Virtual Reference Stations (VRS)** originated as one of the earliest and most widely adopted NRTK methods for reducing baseline distances. Rather than transmitting partial data from multiple stations, VRS constructs a “virtual” station near the rover, effectively shortening the baseline to a few meters (Wuebbena et al., 1996). Unlike MAC’s one-way broadcasts, VRS involves two-way communication: the rover submits its approximate position, and the network software tailors a custom set of reference data to mimic a base station located immediately adjacent to the user (Vollath et al., 2000; El-Mowafy, 2012). These observations are then transmitted in a standard RTK format, allowing the rover to process them as though it were using single-baseline RTK with a very short baseline. Figure 2.17 depicts this VRS setup, which can reduce distance-dependent errors more dramatically than the master-auxiliary model but is limited by the processing center’s capacity to generate individual “virtual” solutions for multiple concurrent users.



**Figure 2.17: VRS technique.**

Another variant, **Pseudo-Reference Stations (PRS)**, blends elements of VRS while avoiding the need for each rover to send its position in real time. Instead of placing the virtual station precisely at the rover’s reported coordinates, PRS relies on a set of preselected grid points (Takac & Zelzer, 2008). Network software refines the observables as if these points were actual base stations, thereby shortening baseline lengths in practice, though usually not as drastically as VRS. PRS may allow one-way or two-way communication depending on the specific implementation, but its hallmark is that virtual station locations are determined beforehand rather than created on demand for each user.

With **Flächen-Korrektur-Parameter (FKP)**, the network processing center broadcasts polynomial surfaces describing how ionospheric, tropospheric, and orbit errors vary over the coverage region (El-Mowafy, 2012). These surfaces are typically referenced to a “master” station but expressed as coefficients that model the spatial variation of dispersive and non-dispersive errors. Rover software then applies these polynomial corrections for its specific location, relying on standard raw data from one physical station plus the FKP parameters. Because FKP calculations occur primarily at the rover, it remains a one-way approach that saves bandwidth and supports many concurrent users. However, it requires advanced rover software to handle polynomial interpolation of the corrections.

Table 2.6 presents a concise overview of the benefits and drawbacks of MAC, FKP, and VRS, emphasizing factors such as one-way versus two-way communication, bandwidth usage, and the extent of re-initialization. In essence, all network-based techniques address the same fundamental requirement: they model ionospheric, tropospheric, and orbit errors more effectively than single-baseline RTK, especially over longer distances. Nonetheless, differences arise in how they generate, interpolate, and deliver those corrections to users in real time. Systems like MAC rely on minimal data overhead and require no feedback from the rover, whereas VRS produces customized solutions for each rover’s

approximate location at the expense of computational overhead. PRS provides a semi-static solution, placing “virtual” stations at known nodes rather than at on-demand user positions, and FKP relies on polynomial corrections that shift some error modeling to the rover. These various approaches give network operators the flexibility to deploy the method best suited to their computational resources, user demands, and available communication infrastructure.

**Table 2.6: Advantages and disadvantages of VRS, FKP, MAC methods (Gümüş & Selbesoğlu, 2019)**

METHOD	ADVANTAGES	DISADVANTAGES
MAC	<ul style="list-style-type: none"> <li>• It uses one-way communication.</li> <li>• The data processing power does not experience computing density because of not being a complex model.</li> <li>• There isn't a limitation on kinematic application in the region covered by the network.</li> </ul>	<ul style="list-style-type: none"> <li>• Distance dependent errors are modelled only for measuring time.</li> <li>• Only observation differences are sent.</li> </ul>
FKP	<ul style="list-style-type: none"> <li>• It uses one-way communication.</li> <li>• The number of concurrent users is not limited.</li> <li>• Re-initializing is not necessary unlike VRS method in kinematic applications because the correction parameters cover a certain zone.</li> <li>• The data processing power does not experience computing density because of not being a complex model.</li> </ul>	<ul style="list-style-type: none"> <li>• FKP is not fully compatible with RTCM.</li> </ul>
VRS	<ul style="list-style-type: none"> <li>• It is compatible with RTCM 2.3 and RTCM 3.1 format</li> <li>• Modelling for ionosphere and troposphere is performed by the data processing center.</li> <li>• Corrections are optimized constantly for each user.</li> </ul>	<ul style="list-style-type: none"> <li>• The number of concurrent users is limited depending on the server capacity.</li> <li>• Two- way communication is used.</li> <li>• It is required to re-initialize when we move a certain distance away from the virtual reference station.</li> </ul>

## 2.4 ALIGNING AN RTN TO THE NSRS

The National Spatial Reference System (NSRS) provides a consistent geodetic reference framework that underpins a wide range of surveying, engineering, and geospatial activities

throughout the United States. Managed by the National Geodetic Survey (NGS), the NSRS ensures that latitude, longitude, height, gravity, and orientation data are all harmonized, allowing datasets from different regions and organizations to be seamlessly integrated (NOAA, 2023). By adopting the NSRS, regional, state, and local governments, private-sector entities, and academic institutions benefit from uniform spatial reference coordinates, enhancing the reliability, comparability, and compatibility of geospatial information (NGS, 2021a).

A Real-Time Network (RTN) provides near-instantaneous GNSS corrections to users in the field, often via cellular or internet connections, enabling precise positioning in real time. For users to receive solutions that are tied to the NSRS, the RTN itself must be accurately tied to the NSRS. Achieving such alignment can be challenging due to factors such as local crustal motion, datum updates, and station coordinate errors. Proper alignment, however, ensures consistent, high-quality spatial data that conforms with the broader national framework, avoiding mismatches when datasets are shared or combined.

NGS offers several recommendations and tools to help RTN managers establish and maintain reference station coordinates in conformance with the NSRS (Henning et al., 2011). Among these guidelines are: (a) including NGS CORS as part of the RTN, (b) limiting station coordinate discrepancies to within 2 cm horizontally and 4 cm vertically relative to published CORS positions, and (c) verifying station coordinates with services such as OPUS on a routine basis (NGS, 2019). These practices help ensure that an RTN's reference stations, often referred to as RTN CORS, remain consistent with the national framework as the Earth's crust shifts or as new data improve coordinate estimates.

In broad terms, there are two NGS-endorsed approaches for determining RTN reference station coordinates: (1) using the average of multiple OPUS-Static (OPUS-S) solutions collected over many days, and (2) performing a network adjustment that incorporates both RTN station data and as many NGS CORS as possible. The first method involves submitting multiple 24-hour GNSS data files (from at least ten different days) to OPUS-S, removing outliers, and averaging the results. The second method relies on adjusting large sets of simultaneously observed data using software such as ADJUST within OPUS-Projects. Whether a manager opts for a relatively quick multi-OPUS approach or a more comprehensive network adjustment, tying the RTN to the NSRS demands careful data collection, well-considered station constraints, and ongoing quality assurance checks.

In practice, many RTN providers conduct full network adjustments that incorporate several days of 24-hour observation data from each station, referencing multiple NGS CORS. The final coordinates are then validated against the published NAD 83 (or other relevant datum) CORS positions, with RMS and residual checks to ensure that no station's coordinates differ from these authoritative coordinates by more than the recommended 2 cm horizontal and 4 cm vertical tolerances. The Oregon Real-Time GNSS Network (ORGN), for example, follows a procedure that includes five days of simultaneous data collection, preliminary checks of internal and external consistency, and final constrained adjustments via OPUS-Projects to confirm that each station is correctly aligned with NGS-published positions (Armstrong, 2011).

The sections that follow examine key software and methodologies available for precisely determining station coordinates relative to the NSRS. Section 2.4.1 focuses on the OPUS-Static

workflow, including the upcoming M-PAGES baseline processor. Section 0 explores OPUS-Projects, addresses current modernization efforts involving the ADJUST engine, and illustrates how the Oregon Department of Transportation (ODOT) uses these tools to align the ORGN with the NSRS. Finally, Section 2.4.3 describes Precise Point Positioning (PPP) techniques in general and then discusses Canada’s CSRS-PPP online service as an example of a robust PPP workflow.

### 2.4.1 Overview of OPUS-Static (OPUS-S)

OPUS-Static (OPUS-S) is a long-standing service provided by the National Geodetic Survey (NGS) for processing static, dual-frequency GPS data. Popular among surveying and civil engineering professionals, OPUS-S offers a streamlined path to achieve consistent geodetic coordinates aligned with the National Spatial Reference System (NSRS) and, by extension, the International Terrestrial Reference Frame (ITRF) (Jamieson & Gillins, 2018). In this workflow, users upload RINEX files (minimum of two hours of dual-frequency data) via an online portal. OPUS-S then processes each dataset independently, deriving station coordinates by averaging three single-baseline solutions computed against up to three active stations from the NGS CORS or International GNSS Service (IGS) networks (Stone, 2006). The underlying engine performing these double-difference baseline calculations is PAGES (Program for the Adjustment of GPS Ephemerides), which applies various models and precise orbits to minimize ionospheric and tropospheric errors (Soler, 2011; Jamieson & Gillins, 2018).

The reported OPUS-S result includes “peak-to-peak” error estimates for the east, north, and up components, providing a sense of internal consistency across the three baselines used. Although these values are not formal standard deviations, users can approximate one-sigma uncertainties by applying empirical formulas. In one such approach, Schwarz (2006) suggests dividing the range (maximum minus minimum among the three solutions) by an empirically determined factor (2.9317), or alternatively, combining residuals or leveraging a covariance matrix approach. Additionally, Soler et al. (2006) introduced a more comprehensive formula (Equation 2-3) that relates RMS values from iono-free carrier phase solutions, session duration, and peak-to-peak measures to approximate standard deviations for each coordinate component. Under favorable conditions, multi-hour OPUS-S solutions can often achieve an accuracy of ±3 cm in both horizontal and vertical positions (Gillins et al., 2019).

$$\sigma(cm) = \sqrt{\left(\frac{RMS_{\theta}}{1.5}\right)^2 \times \left(\frac{k}{\sqrt{T}}\right)^2 + \left(\frac{p}{1.7}\right)^2} \begin{cases} east: & k = 1; & p = p_e \\ north: & k = 1; & p = p_n \\ up: & k = 3.7; & p = p_u \end{cases}$$

2-3

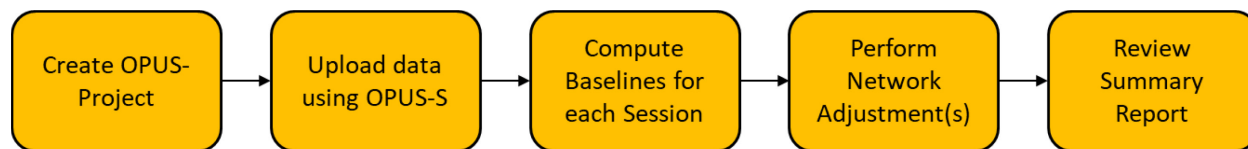
Where:  $RMS_{\theta}$  (cm) represents the overall RMS for the double differenced iono-free carrier phase observables for the three single baseline solutions as given in the OPUS output,  $T$  represents the total session duration in hours, and  $p_e$ ,  $p_n$ ,  $p_u$  (cm) represents the peak-to-peak errors along the east, north, and up components as given in the OPUS output.

Although OPUS-S remains a reliable tool for many professionals, the current PAGES engine processes only GPS L1/L2 data, limiting its capacity to incorporate signals from modern constellations or frequencies. As part of a broader NGS modernization effort, a new single-difference baseline processor called M-PAGES is being developed (Stressler et al., 2021). Unlike

its predecessor, M-PAGES accommodates additional GNSS constellations (e.g., GLONASS, Galileo, BeiDou) and newer signals such as GPS L5. This improvement allows it to deliver more robust positioning results, particularly for shorter observation sessions, and to handle RINEX data in versions beyond the older 2.x format. By employing single differences rather than double differences, M-PAGES can more readily resolve carrier-phase ambiguities across mixed constellations, overcoming limitations that frequently left integer ambiguities unresolved in earlier multi-frequency scenarios (Chen et al., 2019). Once fully integrated, M-PAGES is expected to enhance the accuracy and versatility of OPUS-S, enabling consistent multi-constellation solutions for users and further solidifying the service’s role in aligning project data with the NSRS.

### 2.4.2 Overview of OPUS-Projects (OPUS-P)

OPUS-Projects (OPUS-P) is a web-based geodetic application provided by the National Geodetic Survey (NGS) for project-scale GNSS data management, network processing, and rigorous least-squares adjustments that align observations with the National Spatial Reference System (NSRS) (Weston et al., 2015; Gillins et al., 2019). By going beyond single-station processing in OPUS-Static (OPUS-S), OPUS-Projects allows users, known as “managers”, who have completed specialized NGS training to upload and process data from multiple stations and sessions, ultimately delivering a unified solution aligned to the NSRS. An overview of the general OPUS-Projects workflow is shown in Figure 2.18.

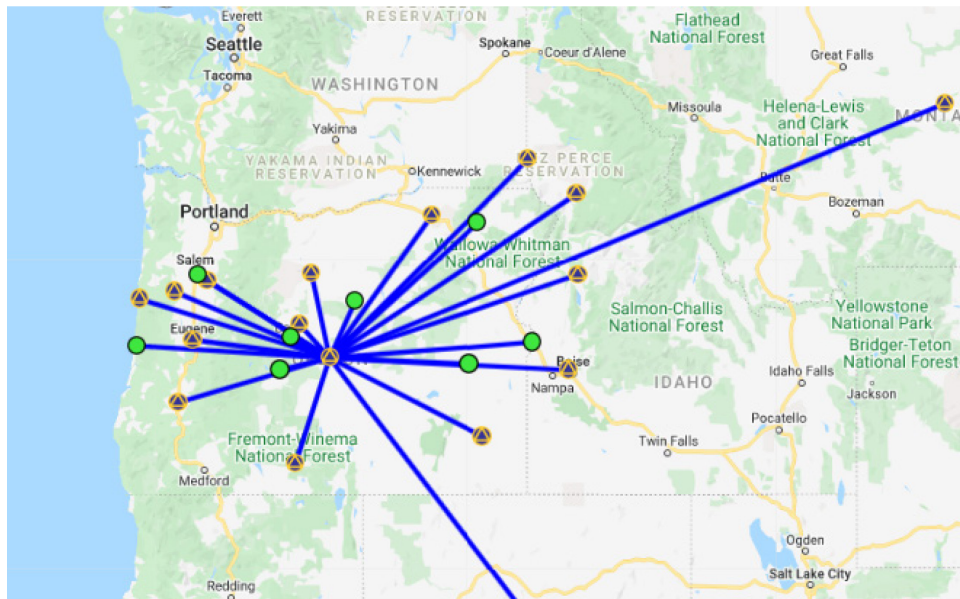


**Figure 2.18: Flowchart summarizing the general workflow for using OPUS-Projects.**

A typical workflow begins when the project manager creates a new OPUS-Projects workspace via an online portal. This process generates a unique project ID and keywords that must be referenced in subsequent data uploads. Each RINEX file (dual-frequency GNSS, at least two hours in duration, 30-second observation intervals) is then submitted through the OPUS-Static page, identifying the relevant project ID. OPUS returns email reports with single-station solutions for each upload, which serve as a preliminary quality check. If these solutions show suspiciously large errors or residuals, they are flagged for manager review before the data enter the multi-station portion of OPUS-Projects.

Once a sufficient number of RINEX files have been uploaded, the manager can open OPUS-Projects’ web interface to organize observations into “sessions,” each representing simultaneous static observations. Within a session, at least one “hub” station is chosen; in many cases, multiple CORS or a trusted project mark might serve as hubs. These hubs anchor baselines and help tie the dataset to the NSRS. Because OPUS-Projects limits sessions to a maximum of 99 stations (including user marks, CORS, and IGS sites), large surveys often require strategic subdivision. The manager must also select a “network design” approach: USER, CORS, or MST (minimum spanning tree). While the CORS design treats all included CORS as hubs and MST builds minimal spanning trees, the USER design remains the NGS-recommended method for

official submissions because it allows managers to explicitly define which marks function as hubs, often favoring stable, centrally located references to ensure robust geometry (OPUS-P User Guide, 2023), as shown in Figure 2.19.



**Figure 2.19: Screenshot of GNSS baselines from Hub to observations, near and distant CORS.**

With sessions and hubs specified, OPUS-Projects calls on the same baseline processor (PAGES) used by OPUS-S, but now in a multi-station capacity. Baselines are computed for every pair of simultaneously occupied marks and hubs, yielding an internally correlated dataset for each session. Managers can then inspect session-level RMS, individual baseline errors, and other metrics. If a station or CORS appears to degrade the solution, the user can remove it or adjust the hub selection and reprocess to improve consistency.

After session processing, OPUS-Projects enters a network adjustment phase where the baselines from all sessions are merged into a unified network aligned with the NSRS. This occurs in three sequential adjustments. First, the “Preliminary Adjustment” combines the multiple session solutions using GPSCOM, an older “Helmert blocking” solver that merges each session’s partial solutions into a single reference frame (Wolf, 1978; Gillins & Eddy, 2017). Because GPSCOM predates upcoming multi-constellation upgrades, NGS plans to eventually replace it with more advanced software, but for now it remains a key tool. Next, OPUS-Projects carries out a “Horizontal Free Adjustment” in ADJUST, fixing only one station’s coordinates (latitude, longitude, ellipsoid height) to tie the network gently to a known point. This minimally constrained solution reveals how well the data fits together internally, with all other marks free to shift as needed. Finally, the “Horizontal Constrained Adjustment” adds more robust constraints to any station whose coordinates are known and published, such as multiple CORS, so that the entire dataset is strongly bound to the NSRS. At each adjustment step, OPUS-Projects evaluates the results using an F-test, comparing variance changes between free and constrained solutions, and applies a Constraint Ratio (CR) measure to gauge whether any station’s forced alignment is artificially distorting the network (Gillins & Eddy, 2017; Hensel et al., 2023).

If the F-test fails or if a station’s CR far exceeds the threshold (commonly 3.0 for any coordinate component), the manager may revisit constraints and remove or down-weight any station with potentially outdated published coordinates. In practice, geophysical motion or inaccurate prior values might render certain stations less reliable as constraints. OPUS-Projects offers iterative opportunities to refine these choices, culminating in a final constrained solution that best fits the raw observations without introducing significant distortions. The user’s final deliverable is a coordinated network of marks that meets target accuracy and is recognized as consistent with the NSRS.

Best practices for OPUS-Projects typically revolve around collecting multiple days of GNSS data on each station to ensure reliable integer ambiguity resolution, diverse satellite geometry, and minimized multipath. Including both short and long baselines in each session helps refine tropospheric modeling, while distributing multiple CORS across the project mitigates single-station biases. Ensuring each session uses consistent hubs also preserves common-mode error benefits. If the manager identifies suspiciously large RMS in any baseline or station residual, it is often wise to remove that station from the session and reprocess, or else investigate whether ephemeral conditions caused the anomaly. In the adjustment phase, constraints should normally be set to moderate weighting, because extremely tight constraints (e.g., 0.1 mm) can artificially fix any coordinate error. If OPUS-Projects repeatedly flags a station’s shift as excessive, the manager should consider unconstraining it or trusting other stable references.

Looking forward, NGS modernization efforts will gradually replace certain OPUS-Projects underpinnings, most notably PAGES and GPSCOM, with multi-constellation engines such as M-PAGES, which handles single-difference solutions across GPS, GLONASS, Galileo, BeiDou, and newer signals like GPS L5 (Stressler et al., 2021). ADJUST, the core least squares engine for the final solution, remains pivotal but is evolving to accommodate more advanced data structures. Despite these planned changes, the fundamental OPUS Projects workflow will remain the same. The system will continue to gather data in sessions, compute baselines, merge them into a single network, and incrementally constrain known stations. This process ensures that each large-scale GNSS campaign is not only internally self-consistent but also properly anchored to the NSRS.

In summary, OPUS-Projects offers a robust path for multi-station GNSS surveys to achieve high accuracy through structured baseline processing and stepwise network adjustments. By adhering to recommended data collection and design principles, project managers can produce thoroughly vetted, NSRS-aligned coordinates with minimal distortion and well-documented residuals, ensuring that the final positions are both locally coherent and *nationally consistent*.

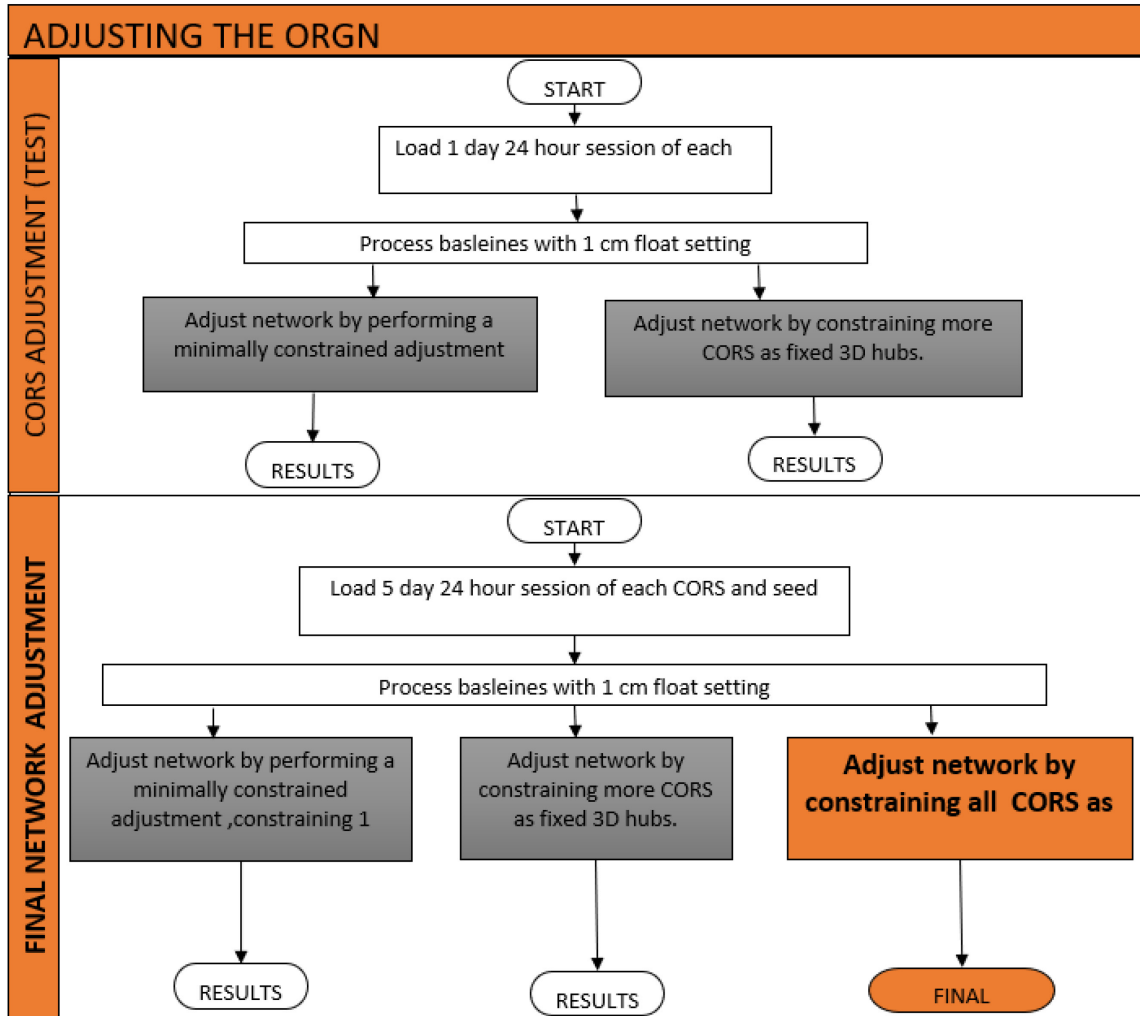
#### **2.4.2.1 ODOT’s Current Approach to Aligning the ORGN to the NSRS**

The Oregon Real-Time GNSS Network (ORGN), operated by the Oregon Department of Transportation (ODOT) Geometronics Unit, consists of active GPS stations and CORS that provide RTK corrections to field users over the internet via cellular connections. According to ODOT’s 2011 document, *Guidelines for Positioning the ORGN with NGS NSRS Validation*, this network is aligned with the final NGS NAD 83 Multi-Year CORS Solution (MYCS) coordinates. ODOT focuses on a core set of ten published CORS in Oregon, along with selected MYCS CORS in neighboring states (Washington, California,

Idaho, and Nevada). Each ORGN station is assigned three-dimensional coordinates through a least-squares adjustment performed in OPUS-Projects and verified using additional GNSS software. The overarching goal is to ensure that all RTN station positions are accurate to within 2 cm horizontally and 4 cm vertically at the 95 percent (2-sigma) confidence level.

ODOT's procedure relies on five days of simultaneous, 24-hour GNSS observations, incorporating every station into each daily session. Initially, only the CORS stations are involved in a "test" adjustment to gauge their internal consistency and verify their suitability as fixed reference hubs. In this preliminary step, each station's 24-hour file (for a single day) is uploaded to OPUS-Projects, seeded with the appropriate datum coordinates, and processed using a 1 cm float constraint. OPUS-Projects then generates a summary report for the network manager to review. Once any evident discrepancies have been resolved and confidence in the CORS is established, a minimally constrained adjustment follows: one CORS is held fixed in all three coordinates, residuals are inspected, and further constraints are gradually introduced on additional CORS stations if the solutions appear consistent.

After this CORS-only verification, ODOT proceeds to the final adjustment, incorporating both the CORS and the ORGN station data. Five separate sessions are created in OPUS-Projects, each containing 24-hour files from all stations. Again, the CORS are seeded with the datum coordinates and processed with a 1 cm float for every session. A minimally constrained adjustment is initially performed by fixing one CORS as a three-dimensional hub. Horizontal and vertical residuals are evaluated against the seeded values to ensure alignment with the target accuracy. Several iterative adjustments follow, each introducing additional fully constrained CORS while monitoring differences between seeded and adjusted coordinates. Once the final iteration holds all CORS as fixed hubs, ODOT confirms that the entire network meets the established accuracy thresholds. Figure 2.20 summarizes these procedures, illustrating how ODOT systematically validates and adjusts the ORGN within OPUS-Projects.



**Figure 2.20: Flowchart summarizing the current procedures ODOT implements to adjust the ORGN within the NGS tool “OPUS-Projects”.**

### 2.4.3 Overview of Precise Point Positioning (PPP)

Precise Point Positioning (PPP) is a GNSS data processing technique that calculates a user’s absolute position using raw signal observations from multiple satellites, precise orbit and clock corrections, and sophisticated error modeling. Unlike differential or relative positioning, where a user’s coordinates are determined with respect to one or more reference stations, PPP solutions involve processing observations from just the user’s receiver in conjunction with globally distributed data products describing satellite trajectories, clock biases, and other system parameters (Kouba & Héroux, 2001). This independence from local reference stations makes PPP especially appealing for remote areas, where access to CORS or a real-time network may be limited.

In PPP, each GNSS measurement is modeled using high-precision satellite orbit and clock information, typically derived from the International GNSS Service (IGS). Atmospheric effects, such as ionospheric and tropospheric delays, are mitigated through dual-frequency combinations

and corrections. Once integer ambiguities and various biases are resolved (or sufficiently estimated), the rover's coordinates can be computed in a global reference frame, commonly the ITRF. PPP convergence times can range from a few minutes to an hour, depending on factors such as satellite geometry, observation length, and the availability of multi-constellation data. Final solutions often achieve accuracies on the order of a few centimeters horizontally, with slightly higher uncertainty in height (Zumberge et al., 1997).

#### **2.4.3.1 CSRS-PPP – An online PPP Service**

Canada's Geodetic Survey, part of Natural Resources Canada (NRCan), offers the CSRS-PPP service (Atiz & Kalayci, 2021). Similar to NGS's OPUS, it provides users with an accessible, web-based interface to submit RINEX data (GPS, GLONASS, Galileo, etc.) and receive a high-accuracy position report aligned with North American and international reference frames. By leveraging precise ephemerides, clock products, and advanced algorithms, CSRS-PPP estimates positions while also providing reliable uncertainty metrics (Banville et al., 2021). Once the user uploads a RINEX file, CSRS-PPP processes it through an engine that accounts for effects such as precise satellite clocks, modeling of signal path delays, and potential integer ambiguity resolution. The result is returned as a coordinate solution with associated error estimates.

Although primarily designed for Canada's CGVD2013 vertical datum and other Canadian reference frames, CSRS-PPP can produce transformations aligned with NAD 83 or the ITRF, which in turn helps U.S. users tie solutions to the NSRS when local offsets and velocity models are well understood. Like other PPP solutions, the technique works best for sessions of at least one hour, although multi-hour data typically yields superior precision. Because no physical base station is needed, PPP is an attractive option for remote or offshore GNSS campaigns that cannot rely on real-time networks or local reference infrastructure. Moreover, the PPP approach ensures that each station's position is derived from a global datum, facilitating large-scale consistency in cross-border or inter-regional projects. The CSRS-PPP web portal (<https://webapp.geod.nrcan.gc.ca>) provides details on how to submit files, interpret output statistics, and link results to local or regional geodetic systems.

## **2.5 POST DISASTER GEODETIC DATUM MANAGEMENT IN NEW ZEALAND**

When significant ground deformation events occur, Real-Time Network (RTN) managers face the challenge of deciding whether to update the entire reference frame, apply more localized adjustments, or rely on a deformation model to maintain spatial accuracy. The experience of Land Information New Zealand (LINZ) in handling frequent seismic events demonstrates how local patch updates and real-time modeling can preserve a national system's accuracy without necessitating continual, nationwide datum shifts. Their approach offers valuable insights for automating RTN alignment processes within the National Spatial Reference System (NSRS), particularly in tectonically active regions.

New Zealand's highly dynamic environment means that deformation can result both from the long-term tectonic convergence of the Australasian and Pacific plates and from large

earthquakes. LINZ addresses this complexity by maintaining a multi-layered deformation model that, for any given location and time, defines:

1. Horizontal displacement.
2. Vertical displacement.
3. Horizontal error at 95% confidence level.
4. Vertical error at 95% confidence level.

Rather than issuing entirely new reference frames after each earthquake, LINZ releases “patches” to update the deformation model locally. This approach allows users to preserve existing datum coordinates wherever possible while incorporating event-driven shifts where needed. LINZ employs three main patch types to account for seismic changes:

- **Forward Patches** adjust only the deformation model, leaving reference station coordinates unchanged. Users requiring “current” positions must apply the updated model to transform older coordinates. While this approach minimally affects existing datasets (since most remain in the unchanged coordinate realm), it reduces immediate local accuracy unless users explicitly apply the new deformation file.
- **Reverse Patches** update both the deformation model and all coordinates in the affected area. By subtracting the earthquake’s effects from older coordinate estimates, reverse patches effectively reset station positions to remain consistent with real-world shifts. Although this ensures robust local accuracy, it forces a coordinate change for every geospatial dataset in that region, functioning similarly to a new datum release for those stations.
- **Hybrid Patches** combine these methods: forward patches are applied to broader, less severely deformed regions, while reverse patches address the epicentral zone, where large displacements require coordinate resets. This strategy balances accuracy and continuity across the network.

LINZ determines which patch type to employ based on factors such as the event’s magnitude, the severity and spatial extent of displacement, ongoing survey activity, and existing accuracy tolerances. If ignoring a deformation would degrade the system beyond specified thresholds (see Table 2.7 for LINZ’s horizontal accuracy classes), a patch is released, sometimes in multiple stages to capture both co-seismic and prolonged post-seismic movements (Winefield et al., 2010). Each patch release is packaged similarly to a “new datum version,” providing:

1. CSV files specifying coordinate changes for the patch;
2. Documentation on patch usage and constraints;
3. Example Python scripts illustrating how to compute site-specific displacement at any given time (e.g., allowing a user to query the co-seismic shift on day one or incorporate partial post-seismic drift); and
4. Integration into LINZ software such as SNAP and Concord, enabling automated transformations for those who adopt the official model.

**Table 2.7: Horizontal accuracy standard developed by LINZ**

<b>Role</b>	<b>Network accuracy</b>	<b>Local accuracy</b>
National reference frame	0.05m	$0.003\text{m} \pm 3 \times 10^{-8}$
Deformation modelling – national	0.05m	$0.003\text{m} \pm 1 \times 10^{-7}$
Deformation modelling - regional	0.10m	$0.003\text{m} \pm 1 \times 10^{-6}$
Deformation modelling – local	0.15m	$0.01\text{m} \pm 1 \times 10^{-6}$
Cadastral network	0.15m	$0.01\text{m} \pm 5 \times 10^{-5}$
Basic geospatial network	0.15m	$0.01\text{m} \pm 5 \times 10^{-5}$

Table 2.8 lists notable earthquakes that LINZ has integrated into the national deformation model, including their magnitudes, maximum horizontal (Max H), and maximum vertical (Max V) displacements (Crook et al., 2016). Over time, each patch iteration refines the secular velocity model or adds discrete events, making the system dynamic while remaining anchored in a consistent reference framework.

**Table 2.8: Earthquakes incorporated into LINZ deformation models. Includes magnitude, Richter scale, and maximum horizontal and vertical displacements caused by each earthquake (Crook et al., 2016).**

<b>Name</b>	<b>Date (dd/mm/year)</b>	<b>Magnitude</b>	<b>Max H (m)</b>	<b>Max V (m)</b>
Secretary Island	22/08/2003	7.2	0.27	0.72
Macquarie Island	24/12/2004	8.1	0.015	0.005
George Sound	16/10/2007	6.7	0.13	0.27
Dusky Sound	15/07/2009	7.8	1.74	0.39
Darfield	04/09/2010	7.1	3.20	1.75
Christchurch	22/02/2011	6.3	0.31	0.48
Christchurch	13/06/2011	6.3	0.22	0.13
Christchurch	23/12/2011	6.0	0.25	0.36
Cook Straight	21/06/2013	6.5	0.08	0.02
Lake Grassmere	16/08/2013	6.6	0.34	0.26

Although New Zealand’s national reference frame can be too sparse to capture local quake-induced distortions on its own, LINZ ensures that accuracy standards are maintained at the network’s densest points. Table 2.7 shows how they define horizontal accuracy goals, ranging from national-level frames (0.05 m network accuracy) down to local or cadastral networks (0.15 m). If an earthquake threatens to exceed these thresholds, LINZ deploys forward patches for moderate shifts or reverse/hybrid patches when local coordinate changes are substantial. This modular approach avoids frequent nationwide redefinitions, maintains stable published coordinates wherever feasible, and applies the deformation model to track time-dependent motions in quake-affected zones.

### 2.5.1 Relevance to Automated RTN Alignment

Adapting LINZ’s model-based workflow for NSRS alignment could guide the automation of RTN updates following a seismic event or other ground deformation. An automated system might detect displacements via real-time GNSS station data, apply localized coordinate resets (reverse patches) in strongly affected areas, and issue forward patches for broader, lower-magnitude distortions. Such a scheme could use thresholds analogous to LINZ’s accuracy guidelines to trigger partial or major reconfigurations of station coordinates.

By distributing new deformation patch files, including CSV-defined coordinate offsets and user-friendly scripts, RTN operators in the U.S. could rapidly integrate changes into their networks without recalculating all station positions statewide. This approach would allow unaffected regions to remain stable, while epicentral or high-deformation areas receive the thorough resets necessary to maintain centimeter-level accuracy. Ultimately, the goal is a real-time or near-real-time system that flags potential coordinate shifts, issues recommended patch files and ensures that all RTN data streams remain NSRS-consistent, even amid ongoing tectonic changes.

In summary, New Zealand’s patch-based deformation model serves as a flexible blueprint for dynamic datum management. Forward, reverse, and hybrid patches allow LINZ to localize updates according to actual displacements, minimizing user disruption. This paradigm of incremental, event-driven modeling exemplifies how RTNs and broader reference frames can be dynamically maintained, particularly if the process is automated through robust, user-friendly data releases and software integration.



## **3.0 EVALUATING COMMON METHODS USED TO ALIGN RTN'S TO THE NSRS**

### **3.1 INTRODUCTION**

The alignment of Real-Time GNSS Networks (RTNs) with the National Spatial Reference System (NSRS) is essential for ensuring that data are collected within a consistent, national coordinate framework. This integration enhances data interoperability, enabling users to seamlessly combine the accuracy and stability of the NSRS with the real-time accessibility of RTNs. Aligning RTNs with the NSRS is particularly critical for applications that rely on a shared geodetic reference frame, such as precise modeling and prediction of natural hazards, the design and construction of infrastructure projects, and the monitoring of environmental phenomena like sea-level rise. Emphasizing the importance of RTN–NSRS alignment helps provide context for subsequent discussions on these systems.

Real-time networks, which consist of Continuously Operating Reference Stations (CORS), have become a reliable and instantaneous method for achieving centimeter-level positioning using Global Navigation Satellite Systems (Yu et al., 2020). These networks find applications in diverse fields such as surveying, geodesy, mapping, navigation, machine control, structural monitoring, and autonomous vehicles. RTNs offer an efficient and accessible solution for precise positioning by eliminating the need for additional equipment or post-processed data (NGS, 2019).

To ensure the reliability and consistency of geospatial data across these applications, the United States relies on the NSRS, a geodetic reference system that defines positions and elevations of points on the Earth's surface. The NSRS serves as the national foundation for geospatial data integration, providing a consistent geodetic reference for users nationwide. It is based on a network of CORS, which provides precise and traceable latitude, longitude, and ellipsoid height values that constitute the geometric control for the NSRS. Coordinates for the CORS are also determined relative to the latest global International Terrestrial Reference Frame (Snay, 2003). Therefore, aligning RTNs with the NSRS is crucial for integrating these networks seamlessly into the United States' geodetic infrastructure.

Although RTNs can provide coordinates referenced to the NSRS, no standardized procedure currently exists for RTN operators to verify the alignment and consistency of these coordinates or determine their accuracy (NGS, 2019). Recognizing this challenge, the National Geodetic Survey (NGS) emphasizes the need to establish a process that enables RTN operators to ensure proper alignment of their networks with the NSRS. This objective is outlined in the NGS Strategic Plan for 2019–2023.

To address this challenge, this chapter addresses the following research objectives:

1. Evaluate workflows to align RTNs to the NSRS, including OPUS-S, OPUS-P, and CSRS-PPP,
2. Establish a robust and reliable process for aligning RTN's to the NSRS that also ensures the integrity of geospatial positioning data,

3. Investigate methods for monitoring the CORS within the RTN to assess the alignment of their coordinates with the NSRS, providing a comprehensive approach to quality control.

## 3.2 METHODOLOGY

In this study, an evaluation was conducted to assess methods for aligning RTNs with the NSRS. Data from two RTNs, the Oregon Real-Time Network (ORGN) and the South Carolina Real-Time Network (SCRTN), were collected over a 31-day period from January 1 to January 31, 2023 (days 001–031 of the year). The collected data, comprising 24-hour RINEX files from active stations, were processed using three different methods: OPUS-S, OPUS-P, and CSRS-PPP. Each of these methods, commonly used to align an RTN with the NSRS, is described in more detail in Section 2 of this report. In general, the three methods employ different positioning techniques, satellite systems, and orbit sources. A summary of these methods, including their respective positioning techniques, satellite systems, and orbit sources, can be found in Table 3.1. By comparing the results obtained from these methods, the performance in terms of alignment accuracy, precision, and reliability is assessed.

**Table 3.1: Summary of OPUS-S, OPUS-P and CSRS-PPP online GNSS post-processing services.**

<b>Service Name:</b>	<b>OPUS -S</b>	<b>OPUS - P</b>	<b>CSRS - PPP</b>
Positioning Technique	Relative	Relative	PPP
Includes Network Adjustment	No	Yes	No
Elevation cutoff [deg]	10	10	7.5
Satellites Constellations Used	GPS only	GPS only	GPS & GLONASS
Orbit Source	IGS	IGS	IGS & NRCan
Managed by	NGS	NGS	NRCan

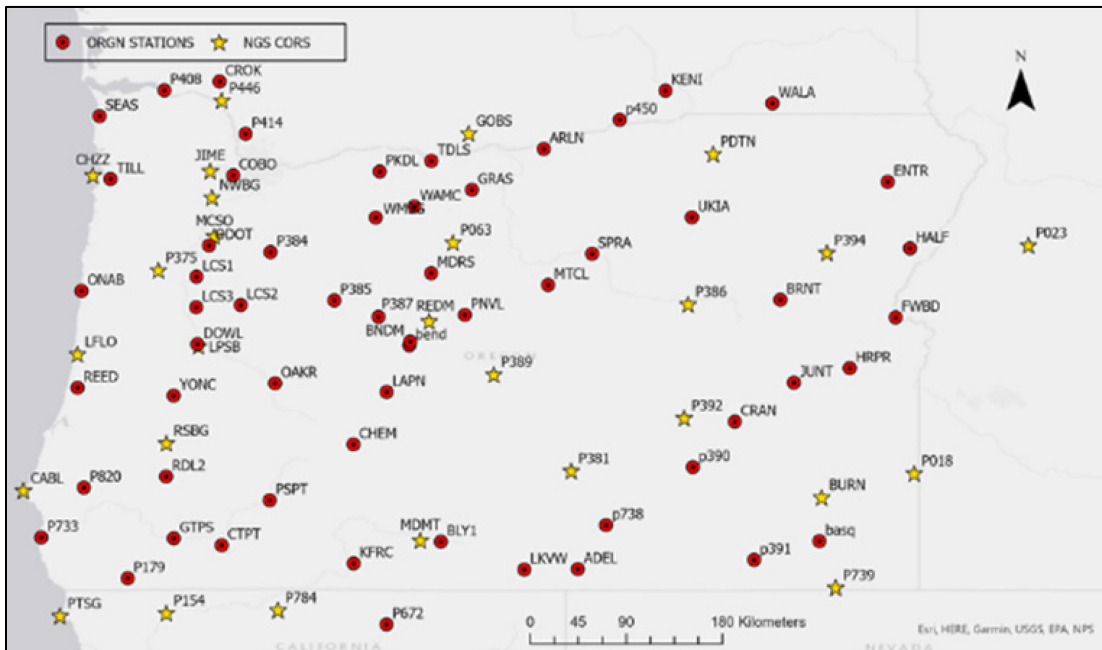
### 3.2.1 Source of Data for Analysis

In this study, an evaluation was conducted to assess methods for aligning RTNs with the NSRS. The data used in this analysis are the 24-hour RINEX files described in Section 3.2, collected from active stations within the ORGN and SCRTN networks during the 31-day period from January 1 to January 31, 2023. The collected data, comprising 24-hour RINEX files from active stations, were processed using three different methods: OPUS-S, OPUS-P, and CSRS-PPP. By comparing the results obtained from these methods, the performance in terms of alignment accuracy, precision, and reliability was assessed.

#### 3.2.1.1 Oregon Real-Time GNSS Network (ORGN)

The ORGN, managed by the Oregon Department of Transportation (ODOT), consists of over 132 CORS, including 29 NGS CORS. These active reference stations are organized

into sub-networks or station clusters, with GNSS stations spaced approximately 70 km apart. To ensure high data quality from the reference stations and provide accurate corrections to field GNSS users, the ORGN relies on Leica GNSS Spider, specialized RTN management software (ODOT, 2023). Leica GNSS Spider is responsible for configuring and monitoring the data quality of the reference stations, as well as computing and delivering the necessary corrections to users. The ORGN provides coverage across the entire state of Oregon, which spans approximately 98,381 square miles. For this study, data from 60 RTN CORS and 27 NGS CORS were used (Figure 3.1). The selection of RTN CORS was based on data availability for the entire 31-day evaluation period and was limited to avoid splitting the project into multiple parts due to OPUS-Projects software limitations, which allow a maximum of 99 stations in a single session (including NGS CORS). Typically, the ORGN network is aligned within OPUS-Projects by dividing it into two parts, separated approximately by the Cascade Mountain Range. Figure 1 shows the positions of the RTN CORS and NGS CORS used in this study.

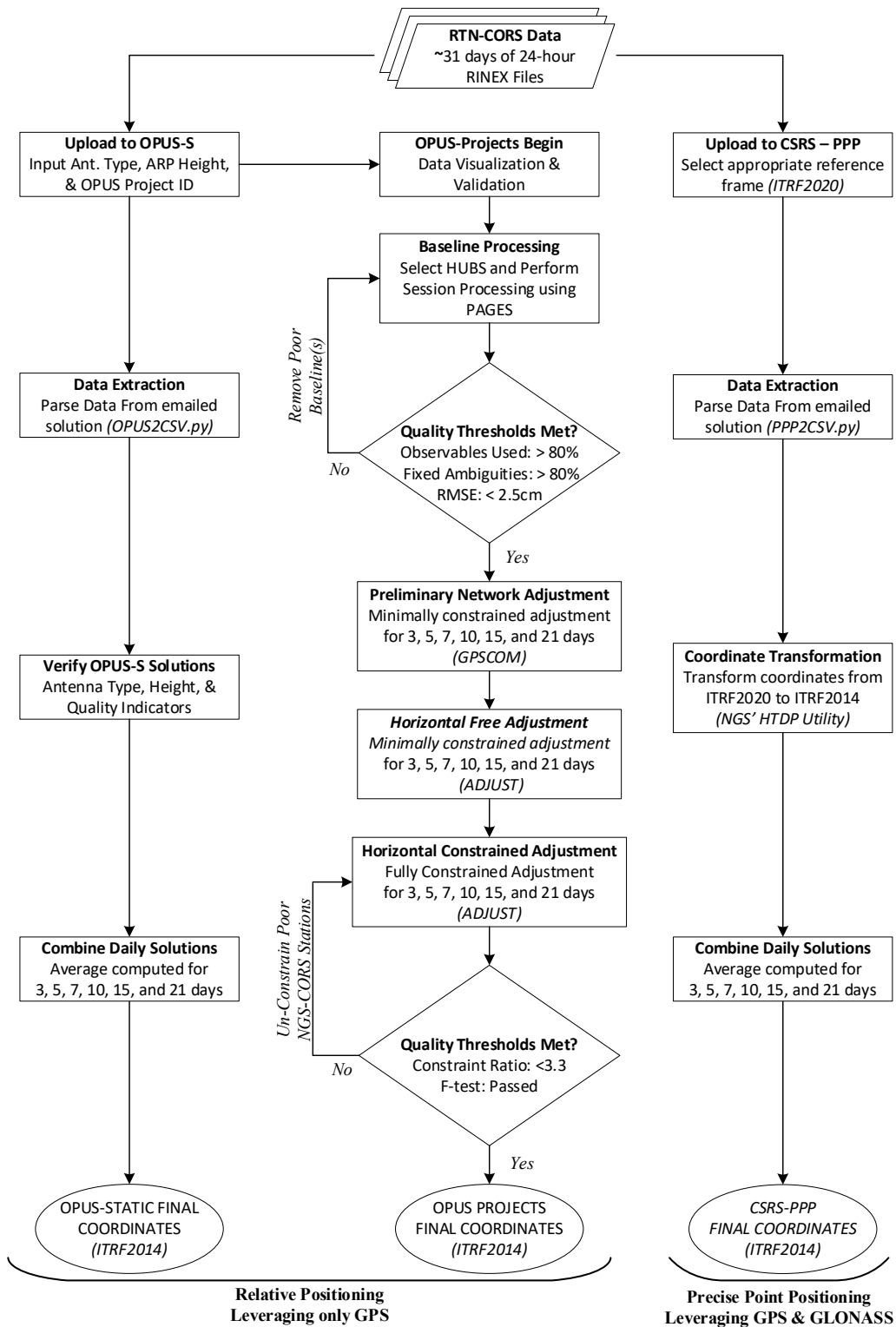


**Figure 3.1: Locations of active RTN CORS and NGS CORS in the ORGN used for this study.**

### 3.2.1.2 South Carolina Real-Time Network (SCRTN)

The South Carolina Geodetic Survey manages the SCRTN, which consists of 55 active stations, including 10 NGS CORS. These stations are positioned less than 70 km apart and provide coverage across the entire state of South Carolina, which spans approximately 32,030 square miles. The SCRTN utilizes Trimble VRS3Net, employing the VRS method, to provide users with continuous corrections and post-processed data. For this study, data from 33 RTN CORS in South Carolina and 23 NGS CORS covering





**Figure 3.3: Flowchart for processing and adjusting a Real-Time Network.**

### 3.3.1 CSRS-PPP

The 24-hour RINEX files for the ORGN and SCRTN RTN CORS were uploaded to the CSRS-PPP webpage as daily zip files. It is worth noting that the CSRS-PPP solutions are referenced to the IGS20 reference frame, so a transformation to IGS14 using the NGS online utility tool, HTDP (Horizontal Time-Dependent Positioning), was required prior to making any comparisons. HTDP transforms positional coordinates between reference frames and epochs by first updating coordinates using velocity and crustal displacement models, and second, applying a 14-parameter Helmert transformation to convert coordinates from the source reference frame to the desired target reference frame (Snay et al., 2014).

### 3.3.2 OPUS-Static

The 24-hour RINEX files for the ORGN and SCRTN RTN CORS were also uploaded separately to OPUS-Static. During the upload process, the OPUS-Projects ID keyword was specified, allowing the data to be seamlessly incorporated into the OPUS-Projects platform. The specific antenna type and vertical height to the Antenna Reference Point (ARP) were also specified during the upload. The analysis included the daily upload of 60 RINEX files from RTN CORS in the ORGN and 33 RINEX files from RTN CORS in the SCRTN. However, 36 solutions could not be processed for some of the ORGN's RTN CORS on certain days. This resulted in a difference in data collection periods: the assessment of the ORGN was based on 27 days of data (instead of the initially planned 31 days), while the SCRTN stations were evaluated using the full 31-day dataset because there were no processing issues. Table 3.2 provides a summary of the number of successful and failed solutions, along with the corresponding quality indicators for the successfully processed solutions.

**Table 3.2: Summary of OPUS-Static Solutions**

<b>OPUS-S Solution</b>	<b>ORGN</b>	<b>SCRTN</b>
Number of stations uploaded	60	33
Expected solutions	1860	1023
Successfully processed solutions	1824	1023
Failed solutions	36	0
Orbits used	IGS Precise	IGS Precise
Number of solutions with overall RMS greater than 3cm	4	0
Number of solutions with less than 50% fixed ambiguities	0	0
Number of solutions with less than 90% observations used	42	110
Number of solutions with less than 80% observations used	0	7
Number of solutions with less than 70% observations used	0	0

### **3.3.3 OPUS-Projects**

#### **3.3.3.1 NGS CORS Selection**

In OPUS-Projects, RTN CORS that did not have data available for all days within the evaluated time span were removed from the analysis. Following this, NGS CORS were carefully selected and added to the projects. The recommendations provided by Armstrong et al. (2015) were followed to establish a selection process for NGS CORS to be included as constraints in the network adjustment:

- The distribution of constrained NGS CORS should aim for as uniform coverage as possible across the RTN service area.
- Preference was given to NGS CORS that demonstrated long-term reliability and stability. This was accomplished by analyzing the root mean square error and standard deviation in short-term and long-term time-series plots provided by NGS.
- Selected NGS CORS were required to have a minimum existence of 2.5 years. This criterion ensured that computed velocities were available. NGS CORS lacking computed velocities were deliberately avoided, as they do not have formal uncertainty estimates (Gillins et al., 2019).

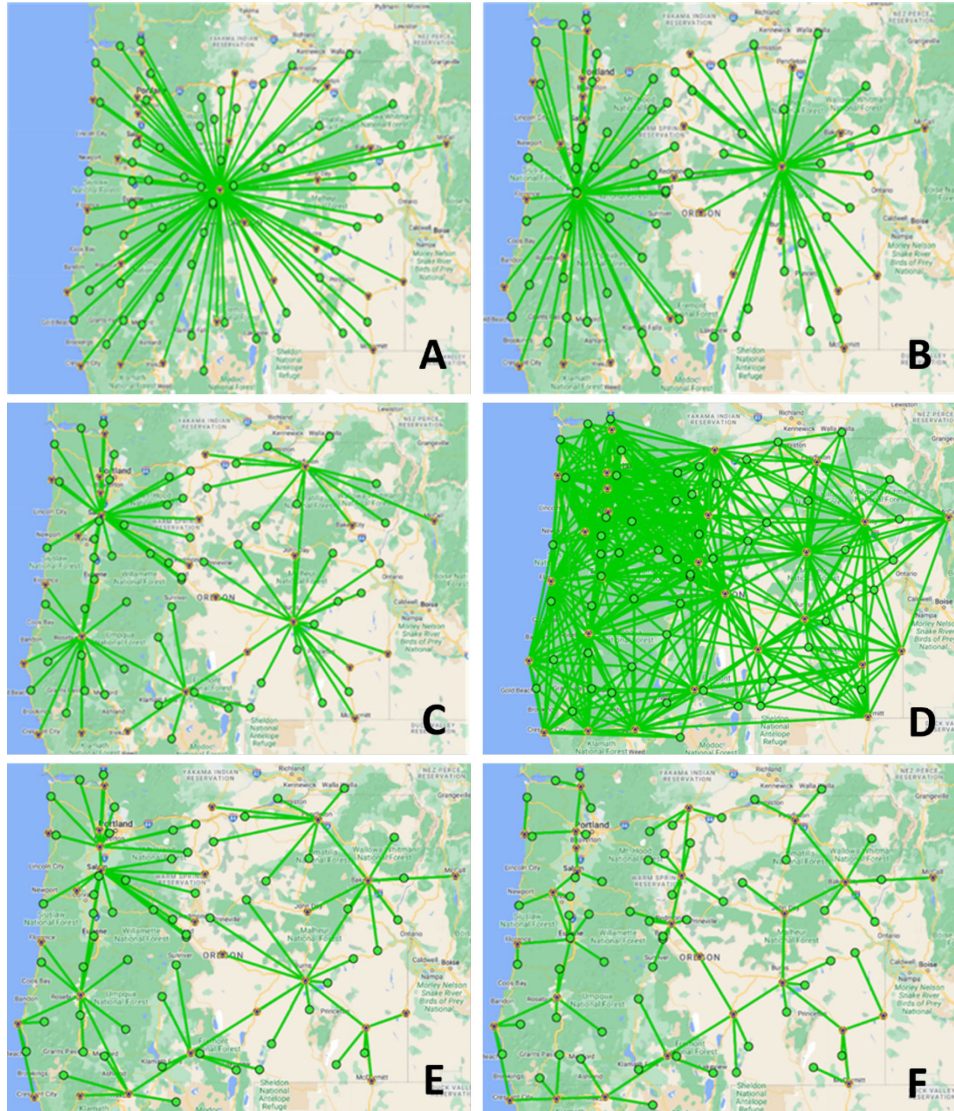
Based on these recommendations and considering data availability for the assessed periods, 27 NGS CORS were included in the ORGN project, while 23 NGS CORS were added to the SCRTN project.

#### **3.3.3.2 Evaluation of Baseline Network Geometry**

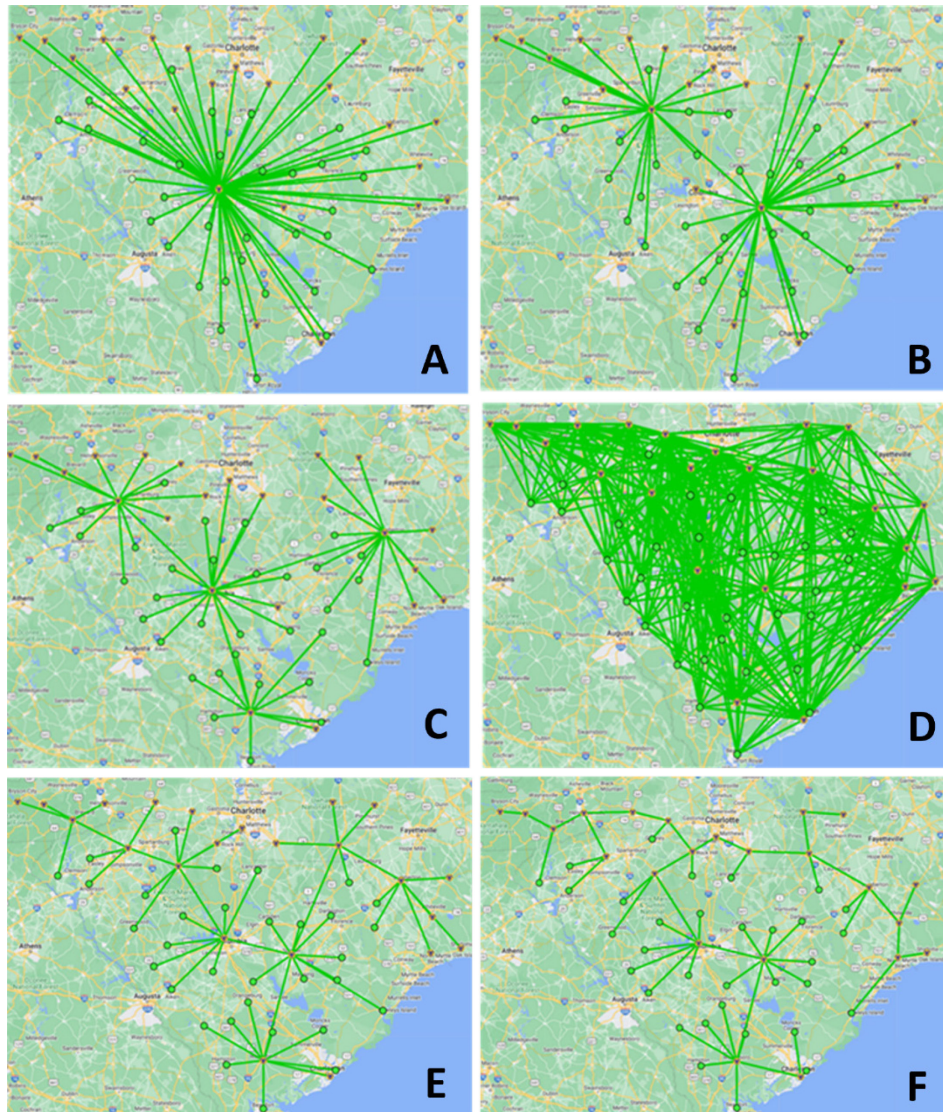
Session baseline processing between RTN CORS and NGS CORS was completed for a variety of network designs, as shown in Figure 3.4 and Figure 3.5. This approach was used to determine whether the network design affects the resulting accuracy of the RTN CORS coordinates. It is important to note that only NGS CORS were considered as "hubs" for the network designs in this study, as the goal is to determine the positions of the RTN CORS relative to the NSRS, which is defined by the NGS CORS network. The session baseline processing was performed and evaluated for six distinct network baseline designs, summarized in Table 3.3, for each of the RTNs in this study.

**Table 3.3: Summary of network being assessed in OPUS-Projects**

<b>Network Design ID</b>	<b>Description</b>
A	A single hub was selected for the entire network. The chosen hub was the most centrally located among the selected NGS CORS within the network. This was determined by computing the baseline lengths between each selected NGS CORS and the active stations in the respective RTNs and identifying the station with the smallest average baseline length. The selected hub remained consistent across all 31 sessions.
B	Two hubs were selected for the entire network. The stations within each RTN were divided into two regions, and the most centrally located NGS CORS in each region was chosen as the hub. This selection aimed to minimize baseline lengths, similar to Network Design A.
C	RTN stations were divided into five distinct clusters for the ORGN and four distinct clusters for the SCRTN using a K-means clustering algorithm. The most centrally located NGS CORS within each cluster was chosen as a hub. The selected hubs were maintained consistently across all 31 sessions.
D	RTN stations were divided into five clusters for the ORGN and four clusters for the SCRTN using a K-means clustering algorithm. The most centrally located NGS CORS in each cluster was selected as a hub. These hubs were maintained consistently across all 31 sessions.
E	Similar to network design C, this design uses two hubs per cluster. The same two hubs are maintained across all sessions.
F	All hub design, where all NGS CORS were used as hubs in all sessions.



**Figure 3.4: Implemented network designs (A-F) for the Oregon Real-time GNSS Network.**



**Figure 3.5: Implemented network designs (A-F) for the South Carolina Real-time GNSS Network.**

### ***3.3.3.3 Session Processing & Network Adjustments***

Daily sessions were processed, and during each baseline processing session, tropospheric modeling was configured using a piecewise linear approximation every 7,200 seconds. The hubs in the network baseline designs were assigned normal constraint weights to allow for minor shifts that might occur if NGS CORS were slightly offset from their reference coordinates. The OPUS-Projects data and solution quality thresholds were successfully met for all analyzed baselines. These thresholds included utilizing more than 80% of observables, fixing more than 80% of ambiguities, and achieving a baseline processing root-mean-square error (RMSE) of less than 2.5 cm. Solution statistics for all sessions were carefully reviewed, including an analysis of "peak-to-peak" (P2P) values. Marks exhibiting high P2P values were thoroughly investigated and, based on the

findings, were either removed from specific sessions or excluded entirely from all sessions. After achieving satisfactory results from session processing, a sequence of three network adjustments was performed, as recommended in the OPUS-P user guide (Hensel et al., 2023) to combine the daily session solutions for the 6 permutations being evaluated in this study. The three adjustments, listed below, were performed in accordance with the recommendations identified in the OPUS-P User Guide (Hensel et al., 2023).

1. Preliminary Adjustment
2. Horizontal Free Adjustment
3. Horizontal Constrained Adjustment

The network adjustment sequence began with a preliminary adjustment using the GPSCOM software package, which combines selected sessions into a single network solution and generates the necessary input files for subsequent adjustments. The outputs from the preliminary adjustment were then used as inputs for performing both the horizontal free adjustment and the horizontal constrained adjustment using the ADJUST software. The analysis of the preliminary adjustment results, prior to the horizontal free adjustment, involved the following steps:

1. Reviewing the processing report for unit weight and constrained mark verification. The standard error of unit weight was checked to ensure it was near 1.0.
2. Checking the estimated a priori coordinate shifts for small deviations (less than  $\pm 2$  cm horizontally and  $\pm 4$  cm vertically).
3. Conducting a session processing review and excluding problematic observations in cases of issues or poor results.

These steps ensured the quality and reliability of the data used for the subsequent analysis. Upon achieving satisfactory results, the horizontal free adjustment was performed. During the horizontal free adjustment (a minimally constrained adjustment), a single NGS CORS was constrained to allow the least squares solution the flexibility to identify any issues or outliers within the network. The analysis after the horizontal free adjustment involved the following steps:

1. Reviewing the summary file and processing report to verify that the standard error of unit weight was around 1.0.
2. Ensuring that only one mark was constrained horizontally, consistent with a minimally constrained adjustment.
3. Checking the estimated a priori coordinate shifts for small deviations (less than  $\pm 2$  cm horizontally and  $\pm 4$  cm vertically).
4. Reviewing the processing log for large residuals, which could indicate problematic observations or marks, and addressing residuals exceeding 2 cm horizontally and 4 cm vertically to improve result accuracy.

After ensuring satisfactory results from the horizontal free adjustment, the horizontal constrained adjustment was performed, constraining all NGS CORS in the project. During the analysis of the horizontal constrained adjustment, various evaluations were conducted to assess the impact of constraints on the network and to ensure the accuracy of the adjustment results. These evaluations included: (1) reviewing the F-test results, and (2) conducting a Constraint Ratio (CR) test to identify constraints exceeding a value of 3.0 and subsequently removing them to address any problematic constraints.

This iterative process ensured that any problematic constraints were addressed and that the adjustment was fine-tuned for improved accuracy. By reapplying the necessary adjustments, the network alignment was completed, resulting in more precise and reliable outcomes. In total, 216 adjustments were performed across both RTNs.

### **3.4 FINAL COORDINATE DETERMINATION**

#### **3.4.1 Single Point Positioning Services (OPUS-S, and CSRS-PPP)**

The daily coordinates for the RTN CORS were collected from the OPUS-S solution reports and CSRS-PPP summary files. These daily positions were used to monitor the alignment of RTN CORS stations with the NSRS, as discussed further in Section 4.3 of this report. To ensure the accuracy and reliability of the average positions, outliers were removed using a per-station 3-sigma test for each evaluated time span. This statistical method identifies and eliminates daily positions that deviate significantly from the mean and standard deviation for that specific time span, treating them as outliers.

#### **3.4.2 OPUS-Projects**

The final coordinates for the RTN CORS stations during each evaluated time span were obtained from the solution reports. Positions determined using the preliminary adjustment (GPSCOM) were extracted from the “network final network processing” report, while positions determined using the horizontal constrained adjustment (ADJUST) were extracted from the “network final horizontal constrained network processing” report. Unless otherwise specified, the results from the horizontal constrained adjustment are used for the analysis in this study.

### **3.5 ACCURACY ASSESSMENT**

To evaluate the accuracy of positions determined by OPUS-S, OPUS-P, and CSRS-PPP, a reference dataset was compiled from 27 days (for ORGN) or 31 days (for SCRTN) of continuous 24-hour RINEX files processed through OPUS-P. This choice reflects recommendations in the literature: Park et al. (2018) observed minimal improvement in estimated uncertainties once observations exceeded approximately one day, and Henning et al. (2011) advised a minimum of 10 days of data for aligning RTN CORS to the NSRS. By using a duration nearly three times the recommended minimum, the resulting reference positions for the RTN CORS were considered suitable of their true locations. A horizontally constrained network adjustment (Network design D) was used for these reference coordinates due to its overall comprehensiveness.

Position residuals were then computed as differences in the local geodetic horizon frame (East, North, Up) between each station's final coordinates and its reference coordinates. Specifically, Earth-Centered, Earth-Fixed (ECEF) coordinates for both the station (derived from latitude, longitude, and ellipsoidal height) and its reference were first calculated. The difference between these ECEF positions was then transformed into the East-North-Up (ENU) coordinate system using a rotation matrix defined by the station's reference latitude and longitude. This process, commonly described in geodetic literature, enables direct comparison of position changes in a local frame.

To ensure the reliability of the computed station positions, a 3-sigma statistical test was applied to identify and remove outliers. The rationale for using three standard deviations is based on the properties of a normal distribution, where approximately 99.7% of data falls within this range. Data points beyond three standard deviations are considered unlikely to occur by chance and are likely significant deviations from expected behavior. For each time span and method, the mean and standard deviation of residuals across all stations were calculated. Any individual station residual exceeding three standard deviations from the network mean was flagged as an outlier and removed. By excluding these anomalous values, the final dataset provided a clearer basis for comparing positional accuracy among OPUS-S, OPUS-P, and CSRS-PPP over different time spans.

## **3.6 RESULTS AND DISCUSSION**

### **3.6.1 Comparison of RTN Alignment Methods**

After removing nine outliers, which represent approximately 1.0% of the total dataset, residuals from OPUS-S, OPUS-P, and CSRS-PPP were compared across various time spans. Figure 3.6 presents the mean residuals (horizontal and vertical) versus time for both the ORGN and SCRTN datasets, including error bars showing standard deviations at the 95% confidence level. While all three methods produce broadly similar results, a few systematic biases are apparent. For instance, comparing OPUS-P and OPUS-S in the ORGN dataset reveals a consistent bias of about 1.0 cm in the horizontal component and 0.5 cm in the vertical component. In contrast, the SCRTN dataset shows a smaller horizontal bias of roughly 0.5 cm but a larger vertical bias of 1.5 cm. Comparing OPUS-S to CSRS-PPP yields an average bias of 0.5 cm in both the horizontal and vertical dimensions, consistent across both ORGN and SCRTN. When OPUS-P is compared to CSRS-PPP, discrepancies remain at or below the centimeter level, suggesting relatively close agreement, although there is slightly more vertical scatter for CSRS-PPP.

Figure 3.7 compares mean network accuracy (at the 95% confidence level) across six baseline designs processed in OPUS-Projects. The horizontal constrained adjustment results for both ORGN and SCRTN indicate that the chosen network baseline configuration has minimal impact on final station positions, demonstrating that any of these designs can be used without substantially compromising positional accuracy. This similarity underscores the robustness of OPUS-Projects when performing a final adjustment.

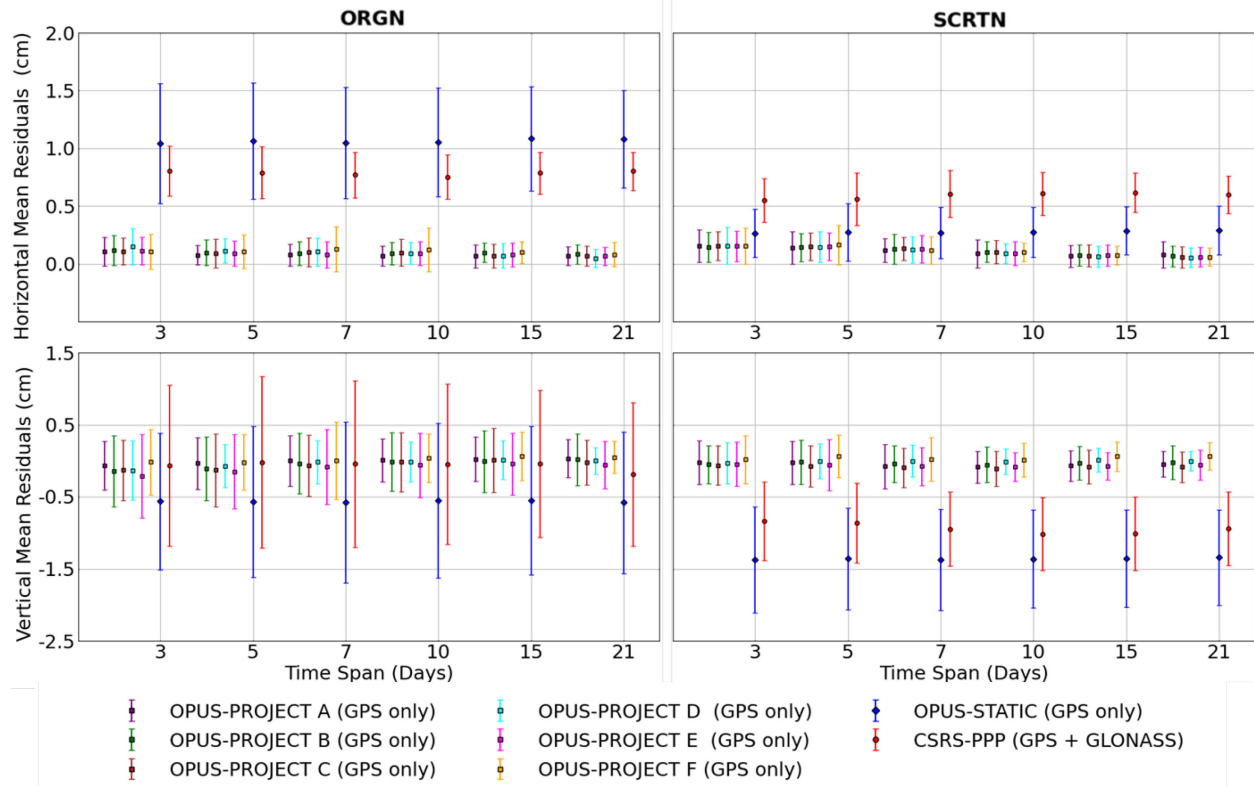
Although the network designs themselves show minimal differences under a horizontal constrained adjustment, distinctions can still arise between the preliminary adjustment (GPS COM) and the constrained adjustment (ADJUST) within OPUS-Projects. GPS COM applies

minimal constraints and helps identify gross errors, while ADJUST enforces the final tie to the datum (NSRS), producing the refined station coordinates recommended for RTN alignment. In practice, differences between these two steps tend to be relatively small, but ADJUST is considered the definitive approach for generating accurate coordinates for RTN CORS.

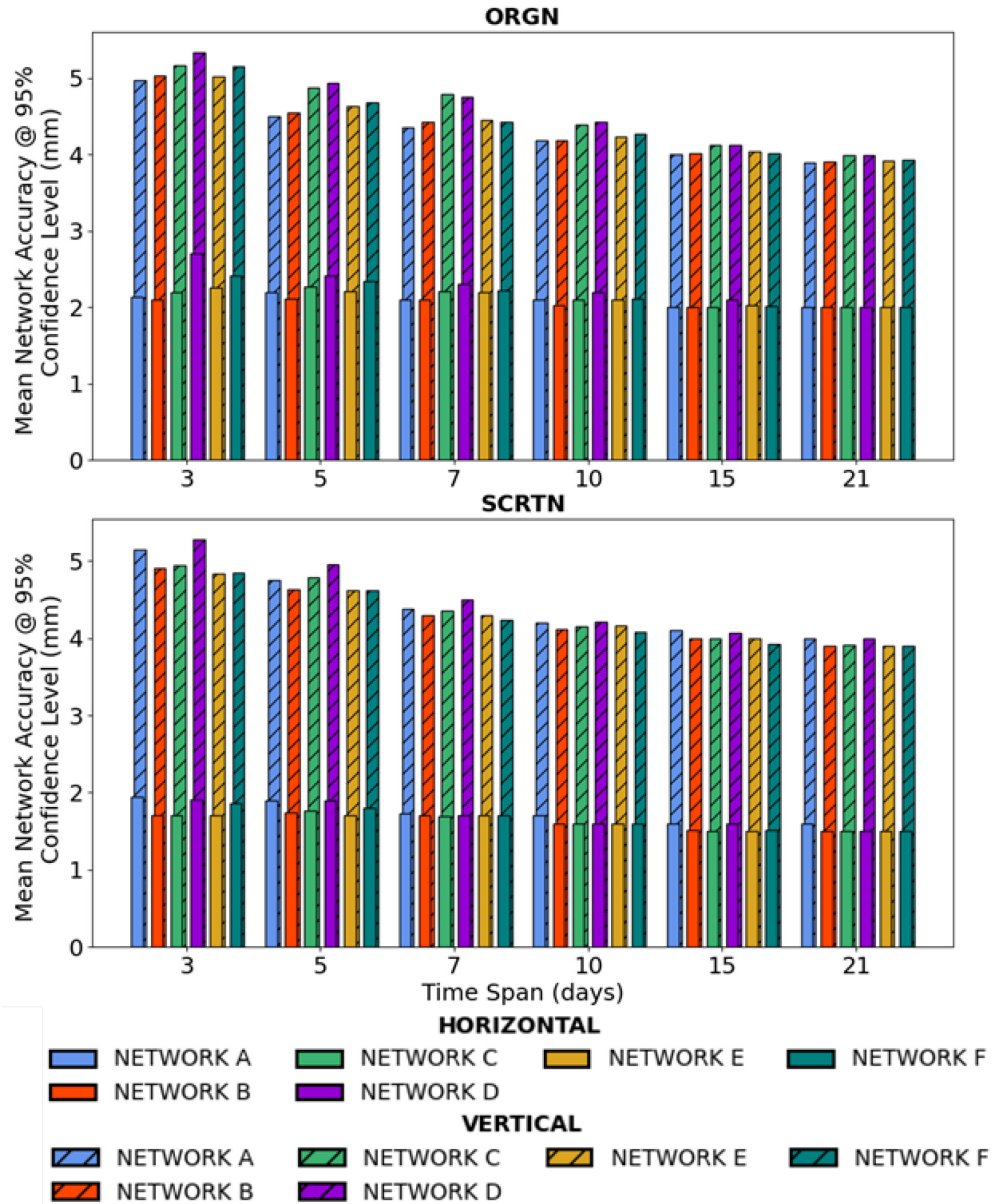
Beyond mean biases, the three methods exhibit differing levels of variability in their solutions. OPUS-P consistently shows the smallest standard deviations, typically around 0.5 mm horizontally and 2 mm vertically in the ORGN dataset, and 0.5 mm horizontally and 1.8 mm vertically in the SCRTN dataset. CSRS-PPP tends to show somewhat larger scatter, averaging about 1.0 mm horizontally and 5 mm vertically for ORGN, and 1.0 mm horizontally and 2.5 mm vertically for SCRTN. OPUS-S generally exhibits the largest spread, with standard deviations of around 2.5 mm horizontally and 5 mm vertically in the ORGN dataset, and about 1.2 mm horizontally and 3.8 mm vertically in the SCRTN dataset.

To investigate the reliability of uncertainty estimates, the formal errors in each of the six OPUS-P baseline designs were compared to the observed residuals. Only the 10-day results are shown in Figure 3.8 as an example, while the remaining daily comparisons (3, 5, 7, 15, and 21 days) can be found in Ohene (2023). In the 10-day plots, the formal errors closely match the spread of the actual residuals for both ORGN and SCRTN, indicating that the uncertainty estimates become more reliable as longer datasets are used.

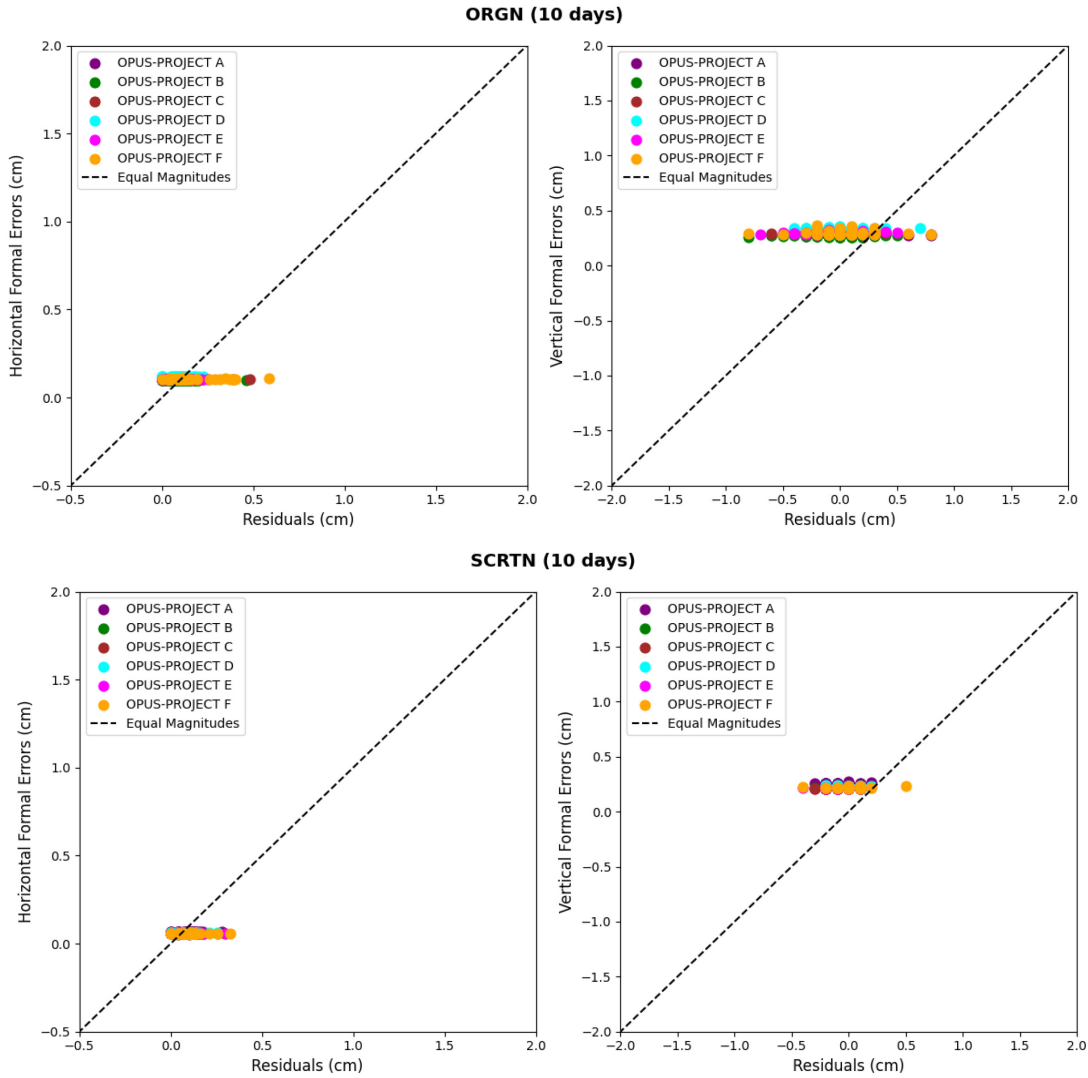
Figure 3.9 illustrates the standard deviation of residuals over time in both networks, whereas Figure 3.10 shows the mean network accuracy (from formal error propagation) across the same time spans. Although all changes are measured in millimeters, there is a trend toward improved accuracy with increasing observation duration, which gradually levels off after around 10 days. As a result, users seeking a balance between observation length and accuracy may find that about 10 days of data are sufficient to achieve stable, reliable solutions for RTN alignment to the NSRS.



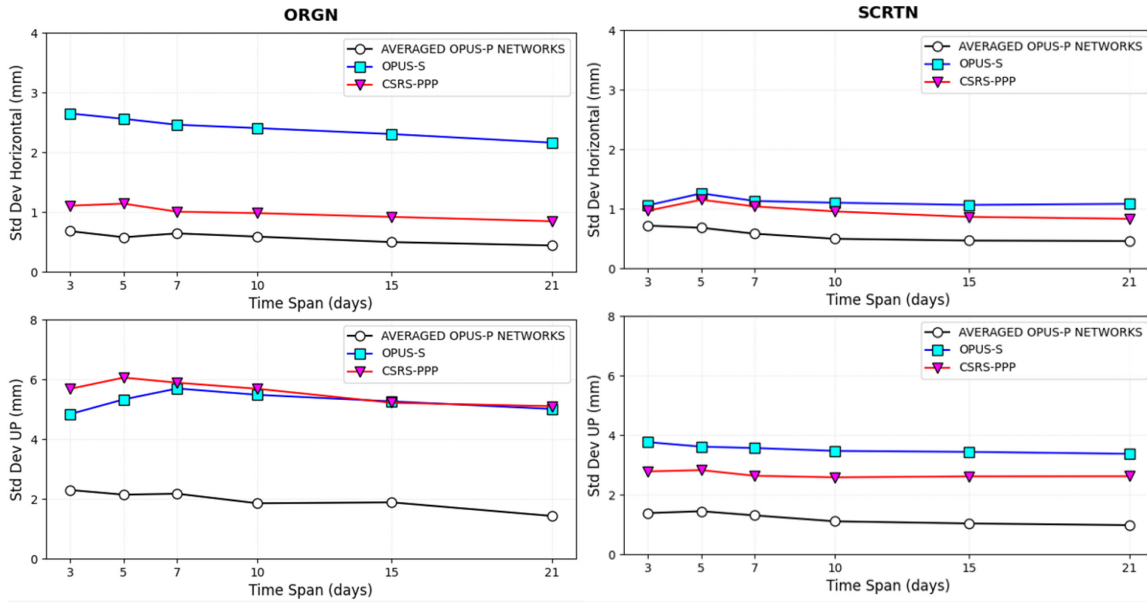
**Figure 3.6: Mean residuals in the horizontal and vertical versus time span for the two RTN's (error bars are standard deviation of the residuals at 95% confidence level). Adapted from Ohene, 2023 with permission.**



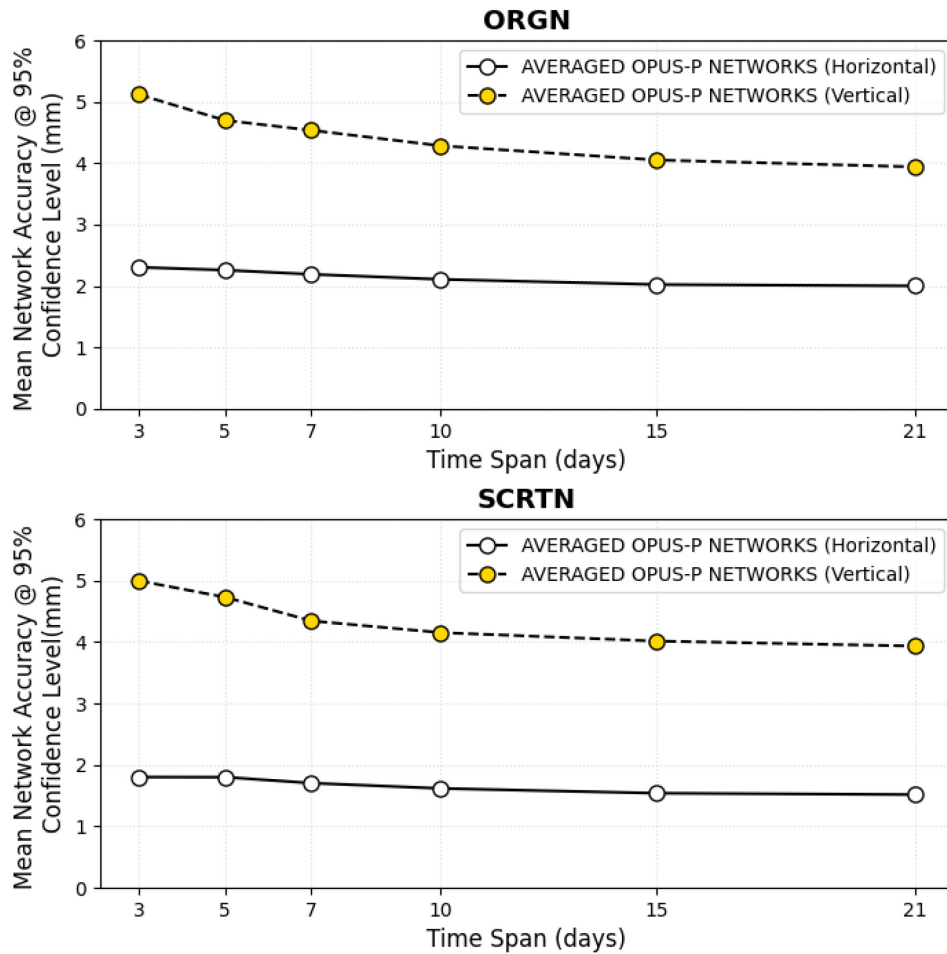
**Figure 3.7: Mean network accuracy at 95% confidence level in the horizontal and vertical coordinate dimensions for the two RTN's, comparing the accuracies of the six different baseline designs evaluated in OPUS-Projects. Adapted from Ohene, 2023 with permission.**



**Figure 3.8: Comparison of Formal Errors and Residuals for ORGN and SCRTN for 10 Days. Adapted from Ohene, 2023 with permission.**



**Figure 3.9: Standard deviation of residuals over time in the ORGN and SCRTN. Adapted from Ohene, 2023 with permission.**



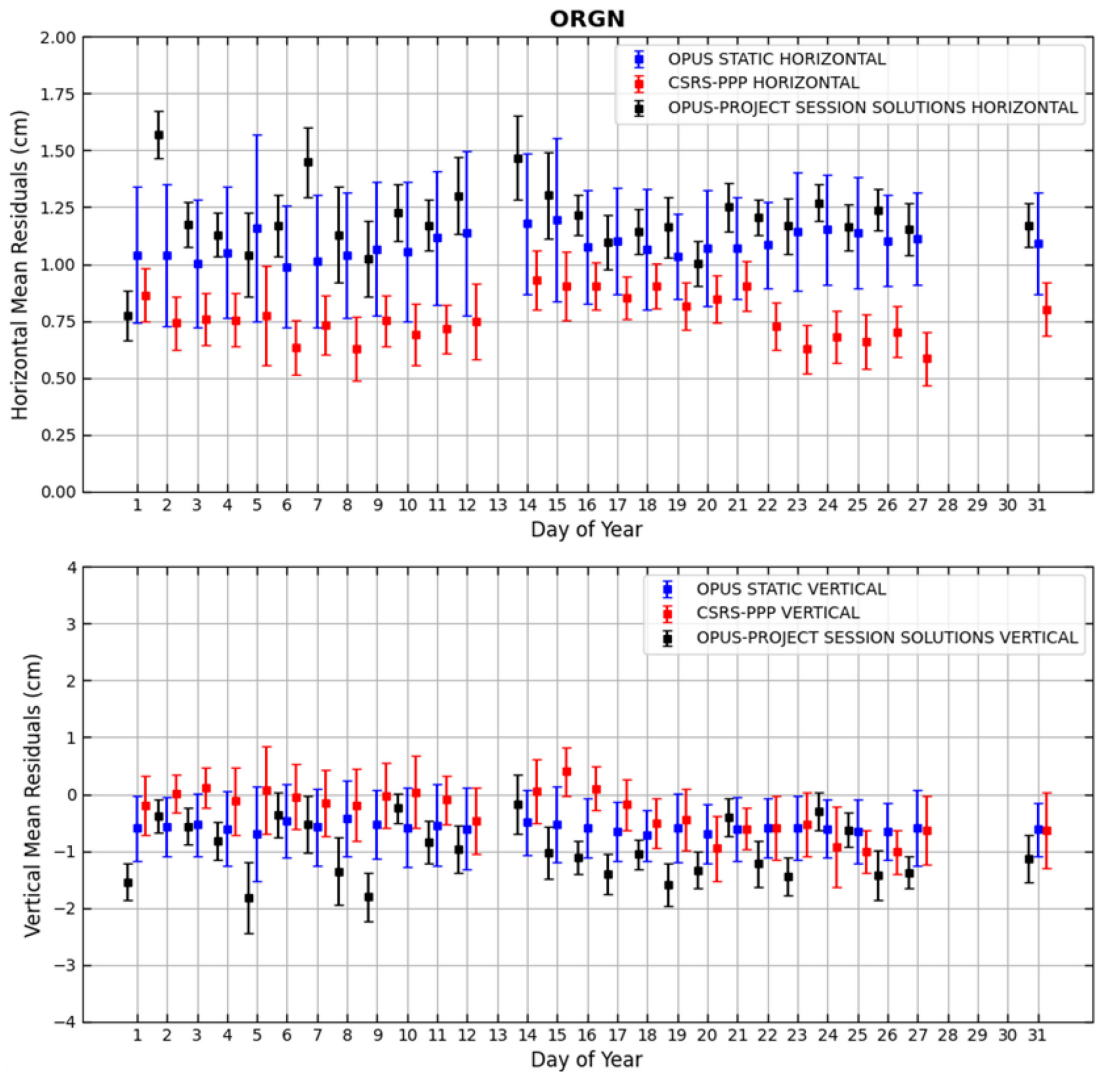
**Figure 3.10: Mean network accuracy at 95% confidence level over time in the ORGN (top) and SCRTN (bottom). Adapted from Ohene, 2023 with permission.**

### 3.6.2 Monitoring RTN Station Alignment to the NSRS

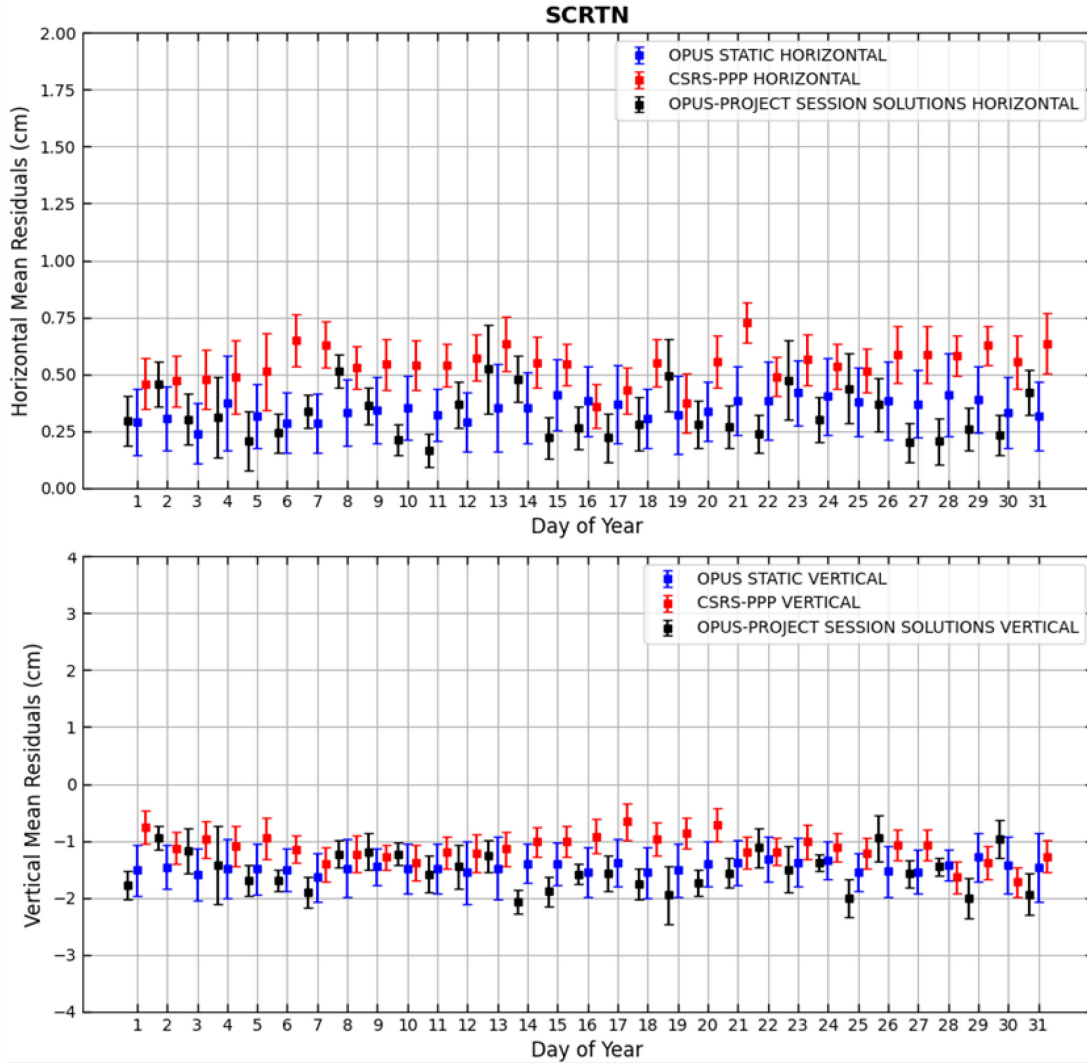
In the context of monitoring RTN CORS positions relative to the NSRS, Figure 3.11 and Figure 3.12 illustrate the daily residuals in the horizontal and vertical components using OPUS-S, CSRS-PPP, and OPUS-P daily session solutions. The error bars in the figures represent the standard deviations of the residuals for all stations on the corresponding DOY. These figures provide valuable insights into the daily alignment of each RTN network with the NSRS. While a per-station analysis would also be beneficial, examining the daily average network residuals offers an overview of the trends exhibited by each method. Monitoring alignment to the NSRS is crucial for promptly identifying and addressing any deviations from the expected accuracy, ensuring the reliability and integrity of the network's geospatial data.

A consistent observation from the figures is that OPUS-P session solutions exhibit relatively lower standard deviations in the residuals. This suggests a higher level of stability and accuracy in the alignment process compared to CSRS-PPP and OPUS-S. However, when comparing the daily residuals across the three methods, no clear trends or patterns emerge. Therefore, further research is necessary to determine optimal thresholds for OPUS-S, CSRS-PPP, and OPUS-P

session solutions. These thresholds would serve as reference values for identifying significant deviations from the reference system, enabling the establishment of effective monitoring practices for network alignment.



**Figure 3.11: Daily residuals in horizontal and vertical components for OPUS-S, CSRS-PPP, and OPUS-P Session solutions in the ORGN. Adapted from Ohene, 2023 with permission.**



**Figure 3.12: Daily residuals in horizontal and vertical components for OPUS-S, CSRS-PPP, and OPUS-P Session solutions in the SCRTN. Adapted from Ohene, 2023 with permission.**

### 3.7 SUMMARY OF KEY FINDINGS AND RECOMMENDATIONS

This study demonstrated that OPUS-P, OPUS-S, and CSRS-PPP each offer distinct advantages for aligning Real-Time Networks (RTNs) to the National Spatial Reference System (NSRS). Analysis of both daily solutions and multi-day averages showed that the preliminary adjustment in OPUS-Projects (GPSCOM) should not be used for final published coordinates, as it can yield results that deviate significantly from those produced by the horizontal free and constrained adjustments (ADJUST). Instead, ADJUST provides more reliable and stable coordinates for RTN Continuously Operating Reference Stations (CORS). Within OPUS-Projects, the specific network geometry used for baseline design has minimal impact on the final solution’s accuracy once the horizontal constrained adjustment is applied, affording RTN managers flexibility in network configuration.

Among the three positioning methods tested, OPUS-P consistently displayed the smallest scatter (standard deviations) in both horizontal and vertical components compared to OPUS-S and CSRS-PPP, indicating that OPUS-P can produce higher-precision coordinates and more realistic estimated uncertainties. Its uncertainties are well aligned with observed coordinate residuals, providing additional confidence in the values reported in the Summary (\*.sum) files. When determining final network coordinates, increasing the number of 24-hour RINEX data files beyond five days produced diminishing gains in accuracy, with little improvement observed after 10 days of data. These findings support earlier recommendations (e.g., Henning et al., 2011) that 10 days of data offer an excellent balance between effort and positional reliability.

Further research is needed to define optimal thresholds for deciding when RTN CORS coordinates should be updated. Session solutions from OPUS-S, CSRS-PPP, and OPUS-P could be compared to these thresholds to identify significant deviations from the NSRS. Based on this study's one-month evaluation of daily station solutions, a threshold of  $\pm 2$  centimeters in the horizontal and  $\pm 3$  centimeters in the vertical appears to be an effective benchmark for flagging and potentially re-publishing station coordinates. Once established, these thresholds would facilitate ongoing alignment checks and monitoring with minimal effort. The methodologies used here, particularly the multi-day processing in OPUS-P, should be automated to streamline routine network evaluations and reduce the burden of manual oversight.

In light of these findings, RTN managers seeking alignment with the NSRS are advised to prioritize OPUS-Projects for final station positioning. While five days of 24-hour data can yield acceptable results, 10 days is preferable to improve confidence in published coordinates, and additional data beyond that provides only marginal benefits. Managers are encouraged to share the estimated uncertainties reported by OPUS-P as part of the final coordinate publication process, enhancing users' understanding of positional reliability. By adopting these recommendations and automating analysis workflows, RTN managers can efficiently maintain network accuracy, proactively address deviations, and uphold a high standard of service for end users.

## **4.0 AUTOMATING OPUS-PROJECTS FOR ALIGNING THE ORGN TO THE NSRS**

Efficiently aligning the Oregon Real-Time GNSS Network (ORGN) to the National Spatial Reference System (NSRS) requires an approach that minimizes repeated user interaction with OPUS-Projects' web interface. This chapter describes the methodological framework of a custom tool, referred to here as the "ORGN Align" application, for semi-automated or fully automated alignment. Specifically, the text details how daily GNSS observations are collected, organized, and submitted to OPUS-Projects, how the network of baseline vectors is defined, and how station coordinates are refined through constrained adjustments. By the end of the process, each station in the ORGN is anchored to accurate, stable coordinates consistent with the NSRS.

### **4.1 AUTOMATED WORKFLOW OBJECTIVES**

The primary goal of this system is to streamline the processes that surveyors typically perform in OPUS-Projects, thereby eliminating repetitive manual steps. Although OPUS-Projects already provides robust baseline processing and network adjustment capabilities, it traditionally requires users to log into a web portal, upload daily RINEX files, specify baseline designs, and repeatedly run adjustments. Such tasks become time-consuming for a statewide GNSS network like the ORGN, where dozens of stations, each with 24-hour data, must be processed daily or weekly.

By contrast, the ORGN Align tool ensures that, once basic parameters such as station lists, date ranges, and desired constraints are set, the software systematically retrieves RINEX files from specified archives, processes them according to OPUS specifications, and submits the data to OPUS-Projects consistently. Internally, it monitors each session's solution for significant error flags, discards poor observations, re-runs preliminary adjustments, and ultimately obtains a fully constrained network solution. This approach reduces the potential for user fatigue or mistakes and delivers stable, repeatable results that maintain the ORGN's alignment with the NSRS.

Through these workflow objectives, a measure of self-sufficiency emerges. Even in a large-scale operational setting, the system performs most alignment tasks without constant manual verification. Surveyors can then focus on critical responsibilities such as diagnosing unexpected station movements or verifying final outputs. Figure 4.1 provides a conceptual overview of how daily or weekly data flows from the raw RINEX archives to the final published station coordinates.

### **4.2 DATA ORGANIZATION AND SHARING SCHEMA**

A fundamental aspect of the ORGN Align approach is a well-structured data management scheme. The tool is designed to find each day's raw GNSS observations in a predictable location, separate from processed data that is directly handed off to OPUS. Maintaining these two categories labeled "original" and "processed" prevents confusion about which files remain unmodified from the source archives and which have undergone decompression or reformatting.

When new data arrive, the application automatically places the raw RINEX files into a directory corresponding to the station identifier, the four-digit year, and the day of the year. For instance, if

station “AGNS” has data for day 110 of 2024, its raw files might reside under a path such as /data/original/2024/110/AGNS/. The software then decompresses or unpacks these files, resamples them to a 30 s epoch rate, and stores the outputs in a parallel /data/processed/... structure. Each station’s processed files now conform to OPUS standards and incorporate consistent naming conventions, including day-of-year or station codes.

In addition to this file structure, the system references shared metadata through CSV or XML files. These metadata include station coordinates, cluster assignments, and user-defined hub preferences. If a user has organized NGS CORS stations in a particular region or designated an internal station to remain unconstrained, the tool respects these flags throughout the process. In effect, the same organizational schema underpins every aspect of the pipeline, from the baseline generator to data upload to final coordinate publication. This consistency ensures that typical daily or weekly runs proceed seamlessly without requiring redefinition of station, network, or processing configurations.

### **4.3 PROPOSED METHODOLOGY**

The methodology described below comprises four main stages: Raw Data Compilation, OPUS-Projects Network Design & Processing, Automation of OPUS-Projects Steps, and Network Monitoring & Final Product Compilation. Each stage is essential for achieving a robust alignment of stations to the NSRS while enabling repeated execution with minimal oversight.

#### **4.3.1 RINEX Data Download and Processing**

This section describes the detailed procedures for acquiring and preparing raw RINEX observation data for subsequent OPUS processing. The process is divided into two main phases: (1) data download and (2) data processing.

The data download process is initiated using a structured input file that lists station identifiers, observation dates, and the designated data source for each station. This information is used to automatically construct the required URLs and retrieve the corresponding RINEX observation files from established sources, including the Oregon Department of Transportation (ODOT) FTP server, the GAGE archive (formerly the UNAVCO EarthScope archive), and the Geodesy/PANGA archive. The downloaded raw files are stored in an organized directory structure, categorized by year, day-of-year, and station identifier.

After downloading, the raw RINEX files are processed to meet OPUS requirements. Files compressed in gzip (.gz) and bzip2 (.bz2) formats are decompressed using Python's built-in gzip and bz2 libraries, while files in Unix compress format (.Z) are handled with the standard uncompress utility. Files provided in the Hatanaka compressed format (.crx) are converted to the standard RINEX (.rnx) format using the CRX2RNX.exe command-line utility.

Following decompression and conversion, the observation data are resampled to a uniform 30-second interval using the gfrnx.exe utility. This step also involves removing unused observables to ensure that the data conform to the required sampling criteria. The processed files are then stored in a separate directory structure that mirrors the organization of the original data.

Detailed logs are maintained throughout the download and processing phases. These logs record file retrieval status, decompression outcomes, conversion activities, and resampling adjustments, including timestamps and file sizes. Such comprehensive documentation ensures full traceability and facilitates prompt troubleshooting, thereby meeting the stringent requirements of the OPUS processing workflow.

### **4.3.2 Baseline Network Design and OPUS Parameter Configuration**

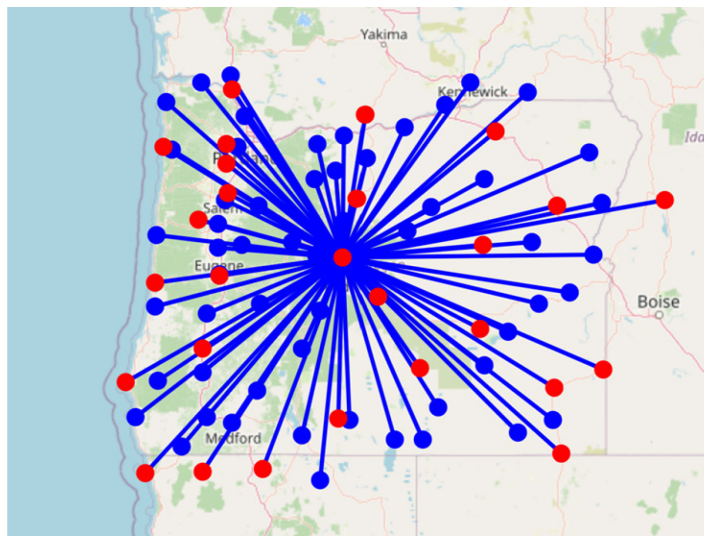
After the raw data is in place, the network design determines exactly which baselines should be processed during each OPUS session. This step is one of the distinctive features of the ORGN Align tool, as it spares the user from manually defining station connections within OPUS-Projects. Instead, the tool references a “baseline generator” module to produce an XML file listing the desired geometry. For instance, if the user wants every ORGN station to connect only to the nearest two NGS CORS, or if they wish to adopt a single-hub star network around a single “master” CORS, that logic is encoded in a template that can be easily updated.

The same XML also carries common OPUS parameters, such as the troposphere interval (e.g., 7,200 s for piecewise modeling), the minimum satellite elevation mask (often 10°), and any weighting constraints for existing published stations. By storing these parameters in a centralized configuration file, the software can pass them as a uniform “instruction set” to OPUS-Projects each time. If the user adjusts one parameter, for example to hold NGS CORS at a two centimeter horizontal constraint and a three centimeter vertical constraint, every subsequent daily or weekly run automatically applies that updated weighting.

Once the network geometry and parameters are ready, the tool proceeds to daily “session processing.” Internally, it divides the stations into a single session or multiple sessions per day, depending on the number of stations and the allocated OPUS-Projects capacity. Each session is automatically assigned the hub(s) selected by the baseline generator. The data are then uploaded to OPUS, triggering a standard set of baseline solutions. If any baselines exhibit high root-mean-square (RMS) values or poor ambiguity resolution, the software can remove them from the solution or retry with different session subdivisions. In short, these tasks replicate what a user would do in the OPUS-Projects interface, except they run programmatically, without the need for a separate user login or repeated manual interaction.

#### **4.3.2.1 *Single Hub Network:***

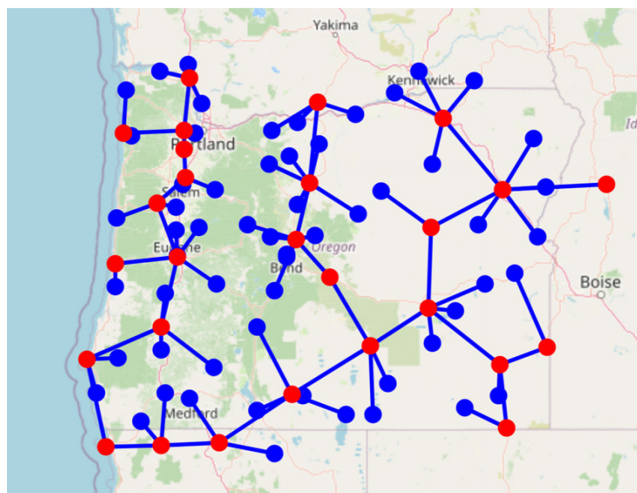
In the Single Hub Network strategy, one NGS CORS is selected as the central hub. All ORGN stations are connected directly to this hub, resulting in a star-shaped configuration that inherently satisfies the independent baseline requirement. As shown in Figure 4.1, this approach produces a straightforward and simple network design.



**Figure 4.1: Single Hub Design Example.** A star-shaped network configuration where one NGS CORS serves as the central hub, with all ORGN stations and other NGS CORS connected directly to it.

**All Hubs Network:**

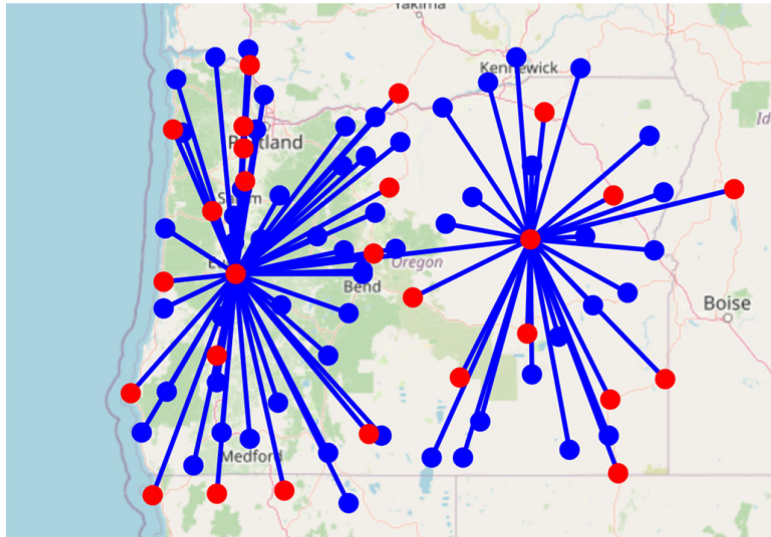
In the All Hubs Network strategy, all NGS CORS are treated as hubs. Each ORGN station is connected to its geographically nearest NGS CORS, and the NGS CORS are interconnected. This design maximizes network redundancy while ensuring that only the independent baselines necessary for network adjustment are employed. This configuration is illustrated in Figure 4.2.



**Figure 4.2: All Hubs Network Example.** A network configuration where each ORGN station is linked to its geographically closest NGS CORS, and the remaining NGS CORS are interconnected to form a fully redundant network.

#### 4.3.2.2 Custom Network Design:

In the Custom Network Design strategy, stations are grouped into clusters based on geographic proximity. For example, in a configuration with two clusters, one NGS CORS is chosen as the hub within each cluster, and all ORGN stations in that cluster are connected to the hub. The clusters are then interconnected to form a cohesive network that adheres to the independent baseline principle. Figure 4.3 presents an example of a two-cluster design with one hub per cluster.



**Figure 4.3: Custom Network Design Example (2 Clusters, 1 Hub Each).** A network configuration where stations are divided into two clusters, each managed by a designated NGS CORS hub, with inter-cluster connections ensuring full network integration.

#### 4.3.2.3 OPUS Projects processing parameters

In addition to defining the network geometry, OPUS processing parameters are configured. Parameters such as constraint weight, elevation cutoff, geoid model, reference frame, GNSS system, and troposphere interval are incorporated into the final configuration. This configuration is automatically exported as an XML file that contains both the network design and the processing parameters. The resulting XML file is then used for subsequent OPUS adjustment processing.

This integrated methodology ensures that the baseline network is robust and that only independent baselines are used for network adjustment. Such an approach enhances both the accuracy and efficiency of the adjustment process while aligning ORGN stations with the NSRS.

### 4.3.3 Automating OPUS-Projects

This section presents a high-level overview of the automated workflow for OPUS-Projects, which leverages the OPUS-Py Python package to interact programmatically with OPUS

functionalities. By automating tasks that traditionally require manual interaction through a web interface, the ORGN Align Tool ensures consistency and efficiency in aligning the ORGN to the NSRS while also enabling ongoing monitoring of this alignment.

#### **4.3.3.1 Leveraging OPUS-Py**

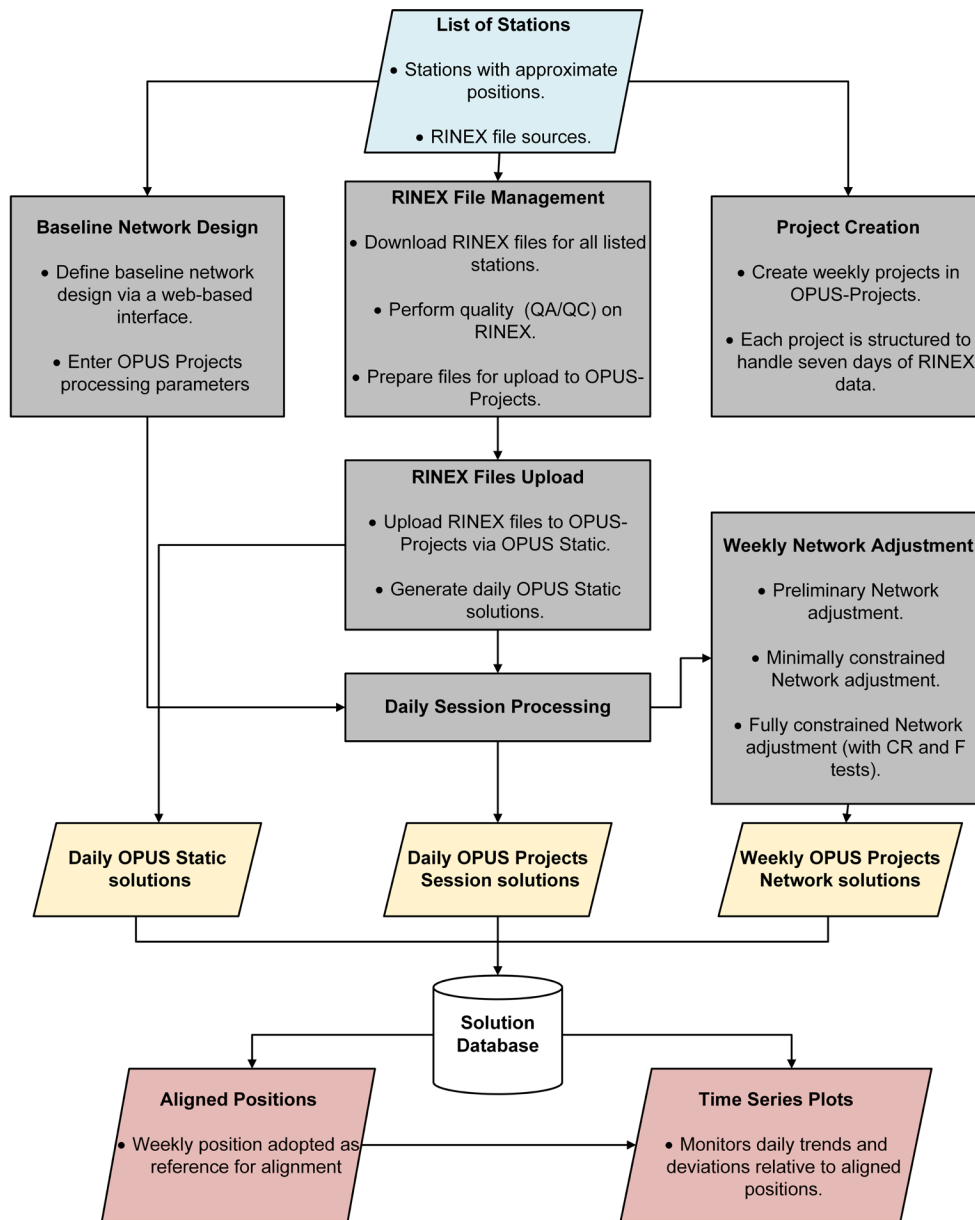
OPUS-Py is a Python package that provides direct, programmatic access to key OPUS-Static and OPUS-Projects functions. It enables authorized users to bypass the conventional web interface by constructing and sending HTTP POST requests directly to OPUS servers. Through its classes, OPUS-Py supports operations such as uploading RINEX files, creating projects, managing CORS, and processing both individual sessions and entire networks. Additionally, it facilitates access to project information by parsing the XML files produced by OPUS.

#### **4.3.3.2 High-Level Workflow**

1. **Creates or Reuses a Project:** If no existing OPUS-Projects environment matches the current dataset, the tool submits a “create new project” request via an OPUS-Projects API or script. For returning days, it simply logs into the same project ID and appends additional data.
2. **RINEX File Upload:** Each station’s processed RINEX file is pushed to OPUS, accompanied by essential metadata such as antenna type and height above the monument. This ensures each baseline solution is consistent with the known station geometry. During this upload, the tool also checks single OPUS-Static solutions to confirm that a station’s data is valid before proceeding to additional steps. If successful, the daily OPUS-S solutions are extracted and added to the database for time-series analysis (monitoring). This ensures that the project captures ongoing results while requiring complete coverage before final adjustments occur.
3. **CORS Management:** After confirming that all RINEX files have been successfully processed, the project’s NGS CORS configuration is updated to align with the baseline design outlined in Section 4.3.2 and the user’s defined preferences. The system examines which NGS CORS are currently included in the project and compares them to the stations specified in the user interface. Discrepancies are then resolved by adding or removing CORS so that the project remains consistent with the intended baseline network and user expectations.
4. **Session Processing:** For each session, the system constructs a data template using the baseline design and user-defined OPUS-Projects processing parameters. These templates are then submitted one at a time to OPUS-Projects via OPUS-Py, ensuring each session is processed under consistent settings. Once session solutions become available, they are parsed into the database for time-series analysis (monitoring).
5. **Preliminary Network Adjustment:** After session processing, the session solutions are combined for a preliminary network adjustment. A template containing OPUS-Projects parameters and session solution outputs is generated and submitted via a CGI request to OPUS.

6. **Minimally Constrained and Fully Constrained Adjustments:** The output from the preliminary adjustment is used for a minimally constrained adjustment to refine station coordinates, which then serves as input for a fully constrained adjustment. If the F-test fails, stations with constraint ratios above the threshold (greater than 3) are unconstrained and reprocessed until the test passes.

After these steps, the script retrieves the network solution summary from OPUS-Projects and stores it in the database for further analysis. Figure 4.4 provides a schematic of the back-end calls and data flows throughout this automated loop, beginning with raw data upload and ending with the final “Constrained Network” solution.



**Figure 4.4: Data flow of the semi-automated workflow being implemented within ORGN-Align.**

### 4.3.3.3 Database Structure

A key component of the automation framework is a centralized database designed to capture and manage all coordinates, session solutions, and station residuals over time. This database underpins ongoing alignment checks by allowing the tool to compare newly computed coordinates to previously published values and by facilitating time-series analyses. To implement this functionality, Django, a Python-based web framework with a powerful yet straightforward Object-Relational Mapping (ORM), was selected.

**Django and ORM Basics.** Django’s ORM allows developers to define “models” (i.e., Python classes) that map directly to database tables. Each model’s attributes correspond to table fields, so manipulations in Python, such as adding a new station solution or updating published coordinates, are transparently converted into SQL statements. By relying on Django, the alignment logic is seamlessly integrated with the code for storing and retrieving station data. This ensures that the entire pipeline, from raw RINEX ingestion to final coordinate publication, remains coherent and testable within a single Python ecosystem.

**Data Flow into the Database.** Once OPUS-Projects outputs a final constrained solution for each station, the tool automatically parses the summary files and writes the essential details into Django models. These models typically include:

1. **Published Coordinates:** Reference the official “current” position of each station.
2. **Daily or Session Solutions:** Derived from the day’s or week’s OPUS runs.
3. **Network Solutions:** Represent the fully constrained coordinates for each station over a particular time window.

By consolidating these solution types, the system can:

1. **Track Residuals:** Compute and store the difference between a station’s new solution and its published coordinate. If it exceeds a threshold (e.g.,  $\pm 2$  cm horizontally,  $\pm 4$  cm vertically), the station is flagged for review.
2. **Build Time Series:** Chronologically order records so that daily or weekly station positions can be plotted, allowing users to diagnose sudden shifts or gradual drifts (see Section 6.0 for real-world examples).

Chapter 5 contains detailed table-by-table descriptions, but it is useful here to note that the database centers on a Stations table (or model) keyed by a unique station code. Each station is linked to multiple Solutions entries (daily or session-based). The solutions are further classified into subtypes for OPUS-Static runs, session-level solutions, and network-level adjustments. Lastly, a Residuals concept is stored either as a field on each solution or as a separate table, depending on the design choice for referencing station offsets.

In practice, storing station solutions in this way ensures that no data from an OPUS run is lost or overwritten. Older solutions remain in the database, providing a historical record that the tool consults whenever it needs to confirm alignment or detect outliers. This architecture also ensures that all relevant alignment data can be accessed through a single interface, greatly simplifying tasks such as generating time-series charts, implementing quality-control queries, or republishing updated station coordinates for the entire network.

### **4.3.4 Network Monitoring and Final Product Compilation**

The final stage of the automated workflow focuses on network monitoring and the production of deliverables for users who rely on up-to-date station coordinates. At this stage, OPUS-Projects has generated a fully constrained solution for all stations, and the ORGN Align tool determines how best to store and interpret these data. In addition to maintaining ongoing awareness of each station's alignment with the NSRS, the tool can automatically compile final station tables or other deliverables for publication.

#### ***4.3.4.1 Local Ingestion of Final Solutions***

After OPUS-Projects completes its constrained adjustment, the ORGN Align application retrieves each station's final coordinates, along with relevant uncertainties, RMS statistics, and flags indicating any large residuals. These outputs are parsed and stored in the Django database described in Section 4.3.3.3. Each station's solution is linked to the corresponding day-of-year (DOY) or GPS week, ensuring chronological organization and maintaining a clear historical record.

This design allows users to review previous solutions to track how a station's position has evolved. For example, one might compare a station's coordinates from the prior month with the newly published solution to investigate suspected antenna changes or local ground motion. Because the ingestion process is fully integrated into the workflow, users do not need to manually download files or copy and paste coordinates; the entire pipeline handles the final data insertion automatically.

#### ***4.3.4.2 Residual Threshold Checks***

Once the new solutions are written to the database, the system computes residuals between each station's updated coordinates and its official "published" coordinates. Typically, this involves comparing the station's latitude, longitude, and ellipsoid height to the older baseline values. If the absolute difference in horizontal position remains within a tolerance (commonly  $\pm 2$  cm) and the vertical difference is under  $\pm 4$  cm, the station is flagged as stable.

In contrast, large discrepancies trigger an alert, allowing operators to investigate potential causes such as hardware malfunctions, soil settlement, or regional seismic activity. The entire process is automated through a Python script or scheduled job that reviews residuals at fixed intervals, either daily or weekly, without manual intervention. In practice, station outliers are sometimes temporary, resulting from a day of poor satellite

geometry or short data gaps; repeated anomalies, however, may indicate genuine station movement.

This threshold-based approach provides near-real-time network monitoring: station shifts are identified as soon as the final constrained solution is posted, enabling immediate user response if the alignment of multiple stations is affected by a regional event.

#### **4.3.4.3 Re-Publication and Deliverables**

When a single station's data consistently deviates from its expected coordinates, an operator might choose to remove that station from the next alignment run or conduct a site visit for further diagnosis. However, if multiple stations display a systematic bias, particularly following a recognized geophysical event, re-publishing the entire network is warranted. This process updates each station's "published" coordinates to match the latest OPUS-Projects solution, effectively resetting the reference baseline for future threshold checks. These newly published values should also be exported and imported into the RTN management software, and notifications sent to users if needed.

Sometimes, station anomalies can be attributed to hardware malfunctions or localized ground instability, but a large number of stations deviating typically signifies that the ORGN as a whole is no longer aligned with the NSRS. In such cases, the operator should evaluate the motion trends of the stations and consider adopting the most recent weekly fully constrained solution from OPUS-Projects as the new published coordinate set for all stations. This ensures the network reestablishes its alignment with the NSRS, rather than allowing residuals to grow unchecked over time. The following steps outline this update process in more detail:

- 1) *Identifying Potential Misalignment:*
  - a) Examine time-series plots to distinguish a single-station anomaly from a network-wide pattern of threshold exceedances.
  - b) Confirm whether enough stations surpass the defined residual limits to suggest full-network misalignment.
- 2) *Adopting the Latest Fully Constrained Solution*
  - a) Once a network misalignment is confirmed, designate the most recent weekly Network Solution as the new published set.
  - b) This action replaces outdated coordinates and restores the network's alignment with the NSRS.
- 3) *Handling Major Geophysical Events*
  - a) Earthquakes or other large disturbances often cause simultaneous shifts at many stations.
  - b) The system allows for a timely re-publication using the most recent fully constrained solution not impacted by the event, keeping daily OPUS solutions relevant despite ongoing ground motion.

- c) This approach ensures that the network remains aligned with the NSRS, while daily OPUS solutions continue to provide current positional data.

By following these steps, the network maintains accurate alignment with the NSRS. The ability to update published coordinates on a weekly basis provides a rapid and effective

After re-publication, the Django database can be used to produce deliverables required by RTN managers and stakeholders. These may include updated station coordinate lists, CSV files tracking each station's new published values, and time-series plots of station residuals. Because the ORGN Align tool orchestrates the entire pipeline, from alignment checks to final data exports, these products are generated with minimal manual intervention, while remaining easily accessible to operators responsible for maintaining network performance and transparency.

## 4.4 QUALITY CONTROL OF GNSS DATA

Quality control (QC) software was developed in MATLAB to monitor and visualize key performance indicators of dual-frequency, multi-GNSS observation data. The QC processing uses only RINEX files as input and does not require any external data (e.g., satellite orbits) to operate. The QC approach relies on linear combinations formed from code and carrier phase measurements observed at two separate frequencies, along with the time variability of these combinations, to output information related to: (1) carrier phase cycle slip detection and repair, (2) the number of satellites available at each epoch, and (3) modeled measurement uncertainties.

This section first provides input and configuration guidance for the QC software, followed by a description of cycle slip parameters and the stochastic modeling approach. Finally, evaluations of the software outputs are presented, with discussions on the interpretation of results for an IGS station located in Ethiopia observed on May 9, 2024. It is important to note that this QC software is not built into the ORGN Align tool; rather, it is a separate application that can be run to evaluate the quality of the raw GNSS files used in the ORGN Align tool.

### 4.4.1 Input Data and Configurations

The QC software is designed to run from the main.m script in MATLAB (or main.py in Python, which is in progress). Configurations for QC processing are set to default values in the options.txt file, while custom settings can be configured within the control.txt file. After the workspace is prepared and the configuration files are read, the software imports RINEX Version 3 files from a directory specified by the homeFolder variable and writes QC results to a folder specified by the outputFolder variable. The measurement rate of the input data is set to 30 seconds by default, as configured by the samplingRate variable. Although any sampling rate can be used by modifying the default in options.txt or specifying a new value in control.txt, the software is most stable when using the default setting.

RINEX files typically contain measurements from multiple GNSS constellations, with several frequencies within each constellation, where measurements are given for individual signals within each frequency band. For QC processing and outputs, the following characters represent individual GNSS constellations: G – GPS (USA), R – GLONASS (Russia), E – Galileo (Europe), and C – BeiDou (China). Among the many available signals, the QC software

prioritizes measurements observed from the following: GPS L1/L2, GLONASS R1/R2, Galileo E1/E5a, and BeiDou B1/B3. In all cases, the first signals (i.e., L1, R1, etc.) are required, while the second signals for Galileo and BeiDou systems are set dynamically when E5a or B3 are missing, depending on which frequencies are available in the RINEX data. Similarly, the RINEX import method uses the following receiver tracking channel priority list to align with International GNSS Service (IGS) priority signals: P, W, C, S, L, X, Y, M, N, D.

#### 4.4.2 Cycle Slip Parameters

Evaluation of carrier phase cycle slips in the QC software uses the TurboEdit approach (Blewitt, 1990) with time-differencing of slip-sensitive parameters (Liu, 2011) to remove short-term trends. The technique employs the Melbourne–Wübbena Wide-Lane (MWWL) combination (Melbourne, 1985; Wübbena and Hannover, 1985) and the geometry-free, or ionosphere (IONO), linear combinations of dual-frequency GNSS code and carrier phase data to detect and repair phase discontinuities. Note that the original RINEX file is not modified; instead, output figures are generated to display the status of any detected cycle slips, providing a visual tool to monitor cycle slip conditions.

The difference of respective code ( $P$ ) and carrier phase ( $L$ ) measurements for a single satellite observed on frequencies  $A$  and  $B$  produces a geometry-free and ionosphere-sensitive combined observable that can be written for carrier phase measurements as:

$$L_{IONO} = L_A - L_B \quad 4-1$$

where  $L_{IONO}$  represents the slant ionospheric delay. Note that  $L_{IONO}$  contains receiver and satellite hardware bias effects and ambiguity parameters for each frequency. In addition, an ionospheric residual term remains within  $L_{IONO}$  making it an indicator of enhanced ionospheric activity.

The Wide-Lane (WL) observable ( $L_{WL}$ ) for carrier-phase measurements  $L_A$  and  $L_B$  (in units of meters), observed on frequencies  $f_A$  and  $f_B$ , can be expressed as:

$$L_{WL} = \frac{L_A \cdot f_A - L_B \cdot f_B}{f_A - f_B} \quad 4-2$$

where  $A$  and  $B$  represent, for example, respective GPS L1 and L2 signal measurements used in the combination. The combined  $L_{WL}$  wavelength in Figure 4-2 is approximately 86.2 cm for GPS L1 and L2 signals. This increased wavelength relative to either of the original measurements gives the Equation 4-2 combination its WL designation and is useful for cycle slip detection when slips of different magnitudes occur on either frequency.

The Narrow-Lane (NL) observable ( $P_{NL}$ ) for code measurements  $P_A$  and  $P_B$  (in units of meters), observed on frequencies  $f_A$  and  $f_B$ , can be expressed as:

$$P_{NL} = \frac{P_A \cdot f_A + P_B \cdot f_B}{f_A + f_B} \quad 4-3$$

where subscripts use the Equation 4-2 definitions.

The MWWL combination is defined by:

$$MWWL = L_{WL} - P_{NL} \quad 4-4$$

which is the difference between the carrier phase wide-lane and code narrow-lane. The resulting MWWL observable becomes ionosphere-free and geometry-free and only retains ambiguity and bias terms from the original GNSS observations.

### 4.4.3 Stochastic Modeling Approach

If the noise properties for measurements of the same type are assumed to be identical, i.e.,  $\sigma_A^2 = \sigma_B^2$ , then error propagation law can be used to find the WL variance ( $\sigma_{WL}^2$ ) expressed as:

$$\sigma_{WL}^2 = \sigma_L^2 \cdot \frac{f_A^2 + f_B^2}{(f_A - f_B)^2} \quad 4-5$$

where  $\sigma_L^2$  represents the carrier phase measurement variance. Therefore, the noise amplification of the combined WL observable in Equation 4-3 is amplified by a factor equal to 5.74 times the original measurement noise when GPS L1 and L2 frequencies are used in Equation 4-5.

Similarly, if identical noise properties are assumed for the code measurements, then error propagation law can be used to find the NL variance ( $\sigma_{NL}^2$ ) expressed as:

$$\sigma_{NL}^2 = \sigma_P^2 \cdot \frac{f_A^2 + f_B^2}{(f_A + f_B)^2} \quad 4-6$$

where  $\sigma_P^2$  represents the code measurement variance. Therefore, the noise of the combined NL observable in Equation 4-4 is reduced by a factor equal to 0.71 times the original measurement noise when GPS L1 and L2 frequencies are used in Equation 4-6.

Error propagation of the respective WL and NL components of the MWWL observable in Equation 4-4 can be used to find the MWWL variance ( $\sigma_{MWWL}^2$ ) expressed as:

$$\sigma_{MWWL}^2 = \sigma_L^2 \cdot \frac{f_A^2 + f_B^2}{(f_A - f_B)^2} + \sigma_P^2 \cdot \frac{f_A^2 + f_B^2}{(f_A + f_B)^2} \quad 4-7$$

Where  $\sigma_{MWWL}^2$  is comprised of noise contributions from both code and carrier phase measurements, multiplied by their respective frequency-dependent scale factors. Although the carrier phase scale factor in Equation 4-7 is much larger than the code factor, the relatively low precision of the code measurements is assumed to govern the noise properties of the combined MWWL observable.

Between-epoch time-difference operations are assumed to eliminate biases and short-term trends in the cycle slip parameter quantities, as remaining hardware delays are relatively stable over short time intervals. In addition, ambiguity parameters are removed by time-differencing due to their time-constant nature, which is retained after successful cycle slip detection and repair. Therefore, the remaining variability in the cycle slip parameters is assumed to consist solely of propagated measurement noise.

A generalized form for  $n$ -order time-differencing can be expressed as:

$$\Delta^n Y_t = Y_{t-n+1} - Y_{t-n} \quad 4-8$$

where  $\Delta$  is the time-difference operation,  $Y$  represents cycle slip parameter data, and  $t$  is the evaluated epoch. Thus,  $\Delta^1 L_{IONO,t}$  is the time-difference between two epochs,  $Y_t - Y_{t-1}$ , using the Equation 4-1 precise carrier phase slant ionospheric parameter, while  $\Delta^2 L_{IONO,t}$  is the time-difference of two first-order differences.

Although the Equation 4-8 expression is useful for cycle slip detection and repair, it amplifies the variance of the original data used in the time-differencing operation by:

$$\sigma_{\Delta^n Y}^2 = 2^n \sigma_Y^2 \quad 4-9$$

where  $\sigma_Y^2$  represents the variance of the cycle slip parameter  $Y$ , and  $\sigma_{\Delta^n Y}^2$  is the variance propagation through an  $n$ -order time-differencing operation. In Equation **Error! Reference source not found.**, it is assumed that  $\sigma_Y^2$  changes slowly for the epochs evaluated in the time-difference, i.e.,  $\sigma_{Y,t}^2 \approx \sigma_{Y,t-1}^2$  for a first-order difference. According to Equation 4-9, the original cycle slip parameter variance is doubled for each order used in the time-difference operation.

According to Equation 4-7, if the MWWL parameter variance is given, then the corresponding code measurement variance can be estimated. Therefore, a moving median absolute deviation (MMAD) filter was selected to compute the  $\Delta^2 \sigma_{IONO}^2$  and  $\Delta^1 \sigma_{MWWL}^2$  parameter variances using the corresponding cycle slip parameter time-series data with a window size equal to 120 epochs, i.e., 1-hour for 30-second measurement rate data. The resulting MMAD values were then scaled using reference noise values, equal to 60-cm and 2-mm for respective code and carrier phase measurements. Carrier phase noise values were computed by scaling the code noise values using a fixed ratio between the code and phase reference noise values (i.e., 600-mm/2-mm = 300).

#### 4.4.4 Observation Availability

The Figure 4.5 time-series of visible satellites represents the default processing configuration output when a RINEX file containing GPS, GLONASS, Galileo, and BeiDou measurements is input to the QC software. This is intended to give an overview of the data contained within a RINEX file by showing the number of satellites available from each system at each epoch, including the total number of satellites. Figure 4.5 also shows data gaps, when detected, as empty space along each time-series, which highlights data outages.

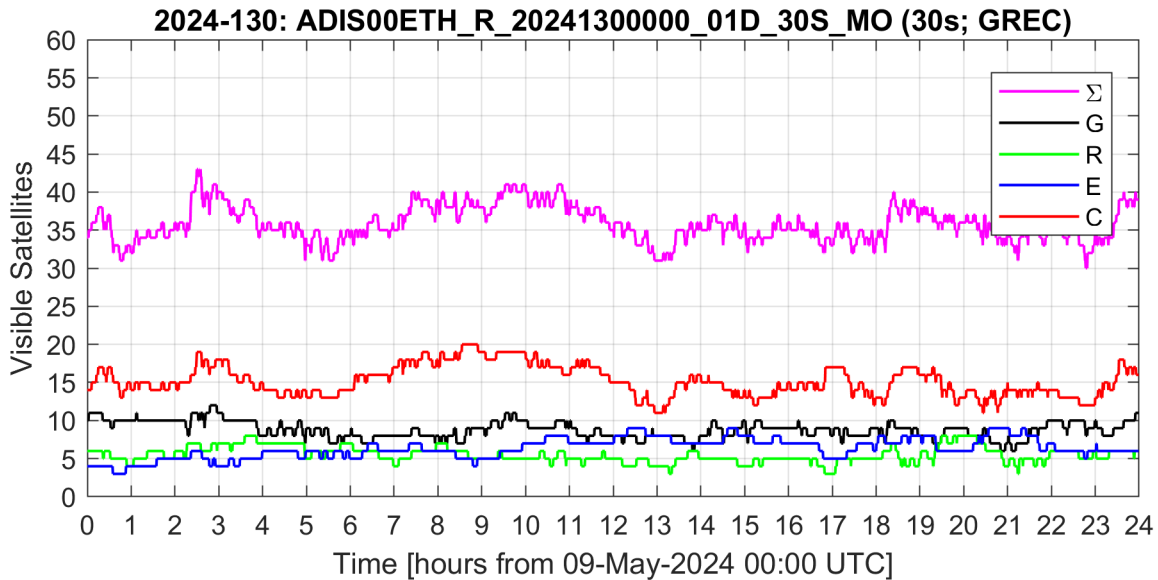
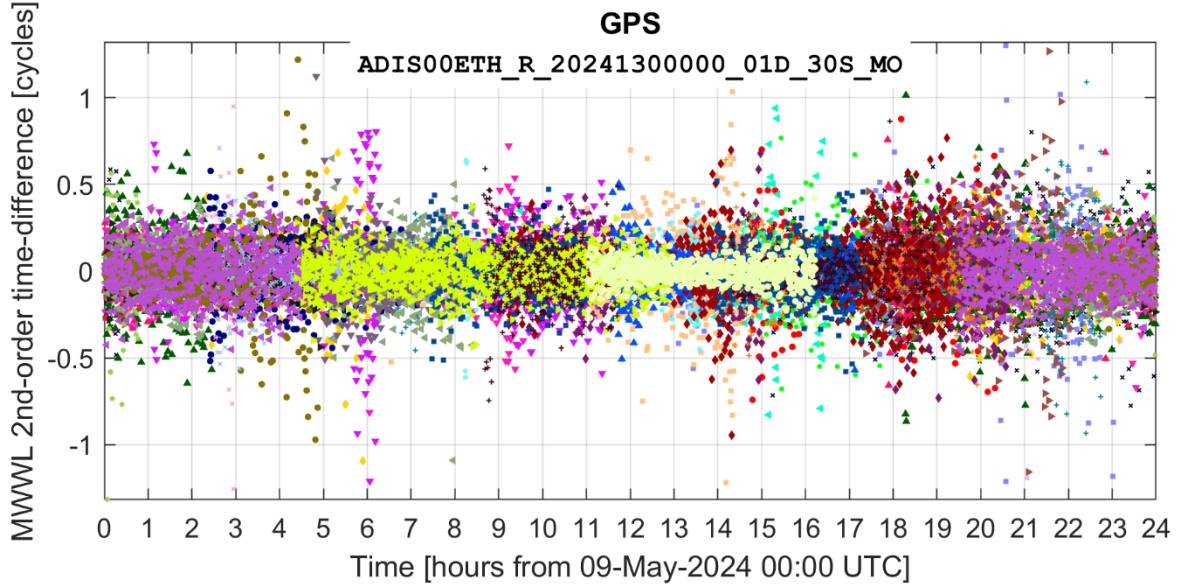


Figure 4.5: Satellite visibility time-series for IGS station ADIS on May 9<sup>th</sup>, 2024.

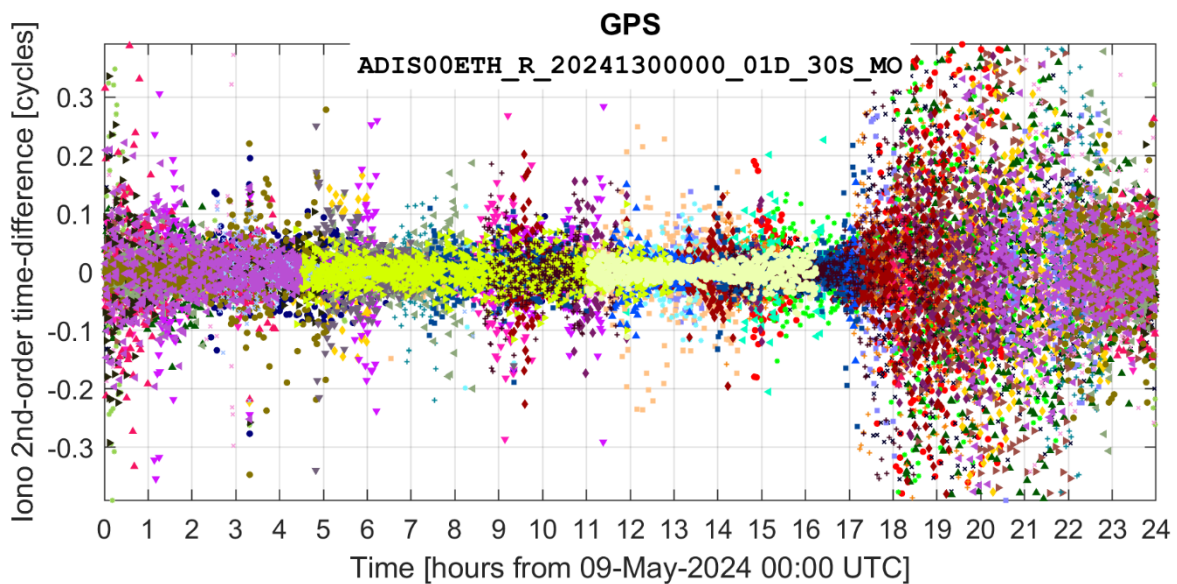
#### 4.4.5 Cycle Slip Evaluation

The scattered MWWL and IONO time-series data in Figure 4.6 and Figure 4.7, respectively, are an example of Equations 4-1 and 4-4. In Figure 4.6, the MWWL data are colored according to each observed GPS satellite and represent the input data used for cycle slip detection and repair. In addition, Figure 4.6 shows the data used for subsequent stochastic modeling. The typical behavior of MWWL in Figure 4.6 across multiple days is typically quite stable.

The IONO time-series data in Figure 4.7 highlights the connection between the cycle slip parameter in Equation 4-1 and the ionosphere, due to the ionospheric residual term that remains in the combination. For example, beginning at approximately 17:00 UTC, the previously stable IONO parameter increases for nearly all observed GPS satellites, while the corresponding MWWL parameter remains stable. At this low-latitude (equatorial) location in May 2024, local sunset occurs around 17:00 UTC, which aligns with the post-sunset amplification of ionospheric activity. Although the same phenomenon is not common in Oregon at mid-latitude, geomagnetic storm events may trigger similar ionospheric activity amplification, resulting in degraded GNSS-based positioning performance. Therefore, it is recommended that the outputs in Figure 4.7 be used as a monitoring tool and compared to known calm conditions to investigate anomalies when needed.



**Figure 4.6: MWWL time-series data for IGS station ADIS on May 9<sup>th</sup>, 2024.**

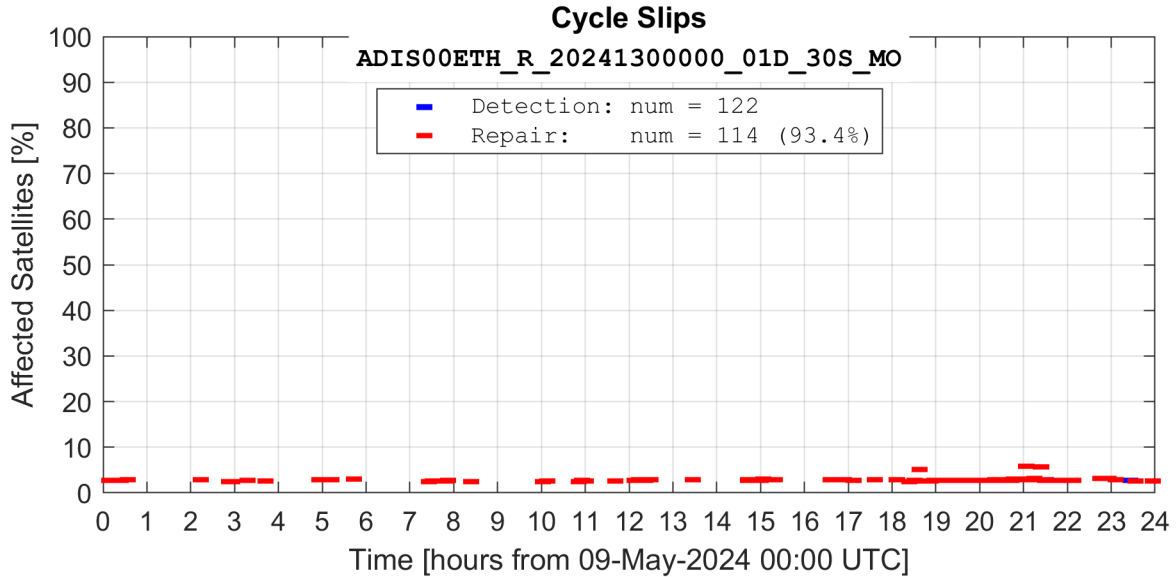


**Figure 4.7: IONO time-series data for IGS station ADIS on May 9<sup>th</sup>, 2024.**

Detected and repaired cycle slips in Figure 4.8 demonstrate the stability of the carrier phase data across the processing interval. In extreme cases, more than 25 percent of the evaluated carrier phase data may be flagged for detected cycle slips, indicating unstable phase data and likely reduced integer ambiguity resolution success. The cycle slip record in Figure 4.8 varies between stations due to differences in receiver hardware. Therefore, it is recommended to compare the results for each station separately to investigate anomalies.

In addition, cycle slips are expected to be non-zero, as no elevation mask is applied in the QC software to exclude noisy low-elevation satellites. Further investigation is warranted if the repair

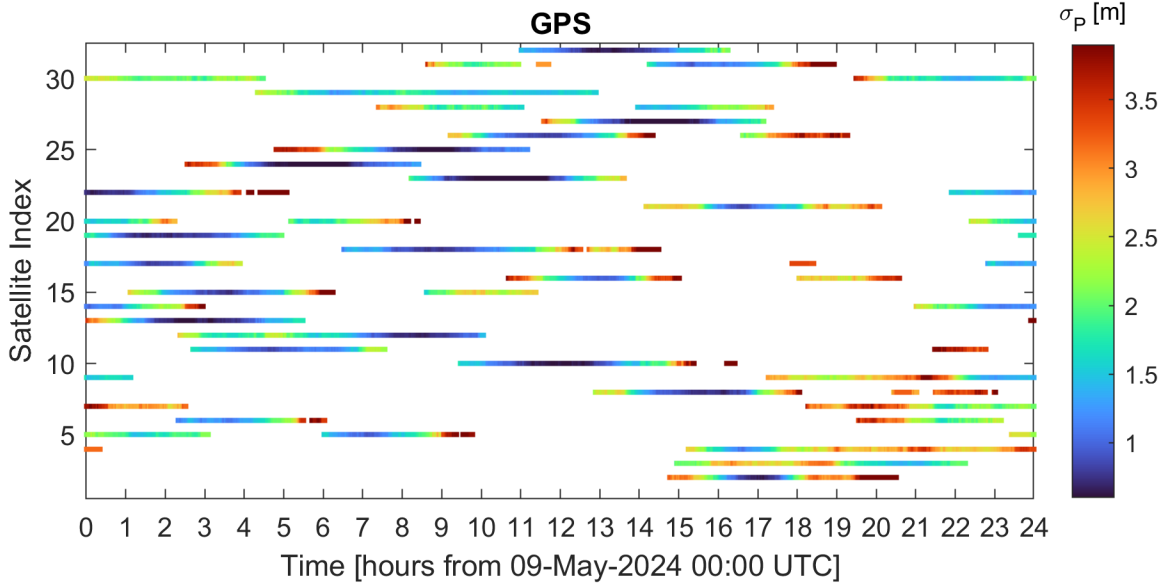
rate in the typical Figure 4.8 output drops below 90%, unless this is a common occurrence for a particular station. In general, correlations between figures can help explain observed conditions. For example, increased ionospheric activity in Figure 4.8, together with more frequent cycle slips during the same amplified interval, may indicate degraded positioning performance.



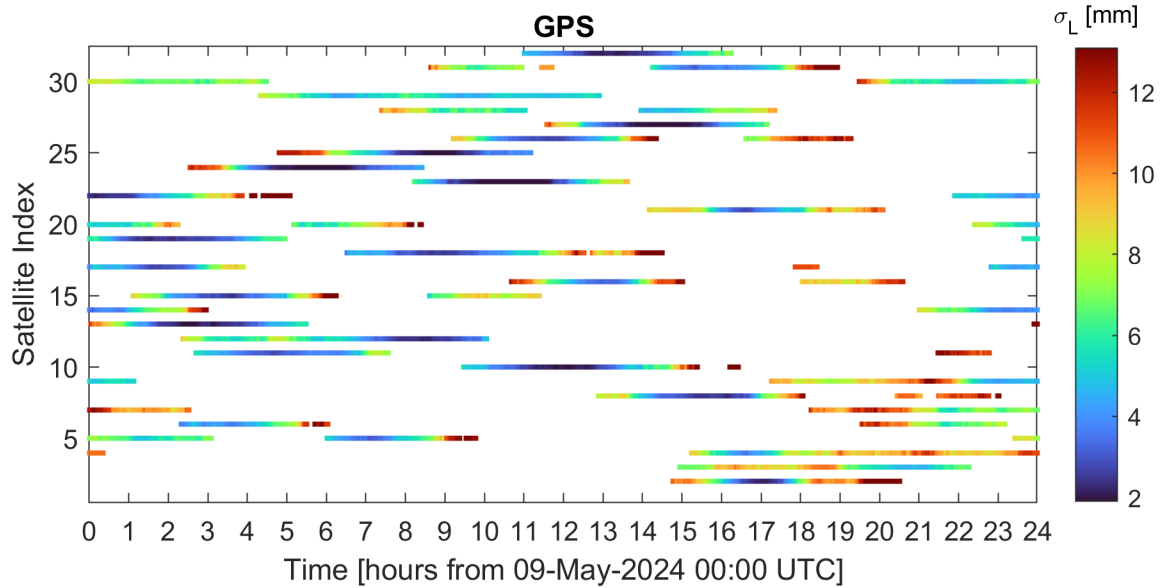
**Figure 4.8: Cycle slip detection and repair, expressed as percentage of the total number of visible satellites for IGS station ADIS on May 9<sup>th</sup>, 2024.**

#### 4.4.6 Stochastic Model Evaluation

Modeled GPS measurement uncertainties in Figure 4.9 and Figure 4.10, for respective code and carrier phase data, represent the noise (1-sigma) for each observation type across the observation interval. Note that Figure 4.10 is a scaled version of Figure 4.9 using the reference noise ratio. Each horizontal line in Figure 4.9 and Figure 4.10 are observation arcs for each observed satellite, where arcs typically begin and end with higher noise (red/orange) with lower noise (blue/green) toward the middle. This is due to satellites reaching their highest elevation, corresponding to the lowest noise, at the mid-point of their arc. Some of the short data gaps are due to missing RINEX data, while others are caused by the cycle slip processing flagging cycle slips. According to Figure 4.9 and Figure 4.10, at approximately 17h UTC, the modeled measurement noise becomes amplified relative to earlier in the day as indicated by the lack of blue markers near the mid-arc regions. This interval corresponds to disturbed ionospheric conditions (Figure 4.7), which may reduce the user’s achievable position accuracy.



**Figure 4.9: Modeled code measurement noise for GPS satellites for IGS station ADIS on May 9<sup>th</sup>, 2024.**



**Figure 4.10: Modeled carrier phase measurement noise for GPS satellites for IGS station ADIS on May 9<sup>th</sup>, 2024.**

## 5.0 ORGN ALIGN TOOL

### 5.1 OVERVIEW OF THE GUI

The Real-Time Network (RTN) Alignment Service Graphical User Interface (GUI), referred to here as ORGN Align, provides a centralized platform for managing daily station data, generating baseline configurations, and producing final GNSS solutions aligned with the National Spatial Reference System (NSRS). By consolidating tasks historically performed through separate manual tools, ORGN Align allows users to organize station coordinates, generate RINEX files, and run OPUS-based adjustments within a single, streamlined application.

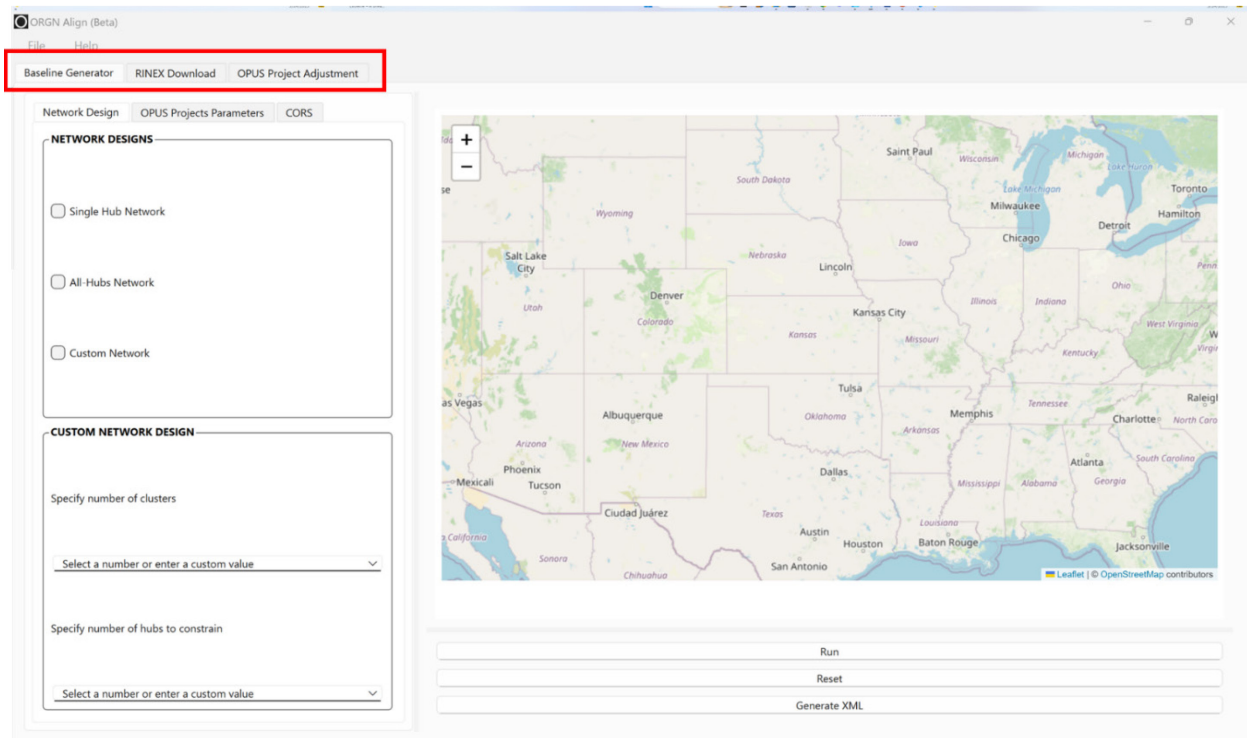
Figure 5.1 presents an overview of the ORGN Align home screen, highlighting the top navigation menu and three main tabs: Baseline Generator, RINEX Download, and OPUS Project Adjustment. Each tab represents a critical stage in the alignment process, guiding the user step by step, from baseline design to final adjustment processing. The application's modular structure ensures that newly acquired GNSS data remain continuously synchronized with the NSRS. Table 5.1 offers a high-level summary of each tab's role within this workflow.

ORGN Align is specifically tailored to the needs of GNSS network managers, with an emphasis on reliability, clarity, and operational efficiency. By replacing multiple manual steps, the software helps maintain consistent settings across daily station operations. For example, the Baseline Generator module automates network geometry creation, the RINEX Download module acquires and organizes observation files, and the OPUS Project Adjustment module streamlines the submission of processed data for final GNSS solutions. Each module is accessed through its respective tab in the GUI, and all modules share a common database to preserve station metadata, daily solutions, and historical adjustments.

While details on each module appear in subsequent sections of this chapter, the overarching goal of ORGN Align remains consistent across all parts of the interface: to provide a structured, semi-automated workflow that minimizes user error and expedites the alignment process. By logging key interactions, applying standard naming conventions, and maintaining threshold-based checks on coordinate solutions, the software consistently delivers robust results. The remainder of this chapter provides in-depth guidance on each of these three modules, illustrating how they function cohesively to maintain accurate, up-to-date coordinates for Oregon's RTN.

**Table 5.1: Description of the features in the main GUI shown in Figure 5.1.**

Tab	Description
Baseline Generator	Design, visualize, and modify GNSS baseline configurations prior to adjustment.
RINEX Download	Acquire RINEX observation files for specified stations and date ranges.
OPUS Project Adjustment	Automate project creation and GNSS data processing using OPUS Projects.



**Figure 5.1: ORGN Align GUI showing the three main functional tabs**

### 5.1.1 Baseline Generator

The first tab, Baseline Generator, focuses on designing and reviewing a baseline network for subsequent processing through OPUS-Projects. As illustrated in Figure 5.2, the interface supports multiple baseline design strategies, such as single hub, custom hubs, and all hubs, and enables users to visualize, refine, and finalize the network layout before running an adjustment. The selected configuration remains active for the entire session and is ultimately applied during network processing.

When creating a baseline design, operators must first load a CSV file containing approximate station positions for both ORGN stations and any relevant NGS CORS stations. This file must include the columns shown in Table 5.2., with clear headers indicating data fields (e.g., site code, latitude, longitude, ellipsoid height, and Boolean flags for NGS CORS). Once loaded, the

Baseline Generator automatically parses the information and integrates it into the network design. To load the file:

- Click **File** in the top menu bar.
- Select **Open**.
- Navigate to and select the input file in the required format.

This import step ensures that the Baseline Generator recognizes each station’s position and identifies which stations are flagged as NGS CORS. An example of the required CSV structure is shown in Table 5.2, where each row corresponds to an individual station.

**Table 5.2: Required Input File Sample for Baseline Design**

Site Code	Lat dec	Long dec	Elip height	NGS CORS
ADEL	42.17650546	-119.8958509	1386.097	FALSE
CABL	42.83609529	-124.5633295	38.207	TRUE

After importing station data, the Baseline Generator displays three main configuration panels that guide you through GNSS network setup. The first panel addresses overall network design, where you choose a hub strategy (e.g., single or multiple) and specify how each station is linked. The second panel allows you to configure OPUS Project parameters, such as constraints on known reference stations or data processing tolerances. The final panel focuses on selecting or excluding particular NGS CORS stations for use in the baseline design, enabling you to refine which references are prioritized in the final solution.

Because these three panels follow a logical progression, operators move systematically from defining station connections to specifying OPUS Project constraints. This eliminates the need for direct manipulation within the OPUS Projects web interface. By consolidating these tasks into a single workflow, the Baseline Generator module ensures consistent, repeatable network designs that minimize the risk of user error. Upon completing the network configuration, all relevant information is saved and ready to be utilized by the RINEX Download and OPUS Project Adjustment tabs for the remainder of the GNSS alignment process.

#### **5.1.1.1 Network Design Panel**

The Network Design Panel is the first step in building a GNSS baseline network within the Baseline Generator tab. This panel allows users to choose from a range of predefined network configurations or to create a custom layout suited to the spatial distribution and operational needs of the ORGN. As shown in Figure 5.2, the interface provides a graphical environment for users to define the structure of their baseline network and visualize station connectivity.

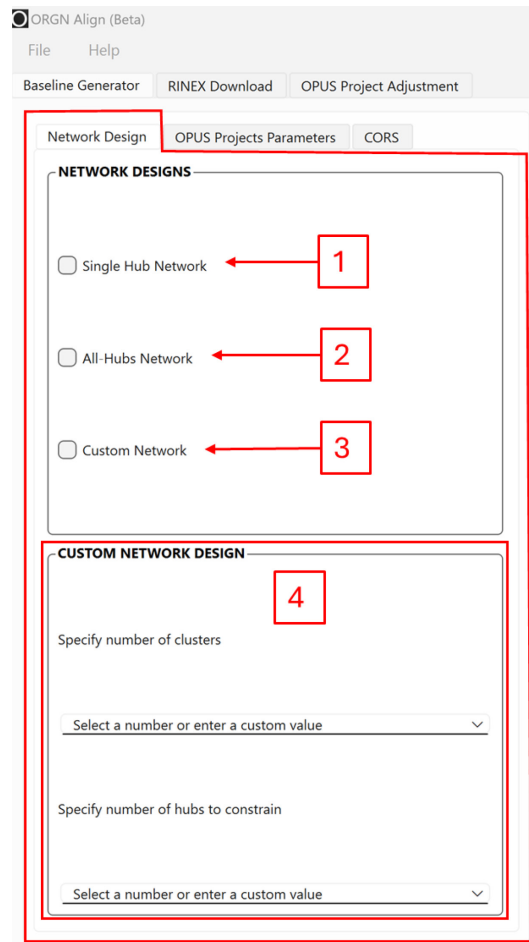
Four primary baseline strategies are currently supported: (1) Single Hub Network, (2) All Hubs Network, (3) Custom Network, and (4) Custom Network Design. These strategies are briefly described in Table 5.3 and fully detailed in Section 4.3.2 of this report. This

modular structure enables network managers to tailor the network design to regional needs while adhering to the independent baseline principle.

**Table 5.3: Network Design Options**

No.	Baseline Design	Description
1	<b>Single Hub Network</b>	All baselines are connected to a single, centrally located NGS CORS hub.
2	<b>All Hubs Network</b>	Baselines are created to every NGS CORS in the input.
3	<b>Custom Network</b>	Users manually define which baselines to create.
4	<b>Custom Network Design</b>	Allows the user to define the number of station clusters and number of CORS stations to constrain for the customized design.

Once a design is selected, it is rendered in the map view and saved as part of the project configuration. This logical foundation supports the processing of all baseline solutions and guides the downstream alignment steps conducted in OPUS-Projects.



**Figure 5.2: Interface view of the Network Design configuration panel.**

### 5.1.1.2 OPUS Project Parameters Panel

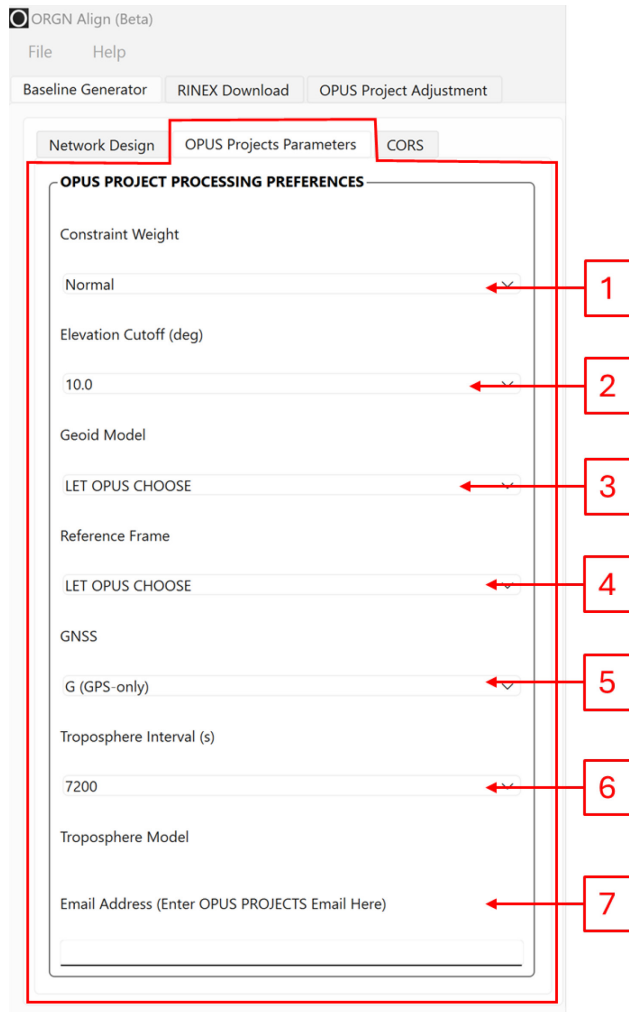
The second panel, OPUS Project Parameters, allows users to define the GNSS processing parameters that are normally configured manually in the OPUS-Projects web interface. By embedding these parameters directly into the output XML configuration file, the ORGN Align tool ensures consistency and reduces the need for repetitive manual entries. The layout of this panel is illustrated in Figure 5.3, with parameter definitions summarized in Table 5.4.

Default values are preloaded for each field, including constraint weights, satellite elevation cutoffs, GNSS system selection, and tropospheric modeling intervals. These defaults can be overridden to meet project-specific requirements. For example, users may choose to tighten or loosen constraint weights on NGS CORS or select a different geoid model when working in coastal regions. Each field is clearly labeled to minimize user error and support transparency in the adjustment process. Users should reference the OPUS-Projects User Manual for additional information on these parameters.

**Table 5.4: OPUS Project Parameters**

No.	Parameter	Description
1	<b>Constraint Weight</b>	Controls how tightly stations are constrained. Default: Normal.
2	<b>Elevation Cutoff (deg)</b>	Minimum satellite elevation for inclusion. Default: 10°.
3	<b>Geoid Model</b>	Specifies the vertical reference model. Default: Let OPUS choose.
4	<b>Reference Frame</b>	Sets the horizontal datum (e.g., NAD83). Default: Let OPUS choose.
5	<b>GNSS</b>	System used in processing. Default: GPS.
6	<b>Troposphere Interval</b>	Interval for estimating atmospheric delay. Default: 7200s.
7	<b>Email Address</b>	Required email address for OPUS Project submissions.

Upon completion, these parameters are merged with the baseline design into a unified XML file. This file is submitted via OPUS-Py and serves as the reference for session and network adjustments during each OPUS run.



**Figure 5.3: Interface view of the OPUS Project Parameters configuration panel.**

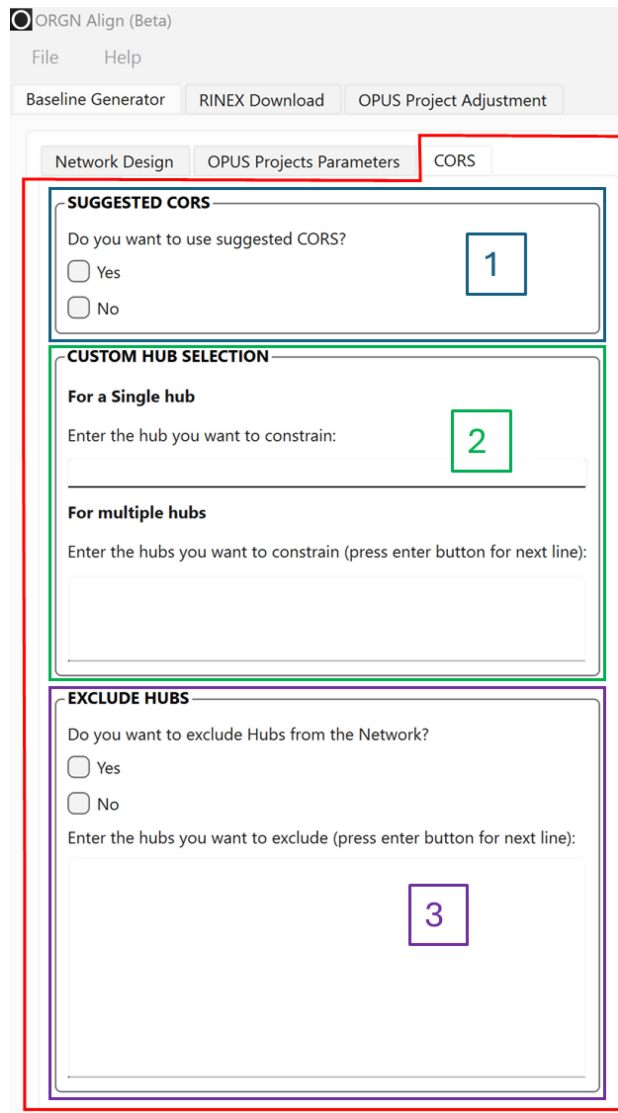
### 5.1.1.3 *CORS Selection Panel*

The final configuration panel in the Baseline Generator tab is the CORS Selection Panel, which provides tools for selecting and managing the NGS CORS stations that will serve as hubs or reference stations in the baseline network. The interface, shown in Figure 5.4, offers a combination of automated and manual options for managing these critical stations. The functionality of each option is summarized in Table 5.5.

Users may allow the software to suggest CORS stations based on station health and spatial distribution, or they may manually designate specific CORS to function as network hubs. Additionally, stations can be explicitly excluded from the design to avoid incorporating poorly performing CORS into the network solution. This level of control enables users to align the configuration with real-world operational and geodetic constraints.

**Table 5.5: CORS Selection Options**

No.	Option	Description
1	<b>Suggested CORS</b>	Toggle to allow automated selection of CORS stations.
2	<b>Custom Hubs Selection</b>	Manually specify which NGS CORS should be treated as hubs.
3	<b>Exclude Hubs</b>	Optionally remove any included NGS CORS from the design.



**Figure 5.4: Interface view of the CORS Selection panel.**

After all selections are made, users can proceed to generate the final XML file, which encapsulates the baseline geometry, OPUS parameters, and CORS configurations. Visualization tools are available to confirm the layout before finalizing, as illustrated in Figure 5.5, which includes map rendering, XML preview, and reset options. This

approach provides a high level of control while streamlining the preparation of data for adjustment processing in OPUS Projects.

#### 5.1.1.4 Finalization and Visualization Display

Once the baseline network design has been fully defined across the configuration panels, including baseline geometry, OPUS Project parameters, and CORS hub selection, users can finalize and export the complete setup using the Finalization and Visualization Display panel. This final step consolidates all network settings into a standardized XML file formatted for direct use in the OPUS Projects processing workflow.

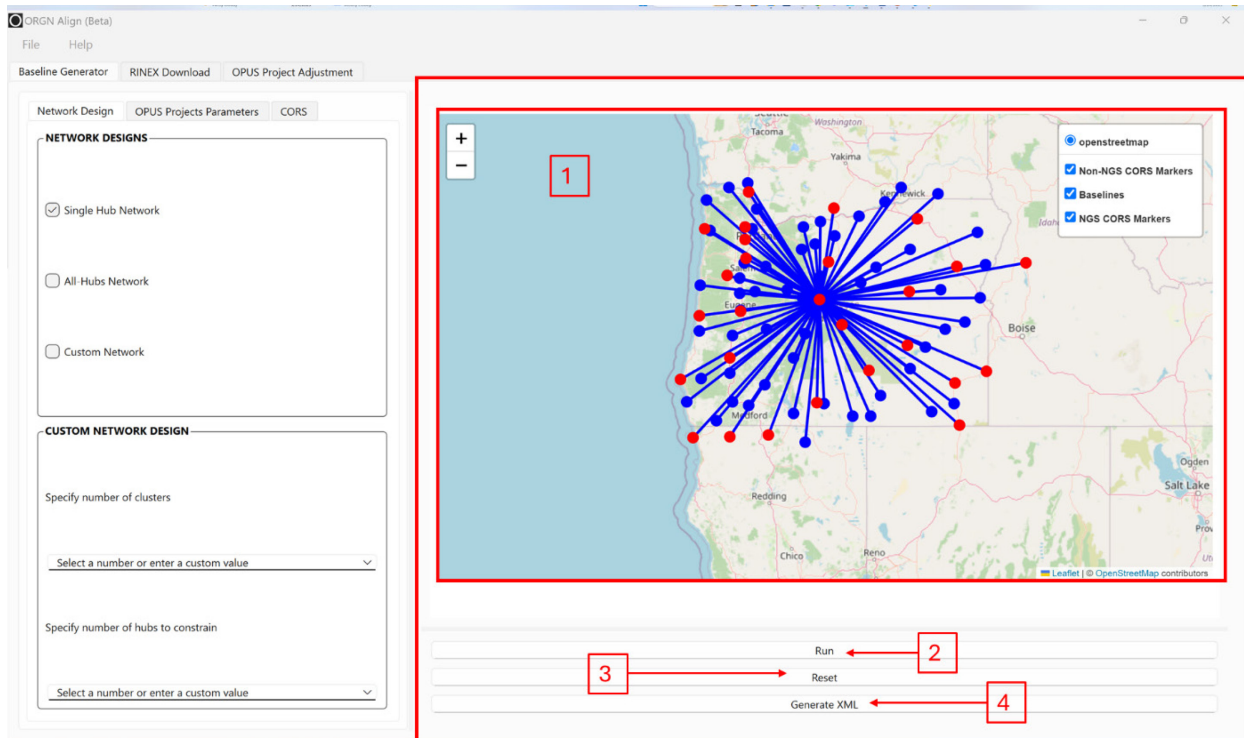
As shown in Figure 5.5, the interface offers several interactive tools that allow users to review and validate the baseline network design before export. These tools are summarized in Table 5.6, which describes the function of each component in the finalization interface.

**Table 5.6: Finalization and Visualization Tools**

No.	Tool	Function
1	Map	Displays a visual representation of the current network design.
2	Run	Renders the design on the map; if modifications are made, execute Run again to update.
3	Reset	Clears all input data and selections, preparing the system for a new dataset.
4	Generate XML	Exports the finalized design as an XML file for subsequent processing.

When the Generate XML tool is activated, the application produces an XML output that encapsulates the complete baseline configuration, along with all user-specified OPUS parameters. This includes constraint weights, troposphere modeling intervals, satellite elevation cutoffs, and reference station settings. The resulting XML file requires no manual editing and is fully compatible with OPUS-Py and other automation tools integrated into the RTN alignment workflow. A sample excerpt from a generated XML file is shown in Figure 5.6, demonstrating the structured format used to encode baselines, station metadata, and processing instructions.

This standardized export process ensures consistency across daily and weekly GNSS processing sessions, minimizes the risk of configuration errors, and allows GNSS network managers to replicate alignment procedures with minimal effort. Once saved, the XML configuration file is used in subsequent steps, most notably during OPUS Project Adjustment, to automate the alignment of ORGN station coordinates with the NSRS.



**Figure 5.5: Tools for finalizing and visualizing the baseline network design.**

```

<?xml version="1.0" encoding="utf-8"?>
<OPTIONS>
  <BASELINES>
    <DISTANCE><FROM>REDM</FROM><TO>ADEL</TO></DISTANCE>
    <DISTANCE><FROM>REDM</FROM><TO>basq</TO></DISTANCE>
    <!-- Additional baseline connections -->
  </BASELINES>
  <CONSTRAINT_WEIGHT>Tight</CONSTRAINT_WEIGHT>
  <ELEVATION_CUTOFF>15.0</ELEVATION_CUTOFF>
  <EMAIL_ADDRESS>tuffourp@oregonstate.edu</EMAIL_ADDRESS>
  <GEOID_MODEL>LET OPUS CHOOSE</GEOID_MODEL>
  <REFERENCE_FRAME>NAD_83(2011)</REFERENCE_FRAME>
  <GNSS>GNSS</GNSS>
  <TROPO_INTERVAL>7200</TROPO_INTERVAL>
  <TROPO_MODEL>Piecewise Linear</TROPO_MODEL>
  <CORS>
    <HUB>REDM<FIX>3-D</FIX></HUB>
    <HUB>JIME<FIX>NONE</FIX></HUB>
    <!-- Additional hubs -->
  </CORS>
</OPTIONS>

```

**Figure 5.6: Example output XML structure generated after baseline design is finalized.**

## 5.1.2 RINEX Download

The RINEX Download tab provides a structured, semi-automated workflow for acquiring and processing GNSS observation data from multiple sources. This module supports downloading raw observation files for specified stations and date ranges, converting them into OPUS-compliant RINEX files, and organizing them into a consistent directory structure. The purpose of this tab is to streamline a process that would otherwise require significant manual effort, particularly when managing daily or weekly data across an entire statewide GNSS network that relies on partnership agreements to densify the number of CORS within the network (i.e., multiple data sources).

As illustrated in Figure 5.7, the user interface includes components for selecting the date range, identifying the target stations, initiating downloads, and viewing download status logs. Descriptions of each interface component are provided in Table 5.7.

**Table 5.7: Functional Components of the RINEX Download Tab**

No.	Component	Description
1	<b>Date Selection</b>	Choose the default daily download or specify a custom date range. For a single-day download, ensure that the start and end dates are identical.
2	<b>Station Selection Method</b>	Select the default ORGN station list from the stations directory or opt for Manual Entry to specify a subset of stations.
3	<b>Manual Entry</b>	Allows users to upload a CSV file or directly input station details, enabling work with a specific subset of ORGN stations and their corresponding data sources.
4	<b>Download RINEX</b>	Initiates the download of RINEX files for the selected stations and specified dates, retrieving data from the designated sources (ftp, gage, or geodesy).

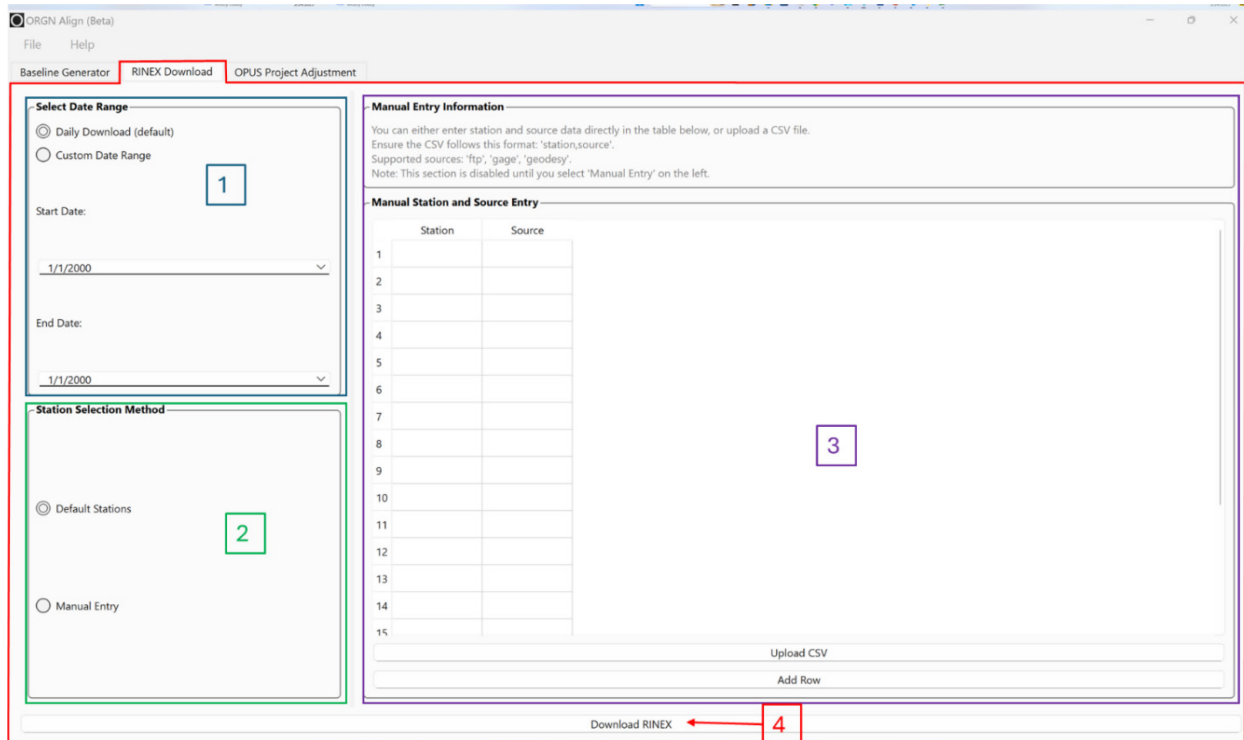
The input required to initiate this process is a CSV file listing ORGN station names and their corresponding data sources. A sample format is shown in Table 5.8, where each row defines a station and its affiliated data source (e.g., ODOT FTP, GAGE, or PANGA). The input CSV should be saved in the application’s stations directory or uploaded manually. Once loaded, the application parses the list and constructs appropriate URLs to download the data.

The software currently supports three data sources:

- ftp – Oregon Department of Transportation FTP server
- gage – EarthScope GAGE data archive
- geodesy – Pacific Northwest Geodetic Array (PANGA) data archive

**Table 5.8: Sample Format of Station List CSV for RINEX Download**

Station	Source
AGNS	gage
BURN	gage
ANAT	geodesy
ADEL	ftp



**Figure 5.7: Layout of RINEX download tab.**

After initiating the download, raw RINEX files are stored under the directory path:

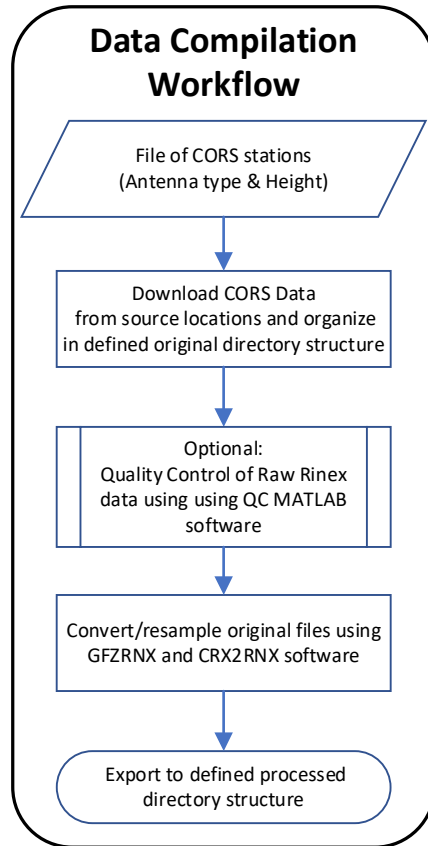
*/data/original/<year>/<doy>/<station\_id>/*

These files retain their original formats, which may include compressed archives such as .gz, .bz2, or .Z, or GNSS-specific formats like .crx (Hatanaka). To prepare these files for OPUS, the application applies a post-processing pipeline that decompresses and converts the raw data as needed.

The file conversion process uses Python’s built-in libraries for common compression types, and CRX2RNX.exe for Hatanaka-formatted files. Once converted to standard RINEX, the application resamples the data to a uniform 30-second epoch interval using GFZRNX, a tool developed by the German Research Centre for Geosciences. The resampled output is saved in a mirrored structure under:

*/data/processed/<year>/<day>/<station\_id>/*

An overview of this pipeline is illustrated in Figure 5.8, showing the flow from raw download to the final OPUS-ready file structure. This preprocessing step is especially important when handling dozens of stations per day. Although OPUS can decompress and resample files internally, the National Geodetic Survey (NGS) recommends user-side preprocessing to reduce server load and prevent processing bottlenecks.



**Figure 5.8: Workflow used to compile CORS data for all RTN stations and prepare them for uploading to OPUS.**

Throughout the download and processing workflow, detailed logs are maintained. These logs include timestamps, file sizes, retrieval status, decompression results, and conversion metadata. This ensures that all steps are traceable and that any issues can be quickly diagnosed and corrected without repeating the entire process.

Ultimately, the RINEX Download module provides a consistent, scalable, and reproducible method for handling GNSS observation data from diverse archives. This automation establishes a critical foundation for the alignment workflow, allowing the next stage, OPUS Project Adjustment, to begin with validated, pre-formatted RINEX files.

### 5.1.3 OPUS Projects Adjustment

The OPUS Project Adjustment tab, shown in Figure 5.9, enables users to automate the process of aligning ORGN station coordinates with the National Spatial Reference System (NSRS) using the OPUS Projects platform. This module eliminates the need for direct interaction with the OPUS Projects web interface by providing a streamlined workflow that includes session creation, data submission, and solution analysis, all integrated into the ORGN Align application. The purpose of each section of this module is briefly described in Table 5.9.

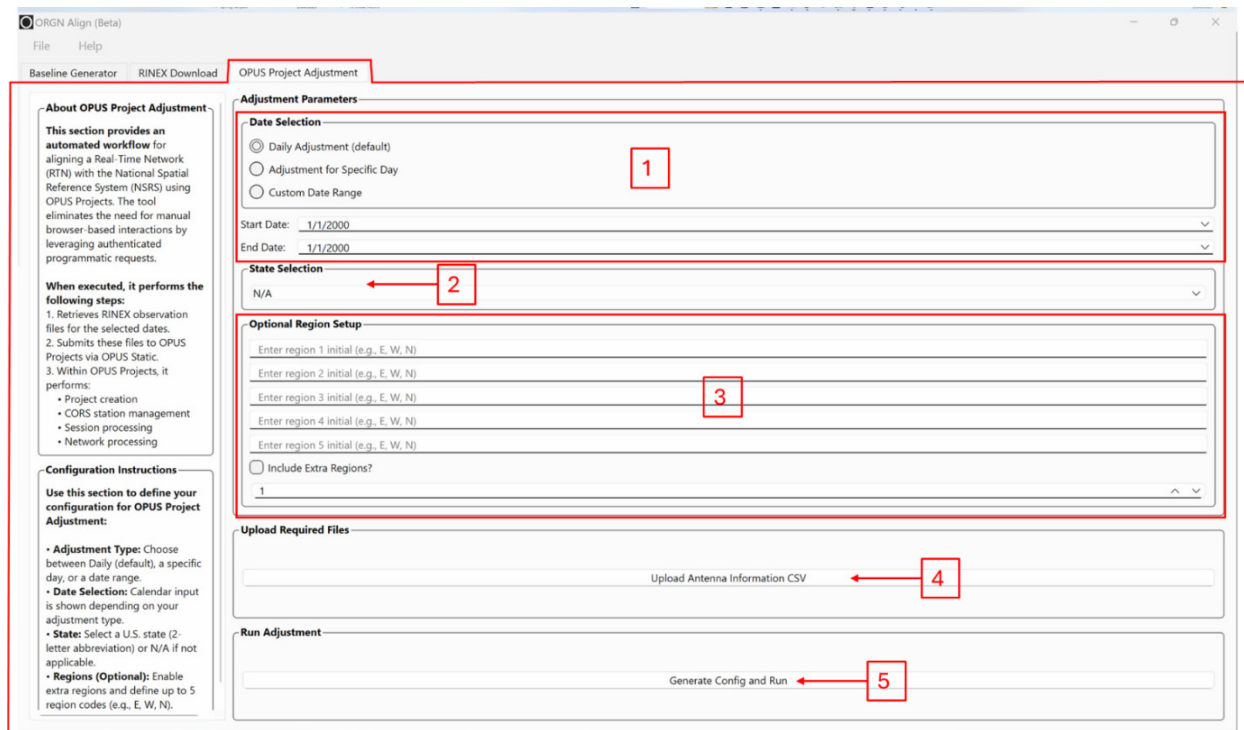
**Table 5.9: OPUS Projects Configuration and Execution Options**

No.	Component	Description
1	Date Selection	Choose between daily run (default), a specific day, or a custom range. Date inputs are dynamically enabled based on the selected mode.
2	State Selection	Select the appropriate U.S. state using its 2-letter abbreviation.
3	Regional Setup	Users may optionally specify between one and five custom region codes (for example, E, W, N) to divide the network into regions. This option is disabled by default and becomes active only when the Include Extra Regions option is selected.
4	Upload Files	Upload supporting CSV files, such as the antenna metadata file. Required for proper configuration during processing.

The information entered in this module is required to perform the repeatable adjustment process in which preprocessed RINEX files and baseline configurations are submitted to OPUS Projects. OPUS Projects then performs a series of GNSS network adjustments using NGS’s GPSCOM and ADJUST tools to derive updated, NSRS-consistent coordinates for all ORGN stations. Throughout the process, quality control metrics such as constraint ratios and F-tests are automatically evaluated to ensure reliable alignment. The adjustment workflow is divided into three main components, described in the following subsections:

- **Section 5.1.3.1: Project Creation** – Defines the project scope, processes user-defined date ranges and regions, and collects antenna metadata to prepare for submission.
- **Section 5.1.3.2: Session Upload** – Handles the automated upload of RINEX files and configuration files to the OPUS Projects system using the OPUS-Py package.
- **Section 0: Solution Analysis** – Describes the constrained adjustment steps, evaluates network quality, and stores finalized coordinate solutions for long-term tracking.

By integrating these capabilities, the OPUS Project Adjustment tab supports efficient and consistent GNSS alignment workflows for daily, weekly, or event-driven ORGN monitoring activities.



**Figure 5.9: OPUS Adjustment Workflow Setup Interface**

### 5.1.3.1 Project Creation

The first step in the OPUS Project Adjustment workflow is the creation of a project for the current processing run. Within the GUI, users begin by selecting a processing mode: a single-day session, a specific date, or a custom date range. The date selection sets the scope for which RINEX files and station configurations are loaded. A dropdown menu prompts the user to select the two-letter abbreviation for the U.S. state where the stations are located. This state identifier becomes part of the OPUS Project metadata and helps organize project files across multiple runs.

Users also have the option to define up to five custom regions within the statewide network, such as "East," "West," "Central," etc., allowing the processing to be split geographically. This is especially useful for managing networks with large numbers of stations. The regioning functionality is activated by checking the “Include Extra Regions” box. Once selected, input fields appear for naming and defining each region. The session creation panel, with all primary input fields visible, is identified by boxes 1 through 3 in Figure 5.9.

Certain backend modules require additional information about the antenna and its height from the monument position (MON) to the antenna reference point (ARP) to proceed with processing. The OPUS Project Adjustment tab provides a section for uploading this information via a specifically formatted file, identified by box 4 in Figure 5.9.

The “Antenna Information CSV” specifies the antenna types and antenna heights used during observation and must be formatted as shown in Table 5.10. The file must be uploaded via the Upload Antenna Information CSV button within the GUI. Once uploaded, the system saves the file for use during the semi-automated workflow. Note that if this tool is set to run daily but a station is physically modified (e.g., a new antenna or a modified mount), the automated workflow should be restarted using an updated Antenna Information CSV file.

**Table 5.10: Antenna Information File Format**

Station	Antenna Type	Antenna Height
ADEL	LEIAT504GG LEIS	0
AGNS	TWIVC6050 SCIT	0.0083
ANAT	TRM115000.00	0
ARLN	SEPCHOKE_B3E6	0

Once these entries are complete, the system bundles them into an XML configuration file to be used in the next stage: session upload and processing.

### **5.1.3.2 Session Upload**

Following session creation, the next step is the upload and submission of RINEX files and configuration parameters to OPUS Projects. This process is managed programmatically using the OPUS-Py package, which interfaces directly with the National Geodetic Survey’s (NGS) backend systems. The tool bypasses the traditional web interface, submitting files and metadata through secure API requests, greatly improving speed and reproducibility.

Upon activation, ORGN Align initiates a structured XML upload containing the complete baseline geometry, antenna metadata, and user-defined OPUS Project parameters. RINEX files located in the /data/processed directory, generated during the RINEX Download stage, are automatically paired with their corresponding stations and included in the upload. Once all required files are transmitted, the OPUS Projects engine initiates the GPSCOM process to generate a preliminary network solution. This GPSCOM solution provides an initial set of coordinates, which serves as the basis for constrained and unconstrained adjustments in the next step.

After the RINEX data has been submitted and the project structure is finalized, ORGN Align enters a monitoring phase to confirm that OPUS has returned valid processing results for each day defined in the configuration. This is achieved by comparing the expected daily station uploads against the processed solutions reported in the project’s XML output. Each day is evaluated for completeness based on the proportion of stations successfully processed. When all days have either met the defined processing threshold or satisfied fallback conditions, the system proceeds to the next phase. Session processing begins only after this evaluation confirms that all required data have been processed by OPUS, ensuring that sessions are initiated on a stable and complete data foundation.

### 5.1.3.3 *Adjustments and Solution Analysis*

Once preliminary processing has been completed in OPUS Projects, the system transitions into solution analysis using the ADJUST software. This process consists of two sequential network adjustments: a minimally constrained adjustment and a fully constrained adjustment. In the first stage, one CORS station is fixed while all others are free to float, providing a reference solution that helps identify problematic stations or unbalanced network configurations.

During this adjustment, the software performs an F-test to evaluate whether the observed network geometry supports the input constraints. It also examines the constraint ratio, which compares residuals from unconstrained and constrained solutions. If this ratio exceeds a predefined threshold, typically set to 3.0, representing a shift within the 99.7% confidence region for that particular station's estimated uncertainty, the solution is flagged, and the constraint is temporarily removed. A second adjustment is then attempted using the remaining stations.

If the network passes these quality control checks, the system proceeds to the fully constrained adjustment, in which all selected NGS CORS stations are fixed to their NSRS-published coordinates. This adjustment provides the final set of aligned coordinates for the ORGN stations. After the adjustment process is complete, an OPUS Project XML file is generated. This file contains comprehensive information, including OPUS solutions, session-level results, and final network adjustments.

ORGN Align parses the XML content and stores the relevant data, including adjusted coordinates, uncertainties, in a centralized database to support downstream time-series analysis. A sample excerpt from a generated XML file is shown in Figure 5.10, illustrating the structure and content of these outputs. All adjustment metadata, including station residuals, coordinate shifts, fixed/free constraint flags, and F-test outcomes, are retained for subsequent time-series analysis and position monitoring. These outputs form the foundation for ongoing alignment monitoring and CORS health evaluation across the ORGN.

```

<?xml version="1.0" encoding="UTF-8"?>
<PROJECT_INFO VERSION="2.3" MTIME="1733129448" SOURCE="project_info.xml">
  <USER_ISID=",,1" ESID="bcut">
    <PREFERENCES>
      <STATE>CA</STATE>
      <GEOID_MODEL>LET OPUS CHOOSE</GEOID_MODEL>
      <REFERENCE_FRAME>USE PREFERENCES</REFERENCE_FRAME>
      <SPCS_UNIT>USE PREFERENCES</SPCS_UNIT>
      <SPCS_ZONE>USE PREFERENCES</SPCS_ZONE>
    </PREFERENCES>
    <POSITION>
      <EPOCH_SYSTEM="GPS">2022.84789999</EPOCH>
      <REF_FRAME>ITRF2014</REF_FRAME>
      <COORD_SET>
        <RECT_COORD>
          <COORDINATE UNIT="m" UNCERTAINTY="0.008" AXIS="X">-2708381.439</COORDINATE>
          <COORDINATE UNIT="m" UNCERTAINTY="0.007" AXIS="Y">-4002879.226</COORDINATE>
          <COORDINATE UNIT="m" UNCERTAINTY="0.003" AXIS="Z">4148018.068</COORDINATE>
          <UNCERTAINTY UNIT="m" AXIS="X">0.008</UNCERTAINTY>
          <UNCERTAINTY UNIT="m" AXIS="Y">0.007</UNCERTAINTY>
          <UNCERTAINTY UNIT="m" AXIS="Z">0.003</UNCERTAINTY>
          <VELOCITY UNIT="m/yr" UNCERTAINTY="0.01" AXIS="X">-0.0070</VELOCITY>
          <VELOCITY UNIT="m/yr" UNCERTAINTY="0.01" AXIS="Y">0.0091</VELOCITY>
          <VELOCITY UNIT="m/yr" UNCERTAINTY="0.01" AXIS="Z">0.0040</VELOCITY>
        </RECT_COORD>
        <ELLIP_COORD>
          <COORDINATE UNIT="deg" UNCERTAINTY="0.006" AXIS="LAT">
            <DEGREES>40</DEGREES>
            <MINUTES>49</MINUTES>
            <SECONDS>42.59569</SECONDS>
          </COORDINATE>
          <COORDINATE UNIT="deg" UNCERTAINTY="0.006" AXIS="EAST_LONG">
            <DEGREES>235</DEGREES>
            <MINUTES>55</MINUTES>
            <SECONDS>2.60620</SECONDS>
          </COORDINATE>
          <COORDINATE UNIT="m" UNCERTAINTY="0.006" AXIS="EL_HEIGHT">-19.213</COORDINATE>
          <UNCERTAINTY UNIT="m" AXIS="LAT">0.006</UNCERTAINTY>
          <UNCERTAINTY UNIT="m" AXIS="EAST_LONG">0.006</UNCERTAINTY>
          <UNCERTAINTY UNIT="m" AXIS="EL_HEIGHT">0.006</UNCERTAINTY>
        </ELLIP_COORD>
      </COORD_SET>
      <SOURCE MTIME="1733122055">opusReports/bcut3100.22o.txt coordinates with HTDP(3.5.0) ITRF2014 velocity</SOURCE>
    </POSITION>
  </POSITION>
  <EPOCH_SYSTEM="GPS">2010.00000000</EPOCH>
  <REF_FRAME>NAD_83(2011)</REF_FRAME>
  <COORD_SET>

```

Figure 5.10: shows a sample portion of the generated OPUS Project XML file.

## 5.2 OVERVIEW OF DJANGO DATABASE

Django is a high-level Python web framework that includes an integrated Object-Relational Mapping (ORM) system. It allows developers to define and manage database models using Python code and provides an admin interface for managing data without writing raw SQL. The Django database serves as the backend for storing, retrieving, and administering structured data through a web-based admin panel.

In this project, the Django database is used to systematically store and manage parsed positioning data from OPUS Project XML files. Specifically, it includes the daily OPUS Static Solutions, daily OPUS Projects Session Solutions, and weekly OPUS Projects Network Solutions (fully constrained). The primary purpose of the database is to facilitate the generation and analysis of daily time-series plots, which monitor the alignment and stability of Oregon Real-Time GNSS Network (ORGN) stations relative to the National Spatial Reference System (NSRS).

On the frontend, users interact directly with Django’s intuitive ORM through the provided admin interface. This design ensures that users can easily view, export, and manage data without engaging with complex SQL queries or Python backend scripts. Figure 5.11 shows the layout of the Django admin interface and its key components.

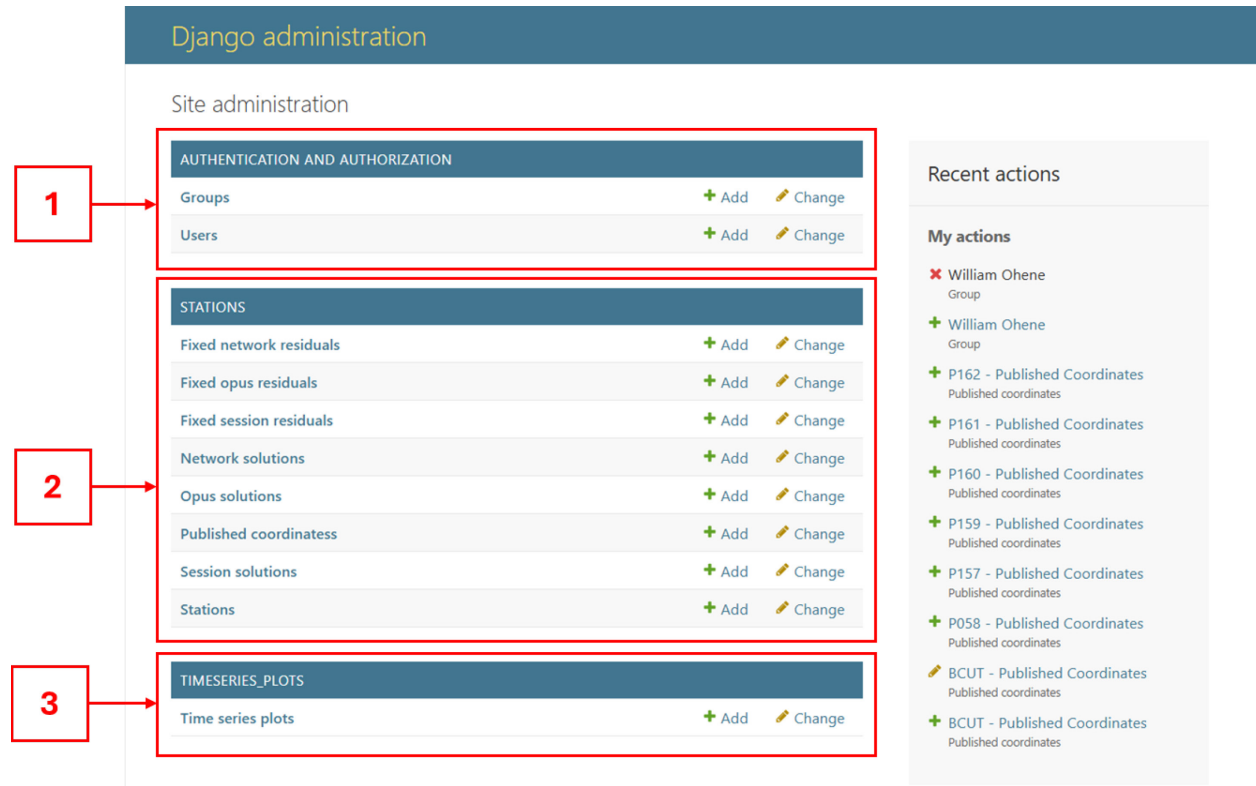
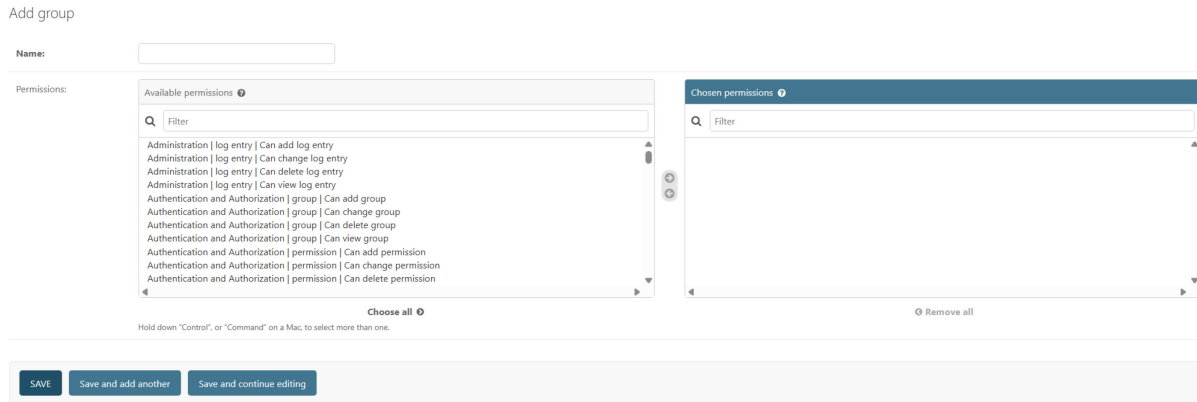


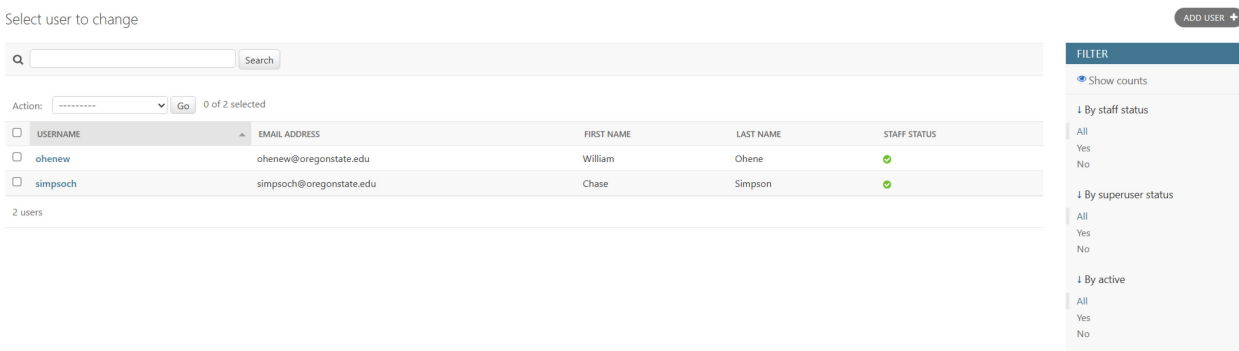
Figure 5.11: Showing the overall layout of the database.

### 5.2.1 Authentication and Authorization App

This built-in Django App manages user accounts, permissions, and access control. It ensures only authorized personnel can access, modify, or view the database entries, enhancing security and data integrity. **Groups**, Figure 5.12, represent collections of users categorized by their roles or responsibilities. Users assigned to specific groups automatically inherit the permissions designated for that group. This simplifies permission management, particularly when multiple users require identical levels of access. The **Users**, Figure 5.13 manages individual user accounts, including credentials, personal information, active status, and associated permissions. Through this interface, administrators can create new user accounts, assign or revoke permissions, and manage user authentication details.



**Figure 5.12: Screenshot of the Django Admin Interface showing the Groups section under the Authentication and Authorization module, illustrating role-based access management.**



**Figure 5.13: Screenshot of the Django Admin Interface displaying the Users management section, demonstrating user account creation, permission assignment, and status management.**

## 5.2.2 Stations App

This custom-developed application manages data related to ORGN stations. It includes models for storing station details, published coordinates, OPUS Static Solutions, session solutions, network solutions, and associated residuals. Users can interact with the application to view, add, modify, or export coordinate data.

The database schema is organized to systematically store and manage GNSS coordinate data and associated residuals. It is specifically designed to handle various solution types, namely Published Coordinates, OPUS Static Solutions, Session Solutions, and Network Solutions, each within a dedicated table.

Each solution table contains geodetic information, including latitude, longitude, ellipsoidal height, and the reference frames used. Furthermore, residual tables associated with each solution

type capture positional differences, known as residuals, between computed coordinates and established fixed references. This structured design facilitates efficient querying, monitoring, and analysis of ORGN station alignment with the NSRS. Table 5.11 through Table 5.14 provides detailed summaries of each database table within the schema, clearly outlining the fields and their respective purposes. While Figure 5.14 through Figure 5.17 include examples of what the user will see for the corresponding database table.

**Table 5.11: Description of fields used in the officially adopted and published coordinates database table.**

Field	Description
STATION	Station identifier (foreign key to Stations)
PUBLISHED LAT	Latitude of the station
PUBLISHED LONG	Longitude of the station
PUBLISHED ELLIPSOIDAL HEIGHT	Ellipsoidal height of the station
REFERENCE_FRAME	Reference frame used (e.g., NAD83, ITRF)
EPOCH	Epoch date of the coordinates

Select published coordinates to change EXPORT ADD PUBLISHED COORDINATES +

Action:  Go 0 of 100 selected

<input type="checkbox"/>	STATION	PUBLISHED LAT	PUBLISHED LONG	PUBLISHED ELLIPSOIDAL HEIGHT	PUBLISHED REFERENCE FRAME	PUBLISHED EPOCH
<input type="checkbox"/>	ADEL	42.176505461111	240.104149127778	1386.097	NAD83(2011)	2010
<input type="checkbox"/>	AGNS	42.552761541667	235.940904291667	51.763	NAD83(2011)	2010
<input type="checkbox"/>	ANAT	46.132859730556	242.864588600000	1087.765	NAD83(2011)	2010
<input type="checkbox"/>	ARLN	45.708201477778	239.816746794444	120.812	NAD83(2011)	2010
<input type="checkbox"/>	ASHL	42.180686941667	237.329846552778	609.147	NAD83(2011)	2010
<input type="checkbox"/>	BASQ	42.411600983333	242.136986172222	1349.14	NAD83(2011)	2010
<input type="checkbox"/>	BCUT	40.828494670000	235.917408300000	-18.812	NAD83(2011)	2010
<input type="checkbox"/>	BEND	44.057154797222	238.684829938889	1096.257	NAD83(2011)	2010
<input type="checkbox"/>	BLYI	42.406840986111	238.950950972222	1313.889	NAD83(2011)	2010

**Figure 5.14: Showing Published Coordinates layout in database.**

**Table 5.12: Summary of OPUS Projects session solution coordinates for each station pulled daily.**

Field	Description
STATION	Station identifier (foreign key to Stations)
YEAR	Year of session
DOY	Day of Year
SESSION ID	Session ID associated with the Opus Session Solution
REFERENCE FRAME	Reference frame used (e.g., ITRF2014)
EPOCH	REFERENCE FRAME EPOCH (e.g. 2024.0560)
ECEF X	ECEF coordinates computed by OPUS
ECEF Y	ECEF coordinates computed by OPUS
ECEF Z	ECEF coordinates computed by OPUS
LAT	Latitude computed for the session
LONG	Longitude computed for the session
ELLIPSOIDAL HEIGHT	Ellipsoidal height computed for the session
UNCERTAINTY (X,Y,Z)	Uncertainty computed by Opus Project
UNCERTAINTY (L,L,H)	Uncertainty computed by Opus Project
EPHEMERIS	Ephemeris type (Rapid, Precise, Final)

Select session solution to change

EXPORT

Action:  Go 0 of 100 selected

<input type="checkbox"/>	STATION	DOY	YEAR	SESSION ID	REFERENCE FRAME	EPOCH	ECEF X	ECEF Y	ECEF Z	LAT	LONG	ELLIPSOIDAL HEIGHT
<input type="checkbox"/>	ADEL	15	2024	2024-015-A	NAD_83(2011)	2010.00000000	-2359984.988	-4104827.521	4261083.867	42.17650543333333	240.10414910555556	1386.104
<input type="checkbox"/>	ADEL	15	2024	2024-015-A	ITRF2014	2024.03965050	-2359986.0233	-4104826.2336	4261083.7863	42.17650851944444	240.10413048055554	1385.605
<input type="checkbox"/>	BASQ	15	2024	2024-015-A	NAD_83(2011)	2010.00000000	-2204664.747	-4170394.823	4280379.802	42.41160092222222	242.1369861388889	1349.133
<input type="checkbox"/>	BASQ	15	2024	2024-015-A	ITRF2014	2024.03965050	-2204665.7679	-4170393.5581	4280379.7024	42.41160415277778	242.13696799722223	1348.592
<input type="checkbox"/>	BLY1	15	2024	2024-015-A	NAD_83(2011)	2010.00000000	-2433210.454	-4041700.897	4279965.529	42.40684077777778	238.95095101666666	1313.871
<input type="checkbox"/>	BLY1	15	2024	2024-015-A	ITRF2014	2024.03965050	-2433211.4717	-4041699.6066	4279965.4729	42.40684393055555	238.95093234444442	1313.404
<input type="checkbox"/>	BNDM	15	2024	2024-015-A	NAD_83(2011)	2010.00000000	-2384764.714	-3921089.178	4415976.046	44.089390725	238.6924780638889	1070.726
<input type="checkbox"/>	BNDM	15	2024	2024-015-A	ITRF2014	2024.03965050	-2384765.7105	-3921087.9333	4415975.9972	44.089393825	238.69245935833334	1070.3
<input type="checkbox"/>	BRNT	15	2024	2024-015-A	NAD_83(2011)	2010.00000000	-2155274.233	-4021034.882	4443996.683	44.44021379722222	241.80869675833335	1213.174
<input type="checkbox"/>	BRNT	15	2024	2024-015-A	ITRF2014	2024.03965050	-2155275.2549	-4021033.646	4443996.6022	44.4402171	241.8086781138889	1212.684

**Figure 5.15: Showing Session Solution Coordinates layout in database.**

**Table 5.13: Summary of the weekly OPUS Project Network Solutions.**

Field	Description
STATION	Station identifier (foreign key to Stations)
YEAR	Year of observation
START_DOY	Start Day of Year for the weekly solution
END_DOY	End Day of Year for the weekly solution
LAT	Latitude from the network solution
LONG	Longitude from the network solution
ELLIPSOIDAL_HEIGHT	Ellipsoidal height from the network solution
REFERENCE_FRAME	Reference frame used (e.g., ITRF2014)
EPHEMERIS	Ephemeris type (Rapid, Precise, Final)

Select network solution to change

EXPORT ADD NETWORK SOLUTION +

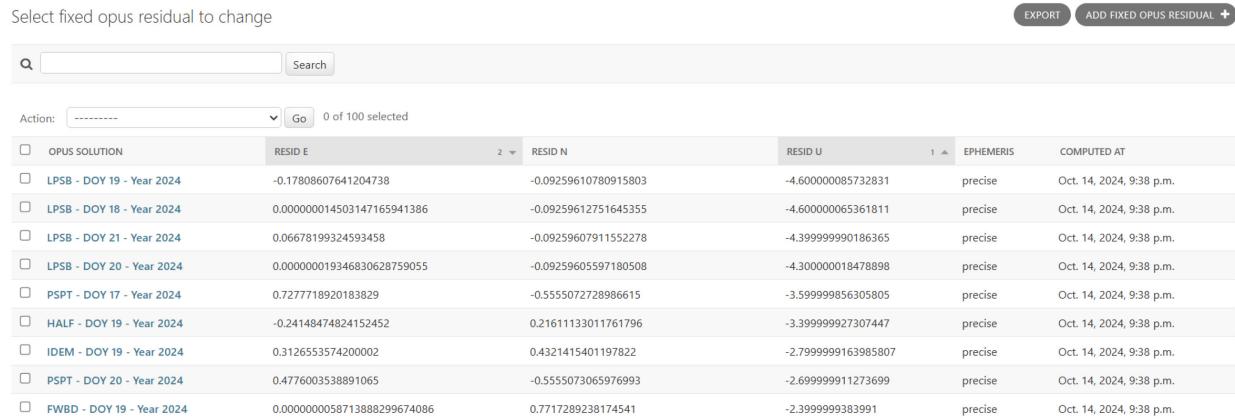
Action:  Go 0 of 76 selected

<input type="checkbox"/>	STATION	START DOY	END DOY	YEAR	NETWORK ID	REFERENCE FRAME	EPOCH	ECEF X	ECEF Y	ECEF Z	LAT	LONG	ELLIPSOIDAL HEIGHT	UNCERTAINTY X
<input type="checkbox"/>	ADEL	15	21	2024	network-final	NAD_83(2011)	2010.00000000	-2359984.993	-4104827.526	4261083.863	42.176505363888886	240.104149083333334	1386.106	0.0007
<input type="checkbox"/>	ADEL	15	21	2024	network-final	ITRF2014	2024.04785573	-2359986.0286	-4104826.2389	4261083.7826	42.176508452777774	240.104130458333332	1385.608	0.0007
<input type="checkbox"/>	BASQ	15	21	2024	network-final	NAD_83(2011)	2010.00000000	-2204664.752	-4170394.826	4280379.797	42.411600858333333	242.13698610277777	1349.133	0.0007
<input type="checkbox"/>	BASQ	15	21	2024	network-final	ITRF2014	2024.04785298	-2204665.7728	-4170393.5612	4280379.6968	42.411604083333333	242.13696796111111	1348.592	0.0007
<input type="checkbox"/>	BLY1	15	21	2024	network-final	NAD_83(2011)	2010.00000000	-2433210.46	-4041700.899	4279965.523	42.406840711111111	238.95095096666665	1313.87	0.0007

**Figure 5.16: Showing Network Adjustment Solution Coordinates layout in database.**

**Table 5.14: Summary of the Residual Differences between computed solutions and a reference coordinate.**

Field	Description
SOLUTION	Associated solution (Session, OPUS, Network)
RESID_E	East residual (cm)
RESID_N	North residual (cm)
RESID_U	Up residual (cm)
EPHEMERIS	Ephemeris type used



**Figure 5.17: Showing Residuals used for time series plots**

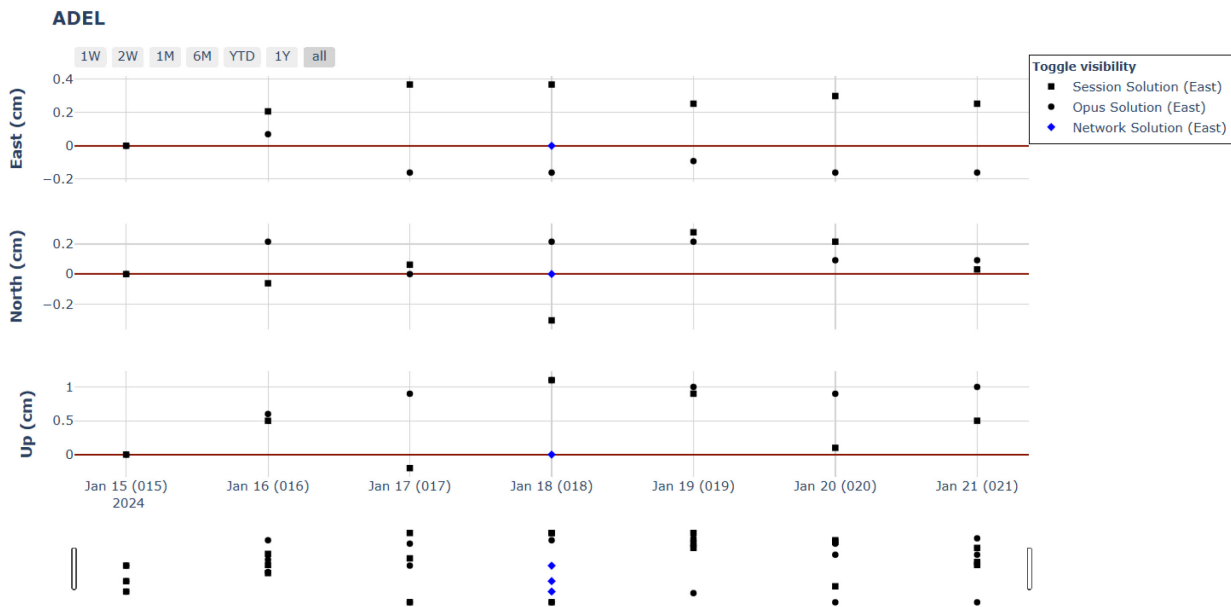
## 5.2.1 Timeseries Plots Module

This application generates and manages interactive time series plots for visualizing station residuals over time. It integrates closely with the Stations app to automatically fetch data and update plots, allowing users to easily monitor ORGN alignment to the NSRS. Each station has a dedicated time series plot, shown in Figure 5.18, clearly presenting positional residuals in three distinct components: East, North, and Up. For each station, the plot integrates three categories of solutions:

- OPUS Solutions** are daily positional solutions computed by OPUS-Static. They are plotted as circles and displayed by default. Residuals within  $\pm 2$  cm for East and North and  $\pm 4$  cm for Up are shown as black markers, while residuals exceeding these thresholds turn red.
- Session Solutions** represent daily positional solutions from the OPUS Projects Session computations (GPSCOM). They are plotted as squares and hidden by default. They can be displayed by selecting the corresponding option in the legend toggle box ("Toggle visibility"). Residual colors follow the same convention as OPUS Solutions: black points indicate the daily coordinate is within the threshold criteria, and red indicates it exceeds the thresholds.

- Network Solutions** represent weekly solutions derived from OPUS Project network adjustments, which combine the seven daily session solutions from a given GPS week. They are plotted as diamonds positioned at the midpoint of each week and are also hidden by default. Like Session Solutions, they can be activated via the legend toggle. Residuals within  $\pm 2$  cm for East and North and  $\pm 4$  cm for Up are shown as blue markers, while residuals exceeding these thresholds turn red.

Each plot offers interactive capabilities for improved data exploration. Specifically, users can manipulate a range slider and use preset range-selection buttons to examine data across various time spans conveniently.



**Figure 5.18: Example Time Series Plot displaying East, North, and Up residuals for ORGN station coordinates. Markers indicate OPUS (circles, black), Session (squares, black), and Network (diamonds, blue) solutions.**

## 6.0 IMPLEMENTING THE AUTOMATED WORKFLOW

### 6.1 CASE STUDY #1: THREE MONTHS OF DATA FROM THE ORGN

#### 6.1.1 Introduction and Objectives

This case study evaluates the long-term stability of the Oregon Real-Time GNSS Network (ORGN) station coordinates over a three-month period using the semi-automated alignment workflow. The objective is to demonstrate how the ORGN Align tool can continuously monitor and maintain the alignment of ORGN stations with the National Spatial Reference System (NSRS) under normal operating conditions. By leveraging the National Geodetic Survey's OPUS solutions (both OPUS-Static and OPUS-Projects), the study aims to identify any gradual drifts or deviations in station positions and assess whether they remain within acceptable tolerance limits over time.

In line with NGS recommendations for RTN management, this case study monitors each station's daily and weekly positions relative to its published coordinates, which serve as the reference for real-time network operations. Daily coordinate solutions are obtained via OPUS-Static, and weekly network adjustments are computed via OPUS-Projects. For each solution, residuals (coordinate differences) in the East, North, and Up components are calculated relative to the station's published reference position, as defined by the ORGN Manager in August 2024. To determine whether a station's coordinates are stable or require updating, the study adopts NSRS-aligned threshold values of  $\pm 2$  cm horizontally and  $\pm 4$  cm vertically. These tolerances represent the maximum acceptable deviation; any persistent exceedance over consecutive days would indicate the need to update that station's published coordinates to preserve network accuracy and integrity.

The analysis period spans January 1 to March 31, 2024, a three-month interval chosen deliberately because it contains no significant seismic events or other known geophysical disturbances. This ensures that any detected movement is likely due to station-specific factors, such as monument instability or equipment issues, rather than external tectonic events. It should be noted that this study was completed retroactively, which is why coordinates from later in the year could be used as the reference published positions. The period also provided a complete, uninterrupted dataset for all selected stations, avoiding data gaps that could bias the analysis.

Within this timeframe, ORGN Align was used to process daily data and compile time-series diagnostics for each station. Key metrics for evaluation include:

- **Residual magnitudes in East, North, and Up** for each day and week, compared against the 2 cm (horizontal) and 4 cm (vertical) thresholds.
- **Frequency of threshold exceedance**, i.e. how often and how long a station's positional error goes beyond the tolerated 2 cm/4 cm limits.

- **Trends and patterns** in the daily and weekly residual time series, indicating whether stations remain stable, exhibit gradual drift, or experience abrupt shifts.
- **Statistical stability measures** such as average residual offset and variation over the three months, to quantify overall station performance.

Through these metrics, the case study's primary goal is to confirm that the ORGN Align workflow can effectively track station alignment over time and flag any stations that deviate from the NSRS alignment criteria. Ultimately, this provides a basis for practical decisions, such as whether to re-publish updated coordinates for any station that consistently exceeds the tolerances or to schedule maintenance for stations showing unusual instability. It also serves to validate that the chosen thresholds ( $\pm 2$  cm horizontal /  $\pm 4$  cm vertical) are appropriate for operational monitoring, capturing meaningful position changes while avoiding false alarms.

## 6.1.2 Study Design and Data Summary

The study monitored a total of 61 continuously operating stations, consisting of 34 ORGN real-time base stations and 27 nearby NGS CORS, which were also incorporated as part of the ORGN. A smaller subset of stations was used to avoid splitting the ORGN into two separate networks, given the 99-station maximum imposed by OPUS-Projects. While two separate networks would be required to monitor and align the entire ORGN, the results of this case study remain applicable, and the workflow would remain identical. All selected stations exhibited high data availability across the three-month period, generally exceeding 90% of days with usable data. This combined network of ORGN and CORS stations (shown geographically in Figure 6.1) provided a robust reference framework for alignment.

Including NGS CORS in the network design ensured that the weekly adjustments could tie into stable NSRS control and also allowed evaluation of ORGN station performance against known reference stations. Each station contributed daily RINEX observation files throughout the period. When both RINEX 2 and RINEX 3 data were available, the RINEX 3 format was used due to its richer metadata and modern compatibility. All observation files were standardized to a 30-second interval, through splicing or resampling as needed, to meet OPUS input requirements.

### 6.1.2.1 Automated Processing Workflow

The ORGN Align tool was configured to execute a four-step alignment and monitoring workflow each day and week, as described below:

1. **Daily OPUS-Static Processing:** Each station's RINEX file was submitted to OPUS-Static, which uses the PAGES software to compute static coordinate estimates. These estimates are derived from three independent single-baseline computations with nearby reference CORS and provide the foundational data for subsequent processing.
2. **Weekly Session Processing:** Daily solutions were grouped into weekly batches (generally seven days per session, aligned with GPS weeks). Using OPUS-Projects, a session adjustment was performed for each week's data. In the session, baselines were formed according to a predefined network design linking ORGN stations to one or more

hub CORS (selected NGS reference stations). Each weekly session was first run as a minimally constrained network adjustment, allowing the stations to float with only enough constraint to define the reference frame, to derive internally consistent coordinates and an associated variance-covariance matrix for that week. This step helps reduce random daily noise by combining observations over a week.

3. **Horizontal Network Adjustment:** After obtaining weekly session results, a multi-step network alignment was conducted to tie all weeks together and enforce NSRS consistency horizontally. First, a preliminary combination of all weekly sessions was performed using NGS's GPSCOM tool to create a unified solution. Next, a free network adjustment (horizontal free adjustment) was run: a single 3D constraint was applied (often to the reference frame origin) to detect any network-wide inconsistencies or bias. Finally, a constrained adjustment fixed the reference stations to their published NSRS coordinates (full 3D constraints on the selected CORS hubs), producing the final adjusted coordinates for all stations.

Throughout this adjustment process, the software automatically applied two key quality checks:

- a. **F-test:** Compares the variance of the constrained solution to that of the free solution, ensuring that adding NSRS constraints did not significantly distort the network (i.e., the network geometry is consistent with the constraints).
- b. **Constraint Ratio Test:** For each station, this test compares the station's coordinate shift between the free and constrained solutions against its expected uncertainty. If any station's shift was too large (constraint ratio  $> 3.0$  in this implementation), it indicated that the station's published coordinates were not in agreement with the rest of the network. Such stations were automatically unconstrained, and the adjustment was re-run, effectively excluding outliers from distorting the final network solution. In this study, no vertical constraints were applied (vertical adjustments were reserved for future work), focusing the alignment on horizontal consistency.

4. **Time Series Generation and Monitoring:** As the final step, ORGN Align aggregated the results into a time series database. After each daily and weekly run, the tool updated a standardized XML and the internal database with the latest coordinate solutions. Residual time-series plots were generated for each station, showing the East, North, and Up differences between the computed solutions and the station's official published coordinates. Both daily OPUS-Static positions and weekly network-adjusted positions were recorded. These time-series plots serve as the primary diagnostic output for long-term monitoring, allowing operators to visually track each station's performance over the three months. The plotting utility automatically overlays the  $\pm 2$  cm horizontal and  $\pm 4$  cm vertical threshold lines on each chart, so any excursions beyond the limits are immediately apparent.

Throughout the study, processing parameters were held constant to ensure consistency. All stations were processed using the same OPUS-Projects settings (e.g., reference frame, antenna models) and the same baseline design each week. Solutions that failed to meet OPUS quality criteria (for instance, if OPUS-Static could not produce a solution on a given day) were excluded from the analysis; however, such cases were rare given the

generally high data quality. Stations with severe data outages (less than ~90% of days available) would ordinarily be omitted, but in this dataset, every included station had substantial data coverage. The result was a complete set of daily and weekly station coordinates over 91 days, against which alignment thresholds could be applied and statistics gathered.

### **6.1.3 Results & Discussion**

Over the January–March 2024 period, each station yielded, on average, approximately 89–91 successful daily solutions (out of 91 possible days) and 13 weekly solutions (for 13 weeks). The inclusion of both ORGN and CORS stations meant that the network spanned all regions of Oregon, from coastal areas to the interior, covering a wide range of baseline lengths and site conditions. Figure 6.1 illustrates the distribution of the stations used. This spatial spread ensured that the monitoring results represent the entire ORGN coverage area. By the end of the study period, the ORGN Align workflow had processed roughly 5,500 station-days of observations, producing a rich dataset of residuals for analysis and discussion.

#### ***6.1.3.1 Network Wide Performance***

Overall, the ORGN showed a high degree of stability over the three-month monitoring window. Nearly all stations maintained their coordinates within the adopted 2 cm (horizontal) and 4 cm (vertical) limits for the vast majority of days. In fact, over 95% of all station-days stayed within threshold in both horizontal and vertical components, indicating that the current published coordinates are largely consistent with daily GNSS measurements. This confirms that no widespread network bias or datum drift occurred during the period, a reassuring result given the absence of major geophysical events. Station data completeness was also excellent: most sites reported daily solutions for almost every single day, and weekly aggregated solutions for every week, so any potential position anomalies would have been captured.

A summary of station performance is provided in Table 6.1, which lists, for each station, the number of daily solutions (out of approximately 91) that exceeded the thresholds, as well as the number of weekly solutions (out of 13) that were beyond thresholds. The majority of stations, representing well over half of the network, recorded zero daily threshold excursions. These stations can be considered very stable, with all daily residuals remaining under 2 cm horizontally and 4 cm vertically. For example, station ADEL (Figure 6.3) had no single day in which its OPUS-Static solution diverged beyond the tolerance in any component, and its weekly adjusted positions were all within limits, with perhaps one minor exception. This level of consistency was typical of stable stations.

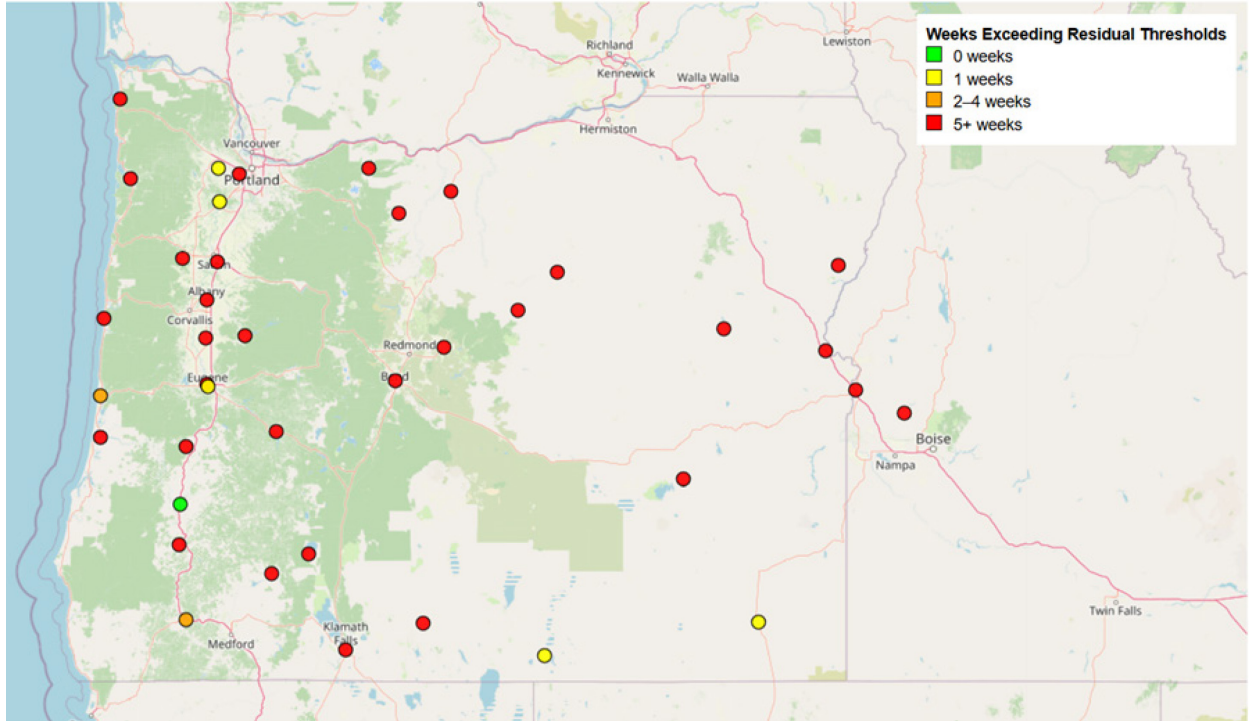
**Table 6.1: number of daily solutions (out of ~91) that exceeded the thresholds, as well as the number of weekly solutions (out of 13) beyond thresholds for all stations.**

<b>Station</b>	<b>Available daily solution</b>	<b>Daily solutions exceeding threshold</b>	<b>Available weekly solution</b>	<b>Weekly solutions exceeding threshold</b>
<b>ADEL</b>	89	0	13	1
<b>BASQ</b>	90	0	13	1
<b>BLY1</b>	90	1	13	13
<b>BNDM</b>	90	0	13	13
<b>BRNT</b>	91	8	13	13
<b>COBO</b>	82	63	13	13
<b>CRAN</b>	87	0	13	12
<b>CRLA</b>	87	77	13	12
<b>DOWL</b>	91	0	13	10
<b>FWBD</b>	91	0	13	13
<b>GRAS</b>	91	46	13	13
<b>GTPS</b>	90	0	13	2
<b>HALF</b>	91	0	13	6
<b>IDEM</b>	79	48	13	13
<b>KFRC</b>	90	0	13	9
<b>LCS1</b>	90	3	13	12
<b>LCS2</b>	91	91	13	13
<b>LCS3</b>	91	52	13	13
<b>MTCL</b>	91	0	13	9
<b>OAKR</b>	89	2	13	13
<b>ODOT</b>	90	2	13	13
<b>ONAB</b>	91	19	13	13
<b>ONTO</b>	90	0	13	8
<b>PCS2</b>	90	34	13	11
<b>PKDL</b>	90	4	13	7
<b>PNVL</b>	90	0	13	13
<b>PSPT</b>	88	4	13	7
<b>RDL2</b>	89	13	13	13
<b>REED</b>	91	90	13	13
<b>SEAS</b>	91	88	13	13
<b>SPRA</b>	91	2	13	13
<b>TILL</b>	90	20	13	13
<b>WAM</b>				
<b>  C</b>	90	19	13	13
<b>YONC</b>	90	2	13	13

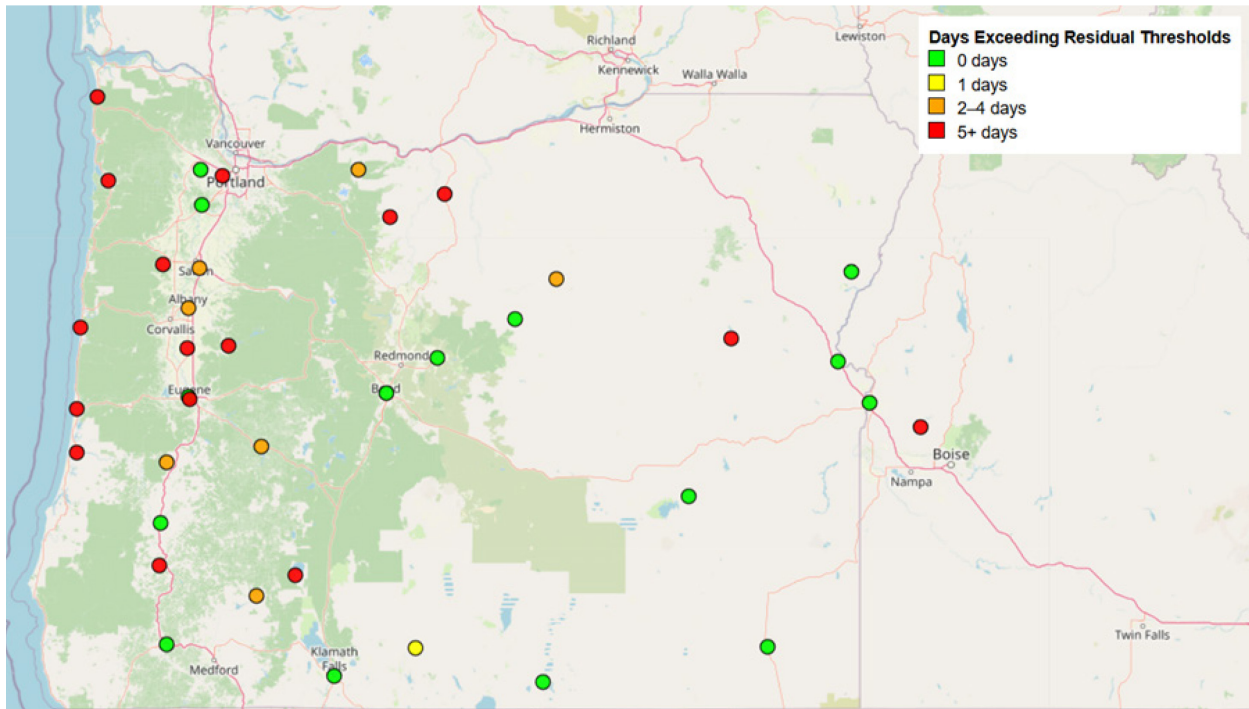
On the other hand, a subset of stations did exhibit notable deviations. As shown in Table 6.1, a few stations accumulated a significant number of threshold exceedances. For instance, station COBO exceeded the thresholds on 63 out of 82 days of data, and REED

showed deviations almost every day (90 out of 91 days). Several others (e.g., CRLA, LCS2) similarly exhibited large persistent residuals. In all these cases, the weekly network solutions for those stations were also flagged as out of tolerance in essentially every week of the study. This pattern suggests that these stations likely have a true offset relative to their “official” published coordinates, possibly due to unmodeled local movement or outdated reference coordinates that require realignment. It is important to note that these problematic stations are the exception rather than the rule: only a handful of stations fell into this category of consistently drifting or biased positions. They stand out clearly in the data and would be prime candidates for further investigation by network managers.

Between the two coordinate components, vertical residuals tended to exhibit more frequent excursions than horizontal. The 4 cm vertical threshold, while double the horizontal tolerance, was still exceeded more often at certain stations. This is not surprising, as GNSS vertical measurements are generally noisier and more prone to local errors (multipath, atmospheric delays) than horizontal measurements. Many stations that had issues showed recurring Up-component deviations. For example, CRLA had significant vertical offsets on 77 of 87 days, likely indicating that its antenna height or monument might have shifted, or that its original published elevation is biased. In contrast, horizontal residuals were very well-behaved across the network; only isolated instances of horizontal errors beyond 2 cm were observed, usually on single days. One station recorded a one-time spike in the East/North residual (a “brief horizontal outlier”) but was otherwise stable. Such one-off horizontal outliers could be caused by transient effects (e.g., unusual atmospheric conditions or poor satellite geometry on that day) and did not repeat subsequently.



**Figure 6.1: Map showing entire network alignment to the NSRS for the OPUS-P weekly solutions.**



**Figure 6.2: Map showing entire network alignment to the NSRS for the OPUS-S daily solutions.**

### 6.1.3.2 *Time Series Visualization*

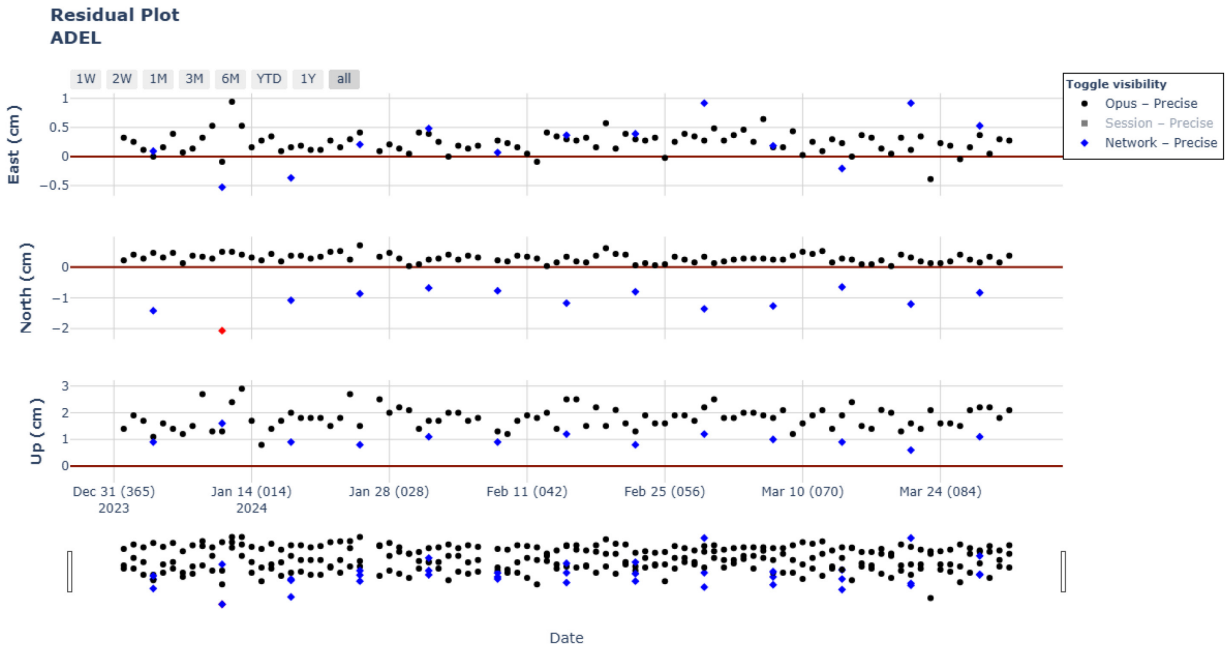
The benefits of the time-series approach are evident when examining individual station plots. Figure 6.3 shows an example time series for a well-performing station, ADEL, over the three-month period. In this figure, the daily residuals in East, North, and Up are plotted relative to the published coordinates. The station performs extremely well, with residuals clustering near zero and daily scatter remaining within approximately  $\pm 1$  cm horizontally and only a few centimeters vertically. The horizontal and vertical tolerance lines at two centimeters and four centimeters are not approached. Weekly network solutions for this station (indicated by distinct markers or a weekly-average line on the plot) coincide closely with the daily solutions and likewise never cross the tolerance bounds. The plot therefore confirms that the station maintains stable alignment and does not require a coordinate update. The time series appears nearly flat with only minor noise, which represents the ideal outcome.

In contrast, Figure 6.6 illustrates a station with recurring vertical excursions. In this plot, the station's Up residual drops below  $-4$  cm. The horizontal residuals for this station may still hover near zero (often the case when only the height component is problematic), but the vertical component shows a clear pattern of excessive deviation. Such a station likely has an unresolved vertical offset, which could be due to slow settling of the monument, an antenna calibration issue, or a reference datum discrepancy. Importantly, the time series reveals that these vertical errors persist day after day rather than being random noise; the station repeatedly breaches the vertical threshold on many consecutive days. The weekly solutions (which average the daily data) for this station are also significantly offset, corroborating that the issue is sustained. From an operational standpoint, plots like Figure 6.5 and Figure 6.6 would prompt the network manager to consider updating the station's published height (after verifying the cause), since the current coordinates are clearly misaligned with actual behavior.

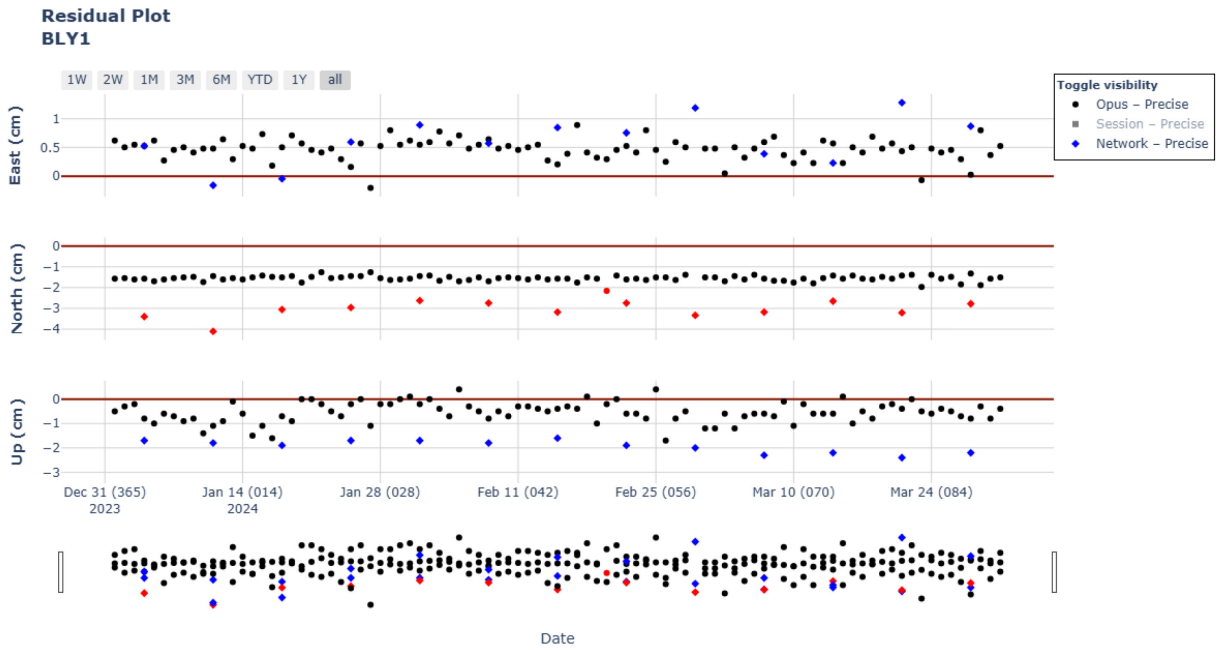
Figure 6.7 provides a different type of behavior and shows a station with greater variability and occasional horizontal outlier events. On some days, this station's East and North residuals remained within the  $\pm 2$  cm band (and the vertical within  $\pm 4$  cm). However, it appears to trend slightly out of alignment toward the end of the study period. The weekly solution for this station seems more stable, as the positions are averaged over the seven-day period. In practice, ORGN Align would flag that day's solution, but the operator might choose to monitor the station closely rather than immediately reset its coordinates. If no further excursions occur, it could be classified as a false alarm or an isolated incident. This example underscores the value of continuous monitoring: even fleeting issues are recorded, and decisions on corrective action can be made in context by examining surrounding days and weeks.

The time-series plots, with their mix of daily points and weekly trends, have proven extremely useful in this analysis. They make it easy to distinguish noise from systematic movement. Stations like the one in Figure 6.3 show only noise within tolerance; stations like Figure 6.5 show systematic, likely real offsets; and stations like Figure 6.6 show singular anomalies (in the horizontal). Having threshold lines overlaid allows the tool to

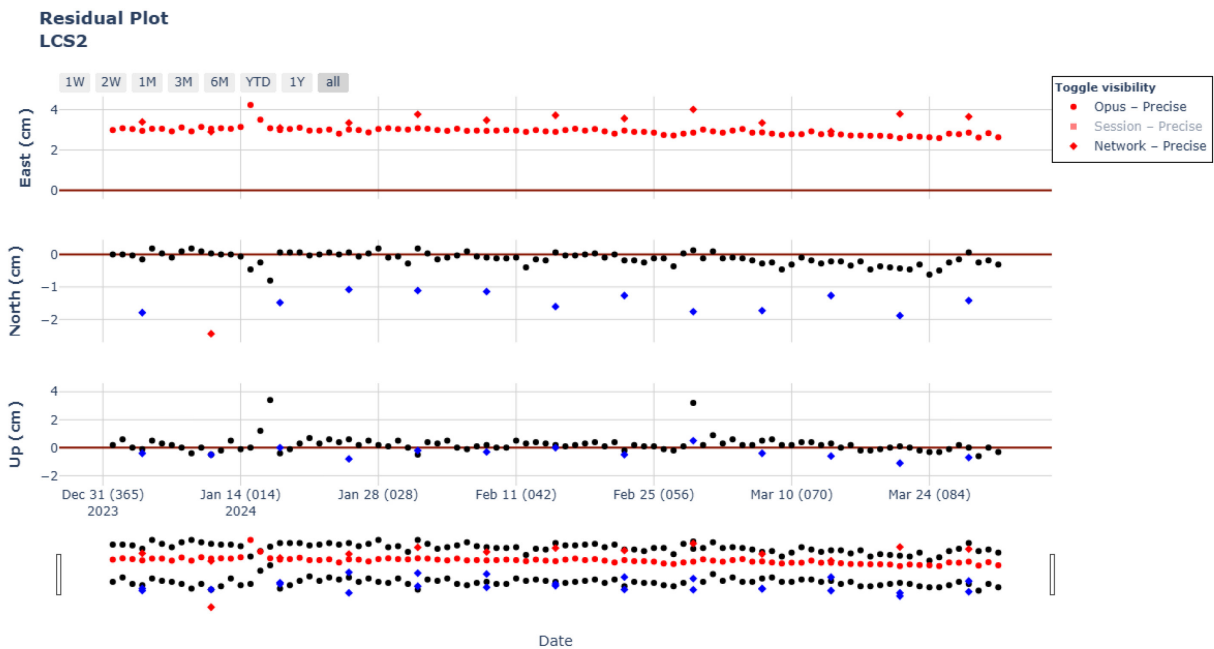
immediately highlight when and where a limit is crossed, simplifying the detection of events of concern.



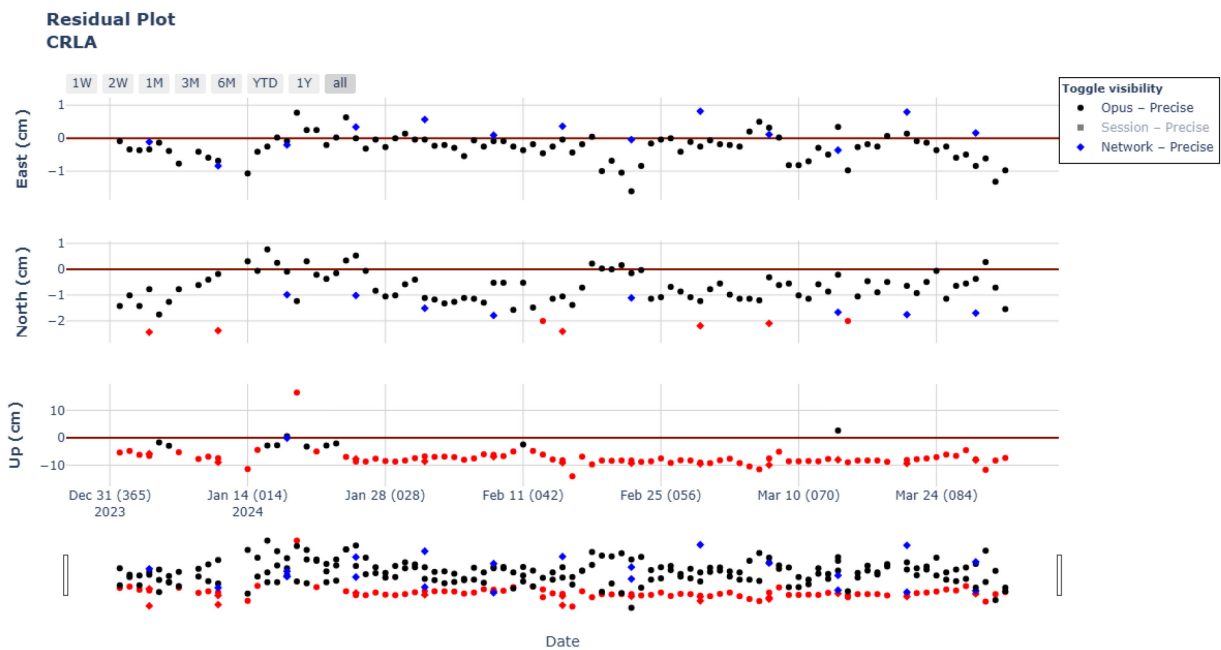
**Figure 6.3: Timeseries for Station ADEL showing daily and weekly residuals within tolerance.**



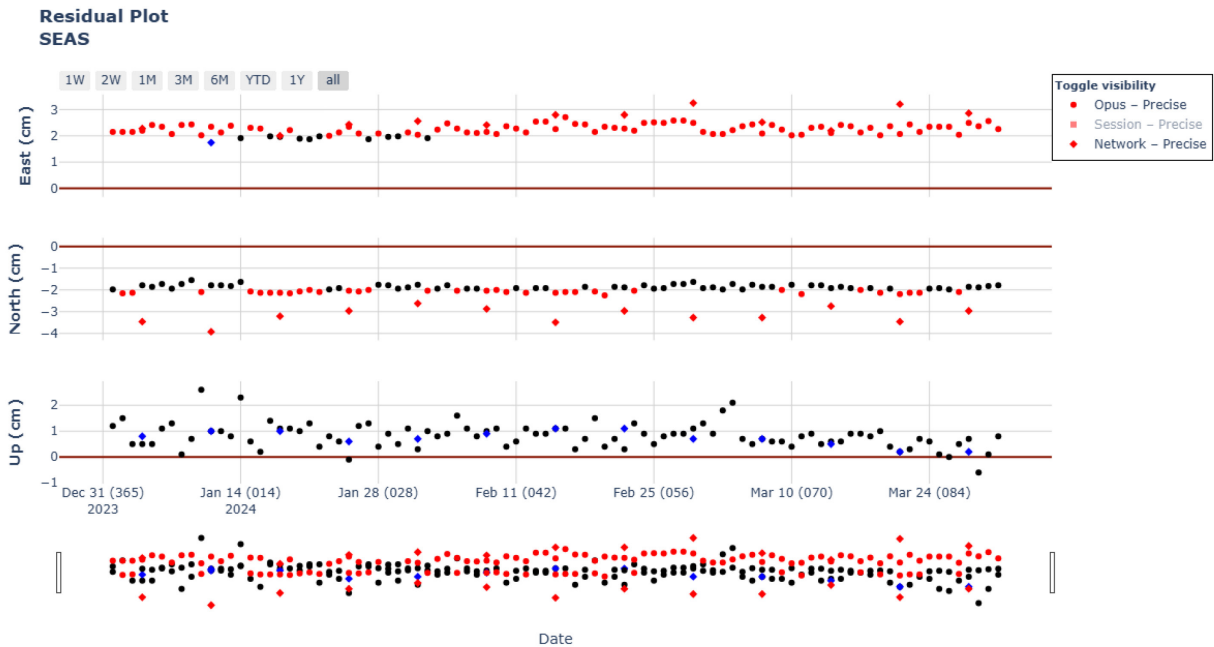
**Figure 6.4: Time series for station BLY1 showing a systematic offset in the North component.**



**Figure 6.5: Time series for station LCS2 showing a systematic East component offset that exceeds the horizontal tolerance.**



**Figure 6.6: Time series for station CRLA showing a persistent vertical offset and increased horizontal variability.**



**Figure 6.7: Time series for station SEAS showing horizontal excursions and elevated vertical variability.**

### 6.1.3.3 Threshold Effectiveness Analysis

The chosen threshold criteria (2 cm horizontal, 4 cm vertical) appear to be effective and appropriately tuned. As noted, more than 95% of station-days did not exceed these limits, indicating that the thresholds are not overly sensitive and do not trigger alarms for normal day-to-day coordinate scatter. When thresholds were exceeded, it was in cases corresponding to meaningful deviations, either persistent biases or obvious outliers. In other words, the thresholds successfully capture significant station shifts without generating false positives. For example, every station flagged for frequent threshold exceedance in Table 6.1 is now known to require attention; in an operational scenario, this would likely lead to republishing coordinates or investigating equipment. Meanwhile, stations that never exceeded the thresholds remained stable by all measures. This alignment between threshold triggers and actual station performance validates the 2 cm/4 cm tolerance choice as a sensible operational rule of thumb for the ORGN.

The system can also be considered for automated alerts or actions. If the ORGN Align software were configured to flag any station that exceeds the thresholds for two or more consecutive days, the results indicate that only the genuinely problematic stations would be identified. Stable stations would remain quiet, and stations with brief one-day excursions would generate a single alert that clears if the issue does not continue. No instances of spurious multi-day alerts caused by normal noise were observed, which suggests that the current thresholds produce very few false positives. One limitation is that a single-day excursion would still count as an exceedance even when no action is warranted. In an automated system, additional logic such as requiring three consecutive

days of exceedance before triggering a coordinate update could be used to prevent unnecessary responses to isolated anomalies.

#### **6.1.3.4 Interpretation and Discussion**

The three-month monitoring paints a picture of a network that is largely stable and well-aligned with the NSRS, with only a few outliers. No systemic drift affecting all stations or large clusters of stations was observed, which aligns with expectations given the absence of seismic or tectonic events in Oregon during early 2024. Any deviations were station-specific, pointing to local issues rather than network-wide frame problems. For instance, stations with large vertical errors may indicate local settling (e.g., soft ground or mounting issues at specific sites), whereas others might simply have outdated coordinates that were never updated to newer datums. There was no clear regional pattern, such as “all coastal stations moving upward”, and the stable and unstable cases were scattered, suggesting that equipment and monument health are likely the primary factors for the few problematic stations.

Highlighting a few stations of concern: LCS2 and CRLA consistently exceeded the thresholds by wide margins. These stations are clear candidates for immediate action. In practice, one would double-check their raw data and metadata; if confirmed, the appropriate response might be to re-survey and publish new coordinates. Another station, SEAS, exceeded thresholds on most days, though by smaller margins. This could indicate a moderate bias that nonetheless persists. If primarily vertical, one might choose to update just the orthometric height used for that station’s reference.

Conversely, a large number of stations demonstrated rock-solid performance. These stable sites provide confidence that the ORGN’s published coordinates are reliable and that the network does not require wholesale adjustment at this time. In fact, the stable stations effectively serve as internal checks on the alignment process: because they did not move, the daily and weekly solutions produced by ORGN Align remained consistent with their known positions, confirming both the software’s accuracy and the robustness of the underlying geodetic control.

Given the results, the 2 cm horizontal and 4 cm vertical thresholds appear to be set at a practical level. Tighter thresholds (e.g., 1 cm horizontally) might trigger alarms at perfectly fine stations due to normal noise, reducing the signal-to-noise ratio of monitoring. Conversely, looser thresholds could miss early signs of real movement. The 2 cm/4 cm limits strike a good balance, capturing meaningful changes, such as centimeter-level shifts that exceed typical daily scatter, while ignoring sub-centimeter variations. This analysis supports continuing with these thresholds for routine monitoring. There is always room for refinement; for example, a station in a geologically unstable area could be assigned a tighter threshold.

#### **6.1.3.5 Broader Implications for Network Management**

The positive outcome of this case study is that it demonstrates how a semi-automated tool like ORGN Align can be integrated into ongoing network maintenance. The analysis

clearly supports the viability of an automated re-publication workflow triggered by empirical data. For instance, if the ORGN were to adopt a policy stating that “any station exceeding 2 cm horizontal or 4 cm vertical for more than three consecutive days will be slated for a coordinate update,” our results provide evidence and traceability for such a policy. We observed exactly which stations would meet that criterion. By incorporating these monitoring results, ODOT can establish concrete rules, supported by NGS guidelines, for when to issue new coordinates to users, ensuring the network remains aligned without waiting for large errors to accumulate.

Additionally, the case study informs maintenance and calibration needs. Stations that frequently approach the thresholds might warrant a site visit; perhaps the antenna needs tightening, or an obstruction causing multipath could be mitigated. It also highlights the value of maintaining a history of station behavior: if a previously stable station suddenly starts drifting, it could indicate equipment malfunction or environmental changes at that site. ORGN Align time series would detect such issues immediately. In essence, this monitoring approach turns daily GNSS data into actionable insight for proactive network management, rather than relying on reactive fixes after users report problems.

#### 6.1.4 Summary and Implications

In summary, the three-month monitoring campaign confirmed that the ORGN’s coordinates are robust and remain within NSRS alignment tolerances under routine conditions. Most stations stayed within  $\pm 2$  cm horizontally and  $\pm 4$  cm vertically of their published positions on nearly all days, validating both the current coordinate set and the threshold values used for quality control. Only a small fraction of stations showed significant deviations, and these were readily identified by the automated workflow:

- **Most of the network is performing within bounds:** Over 95% of station-days were error-free relative to thresholds, and many stations had no threshold excursions at all. This indicates strong overall network stability and suggests that no widespread coordinate adjustments are necessary at this time.
- **Threshold criteria proved effective:** The chosen 2 cm/4 cm horizontal/vertical limits successfully flagged the few real issues (persistent station offsets) without generating excessive noise from normal data variation. The case study supports these tolerances as appropriate triggers for maintenance or re-alignment decisions, capturing meaningful movements while avoiding false alarms.
- **Time-series tools add significant value:** The visual residual plots and systematic tracking of daily and weekly solutions enabled quick diagnosis of station behavior. We could easily distinguish stable stations, gradually drifting stations, and one-off anomalies. This level of insight goes far beyond what manual, one-time checks would provide, underscoring the importance of continuous monitoring. The time-series approach helps GNSS network managers make informed decisions, such as determining whether a coordinate update is warranted only after confirming a sustained shift.

- **Targeted actions for flagged stations:** The analysis highlighted specific stations that were out of alignment. The next practical steps include re-surveying or reprocessing those stations and updating their published coordinates to restore NSRS compliance. In an operational setting, ORGN Align could trigger alerts for these cases, prompting timely intervention, such as notifying users of temporary coordinate changes or scheduling hardware inspections.

Looking ahead, this case study demonstrates a framework that ODOT can adopt for continuous quality control of the ORGN. By integrating daily or weekly network checks into routine operations, the agency can ensure that all stations remain correctly positioned. Over time, the tool could be enhanced with automated alerts, for example, notifying staff whenever a station's residual exceeds thresholds, further streamlining the monitoring workflow. Additionally, extending this monitoring over longer periods (seasonal or annual scales) could help detect slow trends that a three-month snapshot might not reveal, such as seasonal ground motion or long-term datum shifts. The success of this three-month trial provides a baseline for such future studies.

In conclusion, Case Study #1 validates the effectiveness of a semi-automated alignment workflow for routine network monitoring. It confirms that ORGN Align can reliably parse and evaluate daily GNSS data, uphold NSRS alignment through statistical checks, and provide actionable outputs to guide maintenance decisions. This lays the groundwork for more complex scenarios, as explored in the next case study, where the tool's capabilities will be tested against abrupt, event-driven station movements. The lessons learned here, particularly the reliability of thresholds and the clarity of time-series diagnostics, will inform responses to these more acute events, ensuring that even in extraordinary situations, the ORGN can be quickly realigned and kept accurate for all users.

## **6.2 CASE STUDY #2: NETWORK DECISION MAKING FOLLOWING A SEISMIC EVENT**

This case study demonstrates how ORGN Align can be leveraged as a decision-support tool following a geophysical event, focusing on its ability to detect small but meaningful station displacements and support real-time GNSS network management decisions. Unlike the long-term monitoring focus of Case Study #1, this example examines a short-duration, high-impact event: the magnitude 6.4 earthquake that occurred on December 20, 2022, near Ferndale, California.

Although the event did not directly impact the Oregon Real-Time GNSS Network (ORGN), it provided an ideal opportunity to test the alignment workflow on a small, seismically affected network in a neighboring region. The goal was to determine whether ORGN Align could accurately detect abrupt, centimeter-level station displacements and to explore how GNSS network managers might respond to similar events in their own operational context. This case study reinforces a central theme of the tool: ORGN Align does not make decisions for the user, but it empowers them to make better decisions by providing accurate, traceable, and visualized information about GNSS station behavior over time.

### **6.2.1 Seismic Context and Data Collection**

The December 20, 2022, earthquake struck offshore near Ferndale, California, with a reported magnitude of 6.4 and a depth of approximately 16 km. The shaking was felt across much of Northern California and parts of Southern Oregon. To evaluate the potential for station displacement, a mini-network of ten Continuously Operating Reference Stations (CORS) within approximately 150 km of the epicenter was selected for analysis. These stations are managed by a combination of federal and academic agencies and are representative of the type of infrastructure monitored by state-level RTN managers.

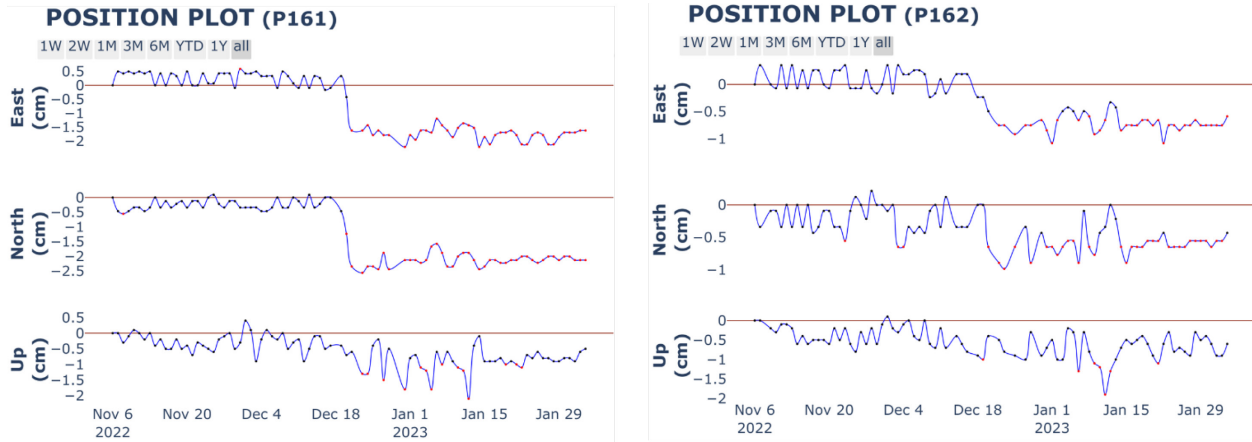
Twelve weeks of GNSS data were collected, spanning November 8, 2022, to February 14, 2023. This period included six weeks before and six weeks after the earthquake. Daily RINEX files were processed using the ORGN Align workflow. All processing was performed using consistent OPUS-Projects configuration parameters, and the results were parsed, visualized, and stored in the application's internal database.

### **6.2.2 Time Series and Displacement Detection**

The ORGN Align application generated daily residuals for each station in the East, North, and Up directions. These residuals were stored and visualized as time series to evaluate the temporal behavior of each station. Two stations, P161 and P162, were selected for detailed review due to their location within 75 km of the epicenter and the clarity of their displacement signals.

As shown in Figure 6.8, both stations exhibited distinct horizontal displacements beginning on December 20, 2022. Station P161 recorded a horizontal shift of approximately 1.6 cm, while P162 recorded a 1.0 cm shift. These values were derived directly from ORGN Align's parsed OPUS-Projects outputs and were confirmed by a consistent jump in East and North residuals. The time series also showed that, following the event, the stations stabilized at their new

positions over the subsequent several days, with no further drift observed during the post-seismic period. Importantly, this displacement was clearly visible against the backdrop of pre-seismic stability. Residuals had remained within  $\pm 0.5$  cm during the six weeks prior to the earthquake, suggesting that the observed movement was not part of a broader trend but rather a discrete geophysical event.



**Figure 6.8: Time series for stations P161 and P162 showing the horizontal displacement associated with the December 2022 earthquake.**

### 6.2.3 From Detection to Decision: Managing RTN Realignment in a Semi-Automated System

The ability of ORGN Align to detect small yet meaningful station displacements, such as those observed at P161 and P162 following the Ferndale earthquake, raises an essential operational question: how should an RTN manager respond? The true value of ORGN Align lies not merely in its ability to process data, but in its capacity to empower informed decision-making through structured, accessible outputs.

Although the workflow produces constrained and unconstrained GNSS solutions, daily residuals, and station-specific time series, it intentionally stops short of automating the decision to update coordinates. This boundary between automation and interpretation is by design. The system is built to support the judgment of qualified geodesists and RTN operators, not replace it. By integrating multiple levels of visibility, including residual analysis, time-series plotting, F-test results, and constraint ratios, ORGN Align equips managers with the tools they need to act confidently when faced with dynamic network behavior.

When a station shift is detected, several realignment strategies may be considered, each with trade-offs that must be carefully evaluated in the context of network geometry, service delivery, and user communication:

1. **Wait for Stabilization and Incorporate into a Future Adjustment:** This conservative approach is often appropriate when the observed displacement is minor, isolated to a single station, or still evolving. If the station does not serve a critical role in real-time correction delivery, and if the residuals remain near or slightly above threshold limits, it

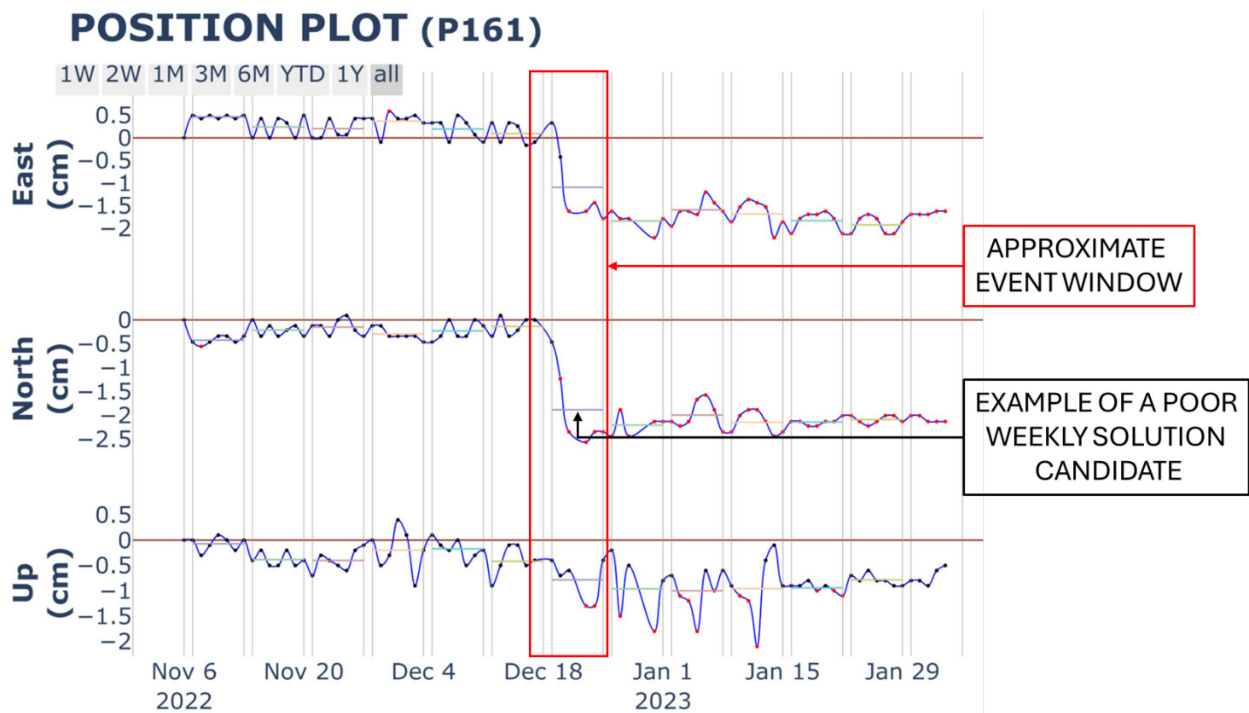
is generally advisable to monitor the time series rather than take immediate action. ORGN Align’s residual tracking and visualization tools make this monitoring process straightforward, allowing RTN managers to determine whether the station continues to drift or has stabilized at a new coordinate. If stabilization is confirmed over multiple days or weeks, the new coordinate can then be incorporated into the next weekly or monthly constrained network solution. This approach preserves the positional integrity of the network, avoids reactive updates based on transient noise, and aligns with best practices that prioritize deliberate, data-supported action. The trade-off is that users relying on the affected station for RTK or post-processing may continue to experience degraded accuracy until the update is made. This risk must be balanced against the benefit of waiting for a more complete and stable solution.

2. **Adopt Daily OPUS-Static Positions Temporarily:** For stations that provide real-time corrections or serve as regional hubs within the RTN, immediate action may be needed to prevent prolonged disruption to end users. In these cases, adopting a daily OPUS-Static position on a temporary basis can restore positional accuracy and service reliability while the full network catches up through its regular adjustment cycle. ORGN Align simplifies this process by presenting daily OPUS-Static solutions in both tabular and graphical formats, enabling managers to verify consistency and evaluate solution quality before taking action. This is particularly useful when a station’s displacement is confirmed and stable but broader network alignment is still pending. The primary advantage of this approach is responsiveness, allowing operators to quickly re-align a key station without waiting for a full network reprocessing effort. However, daily static positions can carry higher uncertainty due to limited observation windows, atmospheric variability, and satellite geometry. Additionally, relying on temporary coordinates for an extended period can lead to inconsistencies if the solution continues to evolve or if the station is re-anchored later using a different baseline configuration. Temporary adoption should be accompanied by documentation and clear user communication to minimize confusion.
3. **Propagate New Coordinates Across a Cluster or Full Network:** In rare but consequential scenarios, such as post-seismic deformation or structural failure at a hub station, a single coordinate update may not be sufficient. If the affected station serves as a primary control point or is deeply integrated into the network’s baseline geometry, any shift in its coordinates could propagate errors throughout its connected subnetwork. In these cases, the RTN manager may consider reprocessing the regional cluster or, in extreme circumstances, initiating a full network realignment. ORGN Align supports this strategy through its customizable hub selection, baseline design interface, and ability to re-run constrained and unconstrained solutions using different control stations. The benefit of this approach is holistic consistency, ensuring that all station coordinates remain internally aligned with respect to each other, reducing the risk of spatial mismatches between RTK users operating in different parts of the state. However, the cost is operational: full network reprocessing requires time, planning, and careful validation. If improperly implemented, it may introduce larger discrepancies than it resolves, particularly if unaffected stations are unintentionally shifted. Propagation strategies should be reserved for cases where multiple stations are demonstrably impacted or where continued alignment with the NSRS requires broad-based correction.

These options are not mutually exclusive; rather, they represent a spectrum of response strategies that can be adapted to the magnitude and spatial extent of observed motion. What is critical is that each decision is rooted in verifiable data, defensible logic, and clear documentation, a principle that ORGN Align supports throughout its workflow.

Figure 6.9 presents the daily GNSS residuals for Station P161, along with horizontal lines representing candidate weekly coordinate solutions. The plot clearly shows three distinct phases. First, in the period before the earthquake, the residuals remained low and stable, and the corresponding weekly solution agreed with the station’s published coordinate. During the week of the December 20, 2022, earthquake, the residuals diverged from the baseline, and the weekly solution computed at that time reflected these transient values.

While the weekly solution during the event might initially appear suitable for adoption, the plot further reveals that as additional data was collected, the station’s position stabilized. In this example, a stable weekly solution emerged approximately one week after the earthquake. Consequently, RTN managers are advised to refrain from updating the published coordinate based on the transient solution computed during the earthquake. Instead, they should adopt the stable weekly solution from the post-event period, ensuring that the new coordinate accurately represents the station’s true, stabilized post-seismic position and maintains alignment with the NSRS.



**Figure 6.9: Time series for station P161 showing the event window and the weekly network solutions.**

It is worth emphasizing that these decisions cannot be fully automated. Geodetic networks exist in the physical world, and that world does not always behave predictably. Monument instability, antenna changes, atmospheric anomalies, multipath effects, and regional tectonics can all

influence station coordinates in ways that resist simplistic rule-based automation. The human operator, armed with experience, context, and local knowledge, remains the essential final authority. ORGN Align recognizes this by functioning as a semi-automated decision support system. It automates what can be reliably automated, including data ingestion, baseline construction, OPUS processing, and residual reporting, while leaving the interpretive and communicative elements to the user. This is particularly important in post-event contexts, when timely and accurate decisions must be made under conditions of uncertainty.

This philosophy aligns with international best practices. As discussed in the literature review, the post-earthquake response by GNS Science in New Zealand following the 2016 Kaikōura earthquake provides a compelling example. Faced with widespread displacements across their national GNSS network, GNS adopted a cautious, criteria-driven approach to realignment. Station updates were deferred until stabilization could be confirmed, and coordinate changes were implemented only after undergoing rigorous internal review and being clearly communicated to users. Temporary positions were adopted for critical stations, but always with contextual justification and published disclaimers.

ORGN Align is well-suited to support this type of response model. Its capacity to visualize movement, track changes over time, and generate both session-based and cumulative residuals enables a workflow that is repeatable and adaptable at once. Network operators using ORGN Align benefit from rapid processing and automated outputs while retaining full control over when, how, and why coordinates are updated. In this sense, the Ferndale earthquake case study is not just an analysis of workflow performance; it is a demonstration of how semi-automated tools, when thoughtfully designed, can bridge the gap between raw data and high-stakes operational decisions. ORGN Align provides not only technical outputs but also a framework for professional judgment that reinforces consistency, transparency, and confidence in the stewardship of real-time GNSS networks.

#### **6.2.4 Summary and Implications**

This case study demonstrates that ORGN Align can accurately detect and quantify seismically induced GNSS station movement at the centimeter scale. The agreement with MGviz confirms the technical validity of the workflow, while the tool's visualization and database features provide valuable support for RTN managers evaluating station performance. Beyond detection, this case study illustrates the broader purpose of the tool: to inform, not automate, operational decisions. By presenting residuals and adjustment outputs in a transparent and repeatable format, ORGN Align enables GNSS network managers to respond confidently and consistently to unexpected station behavior.

We recommend the formal integration of this workflow into RTN operating procedures, particularly for post-event monitoring and recovery planning. Additional value could be gained by coupling ORGN Align with user notification protocols and by defining internal thresholds for republishing coordinates in response to seismic displacement events.



## 7.0 CONCLUSION

This project set out to design and implement a semi-automated workflow to support the consistent alignment of Oregon’s Real-Time GNSS Network (ORGN) with the National Spatial Reference System (NSRS). At the outset, several core challenges were identified: the lack of an integrated tool for managing GNSS baseline design and coordinate validation; the need for a repeatable, operator-guided alignment process; and the absence of tools to assist RTN managers in interpreting daily coordinate solutions across statewide infrastructure. This report documents the resulting system, ORGN Align, as well as the evaluation and validation of its performance through multi-scale case studies and long-term monitoring.

The development of ORGN Align addressed all the original research objectives. Specifically, the system (1) provides a consistent and structured workflow for GNSS network alignment, (2) supports the integration of legacy and real-time station data, (3) enables flexible configuration of baseline design and OPUS processing parameters, (4) offers tools for reviewing daily station performance and displacement, and (5) serves as a decision-support platform for managing RTN coordinate updates. These capabilities position ORGN Align as a critical resource for the ongoing stewardship of Oregon’s geospatial reference infrastructure.

Two case studies were used to demonstrate the system’s application: a three-month statewide monitoring campaign and a seismic response scenario involving stations impacted by the December 2022 Ferndale earthquake. Together, these examples confirm that ORGN Align meets the operational and technical needs of GNSS network managers while reinforcing the importance of coupling automation with professional judgment.

### 7.1 KEY TECHNICAL FINDINGS

The technical findings from this project confirm the effectiveness of the ORGN Align workflow across multiple operational contexts. From daily RINEX ingestion to final OPUS Project solution parsing, the system consistently produced reliable results, with surface-level metrics aligning with independent reference data.

One of the primary strengths of the workflow lies in its modular architecture. By dividing the process into three core stages, namely the Baseline Generator, RINEX Download, and OPUS Project Adjustment, ORGN Align enables users to retain full control over the alignment process while benefiting from automation and structured input handling. Each module includes visualization and validation tools, reducing the likelihood of user error and increasing transparency.

Time-series plots, residual summaries, and constraint tests provide clear indicators of station behavior over time. In the three-month monitoring case study, horizontal and vertical residuals remained within  $\pm 2$  cm and  $\pm 4$  cm, respectively, for more than 95% of all station-days, validating the chosen threshold parameters and confirming long-term station stability across the network. Moreover, the system correctly flagged several short-duration anomalies that could be used to trigger targeted inspection or station maintenance in future deployments.

In the Ferndale earthquake case study, ORGN Align detected centimeter-level displacement at two stations within a seismically active cluster. The magnitude and timing of the observed shifts closely matched independent displacement estimates from MGviz, confirming the workflow’s sensitivity and reliability. Just as importantly, the case study demonstrated how the tool supports a range of response strategies, including adopting temporary daily positions, waiting for stabilization, or triggering a full regional adjustment, without prescribing any single course of action. This reinforces the role of ORGN Align as a semi-automated, operator-informed system.

## **7.2 RECOMMENDATIONS FOR PRACTICE**

The findings of this project support several clear recommendations for future deployment and adoption of the ORGN Align system, particularly in the context of real-time GNSS network operations.

First, it is recommended that ORGN Align be integrated into the standard operational procedures used by RTN managers at ODOT. This includes using the system for weekly or daily alignment checks, pre-event and post-event monitoring, and long-term stability assessments. Regular use of the Baseline Generator and OPUS Project Adjustment modules can ensure that alignment with the NSRS remains current, especially during periods of high station turnover, monument replacement, or tectonic activity.

Second, network managers should establish internal policies and thresholds for coordinate updates, drawing from the diagnostic tools available in ORGN Align. This includes clear criteria for when to transition from OPUS-Static daily positions to constrained network solutions, and when to notify users of changes to published station coordinates. These decisions should be tied to repeatable metrics, such as residual thresholds, constraint ratios, or the frequency and duration of observed excursions in the time series.

Third, user communication protocols should be formalized as part of RTN operations. This may include publishing station status changes, documenting the timing and reason for coordinate updates, and issuing notices when temporary positions are in use. The Ferndale case study illustrates the risk of misalignment between observed station movement and publicly available coordinates, especially for high-precision users. ORGN Align makes it possible to identify and act on such discrepancies promptly, but users must be kept informed throughout the process.

Finally, continued training and documentation will be essential to support the system’s long-term adoption. ORGN Align capabilities go well beyond data processing; they support interpretation and operational judgment. RTN staff should be equipped to use the tool not only as a processor but also as a visual diagnostic environment to inform broader geodetic and maintenance strategies.

## **7.3 ROADMAP FOR IMPLEMENTATION**

Moving forward, a phased implementation of ORGN Align is recommended to ensure smooth integration into Oregon’s RTN operations and to maximize its value to the broader geodetic community:

- **Phase 1: Operational Deployment** – Finalize interface refinements and deploy the system within ODOT’s GNSS operations group. This should include SOP development, training sessions, and integration with existing data archiving and distribution systems.
- **Phase 2: Interagency Coordination** – Collaborate with other regional stakeholders, including universities, federal agencies, and private RTN operators, to expand the use of ORGN Align beyond Oregon. Shared alignment tools can improve interoperability across state lines and reduce redundancy in station management workflows.
- **Phase 3: Continuous Improvement** – Implement a feedback loop from users and operators to guide future updates. Potential enhancements include expanded GNSS constellation support, customizable alerting for time-series threshold violations, and improved integration with real-time correction software or network monitoring dashboards.
- **Phase 4: Broader Community Engagement** – Present outcomes of the project at national and regional conferences, contribute case studies to peer-reviewed publications, and explore opportunities for knowledge transfer to other U.S. states or international RTN operators facing similar challenges.

## 7.4 CLOSING REMARKS

The successful development and validation of the ORGN Align workflow mark a major step forward in the management of statewide GNSS networks. This system bridges the gap between complex geodetic processing and operational decision-making, allowing RTN managers to detect, interpret, and respond to station movement in a timely and informed manner. By combining automation with professional oversight, ORGN Align preserves the integrity of an RTN’s alignment to the National Spatial Reference System while delivering meaningful improvements in efficiency, traceability, and responsiveness. It is a tool not only for managing coordinates but also for strengthening confidence in the coordinates RTN users rely on.

This project was made possible through the continued support of the Oregon Department of Transportation and the contributions of partners at NOAA NGS and others across the geospatial community. The work presented here reflects a shared vision for maintaining geodetic accuracy, operational transparency, and long-term sustainability in a rapidly evolving geospatial landscape.

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