UPDATED SURVEY STANDARDS AND CONTROL GUIDANCE FOR IMPROVED OPERATIONS

Final Report

PROJECT SPR 304-821

Oregon Department of Transportation

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Abstract: Two control survey networks, observed via a traditional survey campaign and NRTK surveying campaign, were established at two independent study areas. To assess the performance of different surveying scenarios, a least squares adjustment was applied to all available traditional survey and NRTK data to create a reference dataset for each project site. Key findings: 1) When four 5-minute independent NRTK observations are made per point and the resulting baselines are adjusted using the Hybrid Network Methodology, a network accuracy of 1.8 cm in the vertical and 1.0 cm in the horizontal at a 95% confidence level is achievable. 2) Two hours between repeat observations is recommended to achieve fully independent solutions. 3) Total station (TS) observations improve overall horizontal accuracy of the network. 4) If vertical accuracies less than 1.8 cm at a 95% confidence level are required, then differential leveling should be performed. 5) When TS and differential leveling survey is required, not all stations need to be occupied with NRTK. 6) When NRTK observations are suitable for a project, static GNSS may not be required. 7) It is not recommended to hold the RTN published coordinates as a constraint in the adjustment. 8) It is recommended that RTN network managers ensure the published coordinates for the RTN base stations align with the NSRS. 9) Observing control stations with NRTK removes the requirement of having a minimum of 2 GNSS receivers observing points simultaneously.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS					APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH					LENGTH		
in	inches	25.4	millimeters	mm	mm	millimeters	0.039	inches	in
ft	feet	0.305	meters	m	m	meters	3.28	feet	ft
yd	yards	0.914	meters	m	m	meters	1.09	yards	yd
mi	miles	1.61	kilometers	km	km	kilometers	0.621	miles	mi
		AREA					AREA		
in^2	square inches	645.2	millimeters squared	mm^2	mm^2	millimeters squared	0.0016	square inches	in^2
ft^2	square feet	0.093	meters squared	m^2	m^2	meters squared	10.764	square feet	ft^2
yd^2	square yards	0.836	meters squared	m^2	m^2	meters squared	1.196	square yards	yd^2
ac	acres	0.405	hectares	ha	ha	hectares	2.47	acres	ac
mi^2	square miles	2.59	kilometers squared	km^2	km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME					VOLUME		
fl oz	fluid ounces	29.57	milliliters	ml	ml	milliliters	0.034	fluid ounces	fl oz
gal	gallons	3.785	liters	L	L	liters	0.264	gallons	gal
ft^3	cubic feet	0.028	meters cubed	m^3	m^3	meters cubed	35.315	cubic feet	ft^3
yd^3	cubic yards	0.765	meters cubed	m^3	m^3	meters cubed	1.308	cubic yards	yd^3
~NOTE: Volumes greater than 1000 L shall be shown in m^3.									
		MASS					MASS		
oz	ounces	28.35	grams	g	g	grams	0.035	ounces	oz
lb	pounds	0.454	kilograms	kg	kg	kilograms	2.205	pounds	lb
T	short tons (2000 lb)	0.907	megagrams	Mg	Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)					TEMPERATURE (exact)		
°F	Fahrenheit	(F-32)/1.8	Celsius	°C	°C	Celsius	1.8C+32	Fahrenheit	°F

*SI is the symbol for the International System of Measurement

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

EXECUTIVE SUMMARY

Surveying is required for the majority of Oregon Department of Transportation (ODOT) construction, maintenance, and emergency repair projects. All survey works require establishing a survey control network, which is the set of physical points on the ground to control the horizontal and vertical positions of all elements of the project. ODOT's recommended procedures in the 2015 Survey Policy and Procedure Manual (SPPM) primarily incorporate the use of static-GNSS (Global Navigation Satellite Systems), sets of angles observed with total stations, and differential level observations to determine the 3-dimensional coordinates of the project control points. The SPPM provides survey procedure recommendations for attaining coordinates with 2 levels of network accuracy: (1) a horizontal and vertical network accuracy of 10 mm (0.03 ft); (2) a horizontal and vertical network accuracy of 20 mm (0.06 ft). Although the current recommendations do provide satisfactory results, these recommendations can be inefficient and unnecessary for many types of projects. The SPPM specifically states that real-time network (RTN) GNSS does not fulfill the accuracy requirements for project control. However, the SPPM references outdated National Geodetic Survey (NGS) bluebook procedures that are based on GNSS capabilities from the 1990s despite the tremendous advances in GNSS in the last 30 years. Recently published results suggest promise for an efficient, campaign style survey method, namely a hybrid network, which combines network real-time kinematic (NRTK) baseline observations with static post-processed baseline observations (Weaver et al., 2018). The Weaver et al. (2018) study presents the feasibility of NRTK for achieving accurate coordinates for a control survey network with the support of modernized GNSS infrastructure.

The objective of this research was to enable modernization of ODOT's survey control protocols by integrating NRTK methodologies for increased cost efficiency and quality standardization across all ODOT projects. Two control survey networks, observed via a traditional survey campaign and a NRTK surveying campaign, were established at two independent study areas. The traditional survey campaigns were completed by ODOT personnel using differential levels, total stations, and static GNSS. The NRTK survey campaigns, completed by Oregon State University with the assistance of ODOT personnel, consisted of hundreds of independent NRTK observations at each study area that were then post-processed using the hybrid survey method proposed by Weaver et al. (2018). To assess the performance of different surveying scenarios, a least squares adjustment was applied to all available traditional survey and NRTK data to create a reference dataset for each project site. Considering that the reference dataset of each project site would produce the most probable coordinates for each project site, an empirical assessment was performed in which the accuracy of the hybrid GNSS survey and NRTK combined with traditional survey methods were assessed. The key findings of the experiments are:

a) When four 5-minute independent NRTK observations are made per point and the resulting baselines are adjusted using the Hybrid Network Methodology discussed in Weaver et al. (2018) a network accuracy of 1.8 cm (0.06 ft) in the vertical and 1.0 cm (0.03 ft) in the horizontal at a 95% confidence level is achievable.

b) A time interval of 2 hours between repeat observations is recommended to achieve fully independent solutions.

c) Total station observations improve the overall horizontal accuracy of the network.

d) If vertical accuracies less than 1.8 cm (0.06 ft) at a 95% confidence level are required, then differential leveling should be performed.

e) When a total station and differential leveling survey is required, not all stations need to be occupied with NRTK.

f) When NRTK observations are suitable for a project, static GNSS may not be required depending on the required accuracies.

g) It is not recommended to hold the RTN published coordinates as a constraint in the adjustment. Doing so will result in the control points being referenced to the current realization/adjustment of the RTN and potentially not to the NSRS.

h) It is recommended that RTN network managers ensure the published coordinates for the RTN base stations align with the NSRS to the best extent possible and are able to each stations health and alignment to the NSRS daily.

i) Observing control stations with NRTK removes the requirement of having a minimum of 2 GNSS receivers observing points simultaneously on a project resulting in less equipment being needed for the GNSS portion of a control network survey.

Considering varying accuracy requirements of different surveying projects, the research findings provide the most efficient and effective methods to satisfy surveying requirements by reducing surveying efforts. More specifically the need for total station surveys can be reduced depending on the level of accuracy required for the project. The results from this study also provide a good baseline of accuracies that the Oregon Real-Time Network (ORGN) can provide and will provide ODOT with information that can be utilized to modernize the ODOT SPPM to leverage the ORGN for establishment of project control.

1.0 INTRODUCTION

Surveying is required for the majority of ODOT construction, maintenance, and emergency repair projects. ODOT Surveyors use total stations, leveling, and Global Navigation Satellite Systems (GNSS) to establish survey control networks. However, current ODOT field procedures and processing protocols are time consuming and not always tailored to the complexity of individual projects with different purposes. Recent innovation in GNSS and Real Time Network (RTN) technologies have enabled rapid acquisition of highly accurate positioning data with errors close to the accuracies achieved with traditional surveying methods (e.g. static GNSS combined with total station and/or differential leveling observations). To accommodate the expected increased workload associated with increased projects from Oregon's 2017 Transportation House Bill (HB2017), integration of more efficient surveying protocols that leverage recent innovations in GNSS RTN may be advantageous.

To develop recommendations for optimizing ODOT survey protocols, standard ODOT survey procedures were compared side-by-side with recently published Network Real-Time Kinematic (NRTK) procedures (Allahyari et al. 2018; Weaver et al. 2018) at two active ODOT project sites in two Phases. Phase 1 pilot testing was designed to determine a baseline accuracy for NRTK derived coordinates using the Oregon Real-Time Network (ORGN) and to compare those coordinates to the current ODOT control survey procedures. Using the results from the analysis of Phase 1, modernized survey procedures leveraging RTN observations were created. Phase II pilot testing was designed to validate and refine the findings from Phase 1 at an independent location. Each Phase of the project was conducted on existing ODOT project control networks to ensure representation of ODOT survey field conditions.

Pilot Phase I focused on answering the following questions:

1. How can the survey methodology leveraging NRTK observations be modified to increase efficiency while still meeting a desired accuracy specification?

2. Regarding NRTK observations, how does the network accuracy vary as more observations are made? More specifically, how many independent repeat observations are required to achieve a desired accuracy?

3. Does the overall accuracy change as the time between repeat NRTK observations changes (e.g. 1 hour, 2 hours, or 3 hours between repeat observations)?

Pilot Phase II was designed to verify the derived optimized NRTK methodology from Phase I at an independent ODOT project site to ensure the results from Phase I were repeatable. In addition to verifying the proposed survey procedure, the following questions were also investigated:

1. If all stations in the control network are observed with NRTK observations, can we minimize the amount of total station work required and still achieve the same levels of network and local accuracies?

2. Do the results from Phase I apply to varying control network geometries? (e.g. a long linear control network vs. a rectangular gridded control network)

1.1 BACKGROUND

Control surveys are the foundation for all survey work on a project as they are used to establish a common network of physical points whose coordinates are used to control the horizontal and vertical positions of all elements of the project. In many cases, these project control points are referenced for years, and sometimes decades after initially being established. ODOT's recommended procedures, as outlined by the 2015 Survey Policy and Procedure Manual (SPPM) (ODOT, 2015), primarily incorporate the use of static-GNSS, sets of angles (i.e. horizontal and vertical angles measured in multiple faces, and distances) observed with total stations, and differential level observations to determine the 3-dimensional coordinates of the project control points. The SPPM specifically states that GNSS observations from a real-time network (RTN) does not fulfill the accuracy requirements for project control due to the lack of redundancy or ability to incorporate those observations into a least square adjustment, which is ODOT's recommended adjustment method for project control (ODOT, 2015). Even though NRTK observations are not recommended in the SPPM, many surveyors in the state have been incorporating the real-time coordinates into their control network adjustments. However, RTNs have limitations, such as, any error between the RTN network station as provided by the RTN network manager and the National Spatial Reference System (NSRS) is propagated to the user. Ideally, this would not be an issue as the RTN network manager should be ensuring the RTN reference stations are accurately referenced to the NSRS (Weaver et al., 2018). To mitigate this issue and to check the alignment with the NSRS, it is best practice to tie the control survey project to multiple nearby continuously operating reference stations (CORS) using static-GNSS observations and post-processing. Note, this requires that the CORS are held as control in the least square adjustment as NGS defines this network of active stations as the backbone of the NSRS.

With the development of the Oregon Real-Time GNSS Network (ORGN), which continuously operates a network of GNSS reference stations across Oregon and neighboring states, together with the updated ability to provide both GPS and GLONASS observation corrections, ODOT is well positioned to modernize survey procedures that balance efficiency, available resources, and accuracy needed for individual projects. Two recent publications with Oregon-based field components provide a comprehensive framework to evaluate possible new control requirements that could enable ODOT to take full advantage of GNSS RTK technology. Weaver et al. (2018) evaluated hybrid survey networks that combine real-time and static GNSS observations. Allahyari et al. (2018) evaluated parameters that affect achievable accuracies of NRTK data including observation duration, inclusion of GLONASS observables, network based versus single baseline RTK (sRTK), and baseline length. Although there is clear evidence that RTNs can produce accurate absolute coordinates from the previous literature, there is still a need to assess the resulting coordinate accuracies when NRTK observations are combined/compared with direct observations using traditional survey equipment (e.g. total stations and differential levels).

Weaver et al. (2018) proposed a *hybrid network* survey methodology that combines static GNSS observations with the real-time GNSS observation. The hybrid network method requires users to include the observed NRTK GNSS vectors by incorporating them in a least squares adjustment with static GNSS observations derived from the reference base station and other nearby CORS. The NRTK vector is comprised of a delta easting, northing, and elevation from a reference base station to the rover allowing the rover observations to be directly tied to the NSRS assuming the reference base station is also connected to the NSRS. The GNSS vectors also contain other information such as the variance-covariance matrices of the delta easting, northing, and elevation, which is useful for weighting each observation in a least squares adjustment. The benefit of the hybrid network method is that it allows users to combine the NRTK-GNSS observations with additional observation types (static-GNSS, total station, differential leveling, etc.) in a least squares adjustment allowing NRTK observations to be more suitable for control survey applications. Note, Weaver et al. (2018) originally proposed the hybrid survey approach for the purpose of height modernization surveys where the primary goal was to efficiently determine the most probable ellipsoid height of a point by combining only static-GNSS and NRTK observations via a least square adjustment and not incorporating the traditional terrestrial observations (i.e. total station and differential leveling) as proposed in this study.

The objective of this research is to test the applicability of the hybrid GNSS survey campaign approach along with traditional terrestrial observations for the purpose of establishing project control. In determining the applicability of this approach, the research team compared the resulting accuracies from the hybrid network method to the existing ODOT procedures for two geometrically different control networks. The research also assessed the affects traditional survey observations (total station, and differential leveling) have on the resulting accuracies when combined with the hybrid GNSS survey approach.

To accomplish these objectives static-GNSS, NRTK-GNSS, total station, and differential leveling data were evaluated from two existing project control networks in Oregon. The static-GNSS data were post-processed in *OPUS-Projects 1.5 (BETA)* to derive the vectors that would tie the reference base stations utilized at each control network to the NSRS following recommendations in the OPUS-Projects user manual (Armstrong et al., 2015). The static-GNSS vectors were then included in the least squares adjustments performed in *MicroSurvey StarNET v9.0* where they were combined with the NRTK-GNSS, total station, and differential leveling observations.

For comparison, many permutations of the data from each of the two project sites were created and compared to a reference dataset for each project site such that the accuracy of each permutation could be assessed. The reference data set for both Phase I and Phase II pilot sites was developed by combining all data for each site into a single least squares adjustment, one for each Phase, resulting in the most probable coordinates for each of the points within each project site. Typically, a reference dataset will be an order of magnitude more precise than the data being compared, but a dataset of that nature can prove to be difficult to acquire when the data being compared is typically considered “control” for all other projects. The accuracy of each permutation, or dataset combination, were then used to compute and plot the horizontal and vertical errors as a function of: (a) the number of NRTK-GNSS baseline observations per station and (b) the time between repeat NRTK-GNSS baseline observations per station. Similar plots were also created from adjustments that incorporate the addition of the following data sets: (1) sets of angle observations from a total station; (2) differential leveling observations between all stations; and (3) a combination of (1) and (2). An additional assessment was also performed in which only a small number of stations, selected such that they are spaced evenly throughout the control network, were observed with NRTK-GNSS. These sparse NRTK-GNSS observations were then combined with total station and differential leveling observations. This additional assessment was used to evaluate the effect on the overall absolute accuracy of the control network when only a subset of the control stations are observed with NRTK-GNSS. Results from this study directly inform the feasibility of incorporating the GNSS hybrid network survey approach as a recommended survey methodology for the purpose of establishing project control for ODOT.

The following background subsections will elaborate on the following: (1) current ODOT methodology for establishing project control; (2) the importance of network and local accuracy for project control; (3) the progression of NRTK-GNSS and how real-time networks operate; and (4) how the proposed survey methodology will be beneficial for the upcoming updates to the North American vertical and horizontal datums, estimated to be released by approximately 2025.

1.1.1 Current ODOT Methodology

The ODOT procedures for establishing project control outlined in this section are summarized from Chapter 3 of the 2015 version of the ODOT Survey Policy and Procedure Manual (SPPM) (ODOT, 2015).

The SPPM provides survey procedure recommendations for attaining coordinates with two levels of network accuracy, reported at a 95% confidence level, as defined in Table 1: (1) a horizontal and vertical network accuracy of 10 mm (0.03 ft); and (2) a horizontal and vertical network accuracy of 20 mm (0.06 ft). The recommended methods used to achieve these accuracies varies primarily on the level of redundancy made in the observations used to determine a point's location. For example, a strategic point, which is a point established for the purpose of providing an instrument location for mapping, terrain modeling, or other non-control work (ODOT, 2015), requires less redundancy in an observation than the controlled strategic point but is still required to achieve the same level of network accuracy as defined in Table 1. The additional redundancy is typically achieved by incorporating cross ties to additional stations and/or by incorporating multiple measurements for the same observation.

Table 1.1: Summary of Network Accuracy Requirements for Project Control as Identified in the 2015 SPPM (ODOT, 2015).

	Horizontal	Vertical
Horizontal Network Points	10 mm (0.03 ft)	N/A
Vertical Points	N/A	10 mm (0.03 ft)
3D Network Points	10 mm (0.03 ft)	10 mm (0.03 ft)
Controlled Strategic Points	20 mm (0.06 ft)	20 mm (0.06 ft)
Strategic Points	20 mm (0.06 ft)	20 mm (0.06 ft)

For 3D Network Points, the current ODOT specifications outlined in the SPPM requires that the following types of observations are made: (a) Network sets of angles; (b) Differential Leveling between all stations and at least one NGS published vertical control point; and (c) Static GNSS observations on a subset of the stations within the network. *Sets of angles* are total station observations that include horizontal and vertical angles, and slope distances measured between adjacent control points. There are primarily two approaches that are used to acquire sets of angles with a total station and they are defined as *Networks* and *Traverses*. The primary difference between the two is the total number of stations being observed from each instrument setup, where an instrument setup occurs at each control point included in the control network. Figure 1.1 is used to elaborate on the differences between a total station network survey (top) and a total station traverse survey (bottom). As shown, a total station network survey includes more redundancy than a total station traverse survey. To satisfy the redundancy requirement identified in the SPPM for 3D Network Points, it must be possible to remove any observation from the least square adjustments and have enough data remaining to compute, prove, and adjust the point. Based on the inability to achieve this level of redundancy, a traverse, which only requires two stations be observed from a single instrument setup (i.e. a foresight station, and a backsight station), is not currently recommended for the establishment of 3D Network Points in the SPPM. Although it should be noted that a traverse survey could be strengthened by incorporating optional crossties as shown in Figure 1.1, which would result in the traverse survey transitioning to a total station network survey.

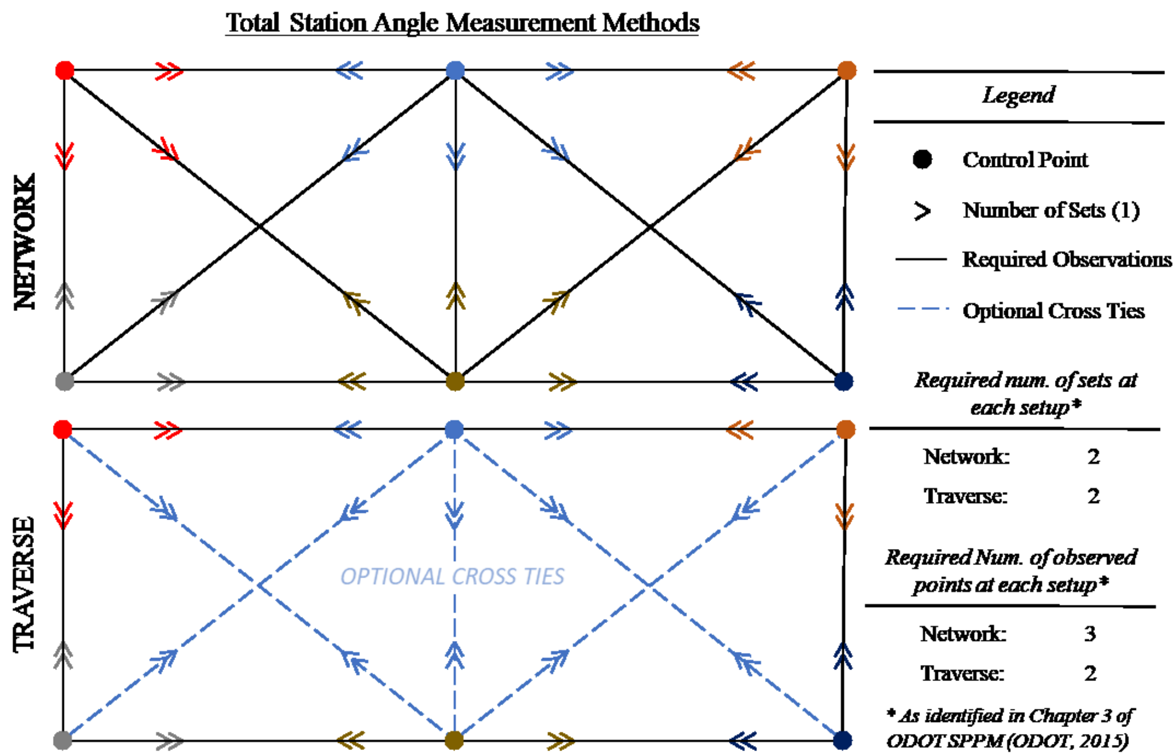

Figure 1.1: Depiction of the differences between a traverse total station survey (bottom) and a network total station survey (top) as identified by the 2015 ODOT SPPM (ODOT, 2015).

One of the purposes of this study is to determine if there is a more efficient survey methodology that can achieve network accuracies that satisfy the requirements identified by the SPPM as *3D Network Points*. To accomplish this task, an understanding of the current recommended survey procedures for determining 3D network points needs to be established. To elaborate further on the procedures currently recommended by the SPPM, a simplified control network, represented in Figure 1.2, will be used as an example.

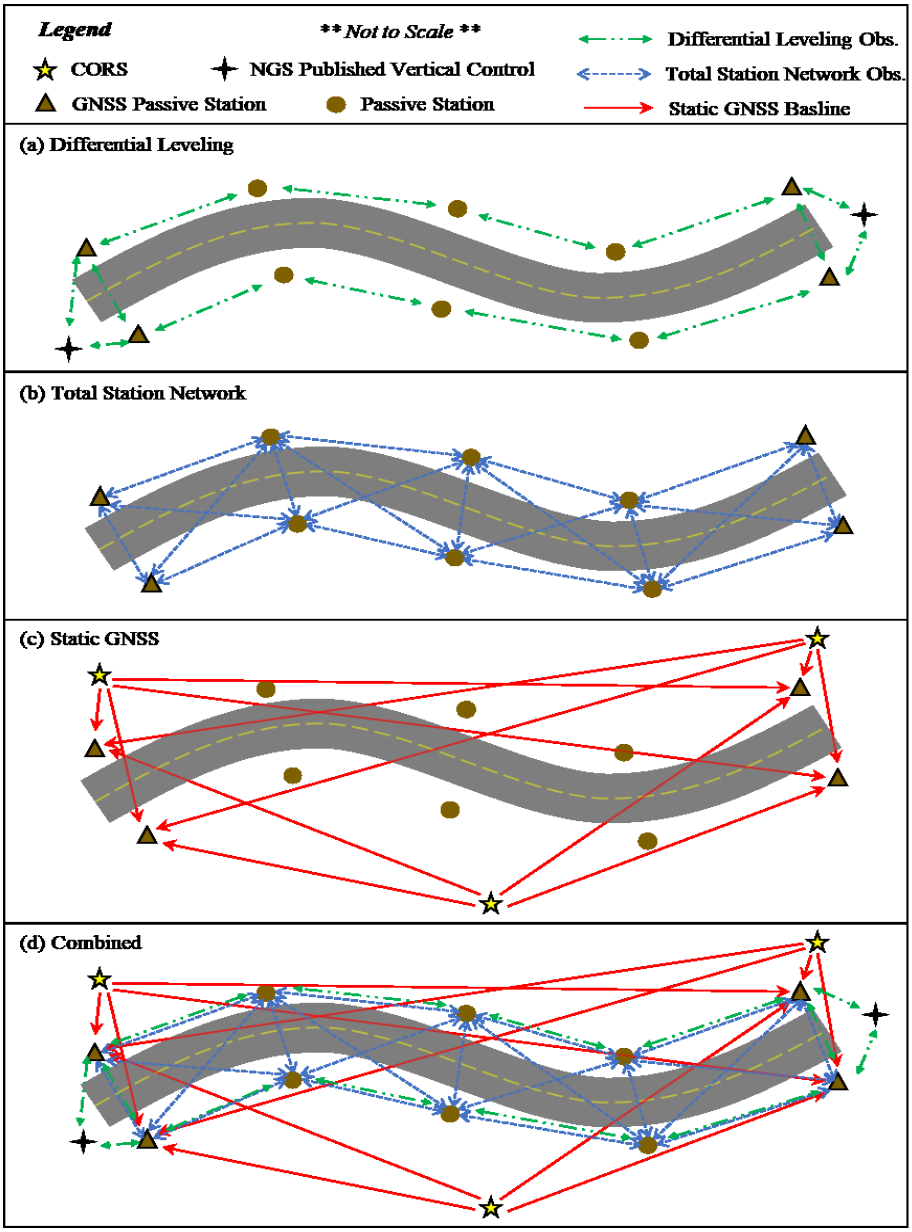

Figure 1.2: A simplified example of a common ODOT control network with the following data types being represented: (a) Differential leveling survey tied into 2 NGS published vertical control benchmarks; (b) Total station network survey including all control points in project; (c) Static-GNSS Baselines from 3 CORS surrounding two subsets of the control points; (d) a representation of the three methods above being combined into a single adjustment.

Static observations using a GNSS receiver are the preferred method for many control survey activities. In fact, static GNSS observations are the current ODOT recommended method to determine the absolute location of the control network relative to the NSRS. The ODOT SPPM provides the static-GNSS survey specifications outlined in Table 1.2, which includes the equipment required and field procedures necessary to achieve the desired *3D Network Point* network accuracies identified in Table 1.1. When performing static GNSS surveys two GNSS receivers are required such that simultaneous observations on control points within the project can be made. These simultaneous observations enable the user to compute baselines between the simultaneously observed points while also computing baselines from nearby CORSs. The duration of these static observations is dependent on the baseline lengths between the CORSs and the receiver observing the unknown points on the project site. Therefore, proper survey planning is essential to satisfy the procedures identified in the SPPM. At a minimum, the survey planning should include pre-selection of the CORSs that will be used for post-processing and the computations of the distance from the selected CORS to the project site such that the appropriate observation times are selected. When selecting the CORSs that will be used in post-processing it is recommended to utilize the NGS published short-term time series plots (see example in Figure 1.3) to ensure that the selected CORS is stable and the NGS published coordinates are in agreement with the current position of the CORS.

Table 1.2: Summary of Static GNSS Survey Requirements Identified by the 2015 ODOT SPPM (ODOT, 2015).

Equipment	
Minimum number of receivers	2
Antenna support setup	Tripod
Field Procedures	
Minimum satellite elevation mask in degrees above horizontal	10
Epoch interval in seconds of time for observations	5
Minimum time in minutes between starts of observations on any one station	45
Minimum number of observed satellites	4
Maximum GDOP/PDOP value during station observations	8/6
Minimum observation time in minutes for baselines less than 5 km	20
Minimum observation time in minutes for baselines 5 to 10 km	30
Minimum observation time in minutes for baselines 10 to 15 km	45
Minimum observation time in minutes for baselines 15 to 30 km	60
Minimum observation time in minutes for baselines greater than 30 km	120

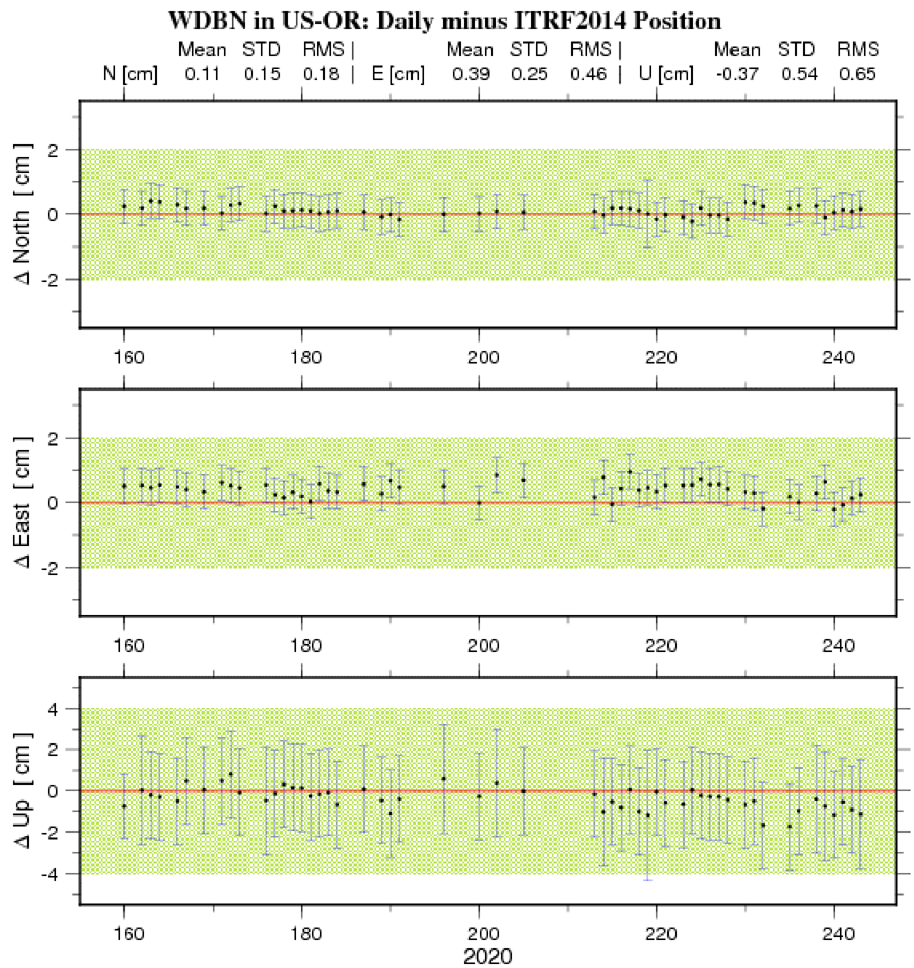

Figure 1.3: An example of a short-term time series plot for a CORS. The red line is the NGS published position, the green hashed area is the tolerance of NGS positions (+/ 2cm horizontal and +/- 4cm vertical). The error bars shown are 1 sigma. For more details on short term plots see NOAA's NGS website (https://ngs.noaa.gov/CORS/coords.shtml).

When performing the static GNSS survey, each point being observed should be observed at least twice for redundancy. The points to be observed with static GNSS should be at the extents of the project. For example, in Figure 1.2(c) the stations being observed with static-GNSS are at the ends of this long linear project. It should be noted that for longer projects, as shown in the bottom of Figure 1.4, the addition of static-GNSS observations is sometimes necessary at points throughout the project in addition to the points being observed at the extents to limit the propagation of errors between the two ends of the project. For a rectangular project, the outermost points to be observed with GNSS should be selected such that the baselines generated between the simultaneous observations create an envelope that bounds the project site as shown in Figure 1.4.

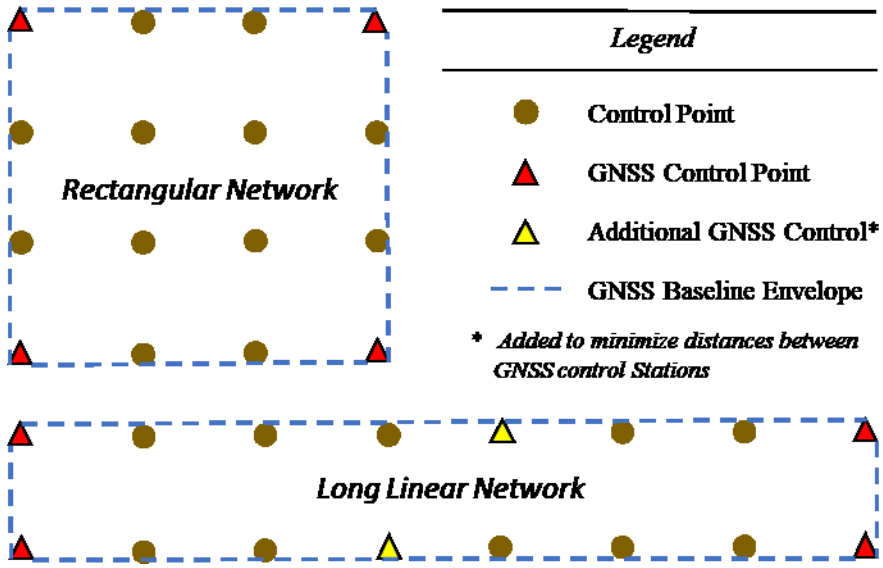

Figure 1.4: Example of where GNSS stations should be selected to ensure the GNSS baseline envelope encompasses the entire project. Note: additional stations may be necessary to limit the distance between GNSS control stations as shown in the longer linear network example.

The last data type that is required for the establishment of 3D Control points identified by the SPPM is differential leveling observations between all points within the project. With some modifications, the ODOT procedure for differential leveling follows those for Third Order leveling in the 1984 Federal Geodetic Control Committee Standards and Specification for Geodetic Control Networks (FGCC, 1984). It also draws from the supplemental FGCS Specifications and Procedures to Incorporate Electronic Digital/Bar-Code Leveling Systems (FGCS, 2008). In summary the differential leveling requirements identified by the SPPM are:

- Limit observation distance to 90 meters (300 ft).
- Balance distances from each setup to within 10 m (30 ft).
- Balance foresight and backsight distances on each run between durable marks to within 10 m (30 ft).
- When leveling with two rods, leapfrog rods such that only one rod occupies each turning point.
- When establishing a turning point, choose a point that is vertically stable for the duration of the survey and has a distinct high point.
- Connect any temporary benchmarks to three or more adjacent project vertical control network points (temporary bench marks) or NGS published bench marks.
- The level loop should include a minimum of one NGS published vertical control point.

After the three required data types for establishing a 3D network point have been collected, they are combined in a least squares adjustment to determine the final coordinates for the control network. When performing the least squares adjustment, an unconstrained or minimally constrained adjustment is initially performed for each data type to identify and remove blunders and outliers from the network measurements. After all tolerances have been satisfied, the three adjustments are combined such that a final fully constrained adjustment can be performed (see Figure 1.2(d)).

The current ODOT SPPM does not recommend the use of NRTK-GNSS for the establishment of 3D Network Points used for project control, but it is an acceptable method for establishing controlled strategic points as identified in Table 1.1. If NRTK GNSS observations are being used for the purpose of establishing or validating the controlled strategic points, the requirements outlined in Table 1.3 must be satisfied. It is important to note that a *Check Shot,* an observation made on a known point, is required at the beginning and end of every NRTK-GNSS survey to validate the GNSS receiver input and output settings.

Table 1.2: NRTK-GNSS Field Procedures Requirements as Outlined by the 2015 ODOT SPPM (ODOT, 2015).

NRTK-GNSS Field Procedures for Establishment of Strategic Points	
Check Shot required before and after other work	Yes
Occupation time in epochs	60
Minimum time in minutes between observations	30
Maximum GDOP/PDOP value during station observations	8/6
Rover satellite mask in degrees above horizontal	15
Maximum horizontal difference in meters (feet) between occupations	0.020 (0.07)
Maximum vertical difference in meters (feet) between occupations	0.025 (0.09)

1.1.2 Relative Accuracy vs. Absolute Accuracy

The accuracy requirements for a survey vary greatly based on the purpose of the project; as such, the recommended survey procedures should also vary based on the project requirements. For example, a GIS database of trees or road signs may only need to have an accuracy of 1 m (3.28 ft), whereas, primary control monuments for a road development project might need an accuracy of 0.02 m (0.07 ft). The survey procedures required to achieve a level of accuracy of 0.02 m (0.07 ft) are typically going to be much more intensive when compared to the procedures required to achieve a level of accuracy of 1 m (3.28 ft). Therefore, a more diverse set of survey methodologies are required based on varying levels of accuracy. However, the level of accuracy is not the only important factor when determining recommended survey procedures, it is also important to define the type of accuracy required.

It is necessary to distinguish between the two categories used to define the accuracy of a point's position. Those two categories are: *relative accuracy* also referred to as local accuracy; and *absolute accuracy*, also referred to as network accuracy. *Absolute accuracy* is used to define the uncertainty of a position relative to a datum or reference system. *Relative accuracy* represents the accuracy of a point with respect to nearby adjacent points within the same set of data. A point with exceptional relative accuracy may not have good absolute accuracy, and vice versa. For engineering related projects (e.g. mapping for engineering design, construction staking, etc.) relative accuracy may be the most immediate concern. However, those tasked with constructing a control network that is referenced throughout the duration of a project will need to determine the project's absolute accuracy or its positional relationship to the realization of the datum on which they are working. Understanding these categories of accuracy is especially critical as GNSS becomes more commonly used for the establishment of control coordinates due to GNSS's ability to allow users to directly tie into an appropriate national geodetic datum. In the United States, this most often means the data is tied into at least one of the Continuously Operating Reference Stations (CORSs) that are considered the backbone of the National Spatial Reference System (NSRS) managed by NOAA National Geodetic Survey (NGS).

The ability of GNSS observations to be directly connected to the NSRS allows the user to determine the absolute accuracy of the observed points but does not always allow for the determination of local accuracy between adjacent stations as there are no direct measurements made between the stations. This is especially true when considering real-time GNSS surveys where the resulting baselines are tied from the reference base station to the rover for each observed station. The baseline is not directly computed between each of the stations being observed. The exception occurs when considering a traditional static GNSS survey campaign where multiple GNSS receivers are used to simultaneously observe numerous stations throughout the project. Using these simultaneous observations between each station the baselines between each station can be computed using linear combinations (e.g. single, double, or triple differencing) resulting in direct measurements between stations on the project site. It should be noted that local accuracies can still be estimated between points that are indirectly connected via a least squares adjustment of the network.

On the other hand, traditional survey methodologies that leverage the use of total stations and differential levels allow for the determination of local accuracy between adjacent stations. This is because these traditional methods are directly observing the angles, distances, and/or changes in elevation between each station. To establish a control network with high local accuracies it is important to leverage the complementary benefits offered by GNSS (static or real-time) and traditional surveying techniques (i.e. horizontal and vertical angles, and distances measured by total stations and changes is elevations measured by differential levels).

1.1.3 Real-Time GNSS Networks

For decades relative-positioning, a specific method of GNSS positioning where the solutions are determined relative to another station, has been a key GNSS technique for determining precise coordinates relative to the NSRS. Real-time kinematic (RTK) is a relative positioning method that can be utilized to derive accurate coordinates of observed points in the field. RTK traditionally uses a single base station that transmits coordinates and GNSS observables of a reference station to a rover receiver to cancel out the errors that are constant between the two receivers (e.g. satellite and receiver clock errors, atmospheric delays, orbit errors) by forming linear combinations of the observation equations. However, using a single baseline real-time kinematic (sRTK) method limits baseline length, to about 10-20 km, due to the decorrelation between the base and the rover stations for long baselines. At greater baseline lengths, distance-dependent biases, such as broadcast satellite orbits error, ionospheric, and tropospheric delays, are not sufficiently mitigated by differencing GNSS observables collected at the base and rover (Bae and Kim, 2018; Gillins et al., 2019; Weaver et al., 2018).

To overcome the limitation of sRTK, a more accurate and stable positioning technique was first proposed in the 1990's by rigorously modeling all error components based on a network of known references, called Network RTK (NRTK) (Bae and Kim, 2018; Vollath et al., 2002; Wübbena et al., 2001). Several techniques have been developed within the scope of NRTK such as Flächen Korrektur Parameter (FKP), Virtual Reference Station (VRS) and Master-Auxiliary Concept (MAC) with the most common techniques adopted in practice being VRS and MAC. The main differences between these methods is primarily how the network corrections are combined or interpolated and the manner in which it is transmitted to the rover (Wang et al., 2010).

The VRS utilizes techniques to create GNSS reference station data for a virtual and unoccupied station in order to improve the positioning results by providing RTK corrections that are based on a network (Janssen, 2009). First, the rover transmits its uncorrected point position to the server, which is assigned as the location of an imaginary virtual base station. The network processing server interpolates network corrections at this virtual location, which are then transmitted to the rover in real-time together with corrected pseudo-observables data (Allahyari et al., 2018; Gillins et al., 2019; Wang et al., 2010; Weaver et al., 2018). As a result, the VRS effectively reduces the baseline to 1-3 m between the virtual station and the rover, integrating the error information obtained from the surrounding network stations. The conventional sRTK algorithms are then applied to solve for geocentric, Earth-centered, Earth-fixed (ECEF) coordinates at the rover (Allahyari et al., 2018; Vollath et al., 2002; Weaver et al., 2018).

In the MAC method, the Phase ranges from all reference stations are reduced to a common ambiguity level, by removing (or adjusting) the integer ambiguity for each satellite-receiver pair at the network processing server. Thus, the integer ambiguities cancel when double differences are formed (Brown et al., 2006; Wang et al., 2010). The most appropriate subset of the reference stations are then selected based on an uncorrected rover location (Gillins et al., 2019). The selection of the stations can be done with the reference station software, which selects the optimal set of stations that give the best solution for the rover while minimizing the amount of data to be transmitted (Brown et al., 2006). Usually, for convenience, the nearest station is assigned as the "master" station, and other stations serve as "auxiliary" stations (Gillins et al., 2019). Afterward, in order to reduce the amount of data to be transmitted, full correction and coordinate information is transmitted only for the master station, while correction differences and coordinate differences between the auxiliary station and the master stations are computed and then transmitted to the rover (Brown et al., 2006; Wang et al., 2010). Finally, by interpolating the received network correction, the rover derives corrections at its location to resolve its ambiguities and determine its position (Wang et al., 2010).

Since the NRTK method was introduced to the industry, the performance of NRTK has been evaluated by many researchers. Allahyari et al. (2018) evaluated parameters that affect achievable accuracies of GNSS NRTK observations including observation duration, inclusion of

GLONASS observables, and network versus single base RTK. Allahyari et al. (2018) confirm that the increased session duration slightly improved the positioning accuracy, and the data collected with NRTK tended to be more accurate and precise than data collected using sRTK. Further, Allahyari et al. (2018) showed that the addition of GLONASS observations helped obtain higher accuracies than solutions that only utilized GPS. To efficiently derive ellipsoid heights with centimeter-level accuracy, Weaver et al. (2018) proposed an efficient, campaign-style survey method, known as a hybrid network, by combining NRTK baseline observations with static post-processed baseline observations. After the least-square adjustment of thirty different hybrid networks for evaluating the proposed hybrid network, Weaver et al. (2018) confirmed that ellipsoid height accuracies were less than 2 cm when using six or more NRTK observations per mark.

Gillins et al. (2019) evaluated the accuracy of three independent NRTKs constructed with differing hardware and software: (1) Trimble KeyNetGPS and (2) Topcon TopNET live which both employ a VRS; and (3) Leica SmartNet which uses a MAC. For the evaluation, the NRTK coordinates are differenced with high-accuracy coordinates from a static GNSS survey campaign. As a result, the coordinate differences were similar in magnitude from each of the three NRTKs, indicating that each NRTK performed alike in terms of accuracy. Furthermore, after developing and adjusting hybrid survey networks, Gillins et al. (2019) found that network accuracies (95% confidence) by formal error propagation theory were less than 1 cm horizontally and 2 cm vertically (ellipsoid height).

For reference, Figure 1.5 represents what the example project shown in Figure 1.2 could look like if NRTK-GNSS observations are leveraged for the establishment of project control. The benefit of utilizing NRTK-observations over static is that the required observation time is significantly less when using the 5-minute occupation times as recommended by Allahyari et al. (2018) compared to that of a static observation which requires an observation time of 30-120 minutes recommended by the ODOT SPPM (see Table 1.2). Recall the time required for a static observation is dependent on the estimated baseline length from the CORSs being used in post-processing to the receiver. There is also a benefit for large control networks that would typically require multiple GNSS receivers to complete the static survey as an NRTK survey would only require a single receiver, thus reducing the amount of person and equipment hours required to complete the survey. It should be noted that when the NRTK survey method is being utilized, multiple repeat observations can be required dependent on the desired accuracy of the project: for example, for a height modernization survey where the absolute vertical accuracy of the observed point needs to be less than 2 cm when referenced to the ellipsoid. To accomplish this, Weaver et al. (2018) recommends a total of 6 independent observations when NRTK GNSS is being used. For this research, the total number of repeat observations per station will be assessed if NRTK-GNSS is exclusively used and when it is used in combination with total station and differential leveling observations.

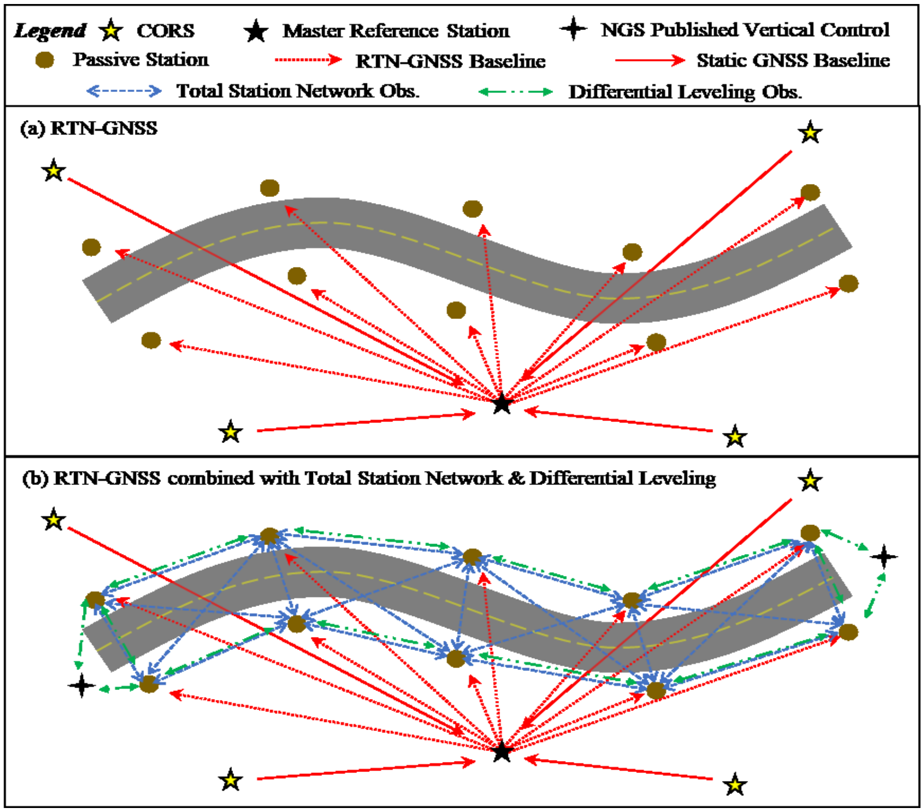

Figure 1.5: Example of how NRTK-GNSS could be utilized to establish a control network with the NRTK-GNSS observations (top) and NRTK-GNSS combined with total station network and differential leveling (bottom).

1.1.4 Upcoming Reference Systems

The North American Datum of 1983 (NAD 83) and the North American Vertical Datum of 1988 (NAVD 88) are the official horizontal and vertical geodetic datums of the National Spatial Reference System (NSRS). However, shortcomings of the current geodetic datums were identified by NGS and the geospatial community. Specifically, NAD 83 is non-geocentric by about 2.2 meters, and NAVD 88 is both biased (by about one-half meter) and tilted (about 1 meter coast to coast) relative to the global geoid model, which is an independently computed geoid model derived from the GRACE satellite (NGS, 2020). Another major issue of NAVD 88 comes from the changes of gravity field over time due to the dynamic motions of the earth. NGS has acknowledged these issues with NAVD 88, prompting the agency to develop a new vertical datum, which will be the North American Pacific Geopotential Datum of 2022 (NAPGD2022) when eventually deployed. Consequently, NGS determined GNSS would be the primary tool used to create a vertical datum that minimizes the reliance upon unmonitored passive control (Smith, 2010). NGS proposes using GNSS observations to determine orthometric heights for a project by converting the GNSS-derived ellipsoidal height to orthometric height using a gravimetric geoid model (i.e., GEOID2022), thus reducing the need to align project control surveys to the NSRS passive control marks through methods such as differential or trigonometric leveling. In particular, with NRTK, the same level of network accuracy can be achieved with much less effort (Weaver et al., 2018). Accordingly, NGS announced the replacement of the U.S.

horizontal and vertical datums (NAD 83 and NAVD 88) with a new geometric reference frame and geopotential datum to be released by approximately 2025. The new reference frames will primarily rely on GNSS CORSs and a purely gravimetric, high-accuracy geoid model resulting from Gravity for the Redefinition of the American Vertical Datum (GRAV-D) (NGS, 2020) project. These new reference frames will be easier to access and to maintain than NAD 83 and NAVD 88. These new reference frames will require users to determine local orthometric heights using a combination of GNSS-derived ellipsoid heights and a precise geoid model. Thus, the ability to determine ellipsoid heights efficiently while still attaining a high level of accuracy will be critical when these modernized datums are released.

1.2 RESEARCH OBJECTIVES AND DELIVERABLES

The main objective of this research was to enable modernization of ODOT's survey protocols by integrating recent advances in GNSS and NRTK methodologies for increased cost efficiency and quality standardization across all ODOT projects. Considering that not all tasks and projects require the same level of accuracy requirements, this guidance also included updating ODOT project control requirements that reflect individual project complexity and needs. The specific objectives of this project were to:

1) Assess the varying levels of network accuracy using the hybrid methodology outlined by Weaver et al. (2018). That is, this research aims to answer the following two questions:

   a) Regarding NRTK-GNSS observations using the hybrid survey approach, how does the network accuracy in the horizontal and vertical vary as more observations are made? More specifically, how many independent repeat observations are required to achieve a desired horizontal and vertical network accuracy?

   b) Does the network accuracy change as the time between repeat NRTK-GNSS observations changes (e.g. 1 hour, 2 hours, or 3 hours between independent repeat observations per station)?

2) Assess the benefits and limitations of incorporating total station and differential level observations with the hybrid survey procedures. More specifically, can the amount of total station and differential level work be reduced while achieving the desired level of local and network accuracies when the proposed hybrid methodology is implemented? For example:

   a) If all stations in the proposed control network are observed using the NRTK-GNSS hybrid methodology can we minimize the amount of total station or differential leveling work required and still achieve the same levels of network and local accuracies in the horizontal and vertical dimensions?

   b) If traditional survey procedures are required (e.g. total station, and differential leveling) then can the number of stations observed using the hybrid survey methodology be decreased? That is, can only a subset of the control points in the control network be observed with NRTK-GNSS while still achieving the desired level of network accuracy?

3) Determine if the proposed hybrid survey methodology is applicable to control networks with varying network geometries. For example, is the level of network accuracy achieved for a long linear control network similar to the level of network accuracy achieved for a rectangular gridded network?

4) Update ODOT Survey and Procedure Manual to incorporate NRTK-GNSS for establishment of project control with a *Recommended Survey Procedure Matrix* that states the recommended survey methodology based on the desired network accuracy in the horizontal and the vertical for the project.

This document describes the proposed methodology used to achieve the research goals listed above. Primary research results include:

1. Comparison of accuracies achieved using the current project control survey procedures outlined in the SPPM (ODOT, 2015) compared to the hybrid survey methodology proposed by Weaver et al. (2018).

2. Summary of horizontal and vertical network accuracies achieved using the hybrid survey methodology proposed by Weaver et al. (2018) as the number of independent NRTK-GNSS observations per station increases from 1 to 6 for two geometrically different control networks.

3. A comparison of the horizontal and vertical network accuracies achieved as the time between independent repeat NRTK-GNSS observations varies from 1 to 3 hours.

4. Resulting network accuracies produced when combining the hybrid survey methodology with traditional survey methods (e.g. total station and differential leveling) for two geometrically different control networks.

5. Comparison of the horizontal and vertical network accuracies of two independent control networks when only a limited number of control stations (4 and 6) per control network are observed using the hybrid methodology combined with traditional observations to all other stations in that network.

6. Recommended Survey Procedure Matrix that states the recommended survey procedures to achieve a desired horizontal and the vertical network accuracy based on the evaluations listed above.

1.3 BENEFITS TO ODOT

Nearly all ODOT projects that depend on surveying have the potential to be positively impacted by this research. By modernizing ODOT survey protocols to include the use of the hybrid network methodology leveraging NRTK-GNSS baselines, both field and processing efforts will be optimized, which will in turn improve downstream customer timelines and overall project costs. As presented in the results and discussion section of this report, the hybrid network approach can achieve similar, and possibly better levels of network accuracy than currently required for all ODOT control projects. Additionally, the decision matrix that has been developed by this study will allow for project tailoring based on the desired level of network accuracy for the control. The procedures outlined also ensure efficiency and standardization for using NRTK-GNSS for control purposes for both ODOT Surveyors and contractors performing survey work for ODOT, further improving product quality, and reducing overall ODOT costs.

2.0 METHODS

To develop recommendations for optimizing ODOT survey protocols integrating NRTK methodologies two existing control networks in Oregon were utilized. The Phase I control network, located in Carlton, Oregon, was used to determine what accuracies are achievable when the NRTK hybrid method proposed by Weaver et al. (2018) is implemented using the ORGN. It should be noted that at the time the Weaver et al. (2018) study was completed the ORGN leveraged GPS only, but since then it has been upgraded to incorporate GLONASS satellite observations as well. Weaver et al. (2018) showed that the RTNs leveraging multiple constellations (i.e. GPS and GLONASS) would result in NRTK vectors that were on average 19.2% more accurate. Therefore, this study provides a more recent reference for the accuracies achievable with the current state of the ORGN. Phase II of the project was performed in Canby, Oregon with the purpose of evaluating the resulting recommended procedures from Phase I and to ensure the resulting accuracies are repeatable.

The data used in this project was collected through two categories of survey campaigns: Traditional Survey Campaign; and NRTK Survey Campaign. The traditional survey campaign includes static GNSS, differential leveling, and total station observations, which was completed by ODOT in accordance with the standard project control requirements in the ODOT Survey Policy and Procedure Manual (SPPM). The NRTK survey campaign acquired for each Phase consisted of acquiring 13 independent, 5-minute, NRTK observations per point in Phase I and 6 independent, 5-minute, NRTK observations per point in Phase II. The 5-minute occupation time per point was adopted by a recommendation provided by a study completed by Allahyari et al. (2018) which assessed the optimal observation time for RTNs. All NRTK observations collected in each Phase were then combined with static GNSS observations for the master reference station for that Phase and surrounding CORSs and adjusted using the hybrid network design proposed by Weaver et al. (2018). Note, the hybrid network was implented for each Phase individually. As shown in Figure 1.5, the static GNSS observations were used to compute the baselines between the master reference station(s) and the surrounding CORSs to determine the postion of the master reference station referenced to the NSRS. The static GNSS baselines, computed using OPUS-Projects, were then combined with the NRTK vectors from the master reference station to the passive marks.

In addition to evaluating the accuracy derived from NRTK observations only, the total station and differential leveling observations were also included with the NRTK observations to assess the level of accuracy achieved when traditional observations are included. When adjusting each of the constructed networks, a minimally constrained adjustment was first performed on each individual data type to check for blunders and to adjust the stochastic model. After all data types satisfied the requirements and no more blunders were detected, the data types were combined in a fully constrained adjustment of the network. Figure 2.1 is a flowchart showing the procedures implemented to adjust each of the constructed networks.

To assess the accuracy of the numerous networks constructed in this study the resulting coordinates for each point in each network were compared to a reference data set. The reference data set for each Phase was created by combining all data in a single least squares adjustment. The procedures for adjusting the reference dataset follow the steps shown in the flowchart in Figure 2.1 where minimally constrained adjustments were performed for each Phase prior to combining them together in the single fully constrained adjustment. In this study, accuracy was computed as the root-mean square error (RMSE) scaled to a 95% confidence level in the horizontal and vertical as defined by U.S. federal standards (FGDC, 1998). The RMSE was computed by comparing the coordinates of each point for each of the constructed networks being tested to the reference data set for each Phase. To compute the horizontal RMSE (HRMSE) and the vertical RMSE (VRMSE) for each of the constructed control networks created Equations (2-1) and (2-2), as identified by U.S. Federal Standards, were used:

$$\boldsymbol{HRMSE_j} = \sqrt{\frac{\sum_{i=1}^{n}\left(\boldsymbol{N_{test,i}} - \boldsymbol{N_{ref,i}}\right)^2 + \sum_{i}^{n}\left(\boldsymbol{E_{test,i}} - \boldsymbol{E_{ref,i}}\right)^2}{\boldsymbol{n}}} \quad \textbf{(2-1)}$$

$$\boldsymbol{VRMSE_j} = \sqrt{\frac{\sum_{i=1}^{n}\left(\boldsymbol{H_{test,i}} - \boldsymbol{H_{ref,i}}\right)^2}{\boldsymbol{n}}} \quad \textbf{(2-2)}$$

Where:

$H_{test;i}$, $N_{test;i}$, $E_{test;i}$, = orthometric height, northing, and easting, respectively, at passive mark i from the constrained adjustment of the constructed network being tested;

$H_{ref;i}$, $N_{ref;i}$, $E_{ref;i}$, = orthometric height, northing, and easting, respectively, at passive mark i from the constrained adjustment of the reference data set for that Phase; and n = number of passive marks in tested network j.

The RMSE values were then scaled to a 95% confidence level to represent the network accuracy of the point. This was accomplished by multiplying the calculated VRMSE by 1.9600 and the calculated HRMSE by 1.7308 as defined by U.S. Federal Standards (FGDC, 1998).

Further details on the data acquisition and the procedures to process the data sets can be found in the following subsections.

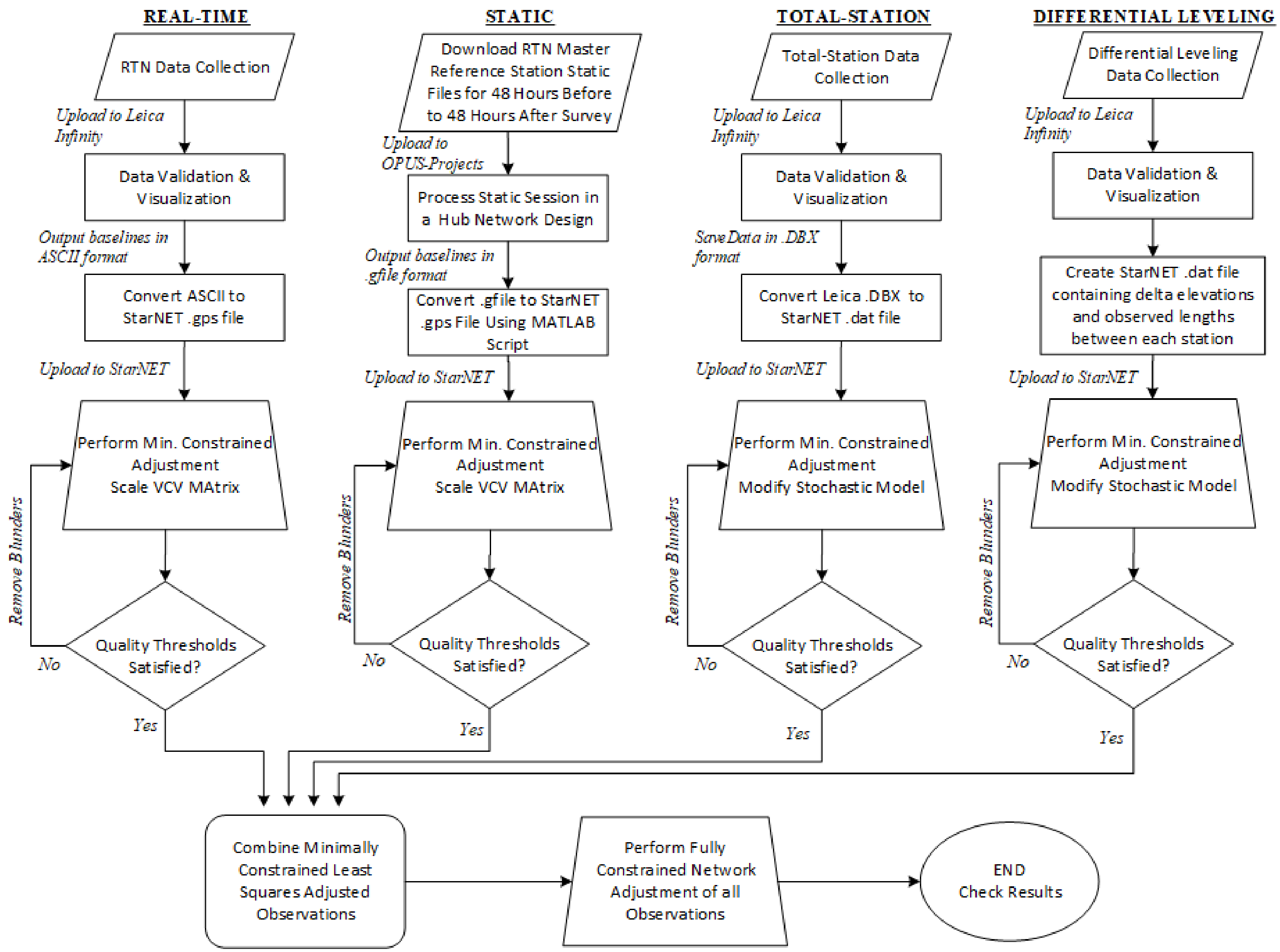

Figure 2.1: Flowchart used for developing and adjusting control networks that include hybrid survey networks (Weaver et al., 2018) combined with total station and differential leveling observations.

2.1 STUDY AREAS

To ensure the results from this study are repeatable for varying control network geometries and localities, it was imperative that the proposed survey procedures investigated by this study were assessed on varying site conditions and network geometries reflective of typical ODOT survey projects.

2.1.1 Phase I Study Area

The study area used for Phase I consists of an ideal control station geometry consisting of a relatively rectangular network with three short spurs coming off of the southern, western, and northern extents of the center of the project area as shown in Figure 2.2.

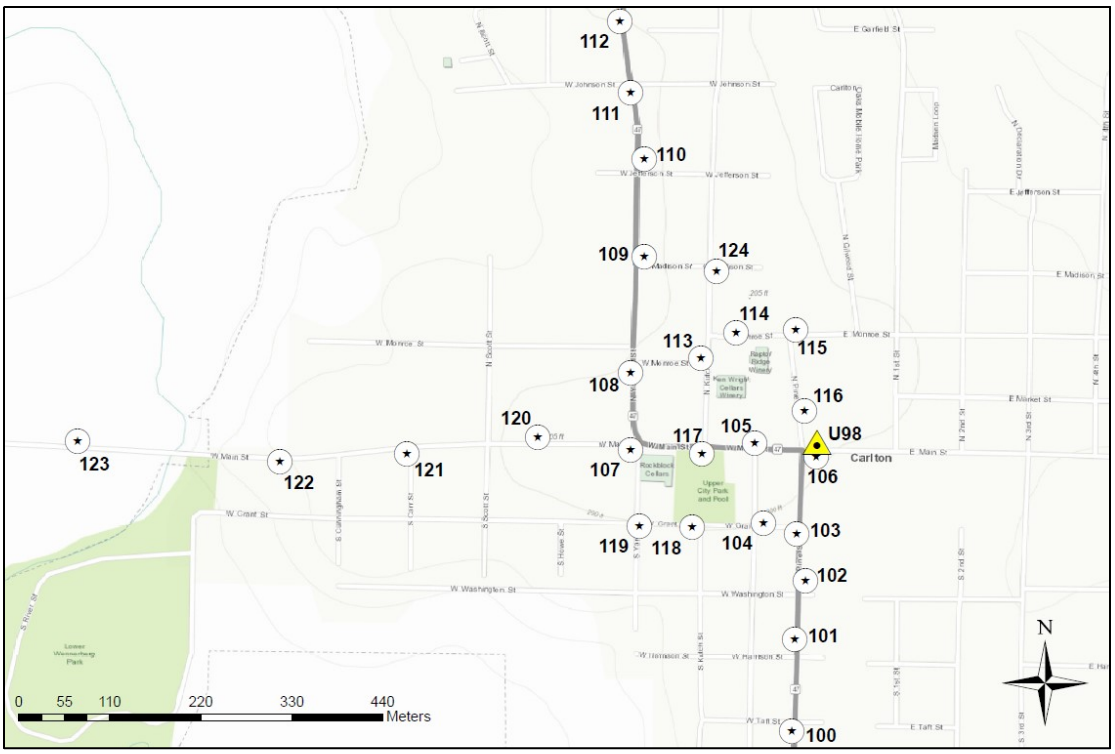

Figure 2.2: Map of control stations utilized in Phase I of this study. This control network is located in Carlton, Oregon and consists of 25 ODOT control marks signified by white circles with black stars and 1 NGS published benchmark signified by the yellow triangle.

The Phase I control network is in Carlton, Oregon and consists of 25 ODOT control marks and one NGS published benchmark. The control points consist of a combination of 1-1/8" brass plugs set in concrete or asphalt and 1" red plastic caps set on 5/8" x 30" iron rods (rebar). All stations were set in areas that are considered suitable for collecting GNSS data with the exception of ODOT control station numbered 117, as it is located directly under tree canopy and was therefore excluded from this study as a fixed solution could not be obtained. Note that the locations of each station in this control network were not set with GNSS observations in mind as this is a real control network that was guided by the current procedures in the ODOT Survey

Policy and Procedure Manual which only recommends stations be observed such that the bounding envelope created by the GNSS observed stations contains the majority of the project. For this Phase of the project those stations were 100, 112, 115, and 123. Therefore, numerous stations were not located in the most ideal locations as many of the remaining stations had multiple nearby vertical obstructions that would be conducive to multipath. Images of each of the control stations for Phase I can be found in Appendix B.

2.1.2 Phase II Study Area

Phase II of this project aims to validate the resulting hybrid control survey data acquisition methodology determined from Phase I to ensure that the newly developed procedures reliably satisfy desired accuracy requirements at an independent and more complex location. The Phase II site located along HWY 99E in Canby, Oregon, was selected as it is representative of a typical linear type ODOT project. It also has a significantly different network geometry when compared to Phase I as shown in Figure 2.3.

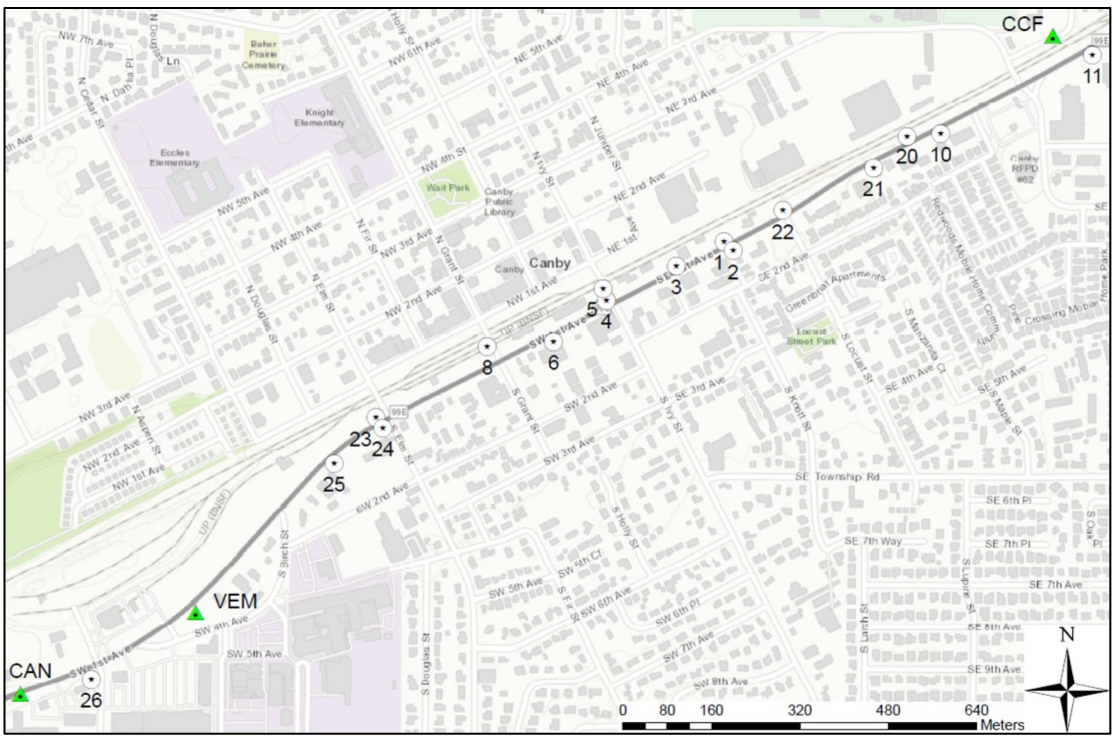

Figure 2.3: Map of control stations utilized in Phase II of this study. This control network is located in Canby, Oregon along Highway 99E and consists of 19 ODOT control marks signified by white circles with black stars and green triangles.

There are 19 ODOT control marks located on the Phase II project site. The control points consist of a combination of 1-1/8” brass plugs set in concrete or asphalt and 1” red plastic caps set on 5/8” x 30” iron rods (rebar). All stations were set in areas that are suitable for GNSS observations except for ODOT control station numbered 6 as it is located directly next to the awning of a nearby building. This data point was observed and included in the assessment as it was a prime example of a necessary station in a non-ideal location, and a fixed solution was attainable for every repeat observation. Images of each of the control stations for Phase II can be found in Appendix B.

2.2 DATA ACQUISITION

The data used in this project are broken up into two categories: 1) Traditional Survey Campaign, which includes static GNSS, differential leveling, and total station observations based on the 2015 ODOT Survey Policies and Procedures Manual (ODOT, 2015), and 2) NRTK Survey Campaign, which only includes the real-time GNSS observations. The methods used to acquire the data for each category are outlined in the following subsections.

2.2.1 Traditional Survey Campaign

For both Phases of this project, a traditional survey campaign was completed by ODOT as part of ODOT's original project control network. Each survey included a combination of static GNSS observations, terrestrial observations (i.e. horizontal and vertical angles measured in multiple faces, and distances) and differential levels in accordance with the standard project control requirement outlined in Chapter 3 of the ODOT Survey Policy and Procedure Manual (SPPM). A summary of the equipment used for these surveys is outlined in Table 2.1.

Table 2.1: Summary of Equipment Used for Each Aspect of the Traditional Survey Campaigns Completed by ODOT for Each Phase of this Study.

Equipment	Model(s) Used
Differential Level	Leica LS 15
Total Station	Leica TS16 & MS60
Static GNSS	Leica GS14 & GS15

Terrestrial observations were completed between all inter-visible points within the project area. A minimum of three adjacent project control stations were observed from each setup. The differential level observations were completed in a loop fashion with 4 loops being completed for each control network. The GNSS vector observations were established by logging rapid-static GNSS observations on four project control stations in Phase I, and six project control stations in Phase II. The four control stations observed for Phase I include 100, 112, 115, and 123. The six control stations observed for Phase II include 3, 20, 24, CAN, CCF, and VEM. Table 2.2 summarizes the procedures implemented in the traditional survey campaign for each Phase of the project. The rapid static data included GPS and GLONASS observables logged at a sampling rate of 5 seconds with a mask angle of 10 degrees from horizontal. The GNSS antenna was positioned over each point using a tripod and tribrach where the height above the points was measured using a hook and tape.

Table 2.2. Outline of Applicable Survey Requirements for the Traditional Survey Campaign Summarized from Chapter 3 of the 2015 ODOT Survey Policy and Procedure Manual (ODOT, 2015).

Criteria	Requirement
Total Station Network	
Instrument and Target support setup	Tripod
Sets of Angles	2
Minimum number of adjacent network points observed per setup	3
Rapid-Static GNSS	
Minimum Observation Length (minutes)	30
Epoch Interval (seconds)	5
Antenna Support Setup	Tripod

2.2.2 NRTK Survey Campaign

For testing purposes, the NRTK Survey Campaigns for each Phase of this project consisted of collecting hundreds of independent NRTK observations for each network. For each survey, three or four Leica GS14 receivers (for Phase I and Phase II respectively) utilizing cellular signals to transmit and receive correction from the ORGN were used. More specifically, the Auto-MAX network corrector was used as it takes full advantage of the additional network messages available in the RTCM 3.x format and enables the network server to optimally select which network stations to utilize.

The following procedures were implemented for each observation for each Phase: (1) Attach rover to a calibrated fixed height rover rod with bi-pod legs for stabilization; (2) Wait for the receiver to initialize or resolve integer ambiguities; (3) Collect and store a 300 epoch (5 minutes) NRTK observation using GPS and GLONASS observables; (4) Invert the antenna such that the receiver loses initialization as the surveyor progresses to the next station; (5) Upon arriving to the next station repeat steps 2 through 4 until all stations have been observed. Note, a consistent 5-min session duration was chosen based on results for optimal session duration presented in the study by Allahyari et al. (2018). The NRTK observations were stored as delta ECEF vectors with a 3 by 3 variance-covariance matrix from the master base station to the rover receiver. Additionally, the ECEF coordinates of said master reference station and the point being observed were also stored. Specific details for the NRTK data acquisition are outlined in the following subsections for each Phase of this project.

2.2.2.1 Phase I

For Phase I, a total of 13 repeat observations for each of the 23 stations was acquired with 11 of those being completed on August 7th, 2019 and the remaining 2 observations per point being completed the following day on August 8th, 2019. Unfortunately, with a survey consisting of so many moving parts and time constraints of maintaining approximately 1 hour between each station not all stations were observed 13 times, mostly due to vehicles obstructing some points for parts of the day. In total this survey campaign resulted 294 independent observations. These observations were then broken into 56 different permutations of NRTK data sets for comparison purposes. Table 2.3 shows a subset of 16 example permutations with the variables being (1) time between repeat observations, and (2) number of repeat observations. Refer to Appendix C for a comprehensive list of all constructed networks for Phase I. To evaluate the effects of varying times between repeat observations, all stations were observed consecutively in "loops" where the time between each of the 13 independent repeat observations was 60 ±15 minutes. Doing this allows for breaking the data into three time intervals of 1, 2, and 3 hour(s) between repeat observations. Additionally, each of those datasets consisted of 2-6 repeat observations for each station.

Table 2.3: Subset of the 56 Data Sets that were created by Taking Various Combinations of the 13 loops Observed for Phase I. Data was Partitioned using Two Variables: (1) Time between Repeat Observations, and (2) Number of Repeat Observations.

Time btwn Observations (min)	# of Repeat Observations	Avg. Time btwn Occupations (min)	# of points	Control Station exclusions (Point ID)
-	1	-	25	-
60 ± 15	2	58	25	-
60 ± 15	3	60	24	114
60 ± 15	4	59	24	114
60 ± 15	5	57	24	114
60 ± 15	6	58	23	105, 114
120 ± 30	2	121	24	114
120 ± 30	3	114	24	114
120 ± 30	4	109	21	109, 111, 112, 114
120 ± 30	5	114	14	100, 101, 102, 103, 104, 105, 106, 107, 114, 118, 119
120 ± 30	6	113	14	100, 101, 102, 103, 104, 105, 106, 107, 114, 118, 119
180+	2	190	25	-
180+	3	176	23	105, 114
180+	4	186	20	105, 109, 111, 112, 114
180+	5	183*	23	105, 114
180+	6	188*	20	105, 109, 111, 112, 114

*Note that this average time between repeat observations does not include the time between observation acquired on different days only between successive observations made on the same day

2.2.2.2 Phase II

The primary purpose of Phase II was to verify that the horizontal and vertical network accuracies achieved in Phase I are repeatable when the same survey procedures are implemented at an independent location. The data for Phase II of this project was acquired on February 27th, 2020 and used the same acquisition procedures that were implemented in Phase I. However, for this Phase, the total number of repeat observations per station was limited to six observations per station and the time between repeat observations was not prioritized based on the lack of variation of achieved network accuracies achieved in Phase I when the time between repeat observations varied between 1, 2, and 3 hours. Note, Phase II averaged approximately 60 minutes between repeat observations. These experimental design conditions were determined from evaluating the results from Phase I which are discussed in detail in Section 3 of this report. In total this survey campaign resulted in 114 independent observations (19 stations, each station was observed 6 times). These observations were then broken into 63 different permutations of NRTK data sets for comparison purposes where the number of repeat observations per point varied from 1 to 6 for each station. Refer to Appendix C for a comprehensive list of all constructed networks for Phase II.

2.3 POST-PROCESSING AND ADJUSTMENTS

2.3.1 Hybrid GNSS Survey Networks

To start the inclusion of the acquired NRTK data, the delta ECEF vectors and accompanying variance-covariance matrices, represented by Figure 2.4(a), were imported into *MicroSurvey StarNET v9.1.4, which* was used to perform the least square adjustment of the hybrid survey methodology for the numerous constructed control networks in this study. The primary benefit to using a hybrid network is that the NRTK observations can be directly referenced to the NSRS. This can be accomplished by first post-processing the RTN master reference station along with nearby CORSs that have been used to define the NSRS, shown in Figure 2.4(a). It is recommended that users download 3-6 days' worth of static data for the RTN master reference base station and nearby CORSs. Note that these multiple days of data should, at a minimum, span the time the NRTK data was collected, but inclusion of data 24 hours before and after data collection are recommended at a minimum to ensure the most probable coordinates of the master reference stations are computed.

To compute the baselines between the master station and the surrounding CORSs, as shown in Figure 2.4(b), *OPUS-Projects* was utilized but please note that other consumer off the shelf software packages (e.g. Leica Infinity or Trimble Business Center) can also be used. For analysis with OPUS-Projects the GNSS data for each of the master reference stations were downloaded from the RTN manager's database and uploaded to OPUS-Projects following the guidelines from the *OPUS-Projects User Manual* (Armstrong et al., 2015). It should also be noted that the version of OPUS-Projects used for this study is only capable of processing GPS observations (i.e. Galileo, GLONASS, BeiDou observations are not utilized). The result of post-processing these data in OPUS-Projects yields baseline solutions between the master reference station(s) and the CORSs, as shown in Figure 2.4(b). These static derived baselines and the NRTK baselines are then combined to form a single network, see Figure 2.4(c), and adjusted by least squares where the NGS published coordinates for the CORSs are used as constraints in the adjustment. Note, because multiple days' worth of observations is being used to determine these baselines it is not anticipated that additional constellations would improve the resulting baselines. It should also be noted that using the NGS published coordinates ensures the resulting coordinates from the final adjustment are aligned with the NSRS. Using the RTN managers published coordinates, assuming they are different from the NGS published coordinates, may result in the final adjusted coordinates not being aligned with the NSRS. Specific details of the hybrid survey network methodology are outlined in further detail in Weaver et al. (2018).

It should be noted that for the comparisons in this study, the aforementioned baselines computed from the static GPS post-processing in OPUS-Projects between the NRTK reference base stations and CORSs were held constant for all networks in each Phase. Doing this removes the possibility of errors being propagated from the reference station due to errors in the coordinates assigned to said reference station by the RTN managers. Again, the published coordinates and their standard deviations for the CORS utilized in each Phase were used as stochastic constraints in the adjustment. The current ODOT SPPM requires that all 3D network points be referenced to the NSRS. That is, all accuracy requirements identified by the ODOT SPPM (see Table 1.1) are in reference to the network accuracy. Therefore, it is recommended that the NGS published CORS positions be used as constraints in the network adjustments and not the ORGN published coordinates. If the ORGN published coordinates are to be used as constraints, then the resulting coordinates for the project control points will be aligned with the current realization/adjustment of the RTN and potentially not to the NSRS. The resulting local accuracies will remain the same but absolute errors of the published ORGN coordinates relative to the NSRS will be propagated to the resulting coordinates for the project. It is for this reason that the RTN network manager should ensure that the published coordinates for the RTN base stations align with the NSRS.

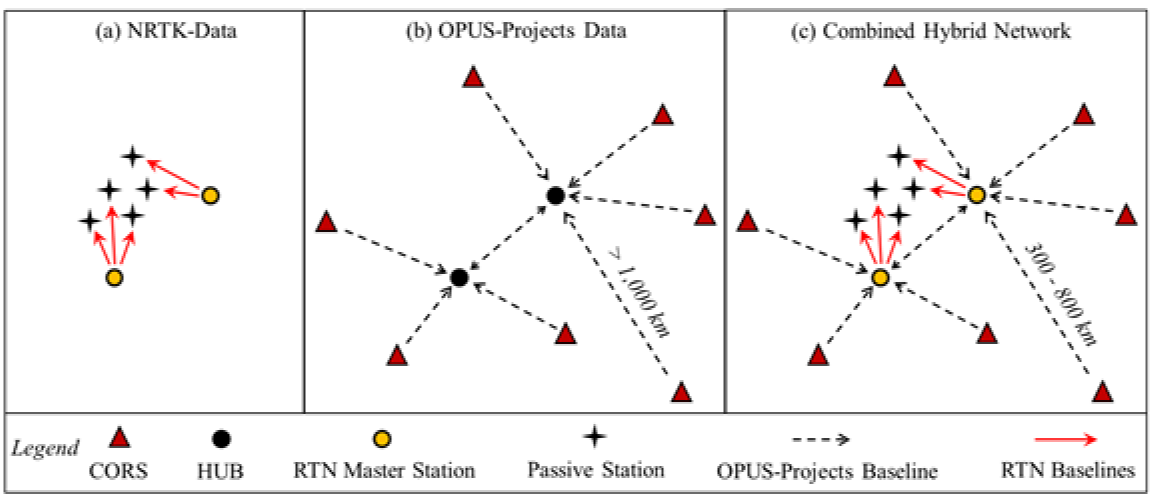

Figure 2.4: Hybrid Network conceptual design for establishing project control: (a) NRTK-GNSS baselines from the reference master station(s) to the passive marks; (b) baselines derived from post-processing static GNSS observations at the active master reference stations and nearby CORS; (c) final combined hybrid survey network.

For Phase I there were two different master reference stations for all NRTK vectors. Those stations were identified as NWBG located 12 km (7.5 miles) east of the project site, and P406 located 16 km (10 miles) south of the project site. The master reference stations were selected by the central server of the real-time network. The central server determines which network station will be the master reference station based on numerous parameters, the most important being: station health, distance to rover where the shortest distance is typically preferred, and number of common satellites observed between the rover and master reference station. The ORGN, which leverages Leica Spider to manage the real-time network, does have the capability for the user to identify which master reference station to utilize but this is not typically recommended as it removes the benefit of the central server's ability to identify and utilize the optimal master reference station. Similarly, for Phase II there were also two different master reference stations used in the NRTK data collection. Those stations were identified as ORGN network station WDBN location 18 km (11 miles) southwest of the project site, and P412 located 9 km (5.6 miles) southeast of the project site. Again, for Phase II the central server for the real-time network determined which master reference station was utilized.

To begin the post-processing of the hybrid networks for Phase I, six days' worth of static data for these master reference stations and nine additional CORSs were uploaded into OPUS-Projects to compute baselines that would tie the master reference stations into the NSRS. For Phase II, seven days' worth of static data for the master references stations and eleven surrounding CORSs were utilized to tie the master reference stations to the NSRS. After the baselines were computed between the master reference stations and the surrounding CORSs, the baselines were imported into StarNET with associated variance-covariance matrices.

The baseline vectors from surrounding CORSs to the RTN master reference stations and the vectors from the RTN master reference stations to the observed control stations were then imported into StarNET. A least squares adjustment was completed to combine the observations to form the hybrid survey networks for each project site, as depicted in Figure 2.4(c), to determine the network accuracies achieved when compared to a reference dataset. As stated in Section 2.2.2, the NRTK data was partitioned into 56 and 63 permutations for Phase I and Phase II respectively by sets consisting of 1, 2, 3, 4, 5, and 6 observations for each passive mark resulting in 119 hybrid networks. These numerous hybrid networks were then used to evaluate the network accuracies the hybrid survey methodology can achieve. The OPUS-Projects baselines for Phase I and Phase II were consistently used for all permutations for each Phase. For each of these 119 hybrid GNSS networks, a minimally constrained least squares adjustment was performed to detect for possible blunders and to scale the variance covariance (VCV) matrix such that the overall estimated error of the baseline components was equivalent with the residuals of the adjusted baseline components (i.e. the standard deviation of unit weight is equal to 1). After all blunders were removed and the VCV matrix adjusted appropriately, a fully constrained least squares adjustment was performed to determine the coordinates of each point within that control network. After the final coordinates of each of the 119 networks were computed they were compared to the reference dataset to compute the horizontal and vertical accuracy of each network.

2.3.2 NRTK Combined with Traditional Observations

Coordinates derived from only NRTK-GNSS observations are not suitable for all projects (engineering mapping, construction, etc.) as some projects demand higher levels of local accuracy, especially in the vertical, than GNSS can reliably provide. To address this concern, in addition to the evaluation of accuracy derived from NRTK observations only, terrestrial and differential leveling observations were combined with NRTK observations via least squares adjustments, and the resulting coordinates were compared to the reference dataset to compute the accuracy of each constructed network. To properly combine the terrestrial observations with the GNSS observations, hybrid geoid model GEOID12B ellipsoidal observations derived from

GNSS observations were made with the total stations and levels which were in reference to the geoid. Note that the deflection of the vertical was not corrected since the average sight lengths for each Phase of this project were approximately 150 meters or less and the AOI (area of interest) was less than 4 square kilometers for each project site. That is, the deflection of the vertical would have minimal impacts on the resulting networks in this study. Additionally, all analysis was completed using orthometric heights relative to NAVD88 and computed using the GEOID12B hybrid geoid model to ensure consistency throughout the comparisons, including the NRTK only networks previously discussed.

Unfortunately, not every possible permutation for each category (identified by the type of data included in the network: i.e. NRTK-GNSS + Total Station + Differential Leveling) were tested, except for NRTK-GNSS only, as that would have resulted in 1000+ control networks. When considering each network is adjusted multiple times (minimally constrained and fully constrained), the analysis of this large number of networks was not feasible for the timeline and budget of this study. To reduce the number of data sets required to assess the affects total station and differential leveling would have on the resulting accuracies when combined with NRTK observations, representative data sets were chosen for each number of observations (i.e. 1, 2, 3, 4, 5, 6) for each Phase. Additionally, Phase I was broken down further by also incorporating the permutation closest to the mean for each time separation (see Table 2.3 as an example). This resulted in 16 representative NRTK data sets for Phase I and 6 representative NRTK data sets for Phase II.

The 16 representative data sets from Phase I were selected by taking the data set whose level of accuracy was closest to the mean for each category identified by the 16 constructed networks identified in Table 2.3. For Phase II, the dataset whose level of accuracy was closest to the mean for that category was also selected as the representative dataset. For example, of the 63 NRTK hybrid networks constructed in Phase II there were 15 hybrid networks that consisted of 2 repeat NRTK observations per point; of those 15 networks, the network that was closest to the mean was selected as the representative data set for 2 repeat NRTK observations in Phase II. The representative data set was then selected for 1 to 6 repeat NRTK observations. The total number of permutations for each network category, where a category is identified by the data included in that network, are outlined in Table 2.4.

Table 2.4: Summary of the Total Number of Networks Evaluated in this Study.

Network Categories	Number of Permutations	
Identified by the data included in that network	**Phase I**	**Phase II**
NRTK GNSS Only	56	63
NRTK GNSS + Total Station (Network)	16	6
NRTK GNSS + Leveling	16	6
NRTK GNSS + Total Station (Network) + Leveling	16	6
NRTK GNSS + Total Station (Traverse)	-	6
NRTK GNSS + Total Station (Traverse) + Leveling	-	6
4 NRTK GNSS + Total Station (Network)	16	-
4 NRTK GNSS + Total Station (Network) + Leveling	16	-
6 NRTK GNSS + Total Station (Network)	-	6
6 NRTK GNSS + Total Station (Network) + Leveling	-	6
6 NRTK GNSS + Total Station (Traverse)	-	6
6 NRTK GNSS + Total Station (Traverse) + Leveling	-	6
Total Number of networks for each Phase:	**136**	**117**
Total Number of Networks in Study:	**253**	

Note: "NRTK GNSS" refers to NRTK observations on all stations included in the adjustment. "# NRTK GNSS" refers to only that specified number of stations observed with NRTK included in the adjustment.

This research also included an analysis of how many GNSS stations should be included when a total station survey is required. For a direct comparison with the current ODOT requirements as outlined in the ODOT SPPM (ODOT, 2015), the same stations that were observed in the Rapid-Static surveys were selected, with all other NRTK observations being omitted from the network. The included stations were 100, 112, 115, 123 for Phase I; and 3, 20, 24, VEM, CCF, and CAN for Phase II.

ODOT is also interested in determining the difference between coordinates derived from a survey network that include a network total station survey compared to a traverse total station survey. The primary difference between the two survey methods is the total number of required adjacent stations that need to be observed at each instrument setup as shown in the example traverse method shown in Figure 1.1. The traverse method only requires a backsight and a foresight (two stations) whereas the network survey requires a minimum of three stations. To accomplish this comparison the sets of angles collected in the network total station survey for Phase II were reduced to create two closed traverse loops that included all 19 stations.

2.3.3 Reference Data Set

To make comparisons between these numerous networks, a reference dataset was necessary. Typically, a reference dataset is an order of magnitude more precise than the data being compared, but that kind of dataset can prove to be difficult to acquire when the data being compared is considered "control" for all other projects. Therefore, in this study the project team chose to create the reference dataset for each Phase by combining all the data acquired from that Phase into a single least squares adjustment. The assumption of this method is that the total number of redundant observations is so large that the most probable coordinates derived from this least square adjustment will, for all intents and purposes, be equal to the true coordinates of those stations. In summary the reference dataset for each Phase was determined using the following data:

- OPUS-Project Baselines from surrounding CORSs to the master reference stations
- All NRTK Vectors from the master reference stations to the control stations
- Rapid-Static GNSS observations on a subset of the stations (4 or 6 stations depending on the Phase of the project), collected with adherence to Chapter 3 of the 2015 ODOT Survey Policy and Procedure Manual (ODOT, 2015)
- Network total station survey collected with adherence to Chapter 3 of the 2015 ODOT Survey Policy and Procedure Manual (ODOT, 2015)
- Differential Leveling survey between all stations. Collected with adherence to Chapter 3 of the 2015 ODOT Survey Policy and Procedure Manual (ODOT, 2015)

To ensure the adjustment was not over-constrained and each data type was weighted appropriately, a minimally constrained adjustment was performed for each data type during which blunders were identified/removed and the stochastic model was scaled such that the standard deviation of unit weight was equal to 1. A standard deviation of unit weight being equal to 1 is a good indicator that the observations are properly weighted in the adjustment, resulting in realistic estimated accuracies. After the stochastic models for each data type were successfully scaled using minimal constraint adjustments, the data sets were combined into a single, fully constrained, least squares adjustment which resulted in final coordinates for each point in that Phase. Note that the estimated accuracies, as reported from the properly weighted least squares adjustments performed in this study, are summarized in Appendix D. The authors have chosen to utilize the empirical results as opposed to the formal accuracy estimates for generating the recommended procedures as the empirical results are more conservative. The formal accuracy estimates will not be discussed further in this report.

3.0 RESULTS AND DISCUSSION

3.1 ADJUSTMENTS AND REFERENCE DATA SETS

To investigate the accuracies achieved by various combinations of survey data, different survey procedures including ODOT's existing survey procedures - ODOT SPPM, hybrid GNSS survey, and NRTK combined with traditional observations were assessed by comparing the results of the 253 constructed networks to the reference datasets (described in 2.3.3). The total 253 networks were adjusted with the variances of unit weight for all networks resulting in a value close to 1, and each passed the χ^2 statistical hypothesis test at the 95% confidence level, indicating that the stochastic models for all of the adjustments were valid. To determine the accuracies of each of the 253 networks, the resulting coordinates for each network were compared to the reference data set. The estimated absolute uncertainties computed using formal error propagation and scaled to a 95% confidence level for each of the reference datasets were 0.5 cm (0.016 ft) in the horizontal and 0.6 cm (0.020 ft) in the vertical (orthometric) for Phase I; and 0.7 cm (0.023 ft) in the horizontal and 0.5 cm (0.016 ft) in the vertical (orthometric) for Phase II.

Initially, the results produced by implementing the current recommended procedures for establishing project control described in the ODOT SPPM were compared to the reference data set for each project area (i.e. Phase I and II). The results of this comparison are summarized in Table 3.1 for each Phase. As defined by the ODOT SPPM the current methods should satisfy a network accuracy of 1.0 cm (0.033 ft) for the horizontal and vertical components as is required for 3D network points. The resulting network accuracies for the current ODOT methods, as compared to the reference data set, for each Phase of this project were: 1.2 cm (0.039 ft) in the horizontal and 1.5 cm (0.049 ft) in the vertical (orthometric) for Phase I; and 0.9 cm (0.030 ft) in the horizontal and 2.8 cm (0.092 ft) in the vertical (orthometric) for Phase II. Only the horizontal component of Phase II satisfied the network accuracy of 1.0 cm.

Table 3.1: Summary Statistics of the Horizontal and Vertical (Orthometric Height) Coordinate Differences between the Current ODOT Methods (ODOT, 2015) and the Reference Data Set for each Point in each Phase.

	Phase I		**Phase II**	
	Horizontal (cm)	***Vertical (cm)***	***Horizontal (cm)***	***Vertical (cm)***
Minimum	0.4	0.7	0.4	1.4
Maximum	1.1	0.8	0.6	1.4
Mean	0.7	0.8	0.5	1.4
St. Dev.	0.12	0.11	0.06	0.01
RMSE	0.7	0.8	0.5	1.4
Accuracy (95% CL)	1.2	1.5	0.9	2.8

3.2 NUMBER OF REPEAT OBSERVATIONS REQUIRED PER POINT

Using the 56 and 63 different permutations of NRTK data for each Phase, an assessment was made on the achievable accuracies as the total number of repeat observations for each station varies. The total number of networks for each number of observations per station (1 through 6) are outlined in Table 3.2. The mean horizontal and vertical accuracies and an error bar signifying the standard error for each number of observations are presented in Figure 3.1 and Table 3.3. The results for each Phase indicate the same trend in network accuracies achievable by NRTK observations as the number of independent repeat observations increases.

Table 3.2: Summary of the Total Number of Constructed Networks by Number of Repeat Observations per Station.

# of Repeat Observations	# of Networks	
	Phase I	Phase II
1	12	6
2	18	15
3	11	20
4	5	15
5	7	6
6	3	1
Total	**56**	**63**

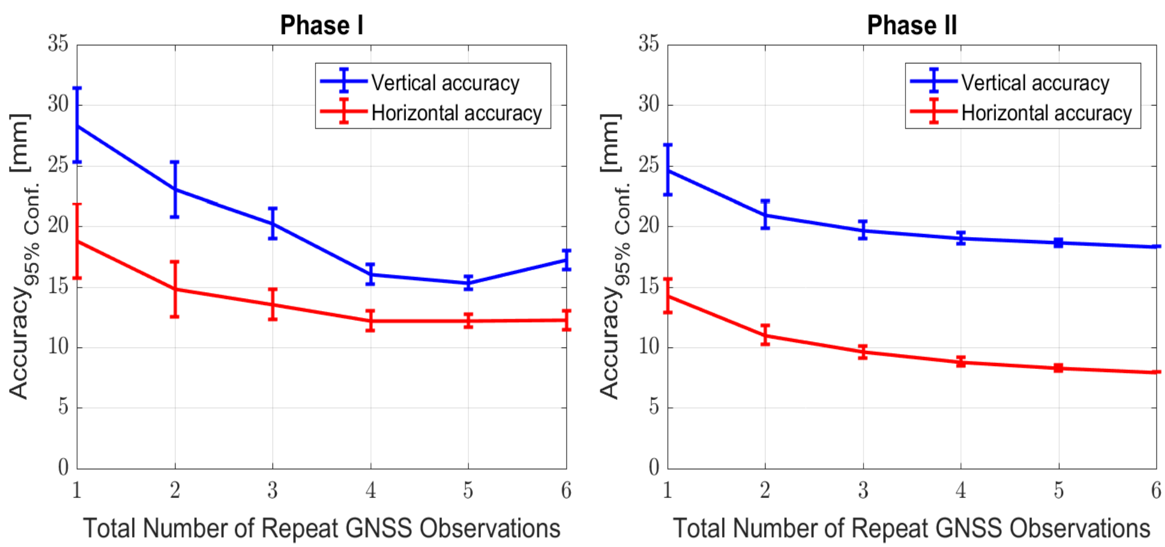

Figure 3.1: Summary of vertical and horizontal network accuracies at 95% confidence level attained using the Hybrid Network Methodology for determining coordinates from NRTK observations only during Phase-I (left) and Phase-II (right).

Table 3.3: Summary Statistics of the Horizontal and Vertical Accuracies in Phase I and Phase II.

# of Repeat NRTK Observations	Phase I [mm]				Phase II [mm]			
	Vertical Accuracy$_{95\%\ Conf.}$		Horizontal Accuracy$_{95\%\ Conf.}$		Vertical Accuracy$_{95\%\ Conf.}$		Horizontal Accuracy$_{95\%\ Conf.}$	
	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.
1	28.4	2.74	18.8	3.16	24.6	2.06	14.2	1.4
2	23.0	2.51	14.8	2.28	21.0	1.13	11.0	0.8
3	20.2	1.43	13.5	1.24	19.7	0.70	9.6	0.5
4	16.0	1.21	12.2	0.83	19.0	0.46	8.8	0.4
5	15.4	0.78	12.2	0.52	18.6	0.29	8.3	0.2
6	17.2	0.98	12.2	0.77	18.3	*	8.0	*

* Only one dataset was tested meaning no empirical standard error could be computed.

As shown, the GNSS Hybrid Network methodology (Weaver et al., 2018) for establishing project control can achieve accuracies, at a 95% confidence level, of less than 3 cm (0.10 ft) in the vertical and 2 cm (0.07 f) in the horizontal on average when each station is observed only 1 time. As the number of occupations increases the realized accuracy in both dimensions, horizontal and vertical, begins to decrease until the improvements in accuracy begin to flatten out once each station has been observed a minimum of 4 times. Also, as the number of repeat observations increases, the standard error decreases indicating a high precision is achieved as more redundant observations are made. Note, the results from Phase I and II of this study consistently show that vertical accuracies under 2 cm (0.07 ft) are achieved when 4 or more observations are made. This result is consistent with results reported by Gillins et al. (2019). This indicates a level of consistency between varying real-time GNSS networks that provide GPS and GLONASS corrections to the user.

For reference purposes, the results from Phase I and Phase II were combined to create a single plot shown in Figure 3.2. The values represented in Figure 3.2 are also summarized in Table 3.4. This combined plot represents the expected vertical and horizontal accuracy as the number of repeat observations increases. This is particularly useful for deciding how many times a station must be independently occupied to achieve a required network accuracy.

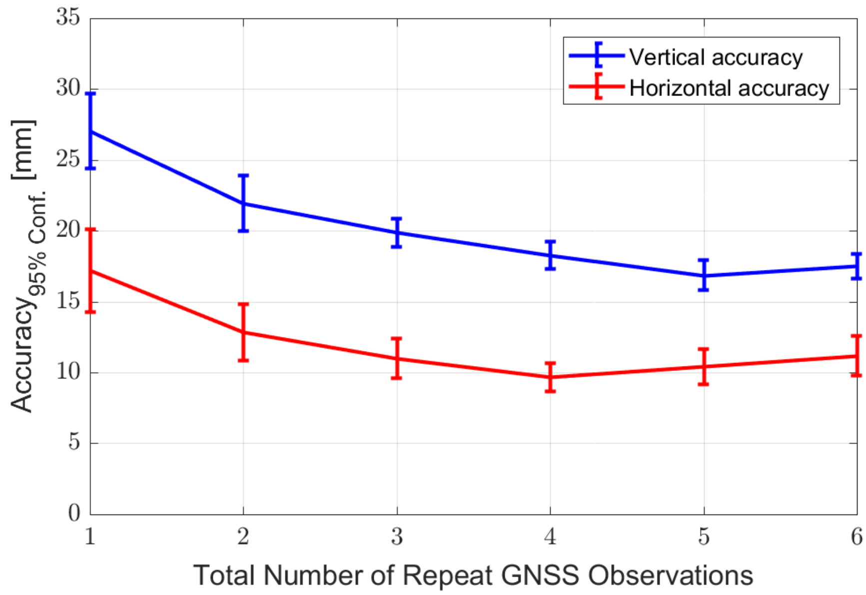

Figure 3.2: Plot of the mean vertical and horizontal accuracies at a 95% confidence level from Phase I and Phase II. Note: the error bars represent the standard error, also referred to as the standard deviation of the means.

Table 3.4: Summary of the Horizontal and Vertical Accuracy after Combining the Results from Phase I and Phase II.

# of Repeat Observations	Vertical Accuracy$_{95\%\ conf.}$ (mm)		Horizontal Accuracy$_{95\%\ conf.}$ (mm)	
	Mean	***Std.***	***Mean***	***Std.***
1	27.1	2.62	17.2	2.92
2	22.0	1.96	12.8	1.99
3	19.9	1.01	11.0	1.38
4	18.3	0.96	9.7	0.99
5	16.9	1.05	10.4	1.23
6	17.5	0.85	11.2	1.39

3.3 TIME BETWEEN REPEAT OBSERVATIONS

A temporal correlation exists in GNSS RTK data due to unmodeled errors (Edwards et al., 2010; El-Rabbany and Kleusberg, 2003). Therefore, the time separation between the two occupations should be long enough to eliminate the time correlated errors. Currently, NGS recommends a time interval between repeat observations of 4-hours. This interval is impractical for NRTK survey campaigns as it reduces the convenience of NRTK as it no longer makes the survey more efficient time wise compared to a traditional static-GNSS survey campaign. Therefore, the influence of the time between repeat observations on resulting network accuracy was also investigated. Note, this analysis was only performed for Phase I of this project, and the results are plotted in Figure 3.3 where the time between repeat observations varied between 1, 2, and 3 hours.

For horizontal accuracy (right plot in Figure 3.3), there is no clear trend that suggests improved accuracy due to changes in time between repeat observations. For vertical accuracy, the difference between each time interval is more defined. For vertical accuracy the 1-hour interval residuals are smaller (overly optimistic) than for 2- and 3-hour intervals. This indicates that the 1-hour time interval between repeat observations per point is not capturing all the unmodeled errors in the GNSS signals. That is, the repeat measurements are not fully independent; meaning repeat observations captured at a 1-hour interval are still correlated. Due to the similarities between the 2- and 3-hour intervals shown in the results it is assumed that the solution has converged at the 2-hour time interval.

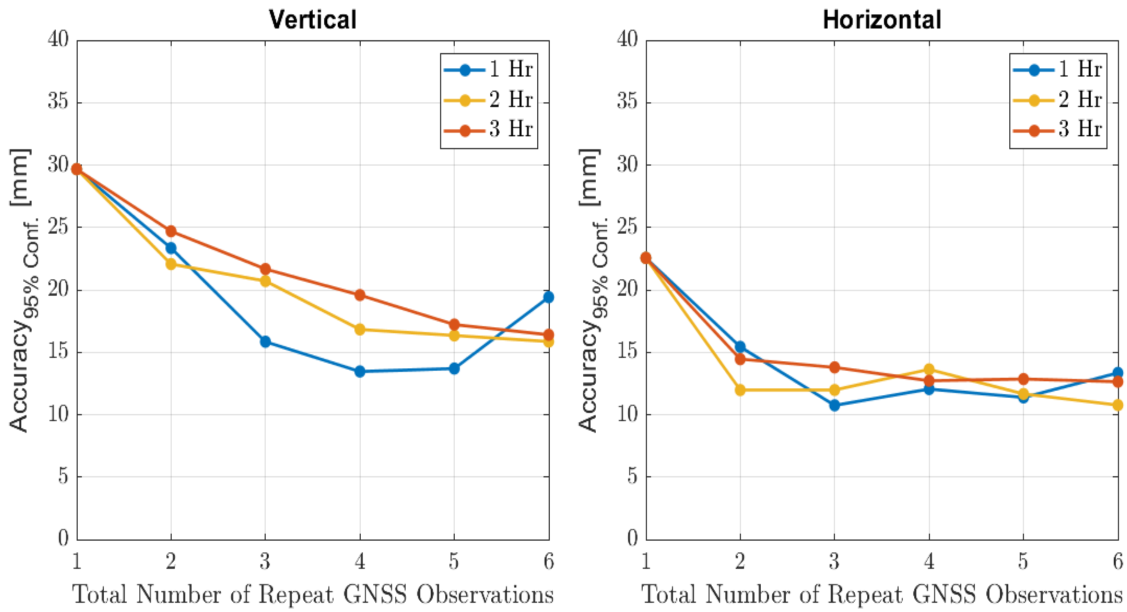

Figure 3.3: Summary of vertical (left) and horizontal (right) accuracies at 95% confidence level attained for a time between post-processed NRTK observations of 1, 2, and 3 hours from Phase-I.

Further research is necessary to evaluate the influence of decreased times between repeat intervals such as 0 - 119 minutes between repeat observations. Note that back-to-back observations are not recommended as this can lead to repeat measurement not being completed independently. For a repeat measurement to be independent, the GNSS receiver should be removed from the station, lose initialization, reinitialize, and then re-occupy the station. This procedure allows the user to identify/omit observations that were occupied with a poor initialization/instrument setup by comparing to the other independent repeat observations on that station. Additionally, to have a truly independent GNSS observation, accounting for the unmodeled error mentioned previously, the GNSS satellite geometry, as viewed from the point of measurement, must also be statistically different. The results from this portion of the study indicate that a truly independent observation is achieved when an interval of 2 hours between repeat observations is used. Note, Satellite constellations repeat every 11 hours and 56 minutes, therefore, subsequent observation should not be performed between 11 to 13 hours or 23 to 25 hours after the previous NRTK-GNSS observation.

3.4 COMBINING NRTK AND TRADITIONAL OBSERVATIONS

To evaluate the influence of total station and differential leveling on the resulting accuracies of a control network observed with NRTK-GNSS and post-processed using the hybrid survey methodology proposed by Weaver et al. (2018), the total station and differential leveling data acquired in Section 2.2.1 were incorporated into multiple control networks via least squares adjustments. As previously stated, the total station data consisted of network observations for Phase I and network or traverse observations for Phase II. The horizontal and vertical accuracies, scaled to a 95% confidence level, for each of the newly constructed control networks were then computed by comparing the resulting coordinates of each constructed network to the reference data set.

3.4.1 NRTK + Total Station (Network OR Traverse)

First, the influence of incorporating total station data in the network was evaluated. The resulting horizontal (red) and vertical (blue) accuracies after adding total station data to the NRTK dataset are shown for each Phase in Figure 3.4. The summary statistics of the vertical and horizontal accuracies of each combination in Phase I and Phase II are organized in Table 3.5 and Table 3.6, respectively. For comparison, each plot also shows the accuracy of the NRTK data set closest to the mean that was supplemented with the traditional survey data. The NRTK data set closest to the mean was selected as the representative dataset for the permutation for each variable being tested (e.g. 1, 2, 3, 4, 5, and 6 independent repeat observations per point for both Phases; and also the time between repeat occupations for Phase I).

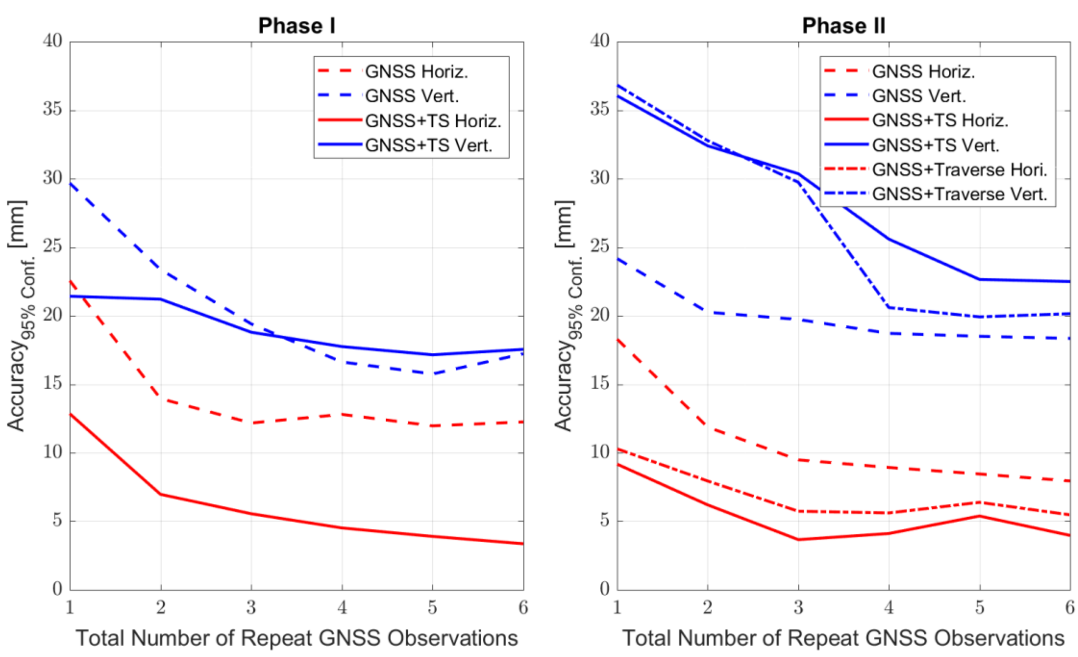

Figure 3.4: Summary of the horizontal (red) and vertical (blue) accuracies achieved in each Phase when total station observations are added to the network.

Predictably, the addition of total station data, acquired in accordance with the 2015 ODOT SPPM, to the NRTK dataset have the largest influence on the horizontal accuracy with an average 8 mm (0.026 ft) and 5 mm (0.016 ft) improvement in Phase I and Phase II, respectively. For vertical accuracies, addition of the total station data to the post-processed NRTK datasets do not show a consistent trend between Phase I and Phase II. For the vertical component in Phase I the improvement in accuracy appears to level off, or become consistent, with the largest improvement only occurring between 1 and 2 repeat NRTK observation(s) per station. For the vertical component in Phase II, there was no benefit to adding the total station data to the network. In fact, adding it resulted in a decreased accuracy in the vertical. Note, when the total station data were added to the network, all observation components were included (e.g. horizontal distance, instrument height, horizontal angle, and target height). The total station observations often carry the most errors in the vertical due to poor target height readings. If desired, to prevent the vertical accuracy from being influenced by the addition of total station data, the vertical total station observations (e.g. instrument and target heights) can be omitted from the network adjustment. This omission was not performed in this study as the effects of incorporating all total station observations was of interest for assessment.

A comparison between the influence of total station network data and total station traverse data was also performed for the Phase II dataset (right plot, Figure 3.4). The average difference in horizontal and vertical accuracies between traverse and network total station data are 1.5 mm (0.005 ft) and 1.6 mm (0.005 ft), respectively. Note: the average was computed by taking the average difference between the traverse and total station network adjustments for all accuracy values from each of the repeat observations NRTK categories (1-6) in the horizontal and vertical. This indicates that the inclusion of the cross ties required in a network total station survey does not result in significantly higher accuracy when each station is also observed using NRTK and adjusted using the hybrid survey methodology proposed by Weaver et al. (2018). It should be noted that if redundant stations (more than 2) can be observed during a traverse survey they should be made even when all stations are being observed with NRTK. The added redundancy from these additional traverse observations will prevent the need to revisit the site to re-observe stations should one of the total station setups need to be removed during outlier detection when adjusting the data.

3.4.2 NRTK + Leveling

The influence on horizontal and vertical accuracy with the addition of differential leveling to the NRTK dataset was also evaluated. Figure 3.5 shows the resulting horizontal (red) and vertical (blue) accuracies when supplementing the NRTK observations with differential leveling.

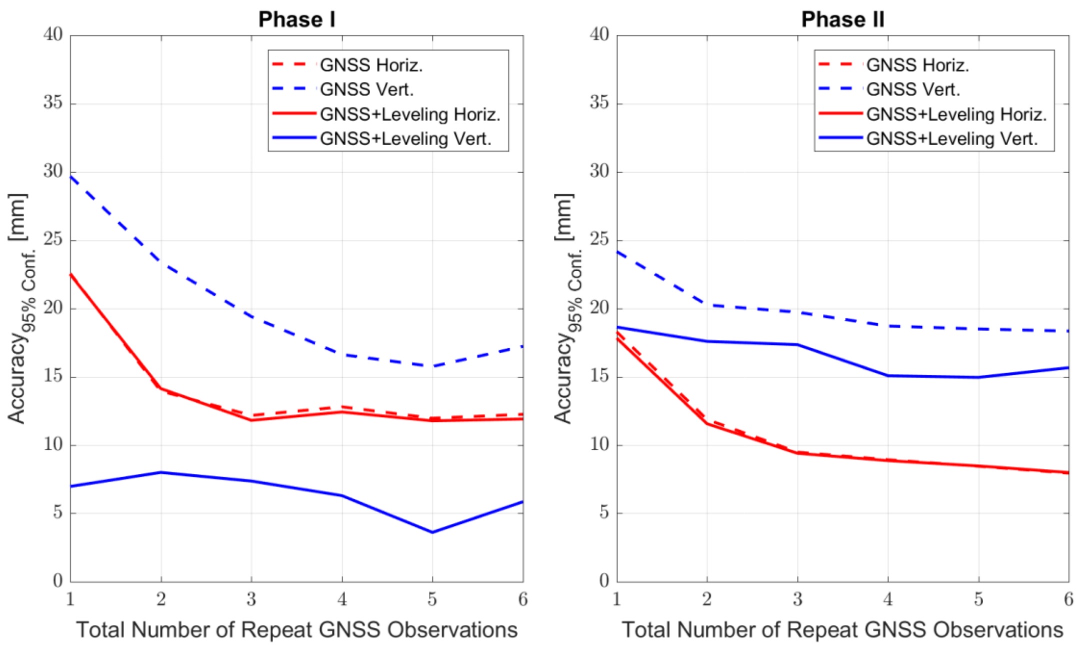

Figure 3.5: Summary of the horizontal (red) and vertical (blue) accuracies achieved in each Phase when only differential leveling observations are added to the network.

As anticipated, the inclusion of differential leveling observations between each station primarily influenced the vertical accuracies of each network with an average improvement of 14 mm and 3 mm in Phase I and Phase II, respectively. The horizontal accuracies essentially remained unchanged for each Phase. Also, when adding differential leveling data, the number of repeat NRTK observations did not have as large of an effect on the resulting vertical accuracies. This is largely due to the low uncertainty differential leveling provides when observing the changes in elevation between each station as compared with NRTK. These low uncertainties result in a much higher weight in the least squares adjustment which in turn leads to these values from leveling controlling the elevations in the adjustment. The two Phases were each improved at different amounts, but the general conclusion is that differential leveling is the optimal method to achieve a higher (better) vertical accuracy. The summary statistics of the vertical and horizontal accuracies of each combination in Phase I and Phase II are organized in Table 3.5 and Table 3.6, respectively.

3.5 COMBINING SPARSE NRTK AND TRADITIONAL OBSERVATIONS

In circumstances where total station and differential leveling surveys are required, it is possible that not all stations need repeat NRTK observations. To evaluate this concept, networks were adjusted as outlined in Table 2.4, where the number of stations in the control network observed by NRTK was decreased to 4 and 6 for Phases I and II respectively. The 4 and 6 stations for Phase I and Phase II respectively were the same stations observed in the traditional survey campaign performed by ODOT following the 2015 ODOT SPPM (ODOT, 2015). That is, stations 100, 112, 115, and 123 were chosen for Phase I; and stations 3, 20, 24, CAN, CCF, and VEM were chosen for Phase II. More specifically, total station and differential leveling data were used to evaluate the influence these traditional survey methods would have on the resulting coordinates for each network. Again, the total station data consisted of network observations for Phase I and network or traverse observations for Phase II.

This analysis is particularly useful as it allows for a more direct comparison to the existing ODOT method for establishing 3D network points in which rapid-static GNSS observations are used instead of the proposed NRTK observations. When acquiring the rapid-static GNSS data the current ODOT SPPM requires observation times of 30-60 minutes per station depending on the baseline length to nearby CORS. By observing these stations with NRTK and post-processing the results using the hybrid survey methodology proposed by Weaver et al. (2018), the total observation time per point could be limited to 5-30 minutes based on the total number of repeat observations required per station. Observing the subset of points with NRTK also removes the requirement of having a minimum of 2 GNSS receivers observing points simultaneously on a project resulting in less equipment being needed for the GNSS survey as discussed in Section 1.1.1.

3.5.1 Sparse NRTK + Total Station (Network OR Traverse)

For the analysis of sparse NRTK with total station network and total station traverse data, 4 to 6 NRTK observed stations were used (e.g. stations 100, 112, 115, and 123 were chosen for Phase I; and stations 3, 20, 24, CAN, CCF, and VEM were chosen for Phase II). The resulting horizontal (red) and vertical (blue) accuracies of these networks are shown in Figure 3.6. The summary statistics of the vertical and horizontal accuracies of each combination in Phase I and Phase II are organized in Table 3.5 and Table 3.6, respectively. For reference, the NRTK based GNSS-only results are also shown using the large dashed lines.

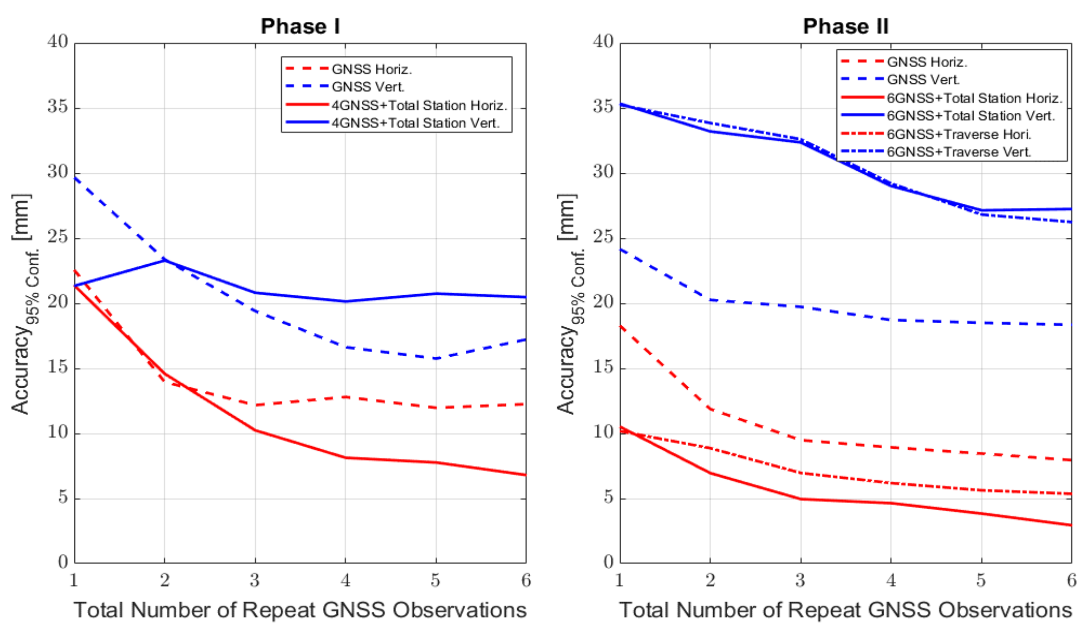

Figure 3.6: Summary of the horizontal (red) and vertical (blue) accuracies achieved in each Phase when only 4-6 NRTK observations and total station observations of the whole control network are used.

Similar to the analysis shown in Section 3.4.1, the primary benefit of this method is with the horizontal component where there is an average improvement in accuracy of 3 mm (0.010 ft) and 5 mm (0.016 ft), at a 95% confidence level, for Phases I and II, respectively. Note that in Phase I the primary increase in accuracy occurs when each of the 4 stations was observed 3 or more times. Whereas, in Phase II the improvement was consistent for each number of repeat observations. This consistent improvement is believed to be caused by the increase in number of stations being observed (i.e. 6 stations in Phase II compared to 4 in Phase I) and by having the 6 stations being spaced evenly along the length of the project. Examining this further, the average spacing between the GNSS control points was approximately 670 m in Phase I and approximately 370 m in Phase II. The additional GNSS stations in Phase II decreased the distance between GNSS control stations which also limits the propagation of errors between the two ends of the project as it is well known that the propagation of errors grows radially from the GNSS control stations.

Comparing these results to the current ODOT method described in Sections 1.1.1 and 3.1, which resulted in a horizontal accuracy of 12 mm (0.039 ft) and 9 mm (0.030 ft), at a 95% confidence level, for Phase I and Phase II, respectively, we can see that the same or better horizontal accuracy is achieved when each of the 4 or 6 stations is observed 3 and 2 times for Phases I and II respectively. Therefore, the same level of horizontal accuracy between the proposed method leveraging post-processed NRTK observations is achieved by observing those stations for 10-15 minutes (2 and 3 repeat 5-minute observations per point) compared to the 30-60 minute rapid-static observations per point required by ODOT. Another benefit is that these observations do not need to be made simultaneously at each station, which would require multiple receivers. Instead, one receiver can be utilized to observe each station multiple times thus reducing the amount of personnel and equipment to achieve the same level of accuracy.

Another benefit to observing points with NRTK is that users can check the precision of the repeat NRTK observations at each mark while in the field to identify possible blunders or poor real-time solutions. This quality control measure is one of the major benefits of conducting real-time survey campaigns and cannot be done in a static survey campaign that requires post-processing before the results can be inspected.

Note that a direct comparison for the vertical component could not be made between this data combination and the existing survey methodology as this data combination does not include differential leveling data which is included in the traditional survey methodology implemented by ODOT. Therefore, a direct comparison will follow in Section 3.5.2 where the adjusted networks also include differential leveling data.

3.5.2 Sparse NRTK + Total Station (Network OR Traverse) + Leveling

For the analysis of sparse NRTK with total station network and total station traverse, together with differential leveling data, 4 to 6 NRTK observed stations combined with total station data were supplemented with differential leveling loops that include all stations in each network. The resulting horizontal (red) and vertical (blue) accuracies of these networks are shown in Figure 3.7. The summary statistics of the vertical and horizontal accuracies of each combination in Phase I and Phase II are organized in Table 3.5 and Table 3.6, respectively. Again, the accuracy of all stations observed with NRTK only is also shown using the large dashed lines for comparison.

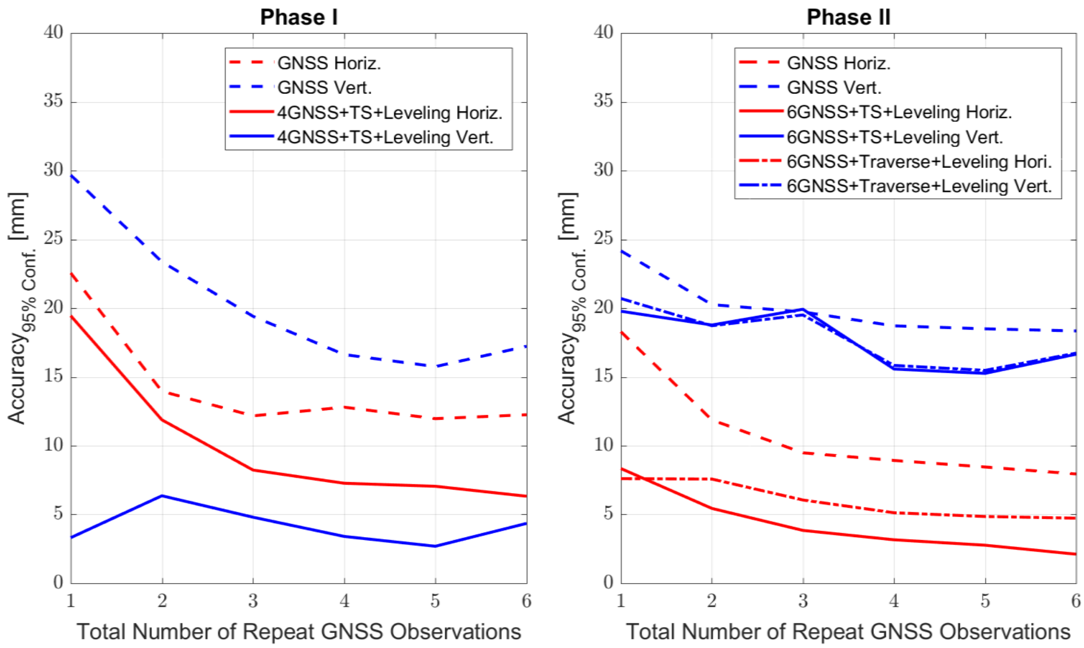

Figure 3.7: Summary of the horizontal (red) and vertical (blue) accuracies achieved in each Phase when only 4-6 NRTK observations are combined with total station and differential leveling observations through the entire control network.

When analyzing the various adjusted networks, both the vertical and horizontal accuracies improved by comparing to the NRTK only dataset. The horizontal accuracies for each Phase are nearly identical to the results from the adjusted networks in Section 3.5.1, which is expected as the only difference is that the differential leveling data is now included. For that reason, only the vertical accuracy will be discussed in this section.

Looking at the vertical accuracies in Figure 3.7 there is an average improvement of 16 mm (0.052 ft) and 2 mm (0.006 ft), at a 95% confidence level, for Phase I and II, respectively, when compared to the network adjustments when all stations were observed with NRTK only. Again, the total number of repeat observations on the 4-6 stations observed with NRTK does not have a large influence on the resulting accuracy due to the higher weight differential leveling carries in the least square adjustment as mentioned in Section 3.4.2.

Recall the current ODOT method (i.e. static GNSS, total station network, and differential leveling), resulted in a vertical accuracy of 15 mm (0.049 ft) and 28 mm (0.092 ft), at a 95% confidence level, for Phase I and Phase II respectively. From the results identified in Table 3.5 and Table 3.6 the same or better vertical accuracy, when compared to the current ODOT method, was achieved when each of the 4 or 6 stations was observed only once with NRTK for both Phases when the NRTK data was adjusted using the hybrid survey methodology proposed by Weaver et al. (2018). Therefore, the same or better vertical accuracy was achieved by observing those stations for 5 minutes each compared to the 30-60 minute rapid-static observation durations as called for in the current ODOT SPPM (ODOT, 2015). Note that even though these plots show it is possible to achieve the same level of vertical accuracy by observing each of the 4 or 6 stations only once with NRTK, it is not recommended as there is no redundancy to determine if one of the observations contains unsuitable errors. For that reason, a minimum of two independent NRTK observations should always be taken for each station.

Table 3.5: Summary of the Vertical and Horizontal Accuracy of each Combination in Phase I.

	Vertical Accuracy$_{95\%Conf.}$ [mm]						Horizontal Accuracy$_{95\% Conf.}$ [mm]					
# of Repeat NRTK Observations per station	1	2	3	4	5	6	1	2	3	4	5	6
NRTK-GNSS Only	29.7	23.4	19.4	16.6	15.8	17.2	22.6	14.0	12.2	12.8	12.0	12.3
NRTK-GNSS + Total Station (Network)	21.4	21.2	18.8	17.8	17.2	17.6	12.9	7.0	5.6	4.5	3.9	3.4
NRTK-GNSS + Leveling	7.0	8.0	7.4	6.3	3.6	5.9	22.5	14.1	11.8	12.4	11.8	11.9
NRTK-GNSS + Total Station (Network) + Leveling	8.1	7.6	6.7	6.1	3.7	6.0	12.1	6.6	5.2	4.4	3.9	3.4
4-NRTK-GNSS + Total Station (Network)	21.3	23.3	20.8	20.1	20.7	20.5	21.4	14.6	10.2	8.1	7.8	6.8
4-NRTK-GNSS + Total Station (Network) + Leveling	3.3	6.4	4.8	3.4	2.7	4.4	19.5	11.9	8.2	7.3	7.1	6.3

Table 3.6: Summary of the Vertical and Horizontal Accuracy of each Combination in Phase II.

	Vertical Accuracy$_{95\%Conf.}$ [mm]						Horizontal Accuracy$_{95\% Conf.}$ [mm]					
# of Repeat NRTK-GNSS Observations per Station	1	2	3	4	5	6	1	2	3	4	5	6
NRTK-GNSS Only	24.2	20.3	19.7	18.7	18.5	18.3	18.3	11.9	9.5	8.9	8.5	8.0
NRTK-GNSS + Total Station (Network)	36.1	32.4	30.4	25.6	22.7	22.5	9.2	6.2	3.7	4.1	5.4	4.0
NRTK-GNSS + Leveling	18.6	17.6	17.4	15.1	15.0	15.7	17.8	11.6	9.4	8.9	8.5	8.0
NRTK-GNSS + Total Station (Network) + Leveling	19.5	18.1	18.1	15.2	15.1	15.9	7.4	5.6	3.7	4.4	5.2	4.1
6-NRTK-GNSS + Total Station (Network)	35.3	33.2	32.4	29.0	27.1	27.2	10.5	7.0	5.0	4.6	3.8	2.9
6-NRTK-GNSS + Total Station (Network) + Leveling	19.8	18.8	19.9	15.6	15.3	16.7	8.3	5.4	3.8	3.2	2.8	2.1
NRTK-GNSS + 6-OPUS-RS	22.0	17.0	16.6	16.8	15.8	15.1	17.0	11.3	9.4	8.9	8.2	7.7
NRTK-GNSS + Total Station (Traverse)	36.8	32.8	29.7	20.6	19.9	20.2	10.3	7.9	5.7	5.6	6.4	5.5
NRTK-GNSS + Total Station (Traverse) + Leveling	20.2	18.5	18.0	15.7	15.2	16.1	9.0	7.3	5.5	5.7	6.2	5.5
6-NRTK-GNSS + Total Station (Traverse)	35.3	33.9	32.6	29.2	26.8	26.2	10.2	8.9	7.0	6.2	5.6	5.4
6-NRTK-GNSS + Total Station (Traverse) + Leveling	20.7	18.7	19.5	15.8	15.5	16.7	7.6	7.6	6.1	5.1	4.9	4.7

4.0 CONCLUSIONS

In this study a total of 253 least squares adjustments were completed with varying data sets that included NRTK, total station, differential leveling, and rapid-static GNSS observations. The adjustments were computed for two separate project sites in Oregon with varying network geometries where the site utilized in Phase I was rectangular and the site in Phase II was linear. From the analysis of these numerous adjustments the following can be concluded:

- Observing control stations with NRTK removes the requirement of having a minimum of two GNSS receivers observing points simultaneously on a project resulting in less equipment being needed for the GNSS portion of a control network survey.

- As summarized in Table 4.1, when all stations are observed with NRTK and the resulting baselines are processed using the Hybrid Network Methodology discussed in Weaver et al. (2018) the following mean accuracies at a 95% confidence level are achievable: for the vertical 2.7 cm (0.089 ft) to 1.8 cm (0.059 ft) is achievable when 1 to 4 independent repeat observations are made, respectively; for the horizontal 1.7 cm (0.056 ft) to 1.0 cm (0.033 ft) is achievable when 1 to 4 independent repeat observations are made, respectively. The improvement in accuracy begins to flatten out after four independent repeat observations have been made with minimal improvements seen at five and six repeat observations. For comparison, the horizontal and vertical accuracy of the current ODOT method is 1.2 cm (0.039 ft) in the horizontal and 1.5 cm (0.049 ft) in the vertical (orthometric) for Phase I; and 0.9 cm (0.030 ft) in the horizontal and 2.8 cm (0.092 ft) in the vertical (orthometric) for Phase II.

Table 4.1: Summary of the Vertical and Horizontal Accuracies Achieved when all Stations are observed with NRTK and the Resulting Vectors are processed using the Hybrid Network Methodology Discussed in Weaver et al. (2018).

# of Repeat Observations	Vertical Accuracy$_{95\%\ conf.}$		Horizontal Accuracy$_{95\%\ conf.}$	
	cm	ft	cm	ft
1	2.7	0.089	1.7	0.056
2	2.2	0.072	1.3	0.043
3	2.0	0.066	1.1	0.036
4	1.8	0.059	1.0	0.033
5	1.7	0.056	1.0	0.033
6	1.8	0.059	1.1	0.036

Note: these are the mean results computed from Phase I and Phase II

- The hybrid network methodology makes use of redundant vectors for checking data and identifying outliers. This approach also provides traceability because the NRTK vectors are referenced to an ORGN base station which can then be referenced to the CORSs. Finally, these hybrid networks ensure the survey is referenced to the NGS published coordinates of the CORSs, which are held as constraints in the adjustment, therefore the resulting coordinates are referenced to the NSRS. It is not recommended to hold the RTN published coordinates as a constraint in the adjustment. Doing so will result in the control points being referenced to the current realization/adjustment of the RTN and potentially not to the NSRS. It is recommended that RTN network managers ensure the published coordinates for the RTN base stations align with the NSRS to the best extent possible.

- When analyzing the time between repeat independent observations the results indicate that a truly independent observation is achieved when an interval of 2 hours between repeat observations is used. Further research is necessary to evaluate the influence of intervals less than two hours between independent repeat observations.

- The inclusion of total station observations improves the overall horizontal accuracy of the network. The accuracies attained when a total station network survey is incorporated vs. a total station traverse survey were comparable. However, the traverse method is much more susceptible to undetected outliers because redundant observations are not included. This can be avoided by taking "side-shots" to adjacent stations as often as possible.

- If vertical (orthometric) accuracies less than 1.8 cm (0.06 ft) at a 95% confidence level are required, then differential leveling should be performed.

- For circumstances where a total station (network or traverse) and differential leveling surveys are required, not all stations need to be occupied with NRTK. The total number of NRTK observed stations vary depending on the horizontal accuracy required. In general, the baseline lengths between the GNSS control stations should be minimized to the best extent possible. The authors loosely recommend a spacing of no larger than 500 meters between NRTK-GNSS observed control stations within a network where all stations are not observed by NRTK-GNSS. In general, the more stations observed the better the accuracy will be with minimal benefit occurring after 4 independent repeat observations per station.

The results from this study provide a good baseline of accuracies that the ORGN NRTK can provide. ODOT can also use these results to modernize the ODOT Survey Policy and Procedure Manual (SPPM) for Project Control. To aid in this modernization, a decision matrix that breaks out common desired accuracies and the recommended survey procedures that can be used to achieve those accuracies using the ORGN is included in Appendix A.

Two separate decision matrices were created: the first incorporates only NRTK observations which are adjusted using the hybrid survey methodology proposed by Weaver et al. (2018); and the second includes recommended survey procedures that incorporate NRTK observations using the hybrid survey methodology combined with traditional observation methods (i.e. total station, and differential leveling data). The decision matrices are comprised of 10 varying levels of desired network accuracies at a 95% confidence level for the horizontal and vertical ranging from 0.005 m (0.015 ft) to 10 m (33 ft). Using the results presented in this study a set of recommended procedures are recommended to achieve each level of desired accuracy in the horizontal and vertical. For example, if a vertical accuracy of 0.015 m (0.050 ft) is desired then the following surveying procedures are recommended:

- Digital or Optical differential leveling with standard rod -AND- (3) independent 5-minute NRTK observations (post processed using the hybrid methodology) on a subset of the stations.

Considering the different requirements for different surveying projects, these research findings provide the most efficient and effective methods to satisfy surveying requirements, thus reducing surveying efforts. More specifically, the need for total station network surveys can be reduced depending on the level of accuracy required for the project. The results from this study also provide a good baseline of accuracies that the ORGN can achieve and will provide ODOT with information that can be utilized to modernize the ODOT SPPM to leverage the ORGN for establishment of project control. By leveraging adjusted NRTK observations using the hybrid survey methodology, ODOT can optimize resources while attaining higher levels of accuracy when compared to the current survey recommendations outlined in the 2015 ODOT SPPM. The utilization of NRTK observations also allow for flexibility in the recommended survey procedures required to achieve varying levels of accuracy.

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APPENDIX A: PROPOSED SURVEY PROCEDURES

PROPOSED SURVEY PROCEDURES: ORGN NRTK OBSERVATIONS ONLY

Required Order of work	STANDARDS	ORGN NRTK RECOMMENDED PROCEDURES	
	Positional Accuracy	Survey Methods	
	Horizontal & Vertical	*Horizontal*	*Vertical*
0.015 ft (0.005 m)	Network accuracy less than 0.015 feet (0.005m) scaled to a 95% Confidence Level	Not Recommended	Not Recommended
0.030 ft (0.010 m)	Network accuracy less than 0.030 feet (0.010 m) scaled to a 95% Confidence Level	(4) independent 5 minute NRTK observations* on each control station	Not Recommended
0.050 ft (0.015 m)	Network accuracy less than 0.050 feet (0.015 m) scaled to a 95% Confidence Level	(3) independent 5 minute NRTK observations* on each control station	Not Recommended
0.070 ft (0.020 m)	Network accuracy less than 0.070 feet (0.020 m) scaled to a 95% Confidence Level	(2) independent 5 minute NRTK observations* on each control station	(4) independent 5 minute NRTK observations* on each control station
0.100 ft (0.030 m)	Network accuracy less than 0.100 feet (0.030 m) scaled to a 95% Confidence Level	(2) independent 3 minute^ NRTK observations* on each control station	(2) independent 5 minute NRTK observations* on each control station
0.150 ft (0.040 m)	Network accuracy less than 0.150 feet (0.040 m) scaled to a 95% Confidence Level	(2) independent 1 minute^ NRTK observations* on each control station	(2) independent 3 minute^ NRTK observations* on each control station
0.200 ft (0.050 m)	Network accuracy less than 0.200 feet (0.050 m) scaled to a 95% Confidence Level	(2) independent 30 second^ NRTK observations* on each control station	(2) independent 1 minute^ NRTK observations* on each control station
0.300 ft (0.100 m)	Network accuracy less than 0.300 feet (0.100 m) scaled to a 95% Confidence Level	(2) independent 5 second^ NRTK observations* on each control station	(2) independent 5 second^ NRTK observations* on each control station
3 ft (1 m)	N/A	(1) 3 second^ NRTK observations on each control station	(1) 3 second^ NRTK observations on each control station
33 ft (10 m)	N/A	(1) 3 second^ NRTK observations on each control station	(1) 3 second^ NRTK observations on each control station

Notes:
* NRTK Observations required to be included in a least squares adjustment using the Hybrid Survey Network methodology proposed by Weaver et. al, (2018).
^ Recommended NRTK occupation times based on findings outlined in Allahyari et. al, (2018).

PROPOSED SURVEY PROCEDURES: ORGN NRTK OBSERVATIONS & TRADITIONAL OBSERVATIONS

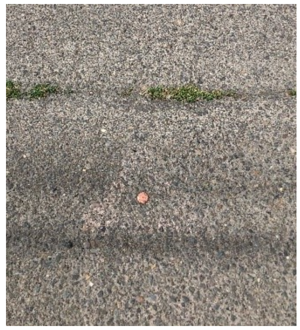
Required Order of work	**STANDARDS**	**RECOMMENDED PROCEDURES LEVERAGING THE ORGN**	
	Positional Accuracy	Survey Methods	
	Horizontal & Vertical	*Horizontal*	*Vertical*
0.015 ft (0.005 m)	Network accuracy less than 0.015 feet (0.005m) scaled to a 95% Confidence Level	(4) independent 5 minute NRTK observations* on each control station OR Static-GNSS survey following NGS specifications -AND- Total Station Network Survey (reference ODOT SSPM for specific guidelines)	Differential Leveling using NGS first order standards or approved ODOT method, refer to ODOT SPPM for specific guidelines.
0.030 ft (0.010 m)	Network accuracy less than 0.030 feet (0.010 m) scaled to a 95% Confidence Level	(2) independent 5 minute NRTK observations* on each control station OR Static-GNSS survey following NGS specifications -AND- Total Station Traverse Survey (reference ODOT SSPM for specific guidelines)	Digital Differential Leveling with bar code rod or approved ODOT alternate, refer to ODOT SPPM for specific guidelines -AND- (4) independent 5 minute NRTK observations* on a subset of the stations
0.050 ft (0.015 m)	Network accuracy less than 0.050 feet (0.015 m) scaled to a 95% Confidence Level	(3) independent 5 minute NRTK observations* on each control station	Digital or Optical differential leveling with standard rod -AND- (3) independent 5 minute NRTK observations* on a subset of the stations
0.070 ft (0.020 m)	Network accuracy less than 0.070 feet (0.020 m) scaled to a 95% Confidence Level	(2) independent 5 minute NRTK observations* on each control station	(4) independent 5 minute NRTK observations* on each control station -OR- Digital or Optical differential leveling with standard rod AND (2) independent 5 minute NRTK observations on a subset of stations
0.100 ft (0.030 m)	Network accuracy less than 0.100 feet (0.030 m) scaled to a 95% Confidence Level	(2) independent 3 minute^ NRTK observations* on each control station	(2) independent 5 minute NRTK observations* on each control station
0.150 ft (0.040 m)	Network accuracy less than 0.150 feet (0.040 m) scaled to a 95% Confidence Level	(2) independent 1 minute^ NRTK observations* on each control station	(2) independent 3 minute^ NRTK observations* on each control station
0.200 ft (0.050 m)	Network accuracy less than 0.200 feet (0.050 m) scaled to a 95% Confidence Level	(2) independent 30 second^ NRTK observations* on each control station	(2) independent 1 minute^ NRTK observations* on each control station
0.300 ft (0.100 m)	Network accuracy less than 0.300 feet (0.100 m) scaled to a 95% Confidence Level	(2) independent 5 second^ NRTK observations* on each control station	(2) independent 5 second^ NRTK observations* on each control station
3 ft (1 m)	N/A	Resource Grade GNSS with corrector or post processed	
33 ft (10 m)	N/A	Resource Grade GNSS without corrector and no post processing	

Notes:
* NRTK Observations required to be included in a least squares adjustment using the Hybrid Survey Network methodology proposed by Weaver et. al, (2018).
^ Recommended NRTK occupation times based on findings outlined in Allahyari et. al, (2018).

APPENDIX B: IMAGES OF EACH STATION USED IN STUDY

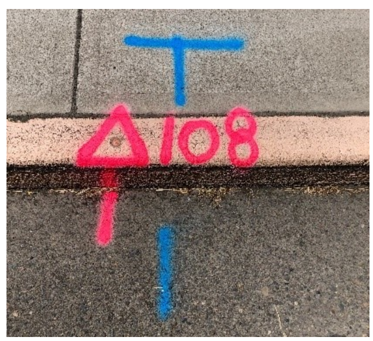
PHASE I STATION IMAGES

115 1-1/8" Brass Plug Oblique image orientation: Looking West		
116 1-1/8" Brass Plug Oblique image orientation: Looking North		
U-98 NGS Benchmark Station Brass Disk Oblique image orientation: Looking West		
106 1-1/8" Brass Plug Oblique image orientation: Looking West		

102 1-1/8” Brass Plug Oblique image orientation: Looking North		
100 1-1/8” Brass Plug Oblique image orientation: Looking North		
101 1-1/8” Brass Plug Oblique image orientation: Looking North		
103 1-1/8” Brass Plug Oblique image orientation: Looking North		

104 1-1/8” Brass Plug Oblique image orientation: Looking North		
105 1-1/8” Brass Plug Oblique image orientation: Looking West		
117 1-1/8” Brass Plug Oblique image orientation: Looking East *Not Suitable for GNSS due to tree canopy*		
118 1-1/8” Brass Plug Oblique image orientation: Looking North		

119 1-1/8” Brass Plug Oblique image orientation: Looking North		
107 1-1/8” Brass Plug No images available		
121 1-1/8” Brass Plug Oblique image orientation: Looking East		
122 1-1/8” Brass Plug Oblique image orientation: Looking West		

123 1-1/8" Brass Plug Oblique image orientation: Looking East		
120 1-1/8" Brass Plug Oblique image orientation: Looking West		
108 1-1/8" Brass Plug Oblique image orientation: Looking West		
113 1-1/8" Brass Plug Oblique image orientation: Looking North		

114 1-1/8" Brass Plug Oblique image orientation: Looking East		
124 Iron rod with red plastic cap Oblique image orientation: Looking North		
109 1-1/8" Brass Plug Oblique image orientation: Looking North		
110 Iron rod with red plastic cap Oblique image orientation: Looking South		

111 Iron rod with red plastic cap Oblique image orientation: Looking North		
112 1-1/8" Brass Plug Oblique image orientation: Looking South		

PHASE II STATION IMAGES

CAN 1-1/8" Brass Plug Oblique image orientation: Looking West		
23 1-1/8" Brass Plug Oblique image orientation: Looking West		
8 1-1/8" Brass Plug Oblique image orientation: Looking West		
4 1-1/8" Brass Plug Oblique image orientation: Looking West		

5 1-1/8" Brass Plug Oblique image orientation: Looking West		
3 1-1/8" Brass Plug Oblique image orientation: Looking West		
1 1-1/8" Brass Plug Oblique image orientation: Looking West		
22 5/8"x30" IR with Brass Cap Oblique image orientation: Looking West		

20 5/8"x30" IR with Brass Cap Oblique image orientation: Looking West		
CCF 5/8"x30" IR with Brass Cap Oblique image orientation: Looking South		
11 1-1/8" Brass Plug Oblique image orientation: Looking West		
10 1-1/8" Brass Plug Oblique image orientation: Looking West		

21 1-1/8" Brass Plug Oblique image orientation: Looking West		
2 1-1/8" Brass Plug Oblique image orientation: Looking West		
6 1-1/8" Brass Plug Oblique image orientation: Looking West		
24 1-1/8" Brass Plug Oblique image orientation: Looking East		

25 1-1/8" Brass Plug Oblique image orientation: Looking West		
VEM 1-1/8" Brass Plug Oblique image orientation: Looking West		
26 1-1/8" Brass Plug Oblique image orientation: Looking West		

APPENDIX C: RESULTING ACCURACIES FOR EACH NETWORK ADJUSTMENT

PHASE I LIST OF CONSTRUCTED NETWORKS AND RESULTING ACCURACIES

Dataset #	GNSS NRTK	Total Station Network	Differential Leveling	Comments	RMSE [cm]			Std. [cm]		
					V	H	3D	V	H	3D
1	6	no	no		1.51	1.30	2.00	1.55	0.75	1.30
2	*8,9*	no	no		1.19	0.89	1.49	1.21	0.35	0.77
3	*7,8,9*	no	no		0.81	0.62	1.02	0.82	0.23	0.44
4	6, 7, 8, 9	no	no		0.69	0.70	0.98	0.69	0.27	0.36
5	6, 7, 8, 9, 10	no	no		0.70	0.66	0.96	0.71	0.29	0.41
6	5, 6, 7, 8, 9, 10	no	no		0.99	0.77	1.26	0.97	0.38	0.67
7	*8,10*	no	no		1.13	0.69	1.32	1.07	0.30	0.78
8	*8,10,11*	no	no		1.06	0.69	1.26	1.00	0.33	0.75
9	6, 8, 10, 11	no	no		0.86	0.79	1.17	0.86	0.45	0.66
10	3, 4, 6, 8, 10	no	no		0.83	0.67	1.07	0.81	0.30	0.54
11	1, 3, 4, 6, 8, 10	no	no		0.81	0.62	1.02	0.71	0.27	0.50
12	12, 13	no	no		1.26	0.84	1.51	0.90	0.48	0.85
13	11,12,13	no	no		1.11	0.80	1.36	0.86	0.44	0.80
14	8,11,12,13	no	no		1.00	0.74	1.24	0.81	0.38	0.69
15	*3,5,8,11,13*	no	no		0.88	0.74	1.15	0.89	0.34	0.58
16	3, 5, 8, 11, 12, 13	no	no		0.84	0.73	1.11	0.82	0.39	0.62
17	6	yes	no		1.09	0.74	1.32	1.05	0.60	0.87
18	*8,9*	yes	no		1.04	0.45	1.14	1.06	0.34	0.65
19	*7,8,9*	yes	no		0.95	0.28	0.99	0.95	0.18	0.56
20	6, 7, 8, 9	yes	no		0.90	0.23	0.93	0.89	0.14	0.52
21	6, 7, 8, 9, 10	yes	no		0.84	0.16	0.85	0.84	0.10	0.47
22	5, 6, 7, 8, 9, 10	yes	no		0.95	0.16	0.96	0.86	0.10	0.56
23	*8,10*	yes	no		0.99	0.32	1.04	1.00	0.20	0.54
24	*8,10,11*	yes	no		0.90	0.30	0.95	0.92	0.19	0.49
25	6, 8, 10, 11	yes	no		0.86	0.24	0.90	0.88	0.16	0.49
26	3, 4, 6, 8, 10	yes	no		0.86	0.22	0.89	0.87	0.14	0.47

Dataset #	GNSS NRTK	Total Station Network	Differential Leveling	Comments	RMSE [cm]			Std. [cm]		
					V	H	3D	V	H	3D
27	1, 3, 4, 6, 8, 10	yes	no		0.86	0.19	0.89	0.84	0.12	0.48
28	12, 13	yes	no		1.22	0.44	1.29	1.00	0.34	0.66
29	11,12,13	yes	no		1.02	0.38	1.09	0.93	0.29	0.56
30	8,11,12,13	yes	no		0.95	0.31	1.00	0.89	0.23	0.53
31	*3,5,8,11,13*	yes	no		0.93	0.30	0.97	0.94	0.21	0.51
32	3, 5, 8, 11, 12, 13	yes	no		0.88	0.24	0.91	0.89	0.18	0.48
33	6	no	yes		0.36	1.30	1.35	0.21	0.76	0.73
34	*8,9*	no	yes		0.25	0.86	0.90	0.21	0.33	0.31
35	*7,8,9*	no	yes		0.33	0.60	0.69	0.20	0.23	0.19
36	6, 7, 8, 9	no	yes		0.33	0.68	0.75	0.20	0.26	0.23
37	6, 7, 8, 9, 10	no	yes		0.27	0.64	0.69	0.21	0.27	0.26
38	5, 6, 7, 8, 9, 10	no	yes		0.51	0.73	0.89	0.16	0.34	0.29
39	*8,10*	no	yes		0.19	0.80	0.82	0.14	0.42	0.42
40	*8,10,11*	no	yes		0.19	0.70	0.72	0.15	0.34	0.35
41	6, 8, 10, 11	no	yes		0.16	0.76	0.78	0.16	0.43	0.43
42	3, 4, 6, 8, 10	no	yes		0.18	0.67	0.70	0.18	0.29	0.30
43	1, 3, 4, 6, 8, 10	no	yes		0.28	0.62	0.68	0.17	0.26	0.28
44	12, 13	no	yes		0.79	0.79	1.12	0.15	0.42	0.32
45	11,12,13	no	yes		0.61	0.75	0.96	0.17	0.37	0.32
46	8,11,12,13	no	yes		0.48	0.71	0.86	0.11	0.35	0.31
47	*3,5,8,11,13*	no	yes		0.11	0.73	0.74	0.09	0.33	0.32
48	3, 5, 8, 11, 12, 13	no	yes		0.11	0.71	0.72	0.08	0.37	0.37
49	6	yes	yes		0.42	0.70	0.81	0.19	0.56	0.57
50	*8,9*	yes	yes		0.21	0.41	0.46	0.18	0.30	0.35
51	*7,8,9*	yes	yes		0.30	0.25	0.39	0.16	0.15	0.21
52	6, 7, 8, 9	yes	yes		0.32	0.22	0.39	0.15	0.12	0.19
53	6, 7, 8, 9, 10	yes	yes		0.24	0.16	0.29	0.14	0.10	0.16
54	5, 6, 7, 8, 9, 10	yes	yes		0.48	0.15	0.51	0.15	0.10	0.17

Dataset #	GNSS NRTK	Total Station Network	Differential Leveling	Comments	RMSE [cm]			Std. [cm]		
					V	H	3D	V	H	3D
55	*8,10*	yes	yes		0.20	0.33	0.39	0.17	0.21	0.23
56	*8,10,11*	yes	yes		0.18	0.30	0.35	0.16	0.19	0.21
57	6, 8, 10, 11	yes	yes		0.16	0.24	0.29	0.16	0.16	0.21
58	3, 4, 6, 8, 10	yes	yes		0.15	0.23	0.27	0.15	0.15	0.18
59	1, 3, 4, 6, 8, 10	yes	yes		0.24	0.21	0.32	0.15	0.13	0.12
60	12, 13	yes	yes		0.76	0.40	0.85	0.18	0.30	0.16
61	11,12,13	yes	yes		0.55	0.34	0.65	0.18	0.26	0.16
62	8,11,12,13	yes	yes		0.45	0.29	0.54	0.17	0.21	0.14
63	*3,5,8,11,13*	yes	yes		0.18	0.28	0.34	0.18	0.20	0.25
64	3, 5, 8, 11, 12, 13	yes	yes		0.19	0.23	0.29	0.17	0.17	0.20
65	6	yes	no	Using 4 NRTK stations	1.09	1.24	1.65	1.09	0.57	0.55
66	*8,9*	yes	no	Using 4 NRTK stations	1.07	0.89	1.39	1.08	0.51	0.64
67	*7,8,9*	yes	no	Using 4 NRTK stations	1.05	0.61	1.21	1.05	0.34	0.53
68	6, 7, 8, 9	yes	no	Using 4 NRTK stations	1.02	0.46	1.12	1.02	0.28	0.50
69	6, 7, 8, 9, 10	yes	no	Using 4 NRTK stations	1.02	0.39	1.09	1.00	0.22	0.48
70	5, 6, 7, 8, 9, 10	yes	no	Using 4 NRTK stations	0.98	0.38	1.05	0.99	0.22	0.46
71	*8,10*	yes	no	Using 4 NRTK stations	1.20	0.74	1.41	1.06	0.36	0.61
72	*8,10,11*	yes	no	Using 4 NRTK stations	1.04	0.56	1.19	1.03	0.28	0.56
73	6, 8, 10, 11	yes	no	Using 4 NRTK stations	1.02	0.45	1.11	1.01	0.24	0.52
74	3, 4, 6, 8, 10	yes	no	Using 4 NRTK stations	1.09	0.46	1.18	1.02	0.23	0.54
75	1, 3, 4, 6, 8, 10	yes	no	Using 4 NRTK stations	1.11	0.39	1.18	1.00	0.18	0.56
76	12, 13	yes	no	Using 4 NRTK stations	1.30	0.89	1.57	1.07	0.35	0.57
77	11,12,13	yes	no	Using 4 NRTK stations	1.09	0.61	1.25	1.05	0.34	0.55
78	8,11,12,13	yes	no	Using 4 NRTK stations	1.04	0.50	1.16	1.02	0.25	0.58
79	*3,5,8,11,13*	yes	no	Using 4 NRTK stations	1.06	0.49	1.17	1.04	0.25	0.54
80	3, 5, 8, 11, 12, 13	yes	no	Using 4 NRTK stations	1.04	0.41	1.12	1.01	0.21	0.54
81	6	yes	yes	Using 4 NRTK stations	0.17	1.12	1.14	0.17	0.54	0.54
82	*8,9*	yes	yes	Using 4 NRTK stations	0.22	0.72	0.75	0.17	0.41	0.43

Dataset #	GNSS NRTK	Total Station Network	Differential Leveling	Comments	RMSE [cm]			Std. [cm]		
					V	H	3D	V	H	3D
83	*7,8,9*	yes	yes	Using 4 NRTK stations	0.20	0.42	0.47	0.15	0.22	0.24
84	6, 7, 8, 9	yes	yes	Using 4 NRTK stations	0.18	0.36	0.40	0.14	0.20	0.21
85	6, 7, 8, 9, 10	yes	yes	Using 4 NRTK stations	0.13	0.34	0.36	0.13	0.18	0.19
86	5, 6, 7, 8, 9, 10	yes	yes	Using 4 NRTK stations	0.26	0.33	0.42	0.13	0.19	0.19
87	*8,10*	yes	yes	Using 4 NRTK stations	0.17	0.62	0.64	0.15	0.29	0.29
88	*8,10,11*	yes	yes	Using 4 NRTK stations	0.14	0.52	0.54	0.14	0.25	0.25
89	6, 8, 10, 11	yes	yes	Using 4 NRTK stations	0.13	0.43	0.45	0.13	0.21	0.22
90	3, 4, 6, 8, 10	yes	yes	Using 4 NRTK stations	0.13	0.44	0.46	0.13	0.22	0.23
91	1, 3, 4, 6, 8, 10	yes	yes	Using 4 NRTK stations	0.24	0.39	0.46	0.13	0.18	0.15
92	12, 13	yes	yes	Using 4 NRTK stations	0.58	0.72	0.93	0.16	0.29	0.20
93	11,12,13	yes	yes	Using 4 NRTK stations	0.41	0.48	0.63	0.15	0.25	0.19
94	8,11,12,13	yes	yes	Using 4 NRTK stations	0.21	0.47	0.52	0.14	0.20	0.20
95	*3,5,8,11,13*	yes	yes	Using 4 NRTK stations	0.15	0.45	0.47	0.15	0.24	0.25
96	3, 5, 8, 11, 12, 13	yes	yes	Using 4 NRTK stations	0.16	0.37	0.41	0.15	0.19	0.20
97	1	no	no		1.64	0.94	1.89	1.13	0.39	0.94
98	2	no	no		1.57	1.73	2.34	1.46	0.63	1.16
99	3	no	no		1.57	1.13	1.93	1.26	0.40	0.93
100	5	no	no		3.06	2.04	3.68	2.39	0.89	1.30
101	7	no	no		1.15	0.57	1.28	1.14	0.27	0.81
102	8	no	no		1.20	0.89	1.49	1.19	0.45	0.72
103	9	no	no		1.78	1.46	2.30	1.80	0.66	1.21
104	10	no	no		1.45	0.88	1.70	1.41	0.33	1.00
105	11	no	no		0.84	0.96	1.28	0.84	0.44	0.47
106	12	no	no		1.54	1.02	1.84	1.19	0.62	1.09
107	13	no	no		1.67	1.08	1.99	1.39	0.61	1.21
108	1,2	no	no		1.66	1.24	2.08	1.24	0.69	1.23
109	2,3	no	no		1.11	1.20	1.63	0.90	0.47	0.65
110	5,6	no	no		1.69	1.42	2.21	1.63	0.76	1.21

Dataset #	GNSS NRTK	Total Station Network	Differential Leveling	Comments	RMSE [cm]			Std. [cm]		
					V	H	3D	V	H	3D
111	7,8	no	no		0.78	0.56	0.96	0.79	0.30	0.50
112	8,9	no	no		1.19	0.89	1.49	1.21	0.35	0.77
113	9,10	no	no		1.39	0.90	1.65	1.39	0.37	0.96
114	1,3	no	no		1.49	0.85	1.72	0.98	0.41	0.87
115	5,7	no	no		1.20	0.80	1.44	0.84	0.31	0.56
116	7,9	no	no		0.97	0.72	1.20	0.97	0.29	0.50
117	8,10	no	no		1.13	0.69	1.32	1.07	0.30	0.78
118	10,11	no	no		1.28	0.78	1.50	1.24	0.35	0.93
119	3,5	no	no		1.22	1.22	1.73	1.23	0.51	0.67
120	5,8	no	no		1.34	1.03	1.69	1.28	0.46	0.73
121	6,9	no	no		1.18	1.20	1.68	1.20	0.58	0.79
122	7,10	no	no		0.72	0.51	0.88	0.73	0.18	0.32
123	1,2,3	no	no		1.30	1.02	1.65	0.83	0.50	0.83
124	5,6,7	no	no		0.93	0.82	1.24	0.68	0.38	0.44
125	7,8,9	no	no		0.81	0.62	1.02	0.82	0.23	0.44
126	8,9,10	no	no		1.14	0.74	1.36	1.13	0.32	0.81
127	5,7,9	no	no		1.06	0.89	1.38	0.89	0.32	0.53
128	8,10,11	no	no		1.02	0.69	1.23	0.98	0.33	0.74
129	5,8,11	no	no		1.01	0.92	1.37	0.98	0.45	0.61
130	11,12,13	no	no		1.11	0.80	1.36	0.86	0.44	0.80
131	5,6,7,8	no	no		0.81	0.74	1.10	0.66	0.33	0.37
132	7,8,9,10	no	no		0.74	0.57	0.93	0.75	0.24	0.41
133	6,7,8,9,10	no	no		0.70	0.66	0.96	0.71	0.29	0.41
134	4,6,8,10,11	no	no		0.71	0.68	0.98	0.72	0.35	0.45
135	3,5,8,11,12	no	no		0.81	0.79	1.13	0.81	0.39	0.60
136	3,5,8,11,13	no	no		0.85	0.74	1.13	0.86	0.34	0.57

PHASE II LIST OF CONSTRUCTED NETWORKS AND RESULTING ACCURACIES

Dataset #	NRTK GNSS	Total Station Network	Differential Leveling	OPUS-RS	Total Station Traverse	Comments	RMSE [cm]			Std. [cm]		
							V	H	3D	V	H	3D
1	1	No	No	No	No		1.23	1.06	1.62	0.79	0.46	0.55
2	2	No	No	No	No		1.13	0.76	1.36	0.87	0.44	0.72
3	3	No	No	No	No		1.10	0.65	1.28	0.82	0.28	0.56
4	4	No	No	No	No		1.43	0.83	1.65	1.19	0.43	0.78
5	5	No	No	No	No		1.07	0.88	1.39	0.90	0.44	0.62
6	6	No	No	No	No		1.58	0.77	1.76	1.19	0.39	0.99
7	1,2	No	No	No	No		1.01	0.69	1.22	0.55	0.34	0.48
8	1,3	No	No	No	No		1.03	0.69	1.24	0.55	0.26	0.41
9	1,4	No	No	No	No		1.15	0.58	1.28	0.76	0.24	0.59
10	1,5	No	No	No	No		1.06	0.74	1.29	0.67	0.36	0.59
11	1,6	No	No	No	No		1.13	0.70	1.33	0.60	0.30	0.54
12	2,3	No	No	No	No		0.98	0.54	1.12	0.60	0.25	0.55
13	2,4	No	No	No	No		1.00	0.58	1.16	0.66	0.31	0.60
14	2,5	No	No	No	No		0.96	0.60	1.13	0.65	0.37	0.54
15	2,6	No	No	No	No		1.11	0.56	1.24	0.68	0.34	0.62
16	3,4	No	No	No	No		0.98	0.56	1.13	0.65	0.21	0.47
17	3,5	No	No	No	No		0.89	0.63	1.09	0.56	0.22	0.46
18	3,6	No	No	No	No		1.26	0.51	1.37	0.88	0.23	0.70
19	4,5	No	No	No	No		1.08	0.75	1.32	0.83	0.38	0.49
20	4,6	No	No	No	No		1.32	0.73	1.51	0.95	0.37	0.73
21	5,6	No	No	No	No		1.08	0.69	1.28	0.73	0.31	0.62
22	1,2,3	No	No	No	No		0.96	0.56	1.11	0.46	0.24	0.40
23	1,2,4	No	No	No	No		1.00	0.52	1.13	0.58	0.26	0.50
24	1,2,5	No	No	No	No		0.95	0.58	1.11	0.50	0.35	0.44
25	1,2,6	No	No	No	No		1.01	0.55	1.15	0.47	0.28	0.44
26	1,3,4	No	No	No	No		0.99	0.50	1.11	0.53	0.23	0.40
27	1,3,5	No	No	No	No		0.93	0.59	1.10	0.45	0.27	0.38

Dataset #	NRTK GNSS	Total Station Network	Differential Leveling	OPUS-RS	Total Station Traverse	Comments	RMSE [cm]			Std. [cm]		
							V	H	3D	V	H	3D
28	1,3,6	No	No	No	No		1.10	0.55	1.23	0.60	0.23	0.52
29	1,4,5	No	No	No	No		1.05	0.59	1.20	0.67	0.26	0.54
30	1,4,6	No	No	No	No		1.11	0.56	1.24	0.63	0.23	0.50
31	1,5,6	No	No	No	No		1.01	0.63	1.19	0.52	0.27	0.44
32	2,3,4	No	No	No	No		0.93	0.50	1.06	0.54	0.25	0.50
33	2,3,5	No	No	No	No		0.89	0.52	1.03	0.48	0.26	0.44
34	2,3,6	No	No	No	No		1.07	0.44	1.15	0.62	0.24	0.59
35	2,4,5	No	No	No	No		0.94	0.58	1.10	0.59	0.32	0.48
36	2,4,6	No	No	No	No		1.05	0.56	1.19	0.63	0.33	0.58
37	2,5,6	No	No	No	No		0.97	0.53	1.11	0.54	0.32	0.47
38	3,4,5	No	No	No	No		0.90	0.60	1.08	0.55	0.24	0.41
39	3,4,6	No	No	No	No		1.13	0.53	1.25	0.73	0.21	0.58
40	3,5,6	No	No	No	No		1.03	0.55	1.17	0.64	0.20	0.54
41	4,5,6	No	No	No	No		1.08	0.69	1.28	0.72	0.33	0.56
42	1,2,3,4	No	No	No	No		0.95	0.47	1.06	0.48	0.23	0.41
43	1,2,3,5	No	No	No	No		0.90	0.52	1.04	0.40	0.26	0.35
44	1,2,3,6	No	No	No	No		1.01	0.47	1.11	0.48	0.21	0.45
45	1,2,4,5	No	No	No	No		0.96	0.52	1.09	0.53	0.28	0.45
46	1,2,4,6	No	No	No	No		1.00	0.49	1.12	0.51	0.25	0.45
47	1,2,5,6	No	No	No	No		0.94	0.52	1.08	0.42	0.28	0.36
48	1,3,4,5	No	No	No	No		0.93	0.52	1.06	0.48	0.23	0.39
49	1,3,4,6	No	No	No	No		1.05	0.48	1.15	0.57	0.21	0.47
50	1,3,5,6	No	No	No	No		0.99	0.53	1.12	0.49	0.22	0.42
51	1,4,5,6	No	No	No	No		1.02	0.57	1.17	0.57	0.25	0.45
52	2,3,4,5	No	No	No	No		0.89	0.51	1.02	0.48	0.26	0.43
53	2,3,4,6	No	No	No	No		1.01	0.46	1.12	0.58	0.24	0.54
54	2,3,5,6	No	No	No	No		0.96	0.47	1.07	0.50	0.23	0.47
55	2,4,5,6	No	No	No	No		0.97	0.55	1.11	0.54	0.32	0.47

Dataset #	NRTK GNSS	Total Station Network	Differential Leveling	OPUS-RS	Total Station Traverse	Comments	RMSE [cm]			Std. [cm]		
							V	H	3D	V	H	3D
56	3,4,5,6	No	No	No	No		1.00	0.56	1.15	0.60	0.22	0.49
57	1,2,3,4,5	No	No	No	No		0.91	0.48	1.02	0.44	0.24	0.37
58	1,2,3,4,6	No	No	No	No		0.99	0.44	1.08	0.49	0.21	0.44
59	1,2,3,5,6	No	No	No	No		0.94	0.47	1.05	0.41	0.22	0.37
60	1,2,4,5,6	No	No	No	No		0.96	0.50	1.08	0.47	0.26	0.40
61	1,3,4,5,6	No	No	No	No		0.98	0.50	1.10	0.50	0.21	0.41
62	2,3,4,5,6	No	No	No	No		0.94	0.49	1.06	0.50	0.24	0.46
63	1,2,3,4,5,6	No	No	No	No		0.94	0.46	1.04	0.44	0.22	0.38
64	1	No	Yes	No	No		0.95	1.03	1.40	0.02	0.45	0.30
65	1,3	No	Yes	No	No		0.90	0.67	1.12	0.02	0.25	0.15
66	1,2,6	No	Yes	No	No		0.89	0.54	1.04	0.02	0.27	0.15
67	1,2,4,5	No	Yes	No	No		0.77	0.51	0.92	0.02	0.28	0.17
68	2,3,4,5,6	No	Yes	No	No		0.76	0.49	0.91	0.02	0.25	0.15
69	1,2,3,4,5,6	No	Yes	No	No		0.80	0.46	0.92	0.02	0.22	0.12
70	1	Yes	No	No	No		1.84	0.53	1.91	1.52	0.09	1.13
71	1,3	Yes	No	No	No		1.65	0.36	1.69	1.36	0.08	1.06
72	1,2,6	Yes	No	No	No		1.55	0.21	1.56	1.27	0.07	1.01
73	1,2,4,5	Yes	No	No	No		1.31	0.24	1.33	1.07	0.10	0.80
74	2,3,4,5,6	Yes	No	No	No		1.16	0.31	1.20	0.89	0.08	0.66
75	1,2,3,4,5,6	Yes	No	No	No		1.15	0.23	1.17	0.82	0.09	0.65
76	1	Yes	Yes	No	No		1.00	0.43	1.08	0.02	0.05	0.03
77	1,3	Yes	Yes	No	No		0.92	0.33	0.98	0.01	0.07	0.03
78	1,2,6	Yes	Yes	No	No		0.92	0.21	0.95	0.01	0.09	0.02
79	1,2,4,5	Yes	Yes	No	No		0.78	0.26	0.82	0.02	0.11	0.05
80	2,3,4,5,6	Yes	Yes	No	No		0.77	0.30	0.83	0.01	0.09	0.04
81	1,2,3,4,5,6	Yes	Yes	No	No		0.81	0.24	0.85	0.01	0.09	0.04
82	1	Yes	No	No	No	Using 6 NRTK stations	1.80	0.61	1.90	1.59	0.31	1.14
83	1,3	Yes	No	No	No	Using 6 NRTK stations	1.69	0.40	1.74	1.53	0.18	1.09

Dataset #	NRTK GNSS	Total Station Network	Differential Leveling	OPUS-RS	Total Station Traverse	Comments	RMSE [cm]			Std. [cm]		
							V	H	3D	V	H	3D
84	1,2,6	Yes	No	No	No	Using 6 NRTK stations	1.65	0.29	1.68	1.48	0.14	1.08
85	1,2,4,5	Yes	No	No	No	Using 6 NRTK stations	1.48	0.27	1.50	1.42	0.13	0.93
86	2,3,4,5,6	Yes	No	No	No	Using 6 NRTK stations	1.39	0.22	1.40	1.33	0.05	0.86
87	1,2,3,4,5,6	Yes	No	No	No	Using 6 NRTK stations	1.39	0.17	1.40	1.27	0.10	0.93
88	1	Yes	Yes	No	No	Using 6 NRTK stations	1.01	0.48	1.12	0.02	0.22	0.12
89	1,3	Yes	Yes	No	No	Using 6 NRTK stations	0.96	0.31	1.01	0.02	0.11	0.05
90	1,2,6	Yes	Yes	No	No	Using 6 NRTK stations	1.02	0.22	1.04	0.02	0.09	0.03
91	1,2,4,5	Yes	Yes	No	No	Using 6 NRTK stations	0.80	0.18	0.82	0.02	0.07	0.02
92	2,3,4,5,6	Yes	Yes	No	No	Using 6 NRTK stations	0.78	0.16	0.80	0.01	0.03	0.02
93	1,2,3,4,5,6	Yes	Yes	No	No	Using 6 NRTK stations	0.85	0.12	0.86	0.01	0.07	0.01
94		Yes	No	Yes	No	Using 6 OPUS-RS Stations	1.53	0.48	1.60	0.44	0.07	0.42
95	1	No	No	Yes	No		1.12	0.98	1.49	1.12	0.50	0.52
96	1,3	No	No	Yes	No		0.87	0.65	1.09	0.84	0.27	0.26
97	1,2,6	No	No	Yes	No		0.85	0.54	1.01	0.80	0.27	0.39
98	1,2,4,5	No	No	Yes	No		0.85	0.51	1.00	0.80	0.28	0.46
99	2,3,4,5,6	No	No	Yes	No		0.81	0.47	0.94	0.70	0.26	0.49
100	1,2,3,4,5,6	No	No	Yes	No		0.77	0.45	0.89	0.62	0.23	0.44
101	1	No	No	No	Yes		1.88	0.59	1.97	1.53	0.20	1.18
102	1,3	No	No	No	Yes		1.67	0.46	1.73	1.35	0.19	1.06
103	1,2,6	No	No	No	Yes		1.52	0.33	1.55	1.21	0.18	0.99
104	1,2,4,5	No	No	No	Yes		1.05	0.32	1.10	0.66	0.13	0.52
105	2,3,4,5,6	No	No	No	Yes		1.02	0.37	1.08	0.65	0.10	0.52
106	1,2,3,4,5,6	No	No	No	Yes		1.03	0.32	1.08	0.59	0.11	0.49
107	1	No	Yes	No	Yes		1.03	0.52	1.15	0.02	0.21	0.10
108	1,3	No	Yes	No	Yes		0.94	0.42	1.03	0.02	0.16	0.07
109	1,2,6	No	Yes	No	Yes		0.92	0.32	0.97	0.02	0.16	0.06
110	1,2,4,5	No	Yes	No	Yes		0.80	0.33	0.86	0.02	0.13	0.06

Dataset #	NRTK GNSS	Total Station Network	Differential Leveling	OPUS-RS	Total Station Traverse	Comments	RMSE [cm]			Std. [cm]		
							V	H	3D	V	H	3D
111	2,3,4,5,6	No	Yes	No	Yes		0.77	0.36	0.85	0.02	0.09	0.04
112	1,2,3,4,5,6	No	Yes	No	Yes		0.82	0.32	0.88	0.02	0.11	0.04
113	1	No	No	No	Yes	Using 6 NRTK stations	1.80	0.59	1.89	1.57	0.25	1.18
114	1,3	No	No	No	Yes	Using 6 NRTK stations	1.73	0.51	1.80	1.57	0.18	1.13
115	1,2,6	No	No	No	Yes	Using 6 NRTK stations	1.66	0.40	1.71	1.51	0.22	1.15
116	1,2,4,5	No	No	No	Yes	Using 6 NRTK stations	1.49	0.36	1.53	1.42	0.21	1.03
117	2,3,4,5,6	No	No	No	Yes	Using 6 NRTK stations	1.37	0.33	1.41	1.31	0.17	0.93
118	1,2,3,4,5,6	No	No	No	Yes	Using 6 NRTK stations	1.34	0.31	1.37	1.20	0.16	0.92
119	1	No	Yes	No	Yes	Using 6 NRTK stations	1.06	0.44	1.14	0.02	0.22	0.09
120	1,3	No	Yes	No	Yes	Using 6 NRTK stations	0.96	0.44	1.05	0.02	0.16	0.06
121	1,2,6	No	Yes	No	Yes	Using 6 NRTK stations	1.00	0.35	1.06	0.02	0.19	0.07
122	1,2,4,5	No	Yes	No	Yes	Using 6 NRTK stations	0.81	0.30	0.86	0.02	0.15	0.05
123	2,3,4,5,6	No	Yes	No	Yes	Using 6 NRTK stations	0.79	0.28	0.84	0.02	0.13	0.03
124	1,2,3,4,5,6	No	Yes	No	Yes	Using 6 NRTK stations	0.85	0.27	0.90	0.02	0.13	0.03
125		No	No	Yes	Yes	Using 6 NRTK stations	1.54	0.54	1.63	0.39	0.17	0.41
126		No	Yes	Yes	Yes	Using 6 NRTK stations	1.41	0.54	1.51	0.01	0.16	0.05

APPENDIX D: ESTIMATED ACCURACIES FROM FORMAL ERROR PROPAGATION

ACCURACIES BASED ON FORMAL ERROR PROPAGATION

The following sections are used to summarize the estimated uncertainties as reported from the least squares adjustments.

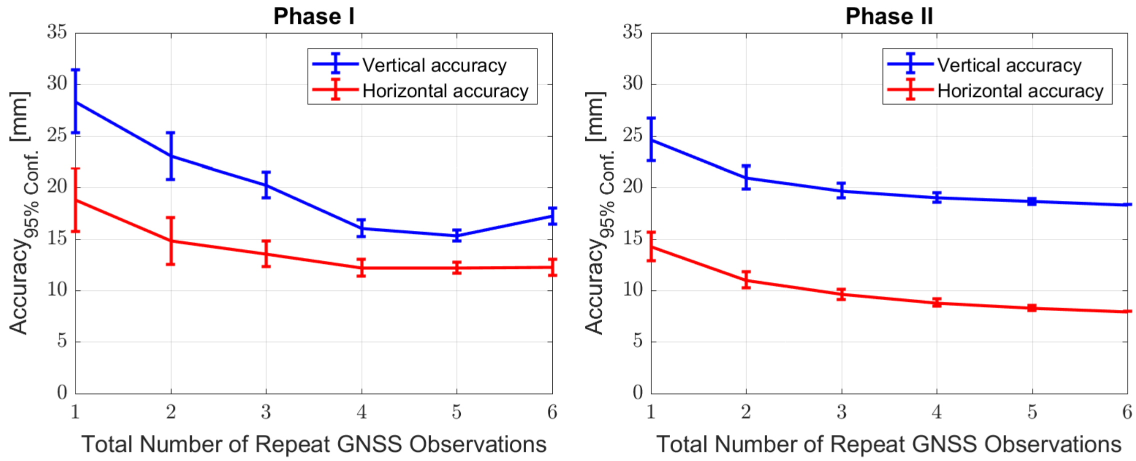
When adjusting each of the constructed networks, a minimally constrained adjustment was first performed on each individual data type to check for blunders and adjust the stochastic model. After all data types satisfied the requirements and no more blunders were detected, the data types were combined in a fully constrained adjustment of the network. Figure 6 is a flowchart showing the procedures implemented to adjust each of the constructed networks. To ensure the adjustment is not over-constrained and each data type was weighted appropriately, a minimally constrained adjustment was performed for each data type during which blunders were identified/removed and the stochastic model was scaled such that the standard deviation of unit weight was equal to 1, see Figure 6 for more details on how the least squares adjustments were performed. The standard deviation of unit weight being equal to 1 is a good indicator that the observations were properly weighted in the adjustment resulting in realistic estimated uncertainties. These estimated uncertainties are summarized in the following sections of this appendix. After the stochastic models for each data type were successfully scaled using minimal constraint adjustments, the data sets were combined into a single, fully constrained, least squares adjustment which resulted in final coordinates for each point in that phase.

Note, both the empirically derived accuracies and the estimated accuracies resulting from the least squares adjustments are shown. This enables readers to visually compare the results between the empirical assessment and the estimated uncertainties more easily. Note, these comparisons are not formally discussed in this document and the figures shown here are only supplementary content. The authors have chosen to utilize the empirical results as opposed to the formal error estimates for generating the recommended procedures as the empirical results are more conservative.

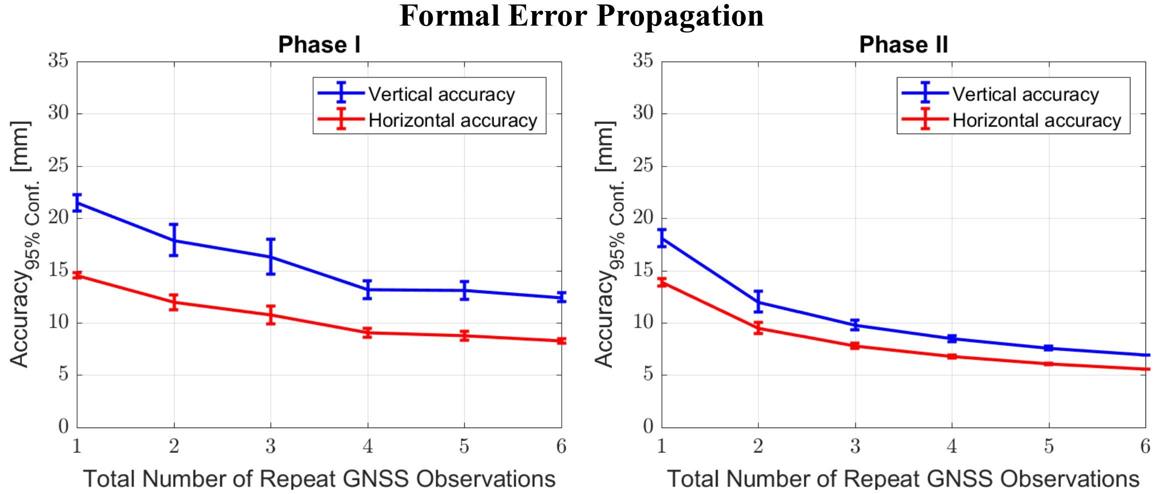
NUMBER OF REPEAT NRTK OBSERVATION REQUIRED PER POINT

These results correspond with Section 3.2 of the main body of the report.

Empirical Assessment

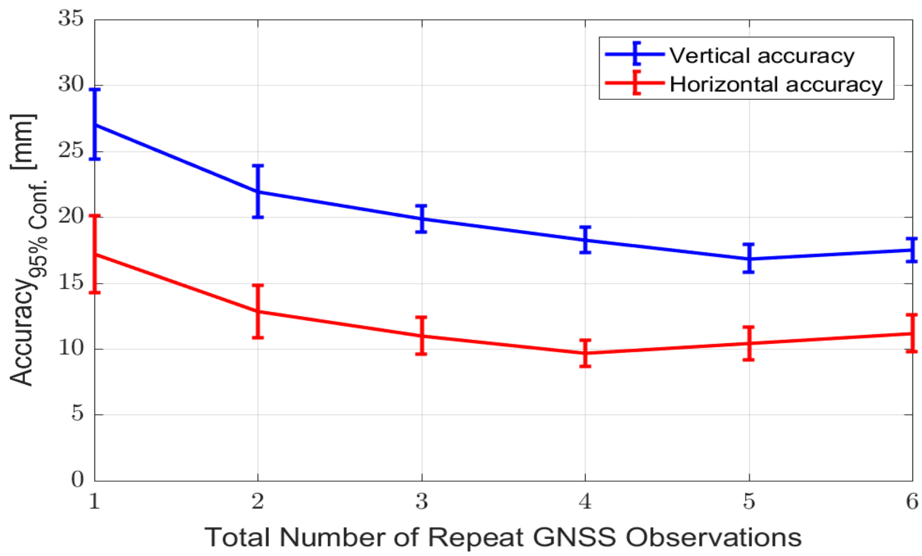


Formal Error Propagation

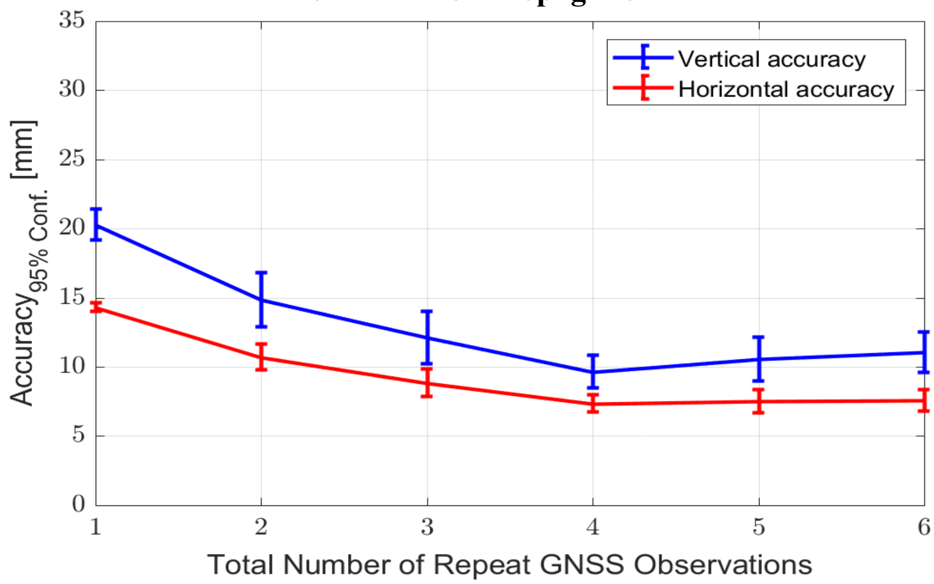


COMBINING THE RESULTS FROM PHASES I AND II

Empirical Assessment



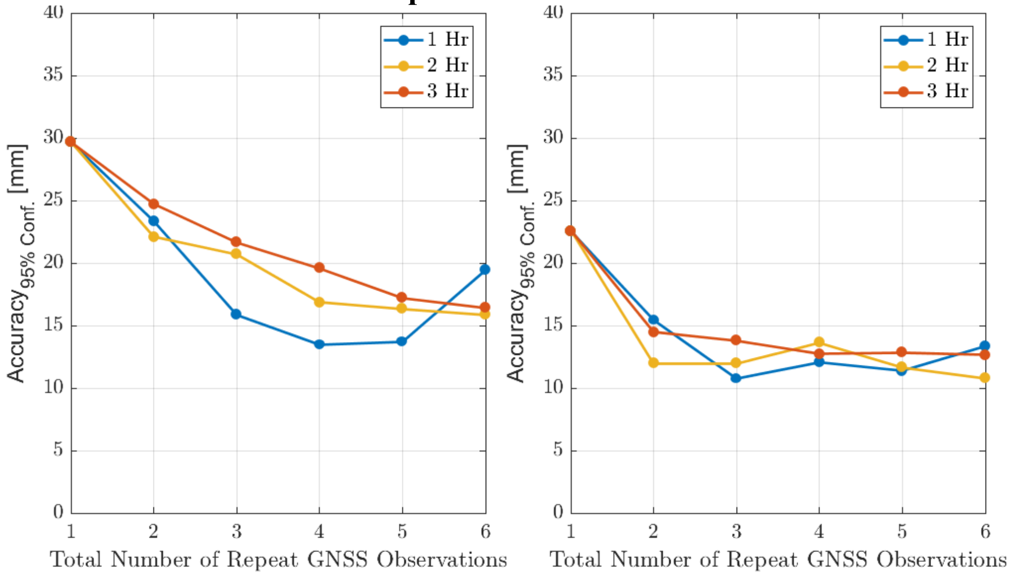
Formal Error Propagation



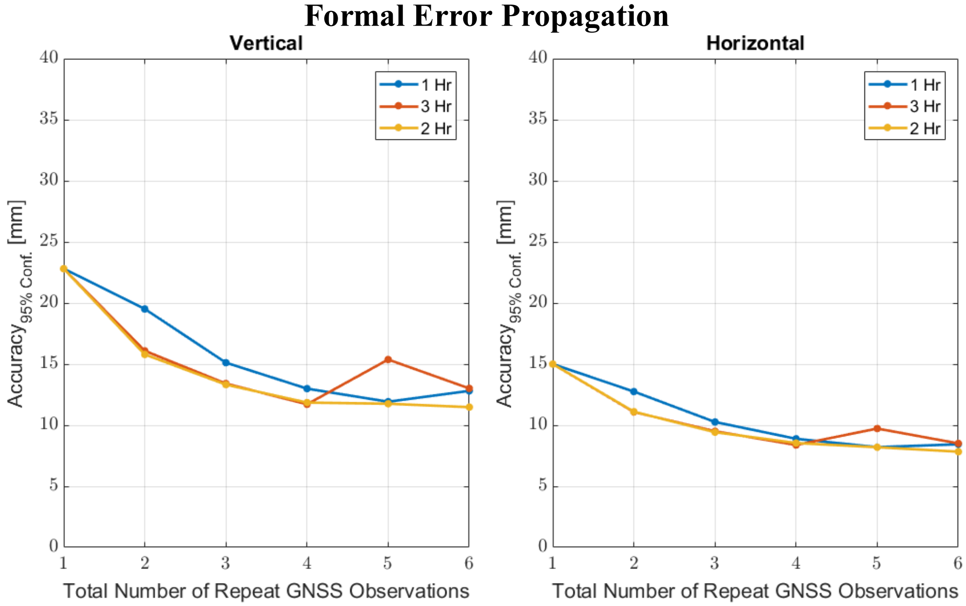
TIME BETWEEN REPEAT OBSERVATION

These results correspond with Section 3.3 of the main body of the report.

Empirical Assessment



Formal Error Propagation

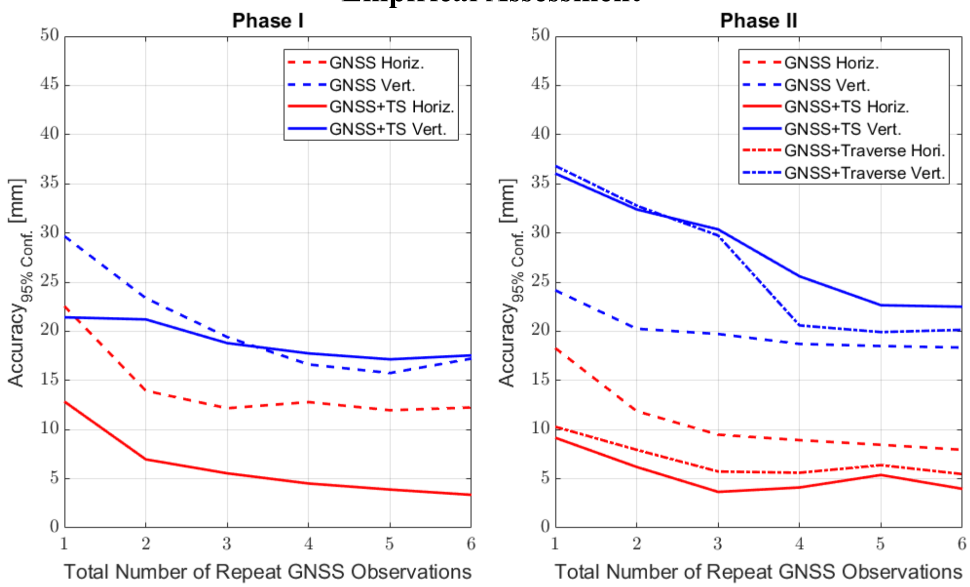


COMBINING NRTK AND TRADITIONAL OBSERVATION

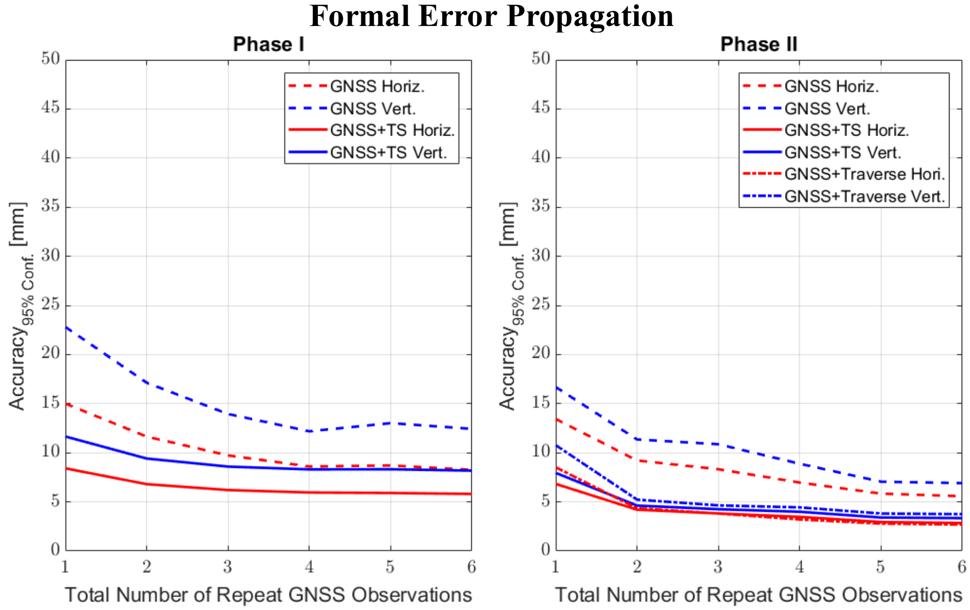
NRTK + Total Station (Network OR Traverse)

These results correspond with Section 3.4.1 of the main body of the report.

Empirical Assessment



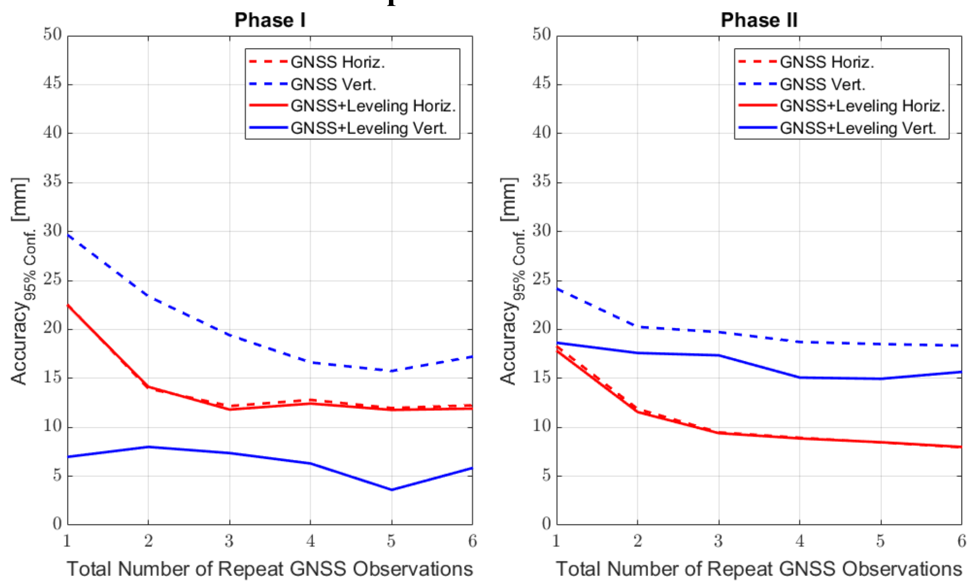
Formal Error Propagation



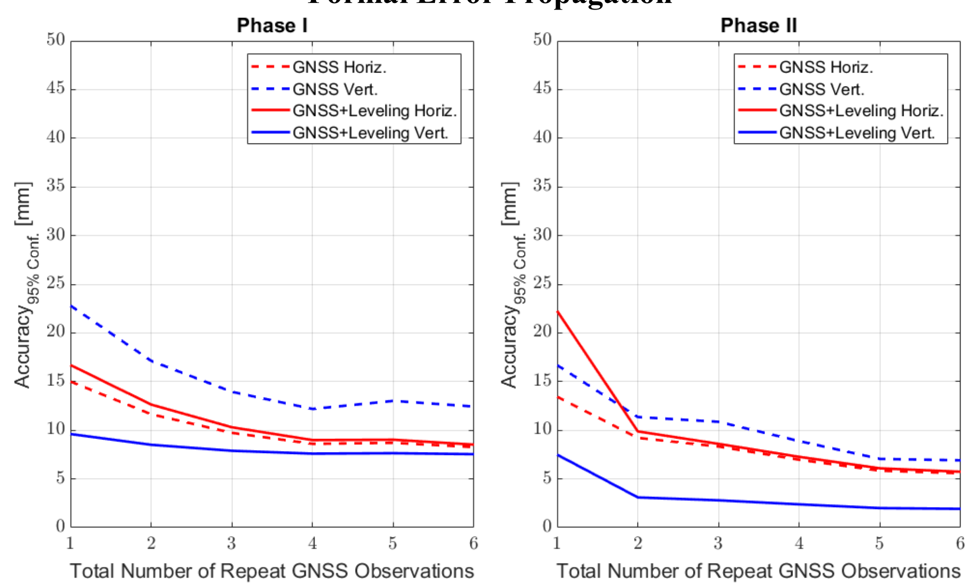
NRTK + Leveling

These results correspond with Section 3.4.2 of the main body of the report.

Empirical Assessment



Formal Error Propagation

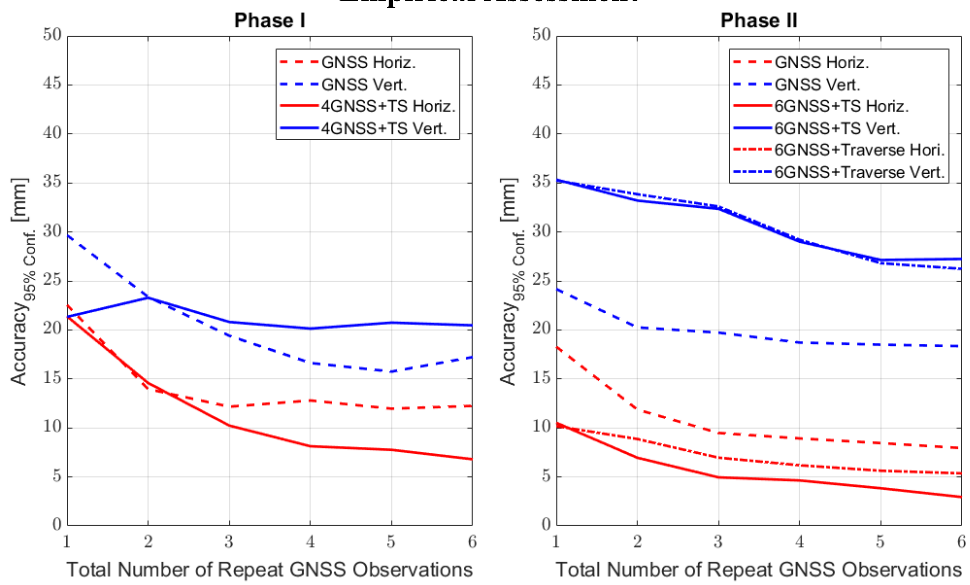


COMBINING SPARSE NRTK AND TRADITIONAL OBSERVATIONS

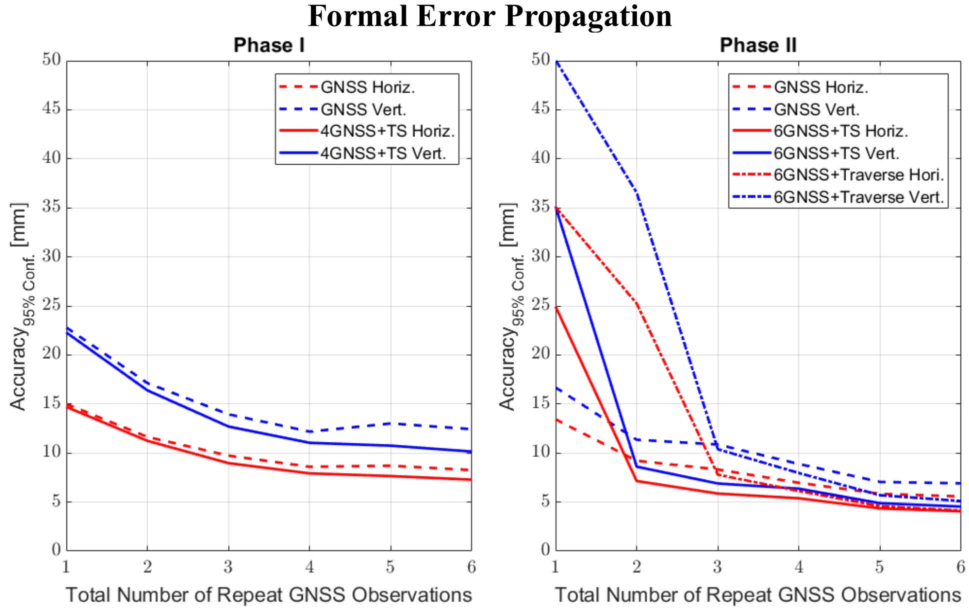
Sparse NRTK + Total Station (Network OR Traverse)

These results correspond with Section 3.5.1 of the main body of the report.

Empirical Assessment



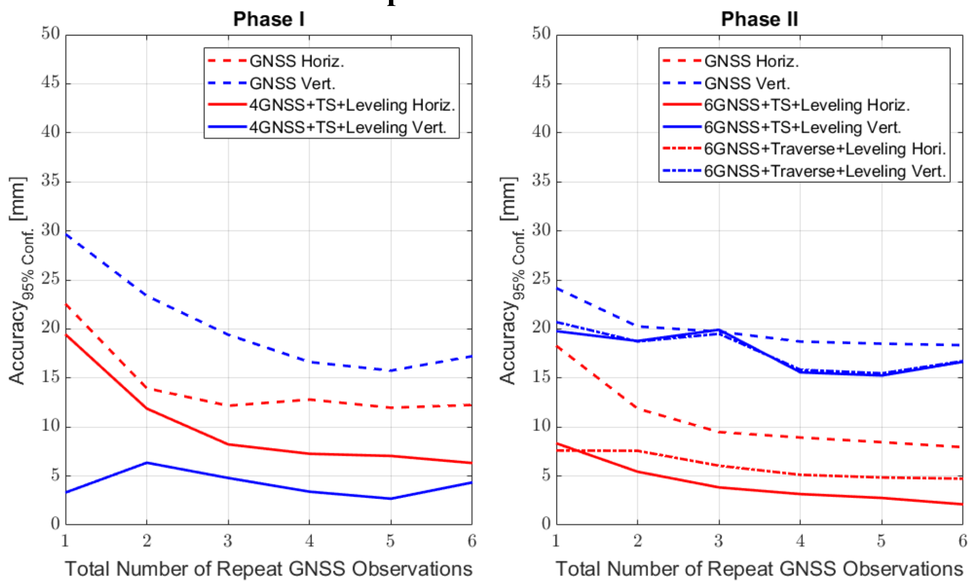
Formal Error Propagation



Sparse NRTK + Leveling

These results correspond with Section 3.5.2 of the main body of the report.

Empirical Assessment



Formal Error Propagation