AN ABSTRACT OF THE THESIS OF

Mahsa Allahyari for the degree of Master of Science in Civil Engineering presented on December 9, 2016.

Title: Accuracy Evaluation of Real-Time GNSS Survey Observations

Abstract approved:

Michael J. Olsen

Real time networks (RTNs) have become popular for Global Navigation Satellite System (GNSS) surveys because highly accurate positions can be derived in seconds to minutes compared to hours as required with static sessions. To evaluate the accuracy of these shorter-duration, RTN GNSS observations and their potential for use as a source for establishing geodetic control, data collected from two National Geodetic Survey (NGS) surveys in South Carolina and Oregon were studied in detail. This case study explores the horizontal and vertical accuracy of real-time observations as a function of observation duration, examines the influence of the inclusion of Globalnaya Navigazionnaya Sputnikovaya Sistema (GLONASS) observables, compares results from real-time kinematic (RTK) positioning using a single base station versus a network of base stations, and assesses the effect of baseline length on accuracy. Thirty-eight passive marks were repeatedly observed with GNSS using a RTN in the two study areas for a variety of different observation time durations, ranging from 5 seconds to 15 minutes. An optimal real-time observation duration was found in the range of 180 to 300 seconds. The real-time data

acquired using a network of base stations tended to be more accurate and precise than single-base RTK data. Further, the addition of GLONASS observables helped obtain more fixed solutions at longer baseline lengths than solutions based solely on GPS observables as well as showed a very slight improvement in accuracy, particularly for stations with poorer satellite visibility.

Accuracy Evaluation of Real-Time GNSS Survey Observations

by

Mahsa Allahyari

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APPROVED:

Major Professor, representing Civil Engineering

Head of the School of Civil and Construction Engineering

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Mahsa Allahyari, Author

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CONTRIBUTION OF AUTHORS

Dr. Daniel Gillins collected data for Oregon survey 2014 and also processed raw data for that survey, edited and commented on the thesis. Graduate student Michael L. Dennis was involved in the South Carolina survey 2013, performed quality checks on the data, and provided technical comments on the thesis.

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Introduction

Real-time Kinematic (RTK) Global Navigation Satellite System (GNSS) enables the acquisition of highly accurate positioning data with improved productivity to support a variety of applications such as geodesy, engineering surveys, deformation monitoring, automated machine guidance, hydrographic surveys, precision agriculture, and geologic and geo-hazard studies. In this approach, the RTK solution utilizes relative positioning algorithms between at least two receivers that are simultaneously collecting GNSS phase-angle observables from common satellite vehicles. One receiver, known as the “rover”, is set up over an object where the user desires to derive a position, and another “base” receiver is set up above a mark with known position. Communication between the rover and base is then established using a UHF radio, cellular data plan, or Wi-Fi link. This communication enables baseline processing of the data collected at the base and rover receivers in order to provide solutions to the user in real-time. By keeping the rover in close proximity with the base (e.g., within 10-20 km), errors such as ionospheric and tropospheric refraction nearly cancel during differencing of the observables (Janssen et al. 2011). It is common practice for a surveying engineer to set up a single, temporary base station; however, this practice requires the expense of the additional equipment including base receiver and radio, may involve additional personnel, has the potential for blunders if the base station is setup incorrectly, and can suffer from blockage or interference for communication between the base station and rover.

Real-time networks (RTNs) are often utilized to overcome these limitations by utilizing a network of permanent reference stations. Many government agencies and commercial companies have developed RTNs utilizing multiple permanent or semi-permanent base stations, enabling baselines to be extended further (Edwards et al. 2010). Nonetheless, there are some limitations in using RTNs in a survey, such as availability in some regions, subscription costs, and communication coverage (e.g., availability of cellular data plans).

RTNs with modern receivers for base stations have the ability to utilize information from other satellite constellations such as Russia's GLONASS, China's BeiDou and European Union's Galileo in addition to the Global Positioning System (GPS) developed by the United States. Aside from GPS, GLONASS is currently the only other system with full global coverage. While it is also possible to collect data from the other systems, most RTN's providers do not currently support them for real-time GNSS surveying. Using GLONASS alongside with GPS may potentially improve the solution accuracy in urban and non-urban environments where buildings and trees may obstruct satellites in the sky and create multi-path problems with the signals (Sarkar and Bose 2015). Anquela et al. (2012) compared results utilizing GPS and GLONASS signals for both static and kinematic Precise Point Positioning (PPP) GNSS solutions. Their results showed improvements in accuracy for the kinematic solution from GPS+GLONASS; however, the accuracy of static PPP solution did not always improve.

Ultimately, many factors influence the quality of GNSS data regardless of whether it is performed as a static, RTK, post processed kinematic (PPK) or other type of GNSS survey. The satellite constellation used during the survey, weather conditions, reference network, communication between base and rovers, and session duration are examples of some of the factors that can affect the accuracy of a GNSS-based survey (Soler et al. 2005). However, the effect of these factors are not fully studied and documented for real-time surveys. The objective of this study is to jointly evaluate the achievable accuracies of real-time GNSS data based on several of these parameters. Specifically, in this paper, we evaluate the following research goals using two case studies encompassing different environments and survey procedures: (1) Determine the "optimal" observation duration for real-time GNSS surveys to balance the accuracy and efficiency, particularly in the context of establishing geodetic control; (2) Assess the influence of the inclusion of GLONASS observables to the results; (3) Compare the network real-time kinematic solutions with single-base real-time kinematic solutions; (4) Evaluate the effect of baseline length on the accuracy of the solution and ability to achieve fixed solutions; and (5) Examine the consistency of the results between RTNs from two case studies.

While many of these aspects have been studied to some extent throughout the literature, few studies have utilized such an extensive dataset for their analyses. Most evaluate accuracy based on observations at a few stations rather than across a larger area such as those analyzed in the presented case studies. Additionally, few studies focus on one or two of the above factors rather than evaluate all of the above factors jointly. For example, few directly compare the influence of adding GLONASS to RTK observations since the full constellation of GLONASS was only recently completed in 2013. This study also attempts to find an "optimal" observation duration as well as compares data from two separate RTNs at different sides of continent, which has not been done in prior work. Finally, this paper also provides new lessons learned from each of the case studies related to using RTNs.

Background

The primary concept of a real-time network (RTN) is that a group of reference or base stations collect GNSS observations and send them in real-time to a central processing system. The user establishes communication between their rover and this central processing system, enabling real-time kinematic (RTK) positioning referenced to a nearby single base station in the network (referred to herein as “sRTK”) or using a network of base stations (referred to herein as “nRTK”). For nRTK observations, the system computes a solution by interpolating ionospheric and tropospheric effects using the network of base stations (Janssen, 2009). With the use of this network solution, the observation errors and their corrections are calculated and transmitted to the rover, or are used to generate “smoothed” observables from a real or virtual base station. The master auxiliary concept (MAC) and virtual reference station (VRS) are both examples of different nRTK methods in use.

In the MAC approach multiple cells are defined, depending on the size of the network, to determine and optimize the transmission of corrections to the rover by reducing the number of stations (Geosystems L., 2005). Master-Auxiliary Corrections (MAX) utilize a newer, proprietary RTCM message which Leica Geosystems developed, whereas Individualized Master-Auxiliary Corrections (i-MAX) uses an older and open-source RTCM message to be utilized with non-Leica receivers.

A VRS creates an imaginary GNSS reference station data based on nearby stations in the network to enhance the positioning accuracy of the results and reduce distance related errors (Petovello, 2011). The rover initially transmits its approximate coordinates, and a VRS is established close to the approximate rover's position. Pseudo range and carrier phase data are geometrically translated from the closest reference station along with interpolated ionospheric and tropospheric errors from the network. The VRS then transmits this information to the rover, which completes the RTK baseline processing in the same fashion as it would from an actual, physical base station.

A study by Janssen and Haasdyk (2011) described the difference between single-base RTK (sRTK) and the network RTK (nRTK) methods. In this study sRTK and nRTK performance examined over varying distances in different days. The outcomes of this study illustrated that the resulting nRTK coordinates were more accurate and precise than single-base RTK.

Henning (2011) assessed the effects of the baseline length, occupation time, and field procedures on a single-base RTK GNSS survey completed in Vermont. After removing some outliers, Henning (2011) found that the horizontal and vertical precisions of the sRTK observations improved as the duration of the observation increased. The dilution of precision (DOP) values, number of satellite vehicles had less effect on the precision of the observations than duration in this survey. Since the number of satellites were always greater than four and PDOP values were kept minimal during the survey, they did not experience the worst case situation for each of these factors. They also found that baseline length had insignificant influence on the relative precision of the baselines and lower field RMS did not result in higher precisions in both directions.

Charoenkalunyuta et al. (2012) evaluated the accuracy of a large number of GPS observations using different reference station spacing (10 to 80 km) within an RTN using the VRS concept in a case study in Thailand. Ionospheric refraction was determined to be the main error source and real-time network performance significantly degraded with increasing reference station spacing. The authors recommended maintaining reference station spacing less than 30 km for reliable real-time network solutions. Wang et al. (2010) evaluated and compared the accuracy of nRTK observations obtained using longer than recommended reference station spacing and using the VRS, MAX, and i-MAX approaches. The results showed that the highest initialization rate for the nRTK solution was achieved with the use of the MAX approach. However, at mean reference station spacing of 69 km, VRS techniques displayed more accurate nRTK results than both the MAX and i-MAX approaches. Janssen (2009) examined the procedures for the two different nRTK approaches, VRS and MAC. Using several reference stations in New South Wales, it was found that the bandwidth required for the MAC is larger than for VRS. Nonetheless, common UHF radio links can still support this bandwidth.

Smith et al. (2014) evaluated the accuracy of RTK data obtained using an RTN in Texas (VRS technique) by comparing with static GNSS observations post-processed using United States National Geodetic Survey software, OPUS-RS and OPUS-Projects. They found root-mean-square differences (RMSD) of 1.5 cm horizontally and 2.7 cm in ellipsoid height when comparing hundreds of 180-s-duration RTK observations with coordinates obtained by post-processing 48-h static GNSS observations in OPUS-Projects. In another study, Aponte (2009) found that nRTK solutions were more accurate than short- and long-baseline sRTK observations. They observed accuracies better than 5 cm over 98% of the time for northing, easting, and height components. In some cases, the accuracy was decreased by factors such as high dilution of precision, low number of satellites, and high age of corrections (AoC).

Recently, Bae et al. (2015) evaluated the influence of baseline lengths and different observation durations on RTK GNSS data accuracy. Three different types of RTK solutions in this study were surveyed: sRTK, multiple-epoch network RTK and single-epoch network RTK. For all the sRTK solutions in this study, biases up to 9 mm were observed for baseline lengths greater than 30km in length when compared with the network RTK observations; however, there was no detectable bias for shorter baselines. The mean values for different observation durations showed no clear differences, but longer durations demonstrated more precise results.

Data Collection

Case I. South Carolina

In December 2013, the National Geodetic Survey (NGS) initiated a study in South Carolina to evaluate the accuracy of RTN-GNSS observations. The South Carolina Real-Time Network operates CORS within the State of South Carolina using the Trimble NTRIP Caster and running VRS approach to provide corrections for real-time surveys (South Carolina Real Time Network, 2017). SCRTN has 45 GNSS receivers which distributed consistently with the average spacing of 70 km across the state

(Lapine and Wellslager, 2007). During this survey, multiple static and real-time GNSS observations were collected on 20 bench marks. Twelve permanent bases (seven NGS CORS and five base stations from SC RTN) were also used. Individual, real-time solutions were determined utilizing several combinations of GPS+GLONASS vs. GPS-only constellations and nRTK vs. sRTK methods across a range of occupation durations and distances. For the sRTK solutions, the distance from NGS CORS COLA (reference station for single-base RTK solutions) to the marks varied from 0.1 to 104 km, in order to capture the effect of baseline length on sRTK solutions. For the nRTK solutions, the vectors were referenced to the nearest base stations and the lengths of the baselines varied from 0.1 to 53 km. The delta Earth-centered, Earth-Fixed (ECEF) Cartesian vector components from the base to the rover (and associated variance-covariance matrix) was stored for every observation, along with other metadata, e.g., DOP, solution RMS, precision estimates, antenna height, start and stop times, etc. (Dennis, 2013).

Throughout three consecutive days, observers recorded and stored a total of 360 real-time observations at each of their assigned stations (120 observations per day). A series of observations was repeated five times each day. Each series of observations consisted of different combinations of duration, positioning technique, and satellite constellations. Six observation times were used: 5 sec, 30 sec, 60 sec, 3 min, 5 min and 10 minutes. Both nRTK and sRTK observations were collected for each duration interval. In addition, a set of observations were made with GPS-Only as well as another set with GPS+GLONASS. The observers rotated through each of these various settings throughout the day. Combining all of these variations resulted in 24 distinct observational samples (with a total of 15 individual observations per sample) for each mark. Every observation was stored regardless of whether a fixed or float solution was obtained during the occupation time.

A total of twenty marks (Figure 1) were occupied in this survey. Ten marks (1901, 2103, 3201, 3203, AIKP, BUTL, G138, J137, LEX_ and R137) were occupied with Trimble Zephyr Geodetic receivers while the other half (W53_, W186, SURV, D138, E176, G176, HUNT, L186, PELI and Q176) used Trimble R-8 Model 2 receivers. For the sRTK solutions, there were not enough fixed observations for 7 of the marks (G136, J137, AIKP, R137, BUTL, 2103 and 1901); resulting in only 13 marks that could be compared for the accuracy assessment. Also, there were 7 observations for sRTK and 37 observations for nRTK solutions that reported zero epochs were utilized in the fixed solution. All of these fixed solutions utilizing zero epochs were reported by Trimble R7 receivers. These observations appeared erroneous and were removed during the evaluations. In some cases, they showed significantly higher (10-30 cm) errors horizontally and/or vertically.

Unfortunately, during post-processing, it was discovered that the Trimble R8-Model 2 rovers used for seven stations (G176, L186, W186, W53_, Q176, HUNT and PELI) had out-of-date firmware (v4.12) installed, which resulted a positive ellipsoid height bias of about 8 cm for nRTK solutions and 4 cm for sRTK solutions. For the Trimble out-of-date firmware, the rover did not recognize the base antenna and identified it as “Unknown External” (the up-to-date firmware correctly identified the bases as “Adv Null Antenna”, the official IGS-defined idealized antenna for real-time applications). This issue was not discovered in the field since the field controller software was up-to-date and does not directly display the base antenna. Upon investigation and follow up conversations with Trimble engineers, it was determined that the nRTK observations were likely biased by +8.546 cm (the nominal vertical antenna phase center (APC) offset for the real-time base antennas, Trimble "Zephyr Geodetic 2" with IGS name "TRM55971.00 NONE") and the sRTK observations were likely biased by +4.13 cm (the nominal L1 vertical APC offset in the phase correction table file for the R8 rover antenna). The ellipsoid heights for the observations at the affected stations were corrected by subtracting these biases. This correction resulted in coordinates much more consistent with respect to ellipsoid heights published at the bench marks in the NGS Integrated Database, as well as found by post-processing the static observations in OPUS-Projects (using absolute NGS antenna models), which will be discussed later.

Unfortunately this simplified fix may not account for all of the bias, because it is a complex problem and there are many possible permutations. The observed height is affected not just by the rover firmware, but also by the NTRIP caster version used by the network and its settings. For this project, the network solution provider also set up a temporary port for sRTK, which required its own NTRIP caster (and is likely why the rover behaved differently for the sRTK solutions). Even if the NTRIP caster versions and settings at that time were known, it would still be necessary for Trimble engineers to analyze the exact version of the firmware used at that time to determine specifically what occurred. Because of such uncertainties, some small ellipsoid height bias may still remain. Although this was an unfortunate occurrence for this research, it vividly illustrates the complexity of the RT solutions and the importance of keeping software and firmware up to date.

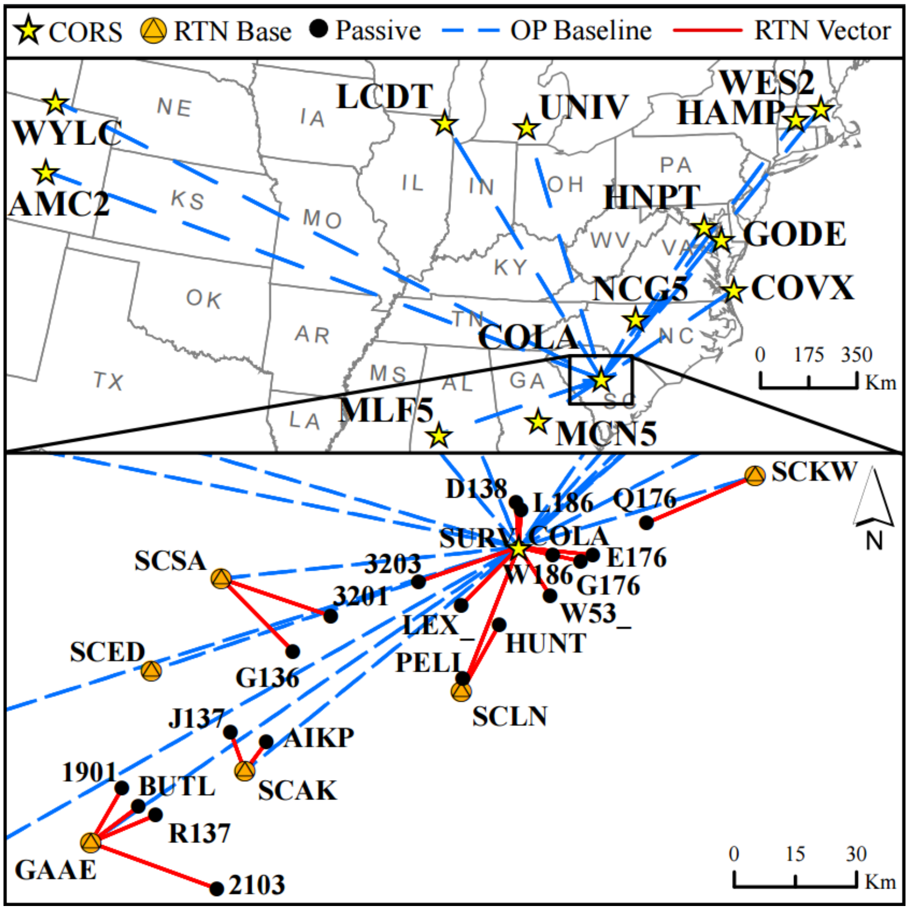

Figure1. Locations of the stations, RT base stations and Continuously Operation Reference Station (CORS) used for post-processing for the South Carolina survey. (from Weaver et al. 2017 with permission)

Case II. Oregon

For the Oregon dataset (Figure 2), eighteen passive marks were selected and occupied in the mid-Willamette Valley area over a one-month period from October to November 2014. The Oregon Real-time GNSS Network (ORGN) provides RTK correctors computed by Leica Geosystems Spider software for RTK surveys, also the typical station spacing in ORGN is around 70 km for approximately 100 stations (more details in Oregon Real-Time GNSS Network, 2017). On all occupied marks, the surveyors collected static GPS and GLONASS data using six Leica Viva GS14 receivers and six Leica CS15 data collectors, which were run simultaneously for baseline processing. In order to investigate for potential systematic errors and model possible receiver noise, the equipment was rotated each day. Additional details of this field collection campaign can be found in Gillins and Eddy (2015) and Gillins and Eddy (2016).

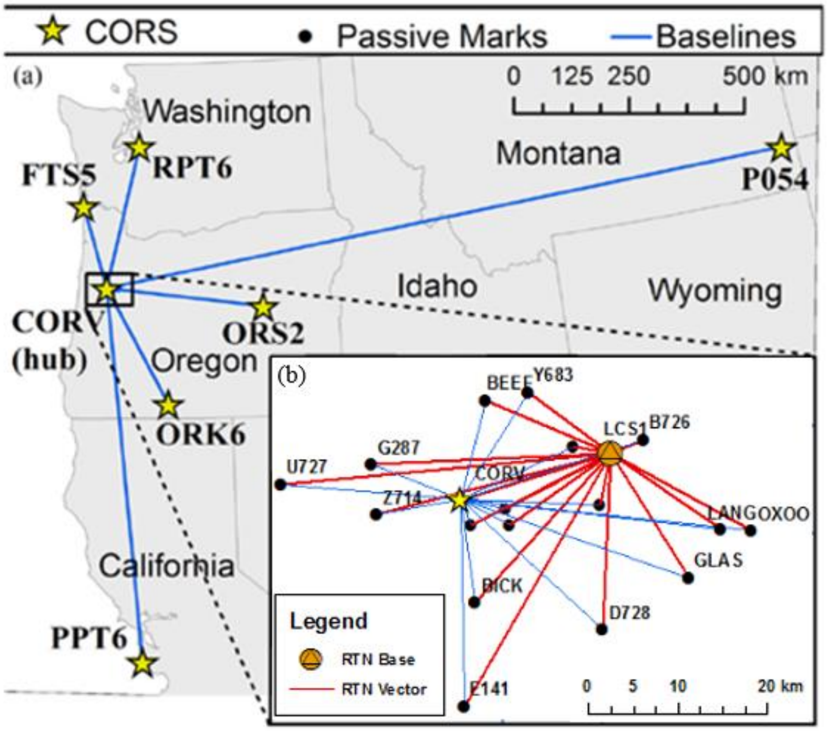

Figure 2. Locations of the passive mark stations, base station (LCS1) and CORS in the Oregon survey (Modified from Gillins and Eddy 2016).

Static GPS and GLONASS observations were logged for at least four 10-h sessions, except for mark (D728), which was occupied for only three 10-h sessions (Gillins and Eddy 2016). During these static sessions, various types of sRTK and nRTK observations were also taken simultaneously using the ORGN. The distance between the real-time base station and the marks varied from 3.8 to 21.2 km. The real-time data were logged as a continuous stream of 1-second, single-epoch observations, half of the time collecting only GPS observables, and the other half of the time collecting GPS and GLONASS. Each single-epoch included the delta ECEF baseline components of the observation with associated variance-covariance matrix. The real-time single-epoch observations were combined into multi-epoch observations of varying duration ranging from 5 s to 10 min, using a custom MATLAB script. In this script, the complete data file on a mark was divided into forty windows (typically 15 min in duration) for each RTK data file at a mark. In each window, the script selected a sequential number of epochs equal to the desired nominal observation duration based on a random starting point. For instance, to produce a 5 s observation, the script randomly selected five sequential 1-s epochs of observations from each 15 minute window. The script also discarded any selected single-epoch observation that was based on a floating RTK solution and replaced it with the next available epoch with a fixed RTK solution. If for some reason the actual duration of the set of selected epochs (from the time of the first selected epoch to the last epoch) exceeded the nominal duration by more than 20%, then the script ignored the data and moved to the next window. (This problem only occurred with 1% of the survey data.) Afterwards, to produce a multi-epoch, fixed, solution, the script used the variance-covariance matrix of the selected epochs and computed the weighted mean baseline observation components in terms of the geocentric coordinate differences. At each mark, approximately 40 multi-epoch solutions were produced at nominal observations durations of: 5, 30, 60, 120, 180, 300, 480, 600, and 900 seconds.

For this survey, the ORGN was set such that all of the sRTK observations referenced the same base station (LCS1). Unfortunately, this unintentionally modified the ORGN such that all nRTK observations were based on a master-auxiliary concept (MAC) where the master station was accidentally forced to always be LCS1. Ordinarily, an RTN assigns the nearest base station as the master station, and additional base stations are chosen as auxiliaries (Leica Geosystems, 2005) for best results. While LCS1 would have been selected as the master station for most of the marks regardless of this setting, the ORGN would have very likely selected a nearer base station as the master station when observing four marks (G287, U727, Z714 and E141). This incorrect setting resulted in nRTK observations with baselines longer than 25 km in length, resulting in poorer performance than under ordinary conditions. Because of this mistake, nRTK observations at these four marks were not included in the aggregate results; however, they remain in the individual results for comparison and to underscore the importance of letting the RTN using a MAC method choose the master station rather than forcing it to a specific base station.

Data Processing

Development of OPUS-Projects Static Coordinates

The static GNSS observations for both case studies were post-processed and adjusted in the same manner as the "OP+ADJUST Hub Network," as described in detail in Gillins and Eddy (2016). First, all of the static GNSS files collected during the surveys were uploaded to NGS software, OPUS-Projects. In addition, 24-h duration static data files for each day of the survey sessions were added from multiple continuously operating reference stations (CORS) in the NGS CORS Network. Certain CORS were selected based on the following criteria: (1) it had data available during the survey campaign; and (2) its daily solutions, as computed and plotted in short-term time series plots by NGS, were within +/- 1 cm of its NGS published position; and (3) NGS had computed its 3-D velocities based on years of continuous observation and monitoring. In order to improve wet-component corrections in the tropospheric delay models, some CORS with distance from 250 to 2,000 km from the project area were selected based on the findings of the Ugur (2013) study. Twelve CORS were used for the South Carolina survey and six CORS were used for the Oregon survey. The location of the stations marks and CORS selected for post-processing the static data in OPUS-Projects are shown in Figures 1 and 2 for South Carolina and Oregon, respectively.

Baseline observations were next computed by post-processing the static data in OPUS-Projects. Afterwards, the baselines were combined into a survey network and were adjusted by least squares using NGS software, ADJUST. The coordinates output from ADJUST were considered “truth” coordinates for evaluating the accuracy of the real-time observations.

Comparison of Real-Time Data versus Computed Static Coordinates in OPUS-Projects

In both case studies, residuals in northing, easting and up were computed between the real-time observations and the coordinates derived from OPUS-Projects static GNSS session solutions adjusted in ADJUST. The statistics are summarized as root-mean-square error (RMSE) differences in both the vertical and horizontal directions. These residuals were determined separately for each sample of real-time observations, subdivided according to observation duration and by each of the four different types: (a) nRTK with GPS-only observables; (b) nRTK with GPS+GLONASS observables; (c) sRTK with GPS-only observables; and (d) sRTK with GPS+GLONASS observables. Horizontal RMSE (HRMSE) and Vertical RMSE (VRMSE) were calculated using Equations 1 and 2:

$$RMSE_{North} = \sqrt{\frac{\sum_{i=1}^{n}\left(P_{i,North} - O_{i,North}\right)^2}{n}}$$
$$RMSE_{East} = \sqrt{\frac{\sum_{i=1}^{n}\left(P_{i,East} - O_{i,East}\right)^2}{n}} \qquad \text{Equation 1}$$
$$HRMSE = \sqrt{(RMSE_{North})^2 + (RMSE_{East})^2}$$

$$VRMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(P_{i,Vert} - O_{i,Vert}\right)^2}{n}} \qquad \text{Equation 2}$$

Where, P_i is the real-time coordinate component from the survey at station *i*, O_i is the adjusted coordinate component from the static survey derived from OPUS-Projects at station *i*, and *n* is the total number of real-time observations in the sample.

Results

Case I. South Carolina

This section provides several figures and tables that illustrate the results of the South Carolina survey. First, Table 1 presents the average of Position Dilution of Precision (PDOP) values and the total number of “fixed” solutions for each mark, grouped according to the data collection technique. As previously mentioned, there were an insufficient number of fixed sRTK solutions at seven marks highlighted in the table. Figure 3 presents the percentage of fixed and float solutions obtained for all observation durations using sRTK GPS-only and GPS+GLONASS versus baseline length.

Table 1: Total number of fixed observations and the average of the PDOP for all stations and solution types used for the South Carolina survey.

Station	# of obs nRTK		# of obs sRTK		PDOP Averages nRTK		PDOP Averages sRTK	
	GPS-only	GPS+GLONASS	GPS-only	GPS+GLONASS	GPS-only	GPS+GLONASS	GPS-only	GPS+GLONASS
1901	89	93	0	5	2.50	1.80	N/A	1.77
2103	90	90	2	10	2.34	1.60	3.18	1.79
3201	87	89	48	82	2.49	1.70	3.13	1.84
3203	90	88	90	92	2.48	1.69	2.96	1.78
AIKP	90	90	5	26	1.91	1.45	2.25	1.58
BUTL	72	89	0	3	2.77	1.71	N/A	1.86
D138	87	90	87	92	1.67	1.32	2.49	1.57
E176	89	86	86	90	1.89	1.44	2.90	1.80
G136	87	86	2	44	2.67	1.90	3.04	1.84
G176	87	86	89	90	1.99	1.52	2.63	1.66
HUNT	96	93	86	91	2.02	1.48	2.70	1.57
J137	76	88	0	5	2.62	1.76	N/A	1.84
L186	85	88	81	88	2.18	1.59	3.14	1.94
LEX_	90	209	86	90	2.09	1.59	2.70	1.56
PELI	89	83	79	81	1.16	0.77	2.25	1.45
Q176	90	86	90	82	1.77	1.37	2.51	1.48
R137	90	89	0	0	2.04	1.55	N/A	N/A
SURV	97	79	94	87	0.97	0.70	1.23	0.77
W186	76	134	72	80	1.69	1.06	2.40	1.43
W53_	89	89	84	88	1.93	1.35	2.34	1.45

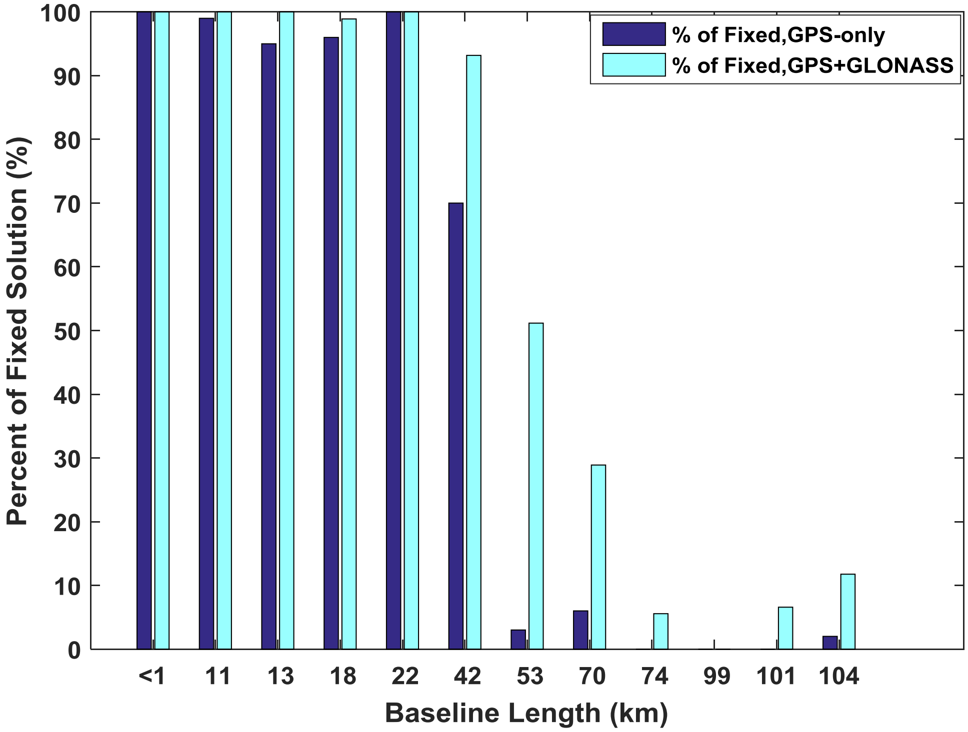

Figure 3. Comparison of the percentage of fixed solutions as a function of baseline length for sRTK with GPS and GPS+GLONASS observables (considering all observation durations).

Figure 4 presents the HRMSE as a function of observation duration for all four observation types (i.e., nRTK GPS-only, nRTK GPS+GLONASS, sRTK GPS-only, and sRTK GPS+GLONASS). Figure 5 shows a similar plot as Figure 4, but in terms of VRMSE.

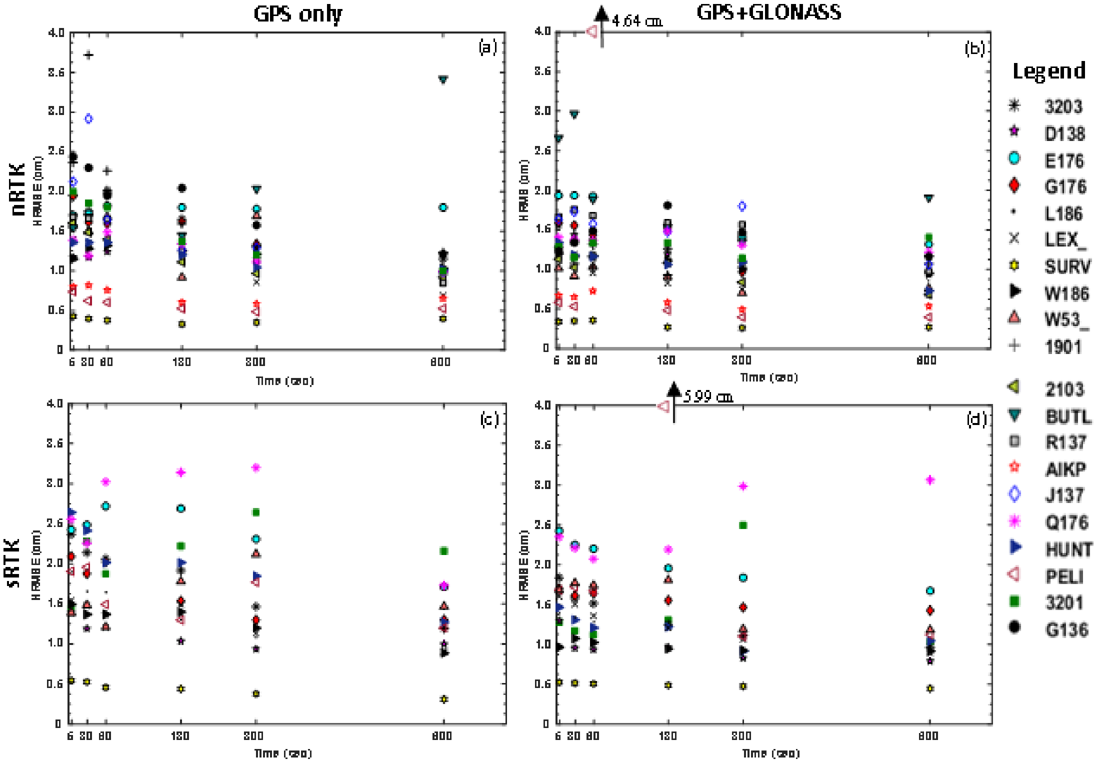

Figure 4. HRMSE at each mark in South Carolina for (a) nRTK GPS-only; (b) nRTK GPS+GLONASS; (c) sRTK GPS-only; and (d) sRTK GPS+GLONASS data versus observation duration.

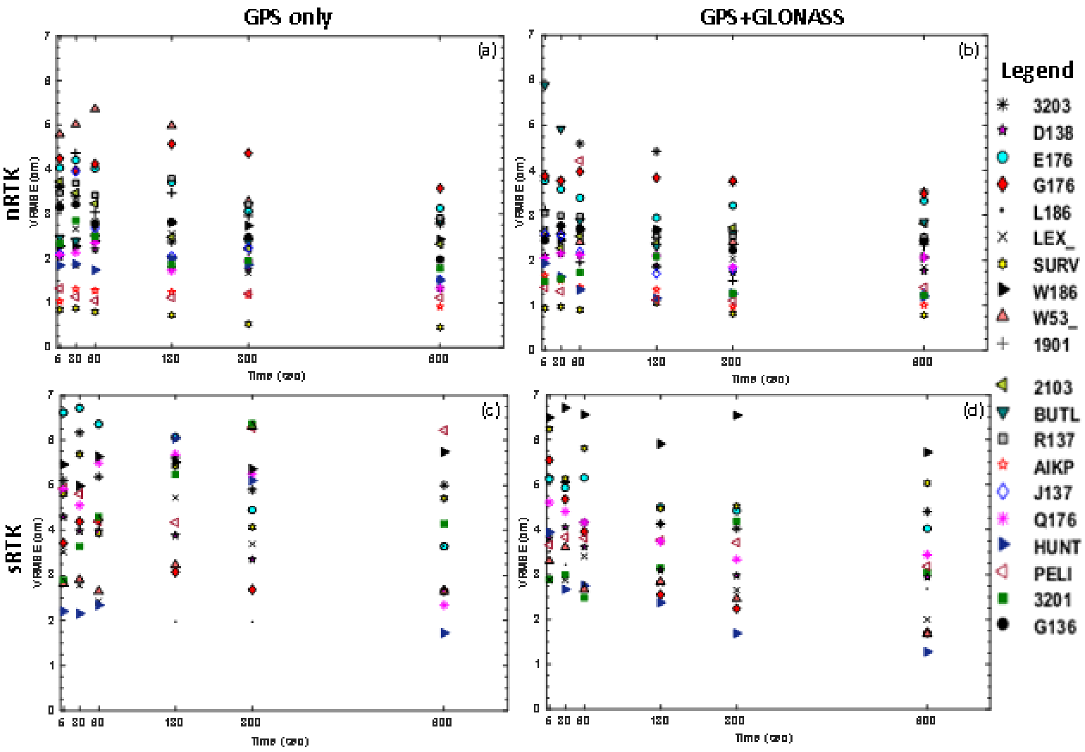

Figure 5. VRMSE comparison between (a) nRTK GPS-only; (b) nRTK GPS+GLONASS; (c) sRTK GPS-only; and (d) sRTK GPS+GLONASS data versus observation duration in South Carolina.

Table 2 shows the variation in HRMSE and VRMSE for nRTK and sRTK between the GPS-only and GPS+GLONASS observations. Significant improvement (positive values) is observed using GPS+GLONASS for the sRTK solution over the GPS-only solution. Note that for the nRTK, only a slight improvement is observed with the inclusion of GLONASS, especially in the horizontal direction.

Table 2. Variation in HRMSE and VRMSE, (between the GPS-only and GPS+GLONASS observations), for both nRTK and sRTK solutions in South Carolina.

	Duration(s)	ΔHRMSE		ΔVRMSE	
		Mean(cm)	St.Dev(cm)	Mean(cm)	St.Dev(cm)
nRTK	5	0.20	0.52	0.09	1.01
	30	0.27	0.74	0.35	0.98
	60	0.06	1.00	0.12	1.12
	180	0.12	0.25	0.26	0.88
	300	0.15	0.33	0.20	0.51
	600	0.14	0.37	-0.08	0.37
sRTK	5	0.26	0.35	1.52	2.68
	30	0.30	0.40	1.53	2.42
	60	0.29	0.43	1.98	2.13
	180	0.02	1.40	2.04	1.84
	300	0.30	0.34	2.40	1.76
	600	0.05	0.53	1.81	1.86

Figure 6 displays scatter plots for the HRMSE and VRMSE versus baseline length. The plot shows RMS values using only the sample of 180-second observations at each mark. The plot also depicts linear regression trend lines and associated R^2 values as the coefficient of determination.

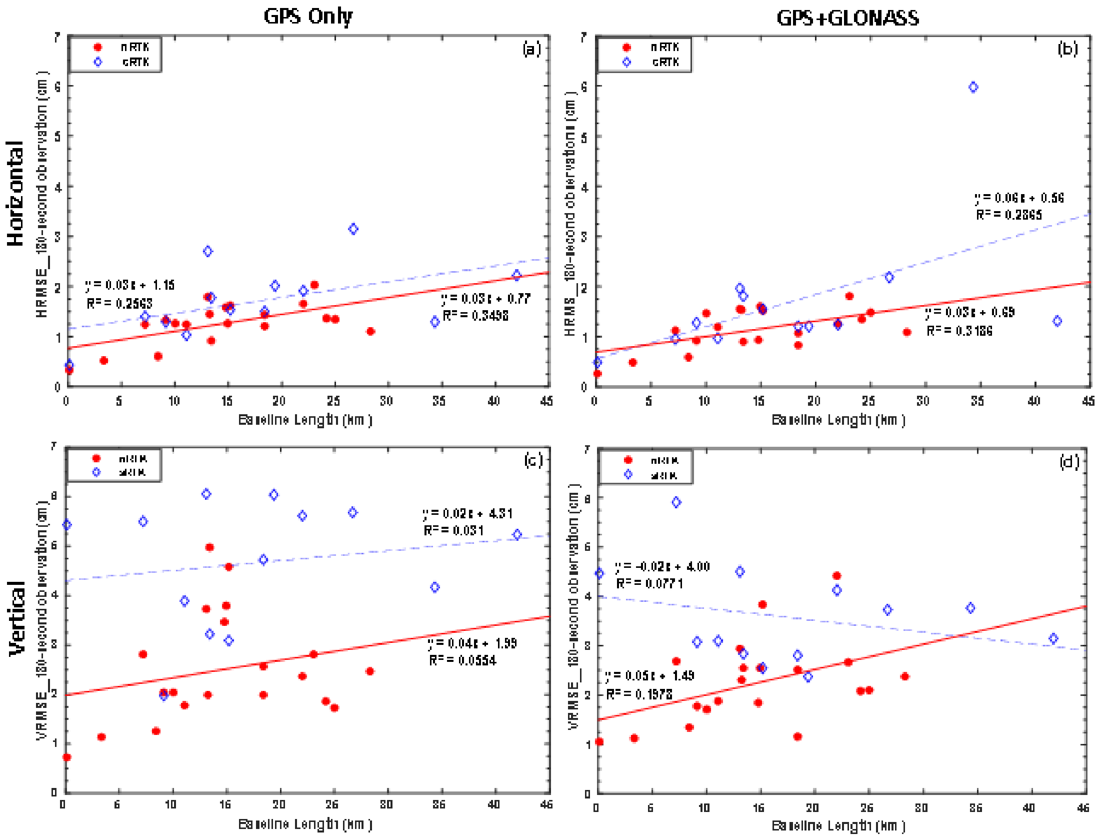

Figure 6. Comparison of HRMSE and VRMSE versus baseline length in South Carolina (a) Horizontal RMSE GPS-only (b) Horizontal RMSE GPS+GLONASS (c) Vertical RMSE GPS-only (d) Vertical RMSE GPS+GLONASS, (180 seconds occupations). nRTK data are represented by circles and sRTK are represented by diamonds.

Case II. Oregon

This section presents the results of the Oregon data in the same manner as the South Carolina data were presented. Table 3 presents the total number of fixed observations for all the stations and different solutions in Oregon.

Table 3: Total number of fixed solutions for all stations and solution types in the Oregon dataset. Note that GPS+GLONASS was not available for the ORGN at the time of survey.

Station	# of obs nRTK	# of obs sRTK	
	GPS-only	GPS-only	GPS+GLONASS
B726	312	359	359
BEEF	345	335	360
BICK	320	360	358
CRVA	336	359	359
D728	337	322	360
E141	258	306	358
G287	343	316	352
GLAS	314	360	359
LANG	349	359	360
LBCC	342	356	360
OXOO	351	359	351
PT35	353	349	359
S714	326	359	290
T714	353	295	360
U727	209	331	354
WASH	338	360	358
Y683	317	345	359
Z714	315	328	359

Figure 7 presents the HRMSE as a function of observation duration for both GPS-only and GPS+GLONASS. Figure 8 also provides VRMSE versus the observation duration. Results are provided both for the nRTK and the sRTK for comparison.

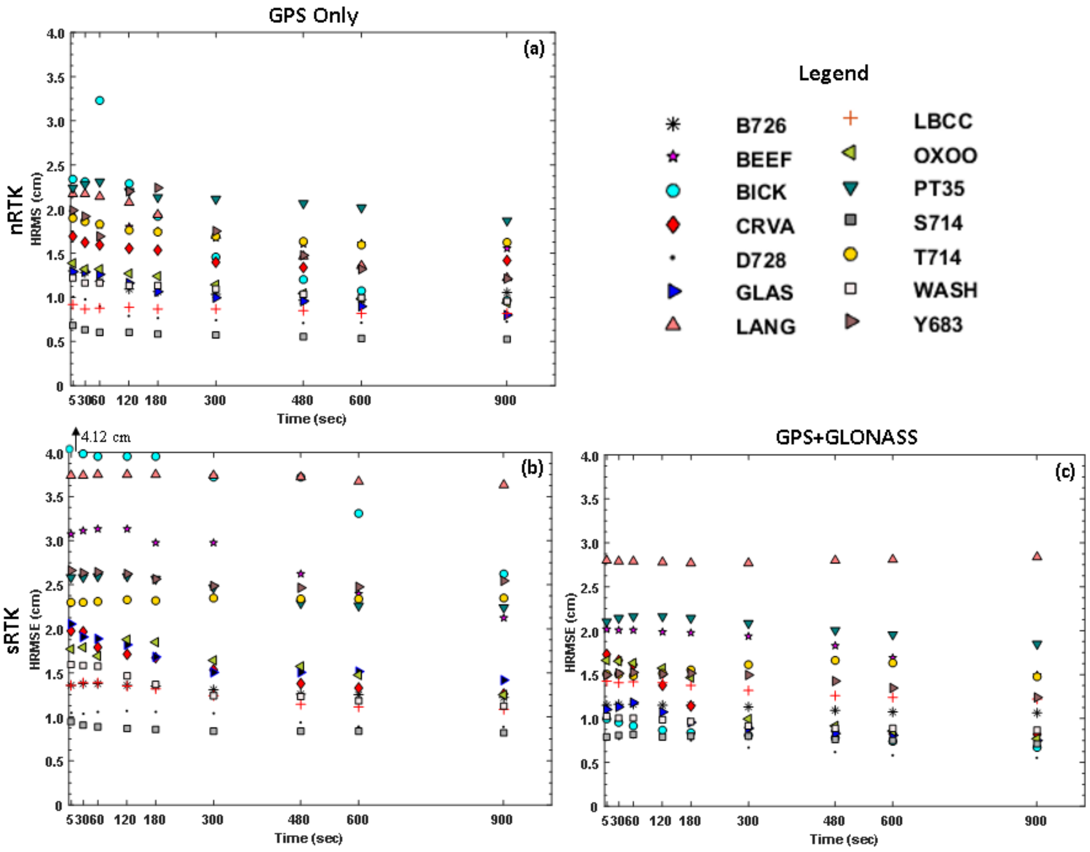

Figure 7. HRMSE at each mark in Oregon for (a) nRTK GPS-only; (b) sRTK GPS-only; and (c) sRTK GPS+GLONASS data versus observation duration. Note that nRTK GPS+GLONASS data was not collected, because the ORGN did not support it at the time of survey.

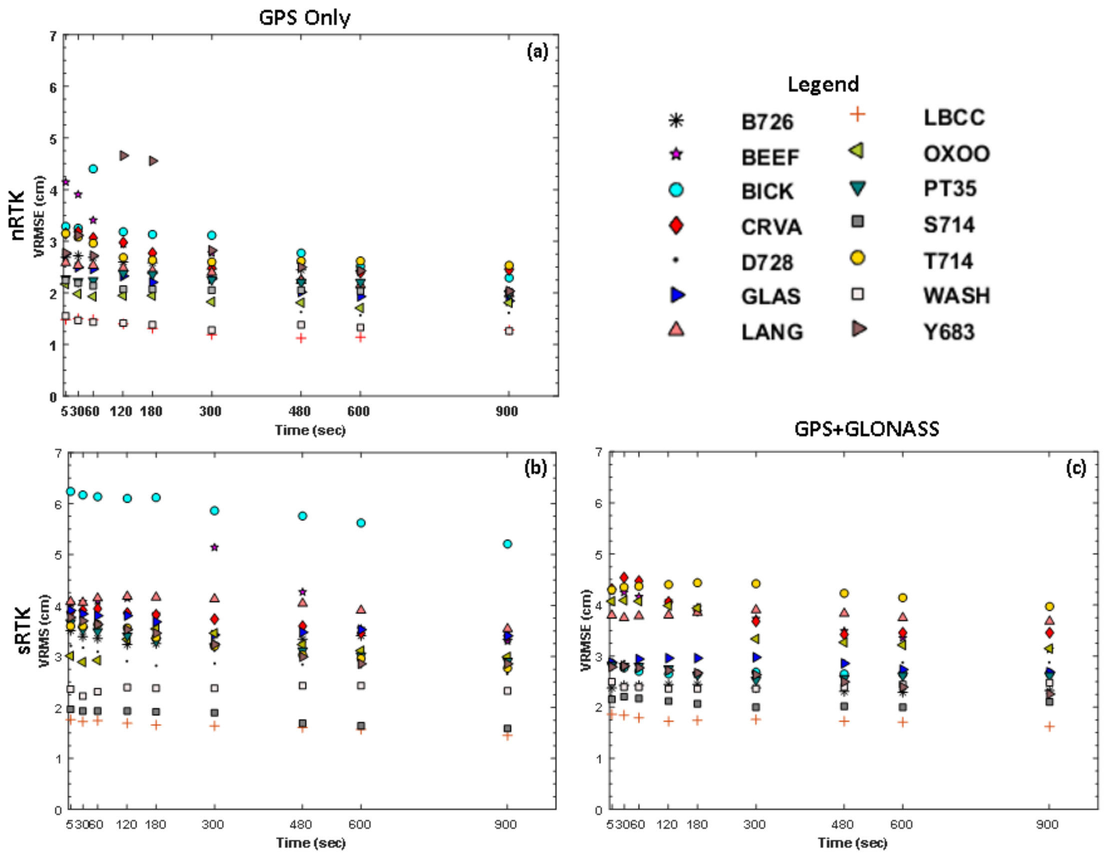

Figure 8. VRMSE comparison between (a) nRTK GPS-only; (b) sRTK GPS-only; and (c) sRTK GPS+GLONASS data versus observation duration in Oregon. Note that nRTK GPS+GLONASS data was not collected, because the ORGN did not support it at the time of survey.

Table 4 provides tabular results of differences in HRMSE and VRMSE for nRTK and sRTK between the two GPS-only and GPS+GLONASS observations. Similar to Table 2, improvement (positive values) is observed using GPS+GLONASS for the sRTK solution over the GPS-only observations.

Table 4: Differences in HRMSE and VRMSE, (between the GPS-only and GPS+GLONASS observations), for sRTK solutions in Oregon.

	Duration(s)	ΔHRMS		ΔVRMS	
		Mean(cm)	St.Dev(cm)	Mean(cm)	St.Dev(cm)
sRTK	5	0.71	0.77	0.36	1.06
	30	0.70	0.74	0.30	1.08
	60	0.68	0.76	0.32	1.05
	120	0.71	0.75	0.36	0.99
	180	0.70	0.75	0.34	1.00
	300	0.70	0.70	0.43	0.96
	480	0.66	0.71	0.37	0.92
	600	0.63	0.63	0.30	0.90
	900	0.59	0.51	0.19	0.84

Figure 9 displays scatter plots for the HRMSE and VRMSE as a function of baseline length, considering the use of GPS-only and GPS+GLONASS observations as well as nRTK and sRTK solutions. Similar to the South Carolina scatter plots (Figure 6), the plot shows RMS values using only the sample of 180-second observations at each mark. The plot also represents linear regression trend lines and associated R^2 values as the coefficient of determination and for GPS+GLONASS observations. nRTK data was not collected because the ORGN did not support it at the time of survey.

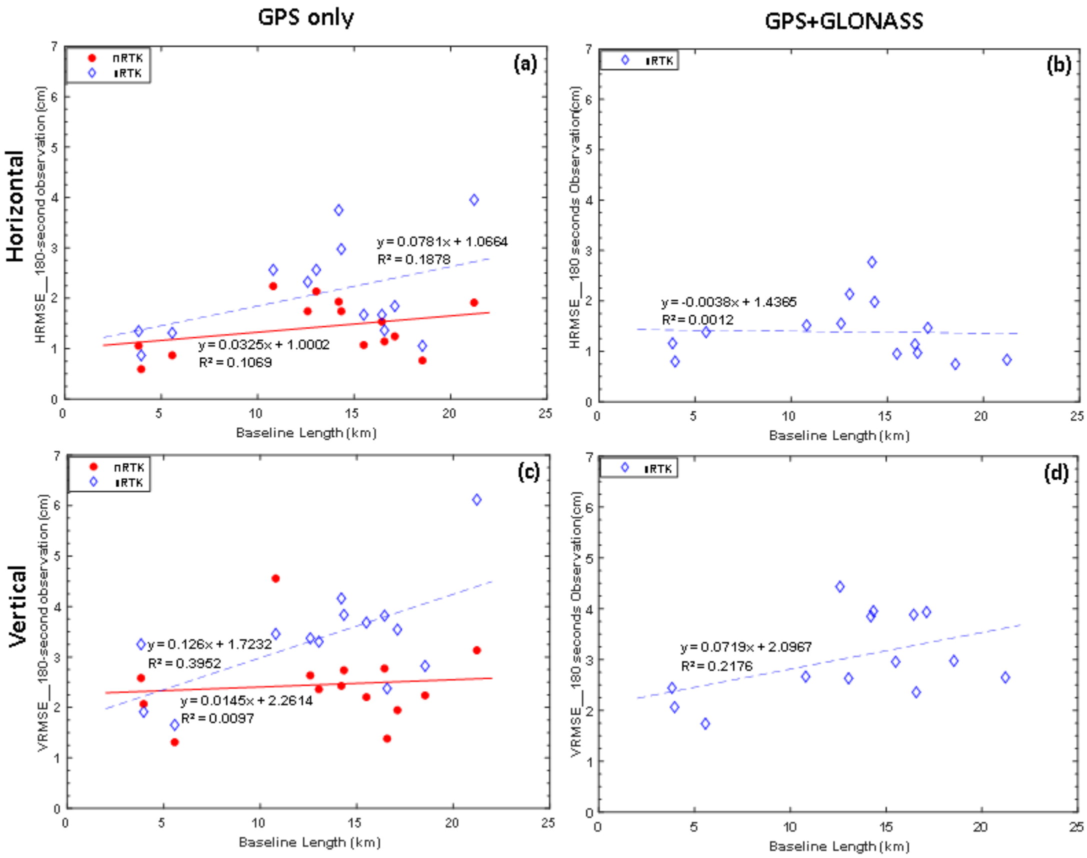

Figure 9. Comparison of HRMSE and VRMSE versus baseline length in Oregon (a) Horizontal RMSE GPS-only (b) Horizontal RMSE GPS+GLONASS (c) Vertical RMSE GPS-only (d) Vertical RMSE GPS+GLONASS, (180 seconds occupations). nRTK are represented by circles and sRTK are represented by diamonds.

Case Study Comparisons

Figure 10 presents the mean and standard deviation for RMSE values for all of the solutions and methods (e.g., nRTK vs. sRTK, and GPS only vs. GPS+GLONASS) in both case studies to compare the accuracies achieved in each of these surveys. The results are for twenty marks in the South Carolina survey for nRTK and 13 marks for the sRTK solutions. For Oregon, the results are based on 14 marks for both solution types (nRTK and sRTK).

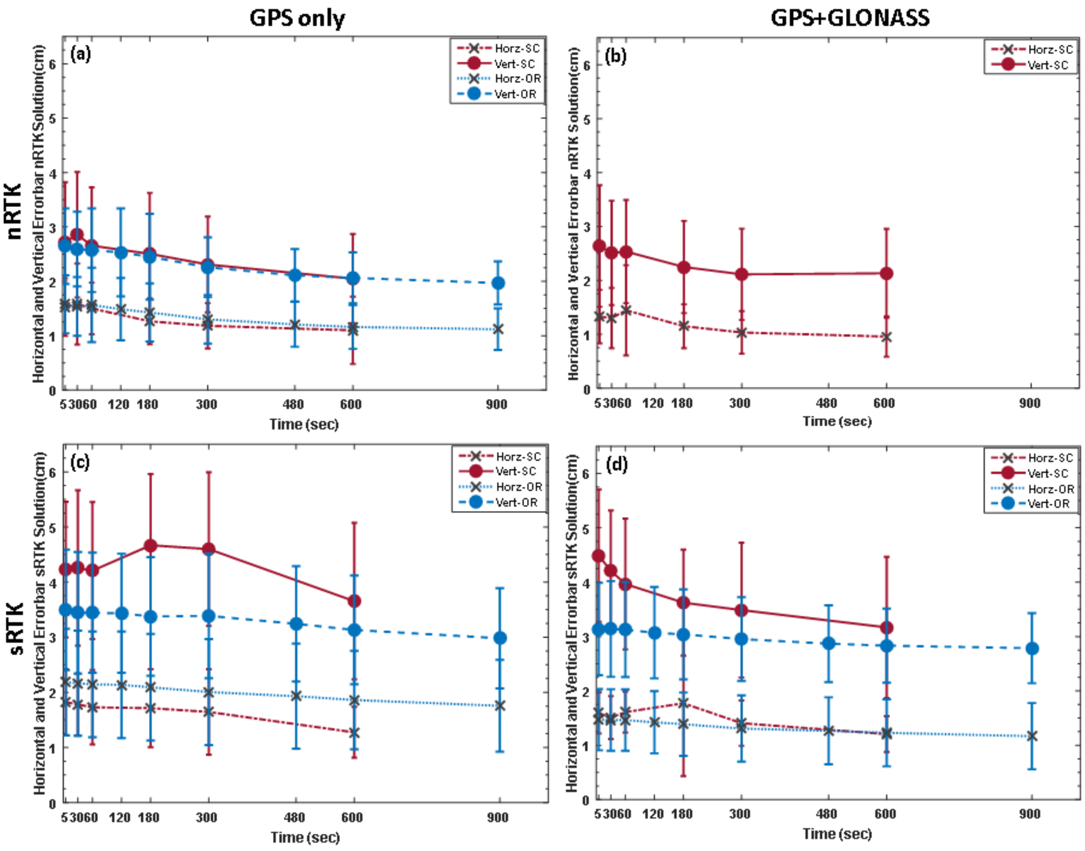

Figure 10. Comparison between two surveys solutions and methods in both case studies. Data points represent the average RMSE values for all stations at each duration and error bars represent the standard deviation of those RMSE values. (a) nRTK GPS-only; (b) nRTK GPS+GLONASS; (c) sRTK GPS-only; and (d) sRTK GPS+GLONASS data

Discussion

In this section we will discuss the results in context of the aforementioned objectives.

- *Optimal observation duration*

For all marks, only subtle improvement based on occupation time was observed; further for most stations the improvement was negligible after 180 to 300 seconds (3 to 5 minutes). In the South Carolina survey, the vertical sRTK observations (GPS+GLONASS) show the most improvement based on the observation duration (Figure 10). Note that the RMSE at some stations actually became worse at the longest tested observation duration (in 300 and 600 seconds), for example Q176 in Figure 5. It is possible that the higher PDOP values for those stations (more over heads obstructions at that time) had an effect on degrading the accuracy of some of the 300-s and 600-s observations.

- *Influence of the inclusion of GLONASS*

  When examining at the overall trend of the data in Figures 4, 5, 7 and 8, it is clear that GLONASS helped provide a slightly more accurate solution. As shown in Tables 2 and 4, including GLONASS with GPS observables generally improved both the horizontal and vertical accuracy of the sRTK solutions for every observation duration sample. This was also observed for the nRTK solutions except for the 600-s duration sample in South Carolina, which again may have been affected by the poorer satellite visibility at some of the stations in that survey. In both surveys, Oregon and South Carolina, GLONASS also helped reduce the scatter both horizontally and vertically (Figure 4, 5, 7 and 8). In the Oregon survey, the sRTK solution with the inclusion of GLONASS significantly reduced the errors for almost all of the stations in the horizontal direction and somehow vertically. Another important aspect of including GLONASS is that it helped improve the ability to achieve fixed solutions in sRTK, particularly at long baselines (Figure 3).

- *nRTK solution compared with sRTK*

  Figures 4, 5, 7 and 8 generally show improvement from the nRTK over the sRTK solutions. The nRTK contains less scatter in both case studies and the RMS errors range are smaller overall, independent of the observation duration. This consistency is likely the result of the improved ability to model ionospheric and tropospheric effects using network RTK. Also, the significant differences between these two solutions in the South Carolina survey is likely due to the shorter baseline length in the nRTK survey compared with the sRTK survey (about 2 times less than sRTK baseline length) in addition to the other advantage such as modeling the errors in nRTK.

- *Effects of baseline length*

  The magnitude of improvement at longer baseline lengths in sRTK with the addition of GLONASS is more significant than that observed in the nRTK data, since the nRTK itself minimizes some of the baseline length dependent errors through using multiple stations such as tropospheric modeling (Figure 6). Nonetheless, caution should be exerted in interpreting these plots. Some of these plots show trends counter to expected results of increased error with base line length (e.g., Figures 6 and 9 with the vertical nRTK GPS-only solutions in both Oregon and South Carolina, and vertical sRTK observations in the South Carolina, and horizontal sRTK in the Oregon survey). However, these plots show very low R^2 values, indicating that there is no determinable trend in the data. These cases could also indicate that the influence of baseline length is masked by other factors that contribute significantly to the overall errors. Lastly, for the single-base solutions in South Carolina, some of the incorrect trend can be explained by the small sample size (13 stations instead of 20), resulting in an inability to determine the actual trend. Despite these limitations, the other cases indicate that by increasing the baseline length, the RMSE values also increase. These findings concur with the result of the Bae et al, (2015) study.

- *Consistency between results from various network across the country*

The results in South Carolina and Oregon demonstrated reasonable consistency between these two real-time networks (Figure 10). The horizontal and vertical positioning are nearly identical for both case studies in the nRTK GPS-only solution. The larger error bars observed in South Carolina are likely due to the fact that the South Carolina survey observed marks have more overhead obstruction (worse satellite visibility than in the OR survey, which generally had clear satellite visibility) and also longer baseline length in South Carolina (almost twice longer than in Oregon). Lastly, some of this error can be explained in the differences of survey style where the South Carolina survey observations were stored based on occupation duration regardless of whether an observation was fixed compared with the Oregon survey where the occupation time was determined based on the number of fixed observations. For example, some of the “zero epoch” solutions in the South Carolina survey resulted in coordinates of poor accuracy even though the station was occupied for a longer duration.

Conclusion

In this study, the vertical and horizontal accuracy of real-time network GNSS survey with respect to the observation duration was studied. Twenty marks in South Carolina were occupied and high accuracy real-time solutions were obtained by relative GNSS positioning for different observation durations. Eighteen marks in Oregon were also occupied in a similar fashion. The results were compared to a least squares adjusted network of static GNSS surveys for the same marks in both datasets. Issues during the data analysis such as lock on a single-base as a master station in real-time network solution, old firmware issue and also zero number of epochs, led us to understand important lessons. Accuracies would increase if the network (ORGN in this case) did not force station LCS1 to serve as the master base station for each of the marks. Observations on marks which were further away from the master station (LCS1) (about more than 20 km) could not achieve high accuracy solutions in the Oregon study.

The resulting analyses confirm that the increased duration of real-time observations slightly improves the positioning accuracy in both vertical and horizontal directions. While longer observations could potentially help improve the accuracy for real-time GNSS network, the accuracy of the survey did not change significantly after 3 or 5 minutes observation. Data collected with the full network corrector (RTN) tended to be more accurate and consistent than the single-base solutions, and the inclusion of

GLONASS improved the accuracy of the observations and helped obtain more fixed solutions at longer baseline lengths compared with single-base RTK surveying.

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