A Tale of Two RTNs: Rigorous Evaluation of Real-time Network GNSS Observations

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Abstract: Real-time networks (RTNs) have become popular for Global Navigation Satellite System (GNSS) surveys because highly accurate positions can be derived in seconds to a few minutes compared to many minutes and hours as required with post-processed 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, especially vertically. Further, the addition of GLONASS observables helped obtain more fixed solutions at longer baseline lengths than solutions based solely on GPS observables and showed a slight improvement in accuracy, particularly for stations with poorer satellite visibility.

Keywords: GNSS, network RTK, Single-base RTK, GPS, GLONASS, baseline length.

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 geodetic research, 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 satellites. 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 an Ultra High Frequency (UHF) radio, cellular data plan, or wireless fidelity (Wi-Fi) link. This communication enables baseline processing of the data collected at the base and rover receivers to provide solutions to the user in real-time. By keeping the rover in close proximity to the base (e.g., within 10-20 km), errors such as in the broadcast orbits and due to 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 used to overcome these limitations by utilizing a network of permanent GNSS reference stations. Many government agencies and commercial companies have developed RTNs consisting of multiple permanent or semi-permanent base stations, enabling baseline observations 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 Globalnaya Navigazionnaya Sputnikovaya Sistema (GLONASS), China’s BeiDou, and the 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 providers in the United States currently only support GPS and GLONASS for real-time GNSS surveying. Using GLONASS with GPS may improve the solution accuracy in urban and non-urban environments where buildings and trees can obstruct satellites and create multi-pathing problems with the signals (Sarkar and

Bose 2015). Anquela et al. (2012) compared results utilizing GPS and GLONASS signals for both static and kinematic post-processed 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.

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 constellations used during the survey, weather conditions, reference network, communication between base and rovers, obstructions, multipathing, and session duration are examples of some of the factors that can affect the accuracy of a GNSS-based survey (Soler et al. 2006). However, many of the effects 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, the following research goals are evaluated using two case studies encompassing different environments and survey procedures: (1) determine the “optimal” observation duration for real-time GNSS surveys to balance accuracy and efficiency, particularly in the context of establishing geodetic control; (2) assess the influence of the inclusion of GLONASS observables; (3) compare network real-time kinematic solutions with single-base real-time kinematic solutions; (4) evaluate the effect of baseline length on solution accuracy and ability to achieve fixed-integer solutions; and (5) examine the consistency of the results between the two RTNs located at opposite sides of the continent.

While many of these aspects have been documented to some extent in the literature, few studies have utilized such an extensive dataset for their analyses. Most evaluate accuracy based on extensive observations at a few stations rather than across a larger area such as those analyzed in this study. Additionally, others studies typically focus on one or two of the above factors rather than evaluate all of them jointly. For example, few fully evaluate 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 and compares data from two separate RTNs. Finally, this paper also provides new, valuable lessons learned from each of the case studies related to using RTNs that were discovered because of problems that occurred in the RTN surveys that have not previously been reported but have significant implications for users of RTNs.

Background

The primary concept of a real-time network (RTN) is that a group of reference or base stations collect GNSS observables 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), virtual reference station (VRS) method, and Flächen Korrektur Parameter (FKP) method are examples of common nRTK methods in use.

The FKP method broadcasts the parameters of a regional plane model (evaluated by the network software) to the rover. The effects of local atmospheric phenomena are not counted, so the disturbances of atmospheric-related issues in GNSS observations are eliminated (Wübbena and Bagge 2002).

The MAC method produces GNSS baselines between the physical location of a reference station, known as the "master station," and the rover. The rover transmits an uncorrected point position to the central server, the server then typically assigns the closest reference station as the master station, and selects several additional or "auxiliary" reference stations within a cell in the RTN (Leica Geosystems 2005). The phase ranges from all selected reference stations are reduced to a common ambiguity level, and errors for each frequency and satellite-receiver pair are computed relative to the master station. Then, the corrections and published coordinates at the master station are transmitted in Radio Technical Commission for Maritime Services (RTCM) format to the rover to generate a RTK solution. Under the MAC method, corrections may be transmitted using either a MAX or i-MAX approach. MAX corrections use a proprietary RTCM format, which Leica Geosystems developed, whereas i-MAX uses an older and open-source RTCM format which is required for non-Leica rovers.

The VRS method produces GNSS baselines between a virtual or imaginary reference station and the rover. In the VRS method, the rover first transmits its uncorrected point position to the central server, and then the server selects this position as the location of an imaginary reference station. Next, the server interpolates ionospheric and tropospheric errors from the network at this location and generates corrected pseudo-observables that are transmitted to the rover for processing using conventional single-base RTK algorithms (Petovello 2011). Therefore, very short delta Earth-centered, Earth-Fixed (ECEF) GNSS vectors (i.e., 1 to 3 m in length) are obtained from the VRS to the antenna reference plane (ARP) for the rover antenna. The server also broadcasts a separate record for each nRTK solution that indicates the ECEF coordinates of the nearest reference station in the RTN, referred to under the VRS method as the "Physical Reference Station (PRS)." Application software, such as *Trimble Business Center*, can be used to move the tail of the GNSS vector from the ECEF coordinates of the VRS to the PRS, thereby providing a GNSS vector that originates from the physical location of an actual reference station rather than from the imaginary, virtual reference station (Graham Briggs, personal communication, March 6, 2017). Such a vector could be added to a survey network for least squares adjustment (Weaver et al. (in press)).

A study by Janssen and Haasdyk (2011) described the difference between sRTK and nRTK methods. In that study, sRTK and nRTK performance was examined over varying baseline distances and on different days. The study found that the resulting nRTK coordinates were more accurate and precise than coordinates derived from sRTK.

Henning (2011) assessed the effects of the baseline length, occupation time, and field procedures on a sRTK 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 and number of satellite vehicles had less effect on the precision of the observations because the number of satellites were always greater than four, and PDOP values were kept minimal during the survey.

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 method 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 recommended and 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 slightly 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.

More recently, Smith et al. (2014) evaluated the accuracy of RTK data obtained using an RTN in Texas (VRS method) by comparing with static GPS observations post-processed using two United States National Geodetic Survey (NGS) Online Positioning

User Service (OPUS) applications: *OPUS-RS* and *OPUS-Projects*. They found root-mean-square differences 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 GPS 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 in South Carolina. Note that Bae et al. evaluated the same South Carolina dataset as used in this paper; however, in that analysis, firmware issues were not detected nor resolved (more details will be provided in the Data Collection section of this paper). Three different types of RTK solutions in this study were evaluated: 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 30 km in length when compared with the nRTK observations; however, there was no detectable bias for shorter baselines. The mean values for different observation durations showed minor differences, but longer durations demonstrated more precise results.

Data Collection

Data were collected from two real-time surveys using real-time networks in South Carolina (I) and Oregon (II).

Case I. South Carolina

In December 2013, NGS initiated a study in South Carolina to evaluate the accuracy of sRTK and nRTK GNSS observations. During the survey, multiple static and real-time GNSS observations were collected on a total of 20 bench marks. In order to investigate the effects of collecting GNSS observations at sites with full to limited view of the sky, six of the 20 marks (3201, LEX, PELI, SURV, AIKP, D138) had minimal obstructions 15 deg. above the horizontal of the antenna, 12 marks were located near power poles or under tree canopies that obstructed up to 25% of the view of the satellites, and two marks (L186, BUTL) were under canopies obstructing up to 50% of the view of the satellites. The idea was to collect data at these challenging locations so that resulting recommendations would be conservative in case surveyors needed to collect GNSS data at similar places.

Utilizing the South Carolina Real-Time Network (SCRTN), 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 baseline distances. The South Carolina Real-Time Network (SCRTN) uses active stations within the State of South Carolina and the Trimble NTRIP caster to provide corrections for real-time surveys using a VRS method (South Carolina Geodetic Survey 2016). The SCRTN has 45 GNSS reference stations distributed at a recommended spacing of 70 km or less across the state (Lapine and Wellslager 2007).

The delta ECEF vector components from the PRS to the ARP of the rover antenna (and associated variance-covariance matrix) were stored for every real-time observation, along with other metadata, including DOP, solution RMS, antenna height, start and stop times, etc. (Dennis 2014).

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 at a 1-sec epoch rate: 5, 30, 60, 120, 180, 300, 480, and 600 seconds. Both nRTK and sRTK observations were collected for each duration interval. In addition, a set of observations were made with only GPS observables as well as another set with GPS+GLONASS observables. 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 desired 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 using Trimble R7 receivers and Trimble TSC3 data collectors with two versions of the Trimble Zephyr Geodetic 2 antenna, one without and one with Restriction of Hazardous Substances Directive (RoHS) compliant solder (IGS antenna names "TRM55971.00 NONE" and "TRM57971.00 NONE", respectively). For the other ten marks (W53_,

W186, SURV, D138, E176, G176, HUNT, L186, PELI and Q176) Trimble R-8 Model 2 integrated antenna/receivers were used (IGS antenna name "TRMR8_GNSS NONE") with Trimble TSC2 data collectors. For the sRTK solutions, there were insufficient fixed observations (only 2 to 10 fixed observations were recorded) for 7 of the marks (G136, J137, AIKP, R137, BUTL, 2103 and 1901) because their baseline lengths were overly long (ranging from 52 km to 104 km); this resulted in sufficient sRTK data on only 13 marks for accuracy evaluation. Further, there were 7 sRTK solutions and 37 nRTK solutions wherein the rover (Trimble R7 receiver) apparently recorded zero epochs of data but reported a "fixed" solution. 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 in a positive ellipsoid height bias of about 8 cm for nRTK solutions and 4 cm for sRTK solutions. These errors are not related to the RTK algorithms; rather, the errors are simply due to outdated firmware. For the out-of-date firmware, the rover did not recognize the base antenna and identified it as "Unknown External." In contrast, the up-to-date firmware correctly identified the bases as "Adv Null Antenna," which corresponds to the official IGS-defined idealized isotropic absolute antenna "GPPNULLANTENNA" used for real-time applications (IGS 2017). This issue was not discovered in the field since the field controller software 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 (NGSIDB), 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 the time were known, it would be necessary to analyze the different versions of the GNSS receiver firmware code to determine exactly how each receiver handled antennas in real time (Graham Briggs, personal communication, October 13, 2016). Unfortunately, this was not possible within the scope of this study. 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 real-time solutions and the importance of keeping software and firmware up to date.

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. Fifteen of the selected marks had only a few minor overhead obstacles (e.g., distant tree canopies) more than 15 degrees above the horizontal of the GNSS antenna. However, two marks (i.e., point names LBCC and GLAS) were located next to traffic signs and had nearby tree canopies as tall as 45 degrees above the horizontal, and one mark (B726) was next to a wooden telephone pole. The three marks with the less-ideal overhead obstacles and nearby features that could cause some multipathing were included in the survey study to simulate some typical types of field challenges surveyors encounter when attempting to make GNSS baseline observations on existing passive marks (Weaver et al. (in press)).

Static GPS and GLONASS observations at a 1-sec logging rate were collected for at least four, 10-h sessions at each mark, except for mark D728, which was occupied for only three 10-h sessions (Gillins and Eddy 2016). For each session, the surveyors simultaneously used five to six Leica Viva GS14 integrated antenna/receivers and five to six Leica CS15 data collectors. 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 2016).

During each session, various types of sRTK and nRTK observations were also collected simultaneously using the ORGN. The Oregon Real-time GNSS Network (ORGN) provides RTK correctors using a MAC method computed by Leica Geosystems Spider software. The ORGN has approximately 100 reference stations with a spacing typically less than 70 km in length (Oregon Dept. of Transportation 2017). The real-time data were logged as a continuous stream of 1-second, single-epoch observations. Half of the real-time solutions were derived using only GPS observables, and the other half using only GPS and GLONASS observables. 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 15 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 station LCS1. Typically, an RTN assigns the nearest base station as the master station, and additional base stations are chosen as auxiliaries for best results (Leica Geosystems, 2005). 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 unusually poor performance at these four marks. Because of this mistake, nRTK observations at these four marks were not included in the aggregate results for nRTK; 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 the static GNSS files collected at the passive marks during the surveys were uploaded to *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 in the NGS CORS Network (in this paper, only those reference stations in this NGS network are referred to as “CORS”). CORS were selected based on the following criteria: (1) had data available during the survey campaign; (2) the daily solutions, as computed and plotted in short-term time series by NGS, were within +/- 1 cm of its NGS published position; and (3) NGS had estimated its formal errors and computed its 3-D velocities based on at least 2.5 years of data in the initial NGS Multi-Year CORS solution (NGS 2013). To improve wet-component corrections in the tropospheric delay models, additional CORS with distance from 250 to 2,000 km from the project area were selected based on the findings of the Ugur (2013) study. Data from fourteen CORS were added for the South Carolina survey and data from seven CORS were added for the Oregon survey. In addition to loading static data at the multiple CORS, static data at other active stations in the RTNs that were used as reference stations but are not part of the NGS CORS Network were loaded to *OPUS-Projects*. For Oregon, 24 h static GPS data files for each survey session at one active station (LCS1) that is not a CORS were loaded to *OPUS-Projects*; for South Carolina, 12 h static GPS data files for each survey session at five active stations that are not CORS but are in the SCRTN were loaded. The location of the passive and active marks elected for post-processing the static data in *OPUS-Projects* are shown in Figures 1 and 2 for South Carolina and Oregon, respectively.

Baseline solutions were computed by post-processing the static data in *OPUS-Projects*. These baselines solutions (vectors) 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* using the static GNSS session solutions that were adjusted in *ADJUST*. All RTK observations with float solutions were removed from the analysis. In addition, all RTK observations (in both GPS-only and GPS+GLONASS) with vectors longer than 50km were removed from the analysis in order to compare results between GPS-only and GPS+GLONASS using samples of fixed solutions based upon similar baseline lengths. This removal was primarily because only a few GPS-only vectors with fixed integer ambiguities could be obtained in the field for baselines longer than 42 km in length; whereas numerous longer, fixed baseline solutions were achieved with GPS+GLONASS. Although the equipment claimed that several of the GPS+GLONASS RTK solutions with vector lengths longer than 50 km were fixed, these long-vector solutions were noisy and sometimes deviated significantly (i.e., > 30 cm) from the coordinates at the mark derived from the static survey. After removal of the long vectors, a small percentage of fixed RTK observations that were obvious outliers were also rejected and removed from the analysis. Any RTK observation with a residual in northing, easting, or up greater than 3.3 times the standard deviation (99.9% confidence level) in any of these three components was considered an outlier and was rejected.

For the comparisons, the statistics are summarized as root-mean-square error (RMSE) differences in both the vertical (i.e., ellipsoid height) and horizontal components. 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: (1) nRTK with GPS-only observables; (2) nRTK with GPS+GLONASS observables; (3) sRTK with GPS-only observables; and (4) sRTK with GPS+GLONASS observables. Horizontal RMSE (HRMSE) and Vertical RMSE (VRMSE) were calculated using Eqns. 1 and 2:

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

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

where, P_i is the real-time coordinate component (in north, east, or up) from the survey at station *i*, O_i is the adjusted coordinate component from the static survey derived from *OPUS-Projects* and *ADJUST* at station *i*, and *n* is the total number of real-time observations in the sample.

To evaluate the benefit of GPS+GLONASS compared with a GPS-only solution, the percent difference between the solutions were compared for each occupation time interval, per the following equations:

$\%difference\ (Horizontal) =$

$$\left[\left({}^{HRMSE_{GPS+GLONASS}}\middle/_{HRMSE_{GPS\ Only}}\right) - 1\right] \times 100\% \qquad (3)$$

$$\%difference\ (Vertical) =$$

$$\left[\left({VRMSE_{GPS+GLONASS}}/{VRMSE_{GPS\ Only}} \right) - 1\right] \times 100\% \qquad (4)$$

Results

Case I. South Carolina

This section provides several figures and tables that illustrate the results of the South Carolina survey. Table 1 presents the average Position Dilution of Precision (PDOP) values and the total number of all "fixed" solutions for each mark, grouped according to the data collection technique. Although some of the marks had less view of the sky than others (due to trees and power poles), the average PDOP values are fairly similar for all 20 marks. It appears that the overhead obstructions at the observed marks were not severe enough to noticeably degrade the accuracy of the results. Interestingly, the PDOP values for the sRTK solutions are generally higher than for the nRTK solutions. In addition, as expected due to the increased number of satellites, the average PDOP values for the GPS+GLONASS solutions are generally lower than for the GPS-only solutions. As previously mentioned, there were an insufficient number of fixed sRTK solutions at seven marks, which are shown as bold and italic in Table 1. Figure 3 presents the percentage of fixed and float solutions obtained for all observation durations using sRTK GPS-only and sRTK GPS+GLONASS versus baseline length (prior to the aforementioned removal of float solutions and vectors longer than 50 km).

Using only the fixed observations and after removal of the vectors greater than 50 km in length and outliers, Figure 4 presents the HRMSE as a function of observation duration for all four observation types (i.e., sRTK GPS-only, nRTK GPS-only, sRTK GPS+GLONASS, and nRTK GPS+GLONASS). Figure 5 shows a similar plot as Figure 4, but in terms of VRMSE.

Table 2 shows the RMSE for the GPS-only and GPS+GLONASS RTK observations, number of observations used for RMSE computation, and the number of observations that were rejected as outliers. The table also shows the percent difference in RMSE values using GPS+GLONASS instead of GPS-only. Negative values indicate improvement in accuracy. The averages of percent difference for both horizontal and vertical RMSE indicate that the GPS+GLONASS RTK observations were generally more accurate compared to the GPS-only RTK observations. The improvement in RMSE was greater horizontally than vertically when using GPS+GLONASS instead of GPS-only.

Figure 6 displays scatter plots for the HRMSE and VRMSE versus baseline length. For the sRTK data, the baseline length was set to equal the 3-D distance from the single reference station to the observed mark. For the nRTK data, the baseline length was computed as the 3-D distance from the PRS to the observed mark. The plot shows RMSE values using only the sample of 180-second observations at each mark. The plot also depicts linear regression trend lines and associated coefficient of determination (R^2) values.

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 solution types in Oregon. As a reminder, nRTK

GPS+GLONASS data were not collected in Oregon because the ORGN did not support nRTK GPS+GLONASS solutions at the time of survey.

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

Table 4 shows the RMSE of GPS-only and GPS+GLONASS RTK observations, the number of observations used for the RMSE calculation, and the number of observations rejected in each time interval. It also displays the percent difference in RMSE using GPS+GLONASS instead of using GPS-only for the sRTK observations. Based on the percent difference values (negative indicates an improvement in accuracy), the GPS+GLONASS sRTK observations were more accurate than the GPS-only sRTK observations. Similar to the findings for the South Carolina case study, the improvement in RMSE was greater horizontally than vertically when using GPS+GLONASS instead of GPS-only.

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 (i.e., Figure 6), the plot shows RMSE values using only the sample of fixed 180-second observations at each mark. The plot also represents linear regression trend lines and associated R^2 values.

Case Study Comparisons

The residuals used at all marks to develop the plots in Figures 4, 5, 7 and 8 were pooled together, and new RMSE values were computed versus the session duration interval, constellation type (i.e., GPS-only vs. GPS+GLONASS), and solution type (i.e., sRTK vs. nRTK) for both case studies. For South Carolina, the nRTK results are based on data collected at 20 passive marks, and the sRTK results are based on data collected at 13 passive marks (since the sample size of fixed solutions was too small at the other 7 marks). For Oregon, the results are based on data collected at 18 passive marks for sRTK solutions and 14 passive marks for nRTK solutions (since nRTK data collected at 4 of the marks used an erroneous master reference station).

Discussion

In this section, we discuss the results in the context of the aforementioned objectives. It is important to clarify that the following discussion is based only on the two case studies completed with the ORGN and SCRTN. More case studies in the future are recommended to more fully characterize the accuracy of nRTK and sRTK observations.

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). When viewing the overall trend as per Figure 10, it is apparent that the accuracy does improve as the session duration increases; however, the improvement is generally subtle. In the South Carolina survey, the vertical sRTK observations (GPS+GLONASS) show the most improvement based on the observation duration (Figure 10). Interestingly, the number of rejected outliers per observation duration interval seems constant. Thus, increasing the session duration did not markedly reduce the likelihood of obtaining an outlier or bad RTK solution.

Influence of the inclusion of GLONASS

When examining 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 nearly all observation durations. Similar results were also observed for the nRTK solutions. In the few exceptions where the GPS-only results were more accurate than the GPS+GLONASS, the differences were not significant. In the Oregon survey, the sRTK solution with the inclusion of GLONASS significantly reduced HRMSE for almost all of the stations (i.e., on average, the percent difference was -32.6%), and it somewhat reduced the VRMSE (i.e., on average, – 5%). Another important aspect of including GLONASS is that it helped improve the ability to achieve fixed solutions in sRTK for longer baselines (Figure 3). However, note that in some cases for very long baselines in the SCRTN survey, GPS+GLONASS enabled solutions to be obtained that were erroneously declared fixed, yet they had significant residuals compared with the results of the static survey.

nRTK solutions versus sRTK solutions

Figures 4, 5, 7 and 8 generally show that nRTK solutions have improved values of RMSE than sRTK solutions. This consistency is likely the result of the improved ability to model atmospheric and satellite orbit errors when using network RTK. Further, some of the differences between these two solutions is likely due to the shorter baseline length in the nRTK survey as compared with the sRTK survey. Per Figure 6 and 9, the length of baselines for only the fixed sRTK observations with adequate sample size in South Carolina and Oregon reached up to 42 km and 36 km, respectively; whereas the length of baselines for only the fixed nRTK observations in South Carolina and Oregon only reached 29 km and 22 km, respectively.

Other factors may have influenced the occasional "fluctuations" in RMSE as session duration increases at each of the individual marks in Figures 4, 5, 7, and 8. Small sample sizes were used to derive each data point in these figures, and just one solution with a large difference from the mean of a sample (which might have occurred due to occasional multipathing or some other anomaly) could cause a jump in the RMSE value. To overcome this challenge and find the general trend in sRTK versus nRTK, the residuals for all marks at each case history were pooled together to find pooled RMSE values as shown in Figure 10. All of the nRTK curves in Figure 10 are generally more accurate (in terms of both VRMSE and HRMSE) than the sRTK curves. It is particularly worth noting that although the improvement in HRMSE values is subtle, the VRMSE values from the nRTK results are far superior for both the SCRTN and the ORGN compared with the sRTK VRMSE values. This finding highlights that when a surveyor is concerned with deriving high-accuracy ellipsoid heights, it appears much better to use nRTK rather than sRTK.

Effects of baseline length

Figures 6 and 9 generally show that as the baseline length increases, the RMSE of the observation also increases, similar to prior studies. As expected, the rate of increase in RMSE is generally smaller for the nRTK data than for the sRTK data, as the network of reference stations are expected to minimize distance-dependent relative positioning GNSS errors. Nonetheless, caution should be exercised in interpreting these plots. Some of these plots shows a trend counter to expected results of increased error with baseline length (e.g., Figure 6 with the vertical sRTK observations, GPS+GLONASS, in the South Carolina). Note that this plot with downward trend line has very low R^2 values, indicating that there is little or no determinable trend in the data. These cases (trend lines with very low R^2 values) could also indicate that the influence of baseline length is masked by other factors that contributed 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 generally increase. These findings concur with the results of the Bae et al. (2015) study.

Consistency between results from the two networks

The results in South Carolina and Oregon demonstrated reasonable consistency (Figure 10). The horizontal and vertical RMSE curves are quite similar when comparing the two case studies. It is important to note that the South Carolina survey involved marks with more substantial overhead obstructions (worse satellite visibility than in the Oregon survey, which generally had clearer satellite visibility). The poorer visibility may have resulted in the generally slightly higher RMSE curves for the SCRTN as compared with the ORGN. Despite some of these slight differences, the results are remarkably consistent between these two case studies on opposite sides of the continent involving entirely different RTNs.

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 using long-duration occupations for the same marks in both datasets. Issues during the data analysis such as inappropriate use of the wrong master station when observing some of the marks in Oregon, use of outdated firmware in South Carolina, and strange solutions generated by the rover utilizing zero epochs of RTK data led us to understand important practical lessons about real-time GNSS surveying. As best as possible, the data that were obtained with these problems were either corrected or removed from the evaluation, as discussed in this paper.

The resulting analyses confirm that the increased duration of real-time observations slightly improves the positioning accuracy in both the vertical and horizontal components. Interestingly, the accuracy of the RTK solutions hardly improved with observation duration, especially after roughly 3 to 5 minutes. Data collected with the full network (nRTK) tended to be more accurate and precise than data collected using a single reference station (sRTK), and the inclusion of GLONASS improved the accuracy of the observations and helped obtain more fixed solutions at longer baseline lengths.

The evaluation completed in this study was limited to data collected in Oregon and South Carolina and is constrained by the inherent limitations of those networks. For instance, the RTN in Oregon was only capable of providing GPS-only nRTK solutions (at the time of this study) utilizing a MAC method as well as GPS-only and GPS+GLONASS sRTK solutions. The RTN in South Carolina was capable of providing both GPS-only and GPS+GLONASS sRTK solutions and nRTK solutions utilizing a VRS method. Similar work could be completed in the future following methods presented in this paper by studying data collected in other climates and geographies, at sites with more challenging overhead conditions (e.g., in urban canyons), at other locations with access to an RTN utilizing different methods (e.g., FKP), and/or other locations with an RTN that has the capability of providing other types of multi-GNSS solutions (e.g., including using Galileo and Beidou satellites). Another future test could investigate how the age of the corrections in an RTCM message affects the accuracy of an RTK solution. Finally, the spacing and configuration of the reference stations in an RTN influences the accuracy of nRTK solutions (Wang et al. 2010). For this study, the reference station spacing was less than 70 km in both the SCRTN and ORGN. Future work could involve testing the accuracy of nRTK solutions from RTNs with interstation distances greater than the recommended distance of 70 km as well as those networks with much closer spacing.

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Table1.

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

Table2.

	Time(s)	GPS Only				GPS+GLONASS				% Change in RMSE		
		HRMSE (cm)	**VRMSE (cm)**	**# of Obs used**	**# of Obs rejected**	**HRMSE (cm)**	**VRMSE (cm)**	**# of Obs used**	**# of Obs rejected**	**Time (s)**	**HRMSE**	**VRMSE**
sRTK	5	1.81	4.34	170	2	1.60	4.52	189	1	5	-11.9	*4.2*
	30	1.72	4.39	170	3	1.46	4.27	180	3	30	-15.3	-2.8
	60	1.71	4.15	179	2	1.36	4.01	185	5	60	-20.2	-3.3
	180	1.60	4.27	177	3	1.48	3.60	191	2	180	-7.5	-15.7
	300	1.50	4.08	176	3	1.33	3.68	185	3	300	-11.3	-9.9
	600	1.31	3.82	185	2	1.09	3.15	184	5	600	-16.9	-17.5
			Total =	1057	15		Total =	1114	19	Mean =	-13.8	-7.5
nRTK	5	1.50	2.84	289	4	1.35	2.87	322	3	5	-9.7	*0.8*
	30	1.58	2.94	289	4	1.34	2.68	321	4	30	-14.7	-8.7
	60	1.54	2.85	292	1	1.26	2.51	318	2	60	-18.3	-11.8
	180	1.30	2.68	285	3	1.14	2.41	316	4	180	-12.2	-10.1
	300	1.17	2.44	296	3	0.99	2.27	312	5	300	-15.0	-7.0
	600	1.00	2.10	277	2	0.92	2.22	312	5	600	-7.7	*5.6*
			Total =	1728	17		Total =	1901	23	Mean =	-12.9	-5.2

Table3.

Stations	**nRTK**	**sRTK**	
	# of observations	# of observations	
	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

Table4.

	Time(s)	GPS Only				GPS+GLONASS				% Change in RMSE		
		HRMSE (cm)	VRMSE (cm)	# of Obs used	# of Obs rejected	HRMSE (cm)	VRMSE (cm)	# of Obs used	# of Obs rejected	Time (s)	HRMSE	VRMSE
sRTK	5	2.21	3.96	669	17	1.49	3.73	701	10	5	-32.5	-5.9
	30	2.23	3.98	671	17	1.46	3.70	700	11	30	-34.5	-7.1
	60	2.10	3.87	668	20	1.44	3.69	699	10	60	-31.4	-4.7
	120	2.07	3.85	667	19	1.40	3.63	699	11	120	-32.2	-5.8
	180	1.98	3.83	667	19	1.35	3.59	698	12	180	-31.8	-6.3
	300	1.92	3.81	669	20	1.30	3.55	698	12	300	-32.3	-6.8
	480	1.87	3.65	665	20	1.27	3.48	697	12	480	-32.3	-4.5
	600	1.83	3.64	664	18	1.24	3.44	696	11	600	-32.5	-5.5
	900	1.79	3.40	651	17	1.17	3.47	689	9	900	-34.4	2.1
			Total =	5991	167		Total =	6277	98	Mean =	-32.6	-5.0
nRTK	5	1.50	2.53	527	8	**nRTK GPS+GLONASS data were not supported at the time of survey**						
	30	1.45	2.48	524	8							
	60	1.41	2.39	519	9							
	120	1.38	2.35	515	8							
	180	1.34	2.26	513	8							
	300	1.28	2.19	509	7							
	480	1.20	2.09	506	9							
	600	1.17	2.06	507	8							
	900	1.13	1.95	501	8							
			Total =	4621	73							

A Tale of Two RTNs: Rigorous Evaluation of Real-time Network GNSS Observations

Table Captions

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

Table 2. RMSE of GPS-only and GPS+GLONASS RTK observations, number of observations used and rejected for RMSE calculation, and percent change in RMSE when using GPS+GLONASS instead of GPS-only; South Carolina. (Negative values indicate improvement in accuracy).

Table 3: Total number of fixed RTK observations for all stations and solution types for the Oregon survey.

Table 4: RMSE of GPS-only and GPS+GLONASS RTK observations, number of observations used and rejected for RMSE calculation, and percent change in RMSE using GPS+GLONASS instead of GPS-only; Oregon. (Negative values indicate improvement in accuracy).

Figure 1 Click here to download Figure Fig1.tif

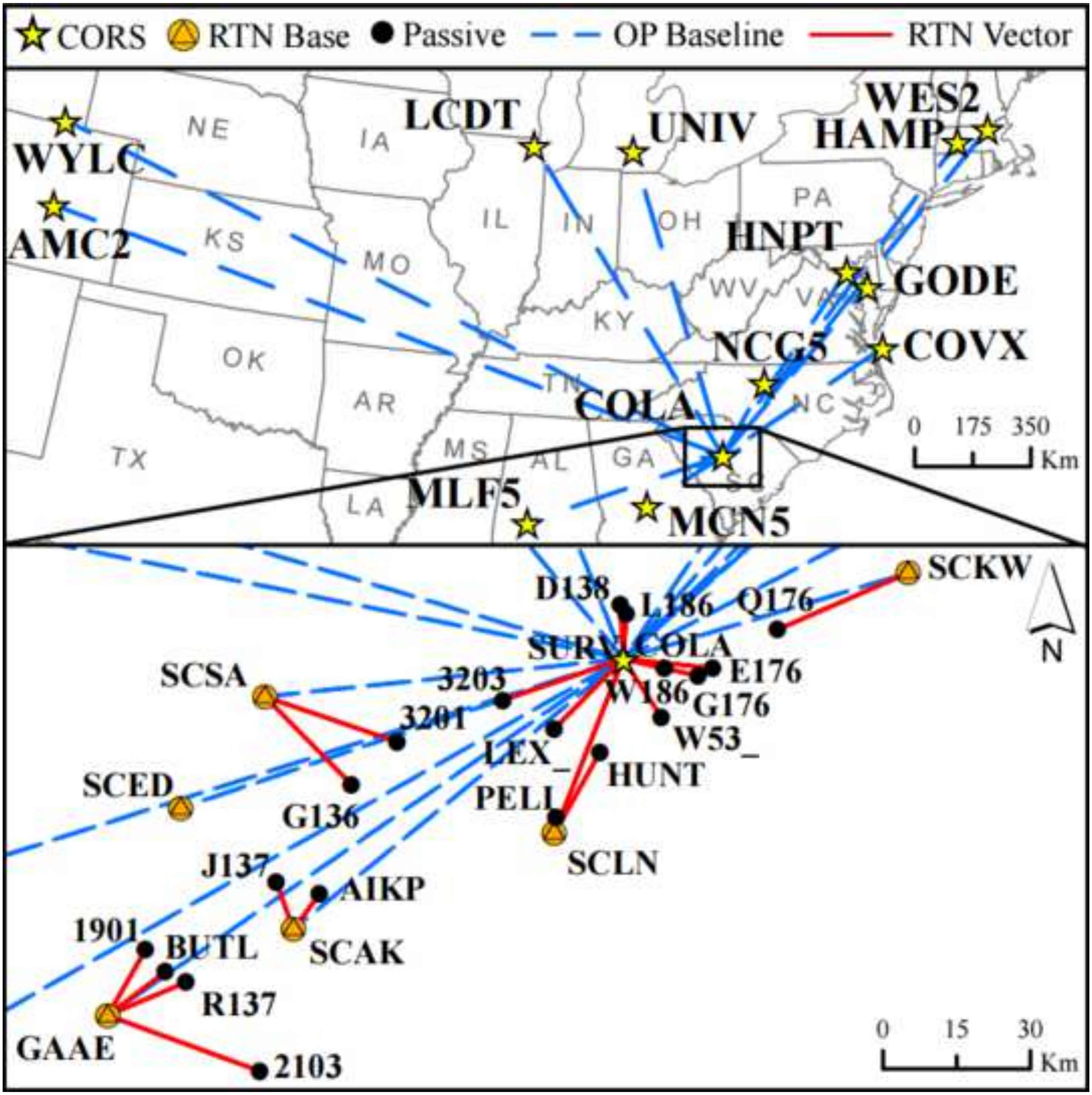


Figure 2

Click here to download Figure Fig2.tif

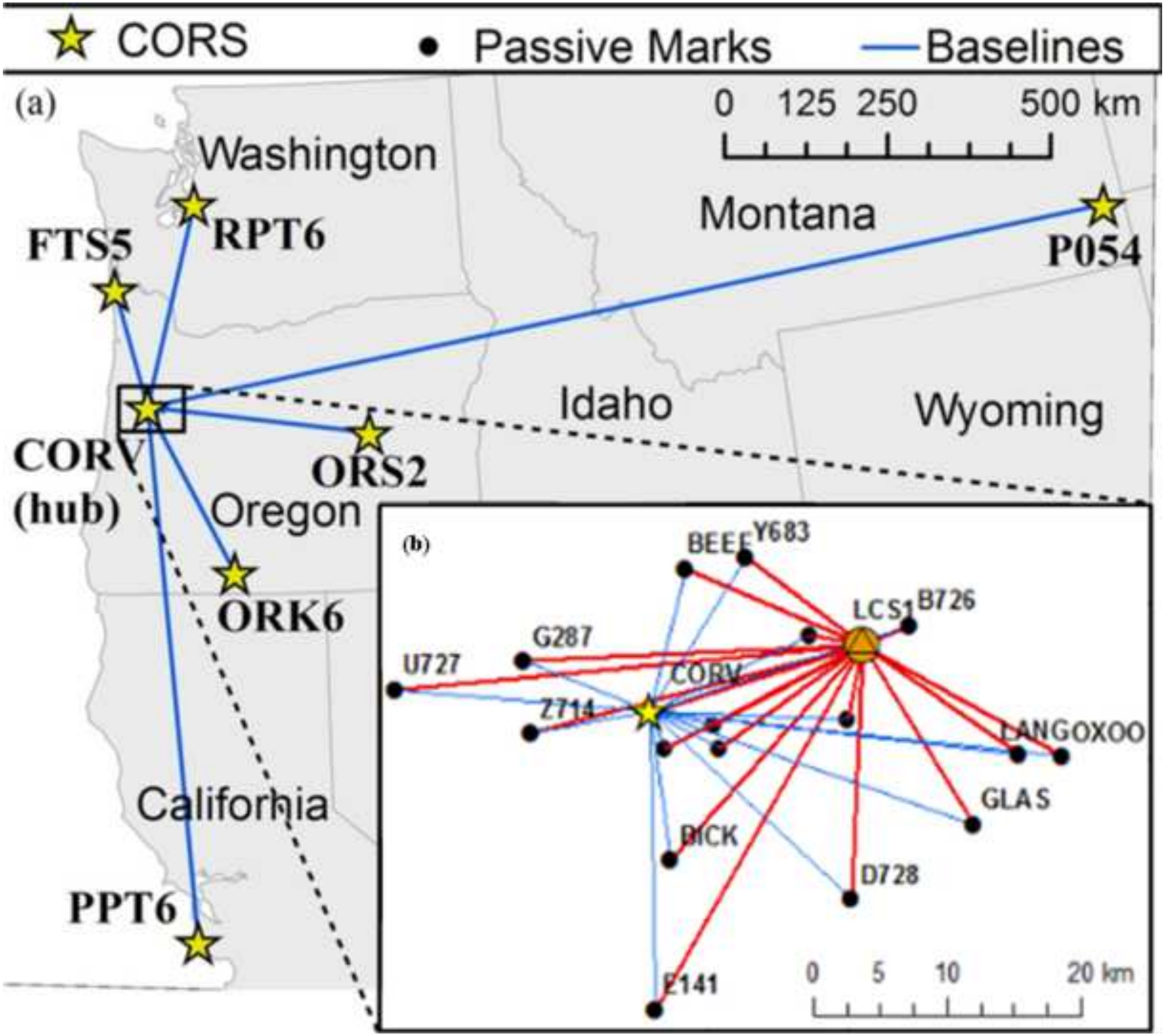


Figure 3

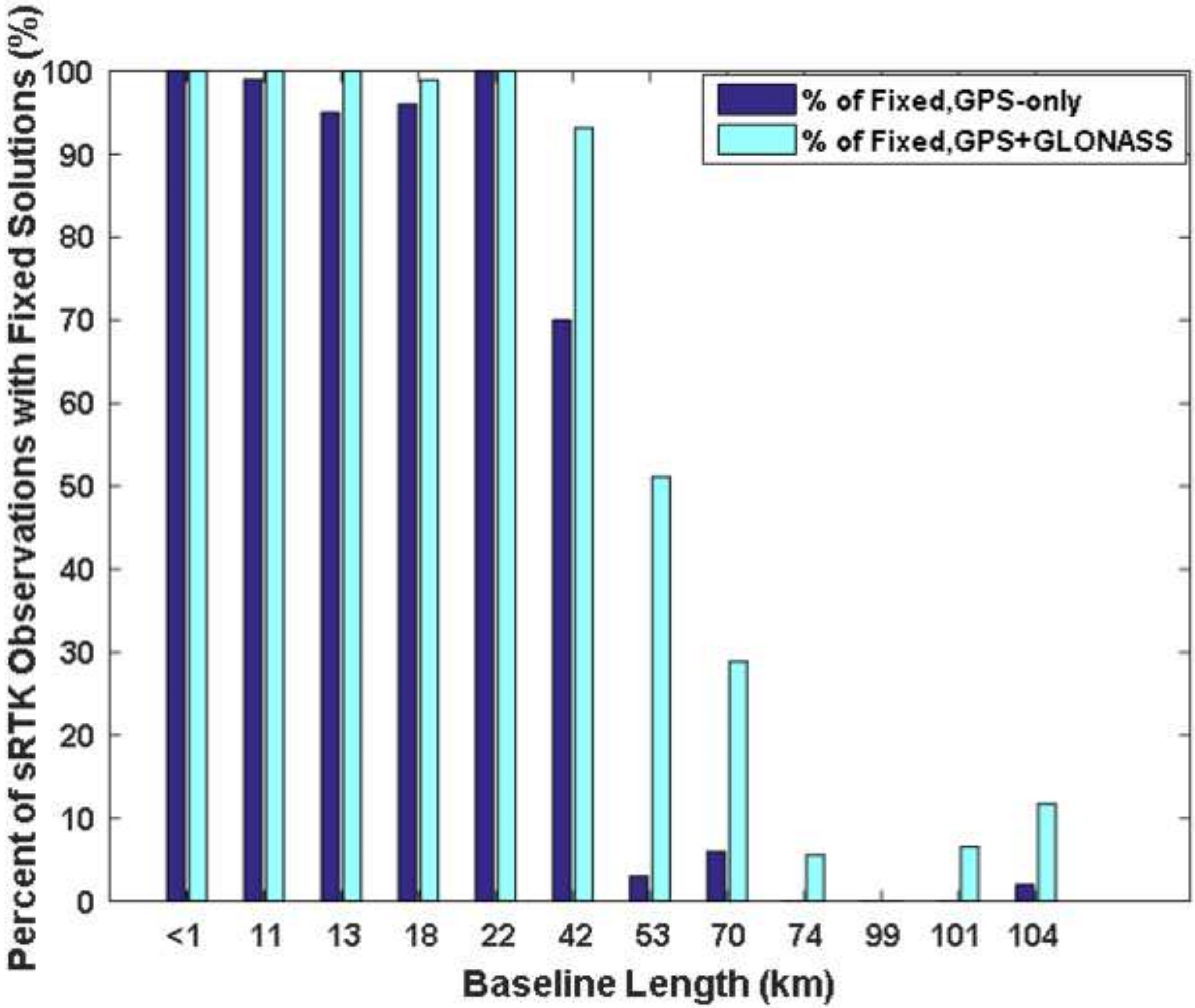

Percent of sRTK Observations with Fixed Solutions (%)
100
90
80
70
60
50
40
30
20
10
0
% of Fixed,GPS-only
% of Fixed,GPS+GLONASS
<1
11
13
18
22
42
53
70
74
99
101
104
Baseline Length (km)

Figure 4

Click here to download Figure Fig4.tif

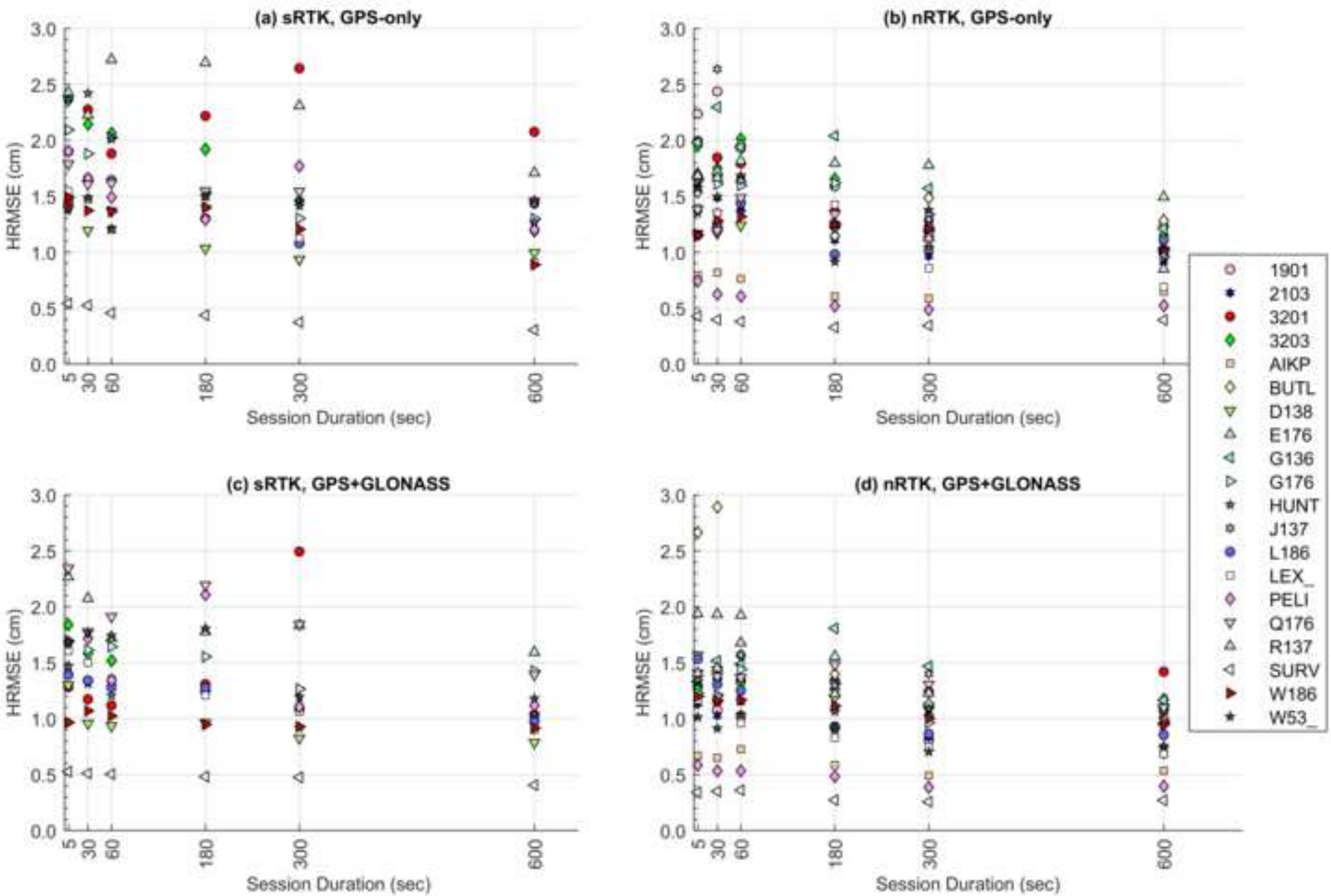
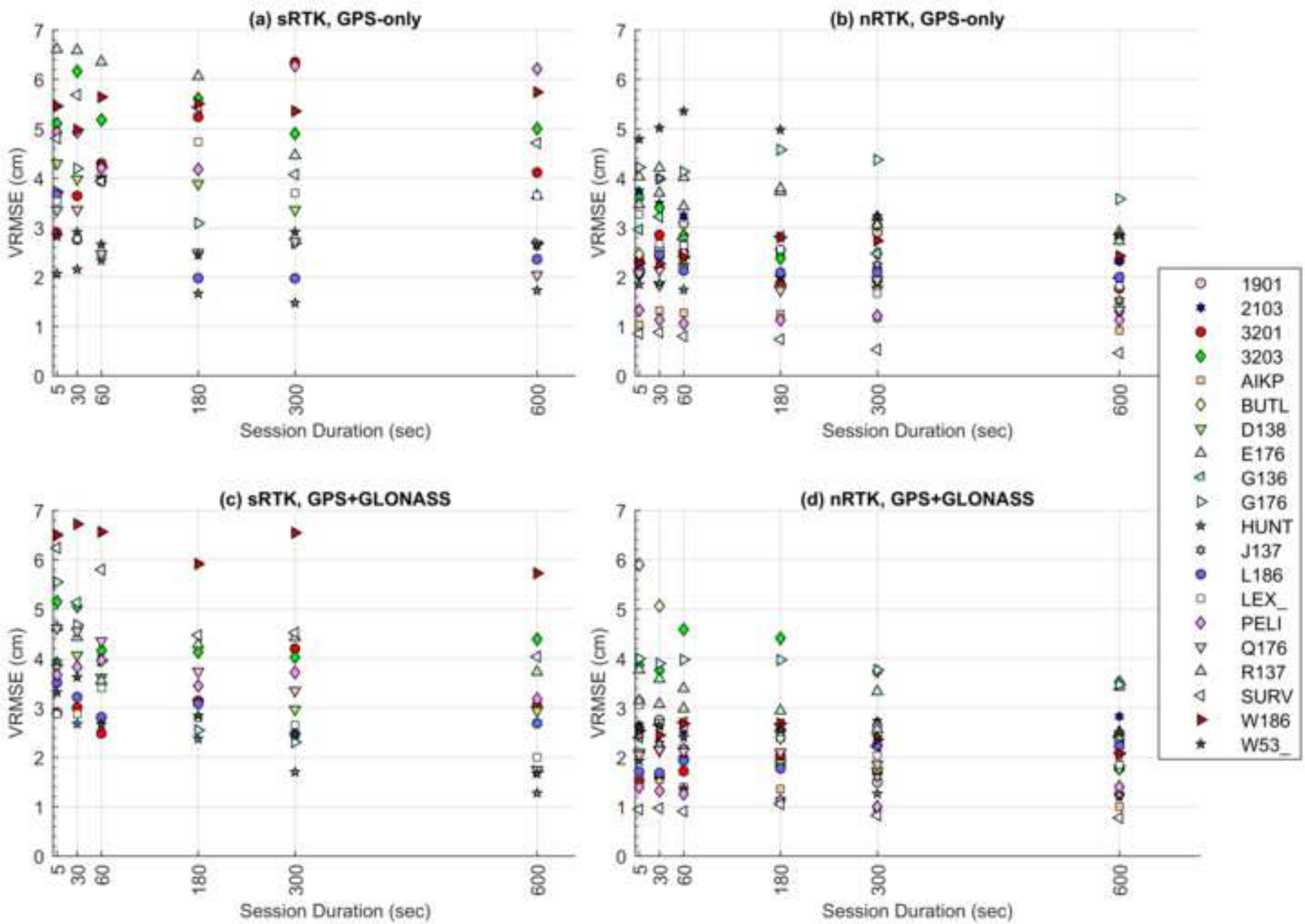


Figure 5



(a) sRTK, GPS-only
(b) nRTK, GPS-only
(c) sRTK, GPS+GLONASS
(d) nRTK, GPS+GLONASS
VRMSE (cm)
Session Duration (sec)
0
1
2
3
4
5
6
7
5
30
60
180
300
600
1901
2103
3201
3203
AIKP
BUTL
D138
E176
G136
G176
HUNT
J137
L186
LEX_
PELI
Q176
R137
SURV
W186
W53_

Figure 6

Click here to download Figure Fig6.tif

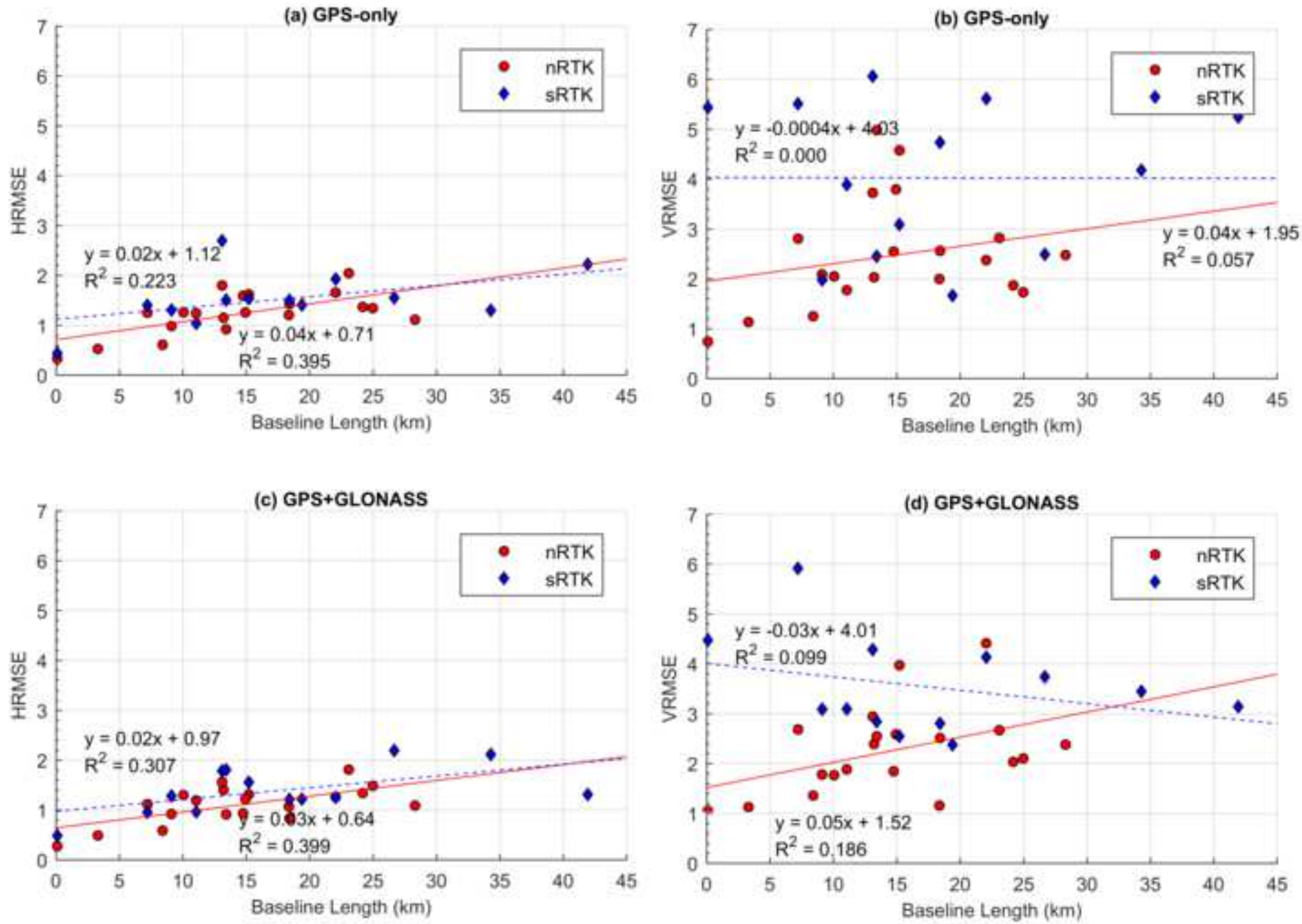
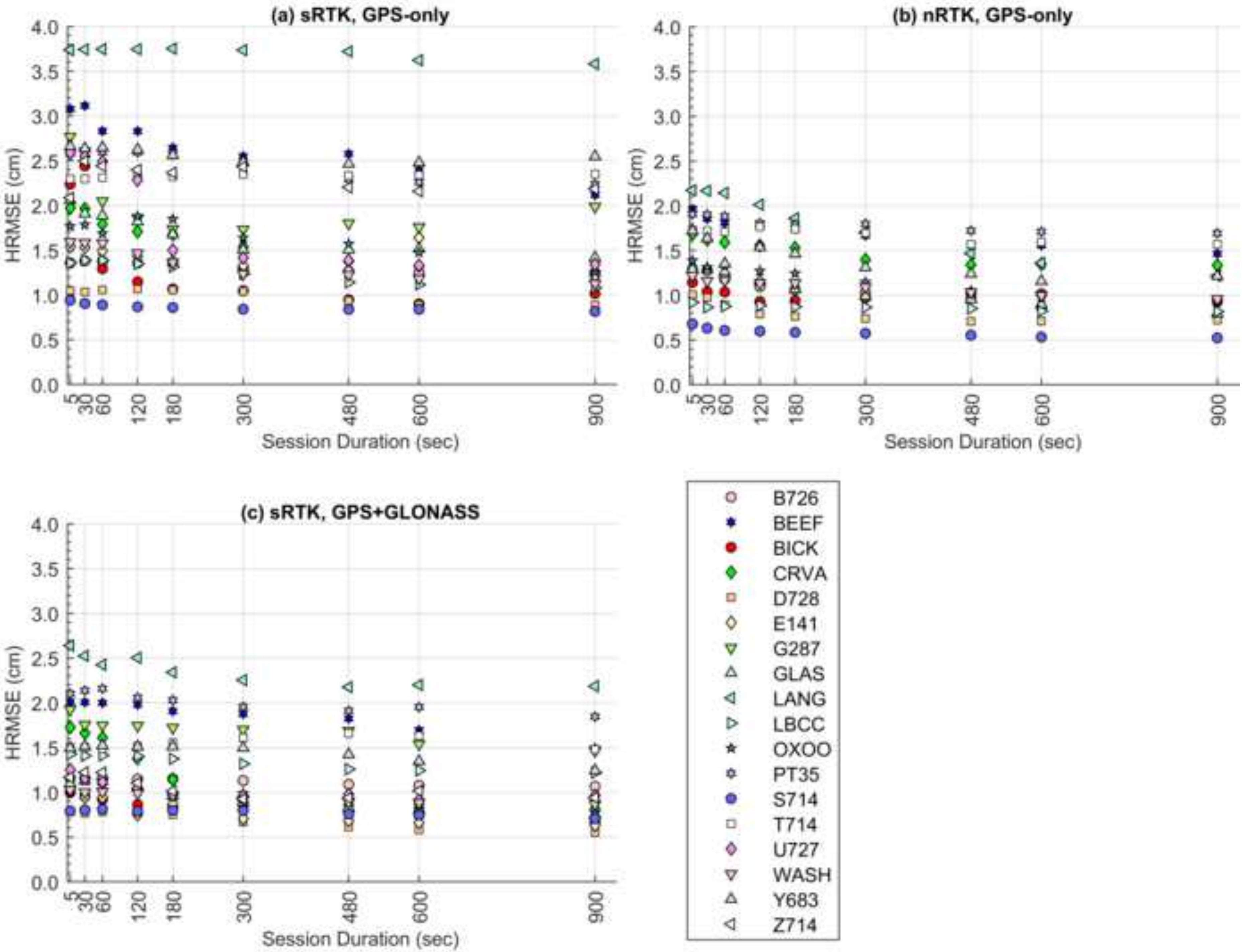


Figure 7



(a) sRTK, GPS-only
(b) nRTK, GPS-only
(c) sRTK, GPS+GLONASS
HRMSE (cm)
Session Duration (sec)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
5
30
60
120
180
300
480
600
900
B726
BEEF
BICK
CRVA
D728
E141
G287
GLAS
LANG
LBCC
OXOO
PT35
S714
T714
U727
WASH
Y683
Z714

Figure 8

Click here to download Figure Fig8.tif

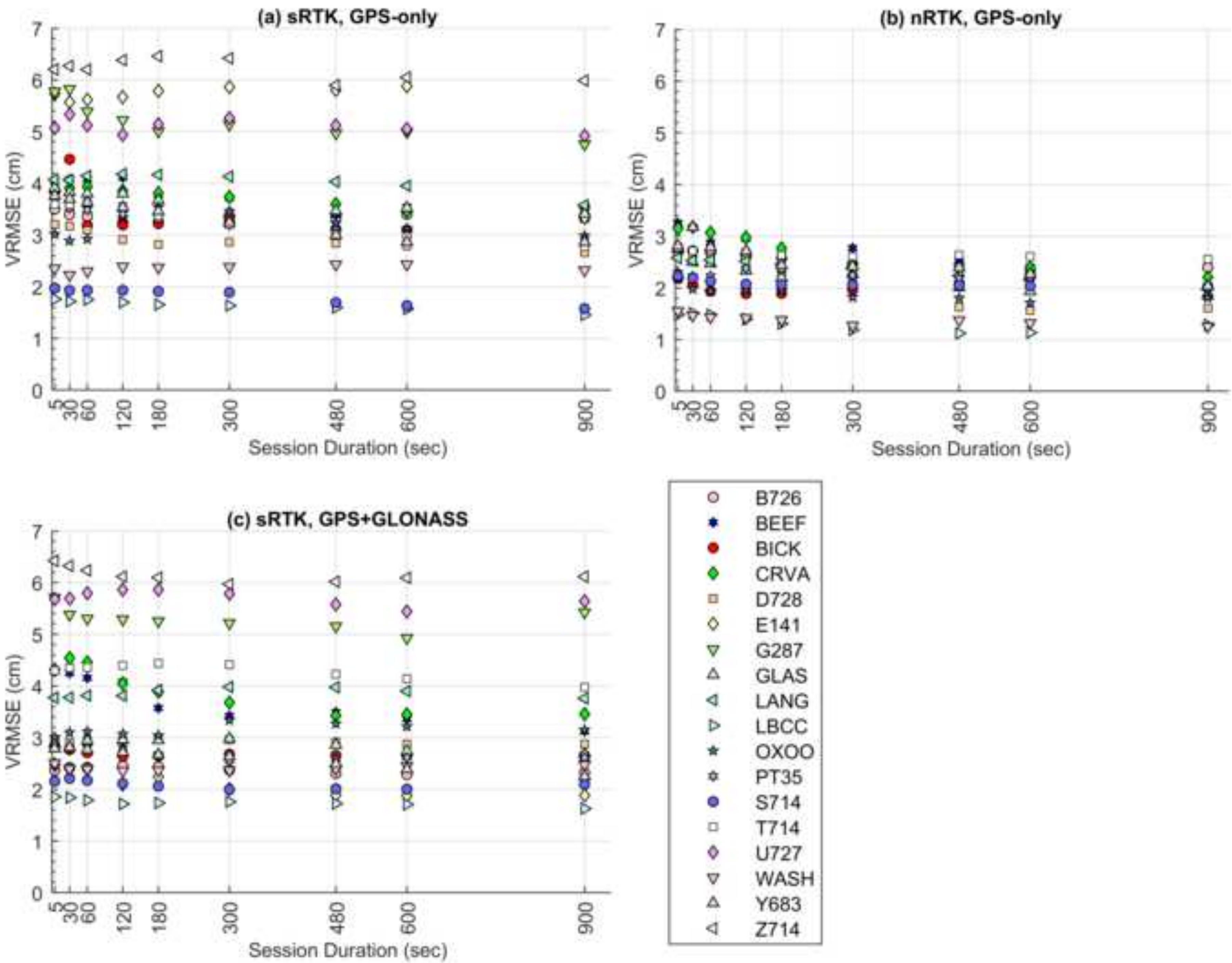


Figure 9 Click here to download Figure Fig9.tif

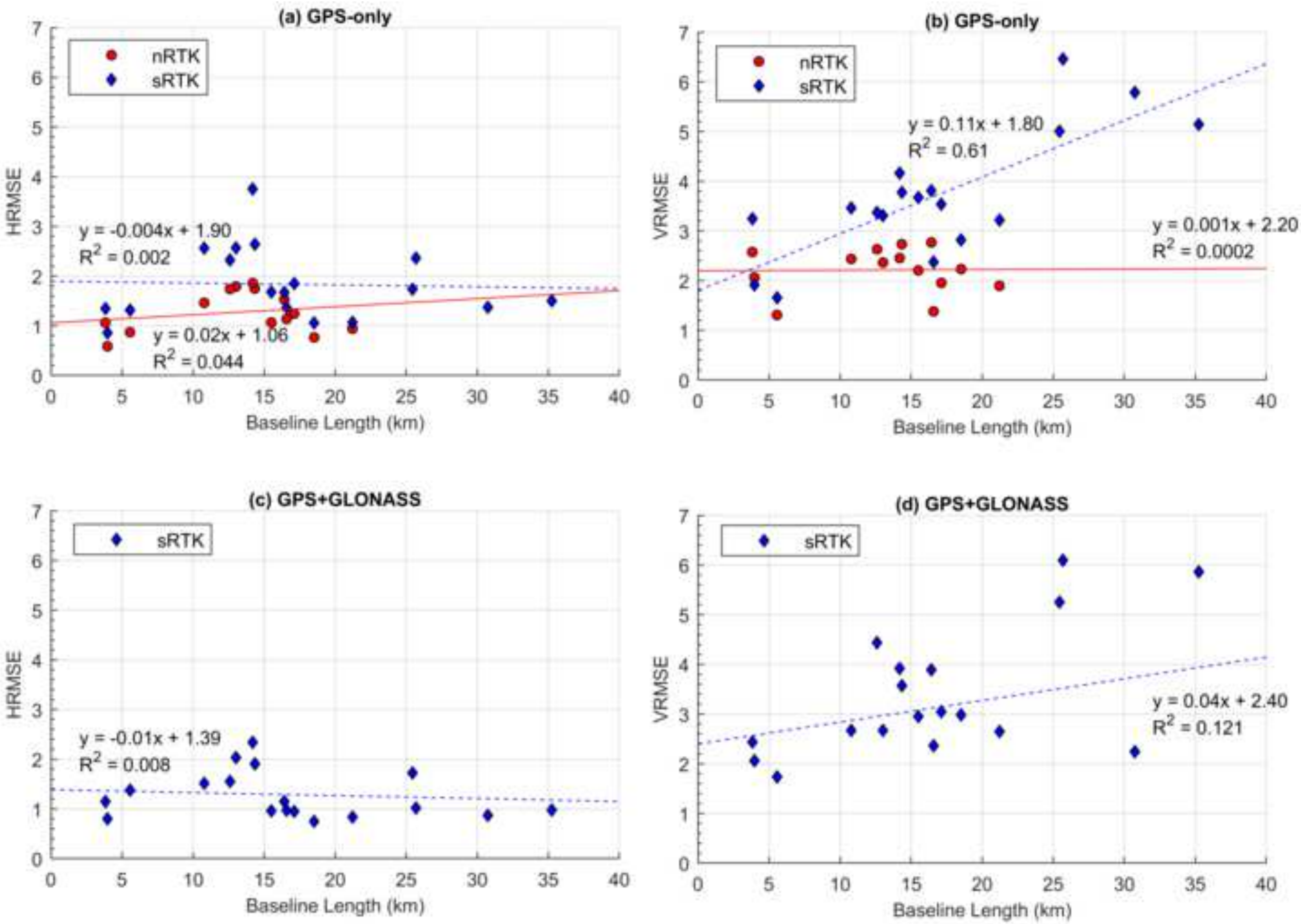
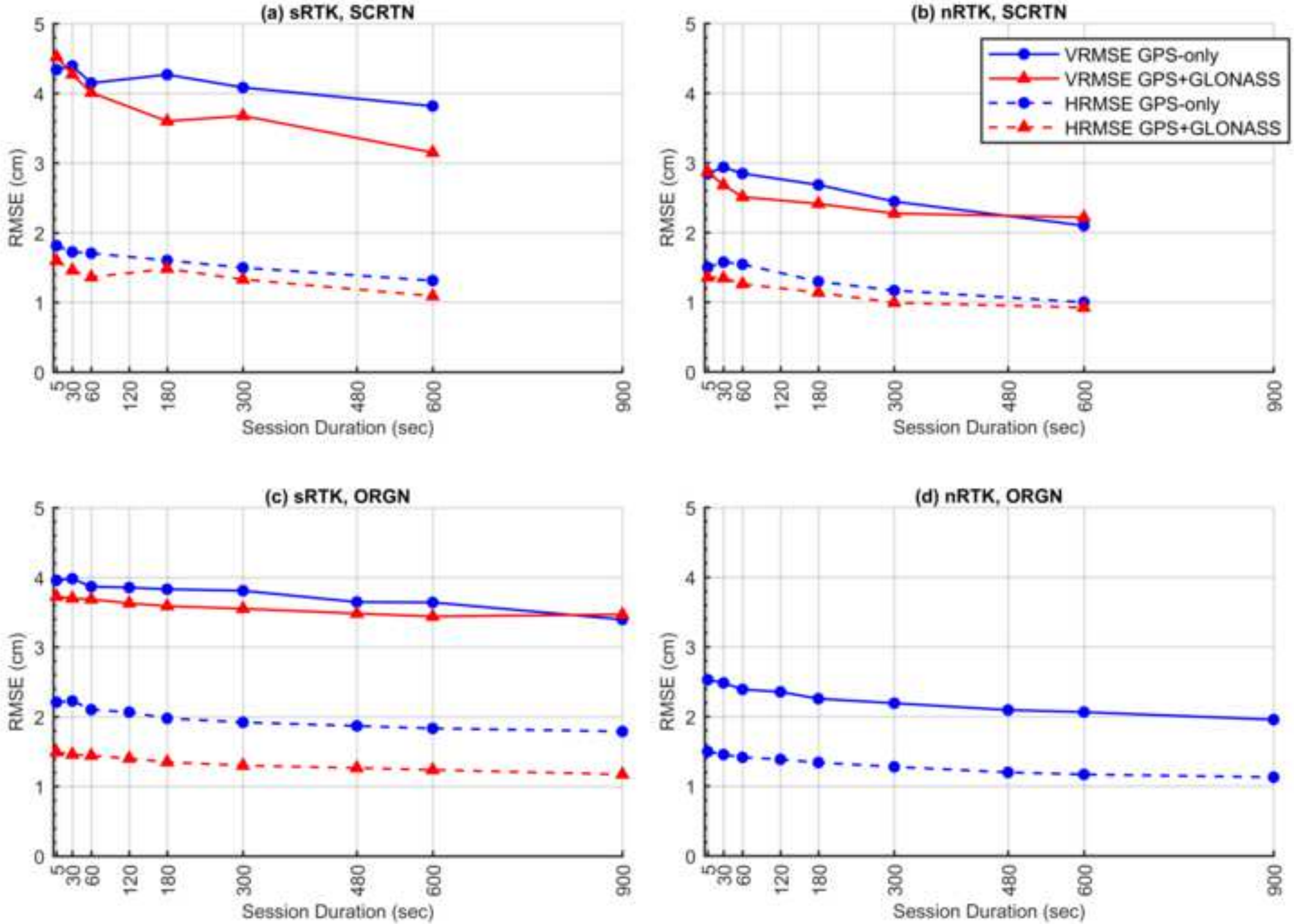


Figure 10 Click here to download Figure Fig10.tif



A Tale of Two RTNs: Rigorous Evaluation of Real-time Network GNSS Observations

Figure Captions

Figure 1. Locations of the passive marks, RTN base stations and CORS used for post-processing for the South Carolina survey. (Weaver et al (in press), with permission from ASCE)

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

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

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

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

Figure 6. Comparison of HRMSE and VRMSE versus baseline length in South Carolina: (a) HRMSE, GPS-only; (b) VRMSE, GPS-only; (c) HRMSE, GPS+GLONASS; (d) VRMSE, GPS+GLONASS; (180-second observations).

Figure 7. HRMSE at each mark in Oregon for (a) sRTK GPS-only; (b) nRTK GPS-only; and (c) sRTK GPS+GLONASS data versus observation duration.

Figure 8. VRMSE at each mark in Oregon for (a) sRTK GPS-only; (b) nRTK GPS-only; and (c) sRTK GPS+GLONASS data versus observation duration.

Figure 9. Comparison of HRMSE and VRMSE versus baseline length in Oregon: (a) HRMSE, GPS-only; (b) VRMSE, GPS-only; (c) HRMSE, GPS+GLONASS; (d) VRMSE, GPS+GLONASS; (180-second observations).

Figure 10. Comparison of HRMSE and VRMSE between the South Carolina and Oregon case studies. Data points represent the RMSE of all fixed, real-time kinematic solutions at all stations in the case study versus session duration: (a) sRTK, South Carolina; (b) nRTK, South Carolina; (c) sRTK, Oregon; and (d) nRTK, Oregon.