Comparative Analysis of Online Static GNSS Post-Processing Services

Marian Jamieson[1] and Daniel T. Gillins, Ph.D., P.L.S., M.ASCE[2]

Abstract: Several precise point positioning or relative positioning services are available online for post-processing static global navigation satellite system (GNSS) data collected on a single mark. The accuracy of five services (*OPUS-S, AUSPOS, CSRS-PPP, GAPS, TrimbleRTX*) were compared by processing the same 490 static GNSS files of varying session duration (from 2 to 10 hours) on six passive marks in minimal or moderate multipathing environments. First, only Global Positioning System observables at a 30-second logging rate were tested using each service. Then, the effects of including observables from Russia's GNSS (i.e., GLONASS) were investigated using *TrimbleRTX* and *CSRS-PPP*, and the accuracy of processing data at faster logging rates were evaluated using *TrimbleRTX*. The results from each service were differenced with coordinates derived from a high-accuracy campaign-style static GNSS survey. Increasing the logging rate from 30 seconds to 10 seconds did not significantly reduce the root-mean-square error (RMS) of the differences. However, adding GLONASS observables significantly reduced the horizontal RMS by an average of 17.1% and 36.7% at sites in minimal and moderate multipathing environments, respectively.

Author Keywords: GNSS, GPS, Precise point positioning, PPP, OPUS

---

[1] Graduate Student, School of Civil & Construction Engr., Oregon State Univ., 101 Kearney Hall, Corvallis, OR 97331; e-mail: jamiesom@oregonstate.edu

[2] Geodesist, National Geodetic Survey of National Oceanic and Atmospheric Administration, 1315 East-West Highway, Silver Spring, MD 20910, former Assistant Professor, School of Civil & Construction Engr., Oregon State Univ.; e-mail: daniel.gillins@noaa.gov

Introduction

A number of free, easy to use, online services have been developed for post-processing a single, static GNSS observational session on a mark. These services include but are not limited to *OPUS-S* (Online Positioning User Service - Static) developed by the United States' National Geodetic Survey (NGS) of the National Oceanic and Atmospheric Administration (NOAA); *AUSPOS* developed by Geoscience Australia; *CSRS-PPP* (Canadian Spatial Reference System - Precise Point Positioning) developed by Natural Resources Canada; *GAPS* (GNSS Analysis and Positioning Software) developed by the University of New Brunswick (Canada); and *TrimbleRTX* (Trimble Real Time eXtended) developed by Trimble, Inc.

Most well known in the United States is *OPUS-S*, a service that has become very popular amongst surveyors, engineers, and scientists for deriving geodetic coordinates referenced to the National Spatial Reference System (Soler et al. 2011). Although *OPUS-S* is widely used, it has some limitations worth investigating. Currently, *OPUS-S* only uses static GPS, ignores observables from other GNSS (e.g., GLONASS, Galileo, BeiDou), and automatically decimates the data files to a maximum data logging rate of 30 seconds. Thus, *OPUS-S* is ignoring data that could be used in the derivation of geodetic coordinates for an observed mark.

Some online services other than *OPUS-S* have the capability of post-processing multiple GNSS observables and/or at faster logging rates. Post-processing more observables, achieved by collecting at faster logging rates and from more satellites on differing orbital planes, could improve the redundancy in the observation and, ultimately, the accuracy of the derived coordinates. Today, it is common practice to use GNSS receivers which are capable of collecting data from multiple GNSS signals. In addition, due to the rapid development of data storage devices, GNSS observables are often collected and stored at logging rates as fast as every 1 to 10 seconds, rather than every 30 seconds.

Accordingly, this study has two primary objectives. The first objective is to compare the accuracy of the aforementioned five online services by submitting and post-processing identical static data files in each and comparing the results. This comparison will provide information on the availability, accuracy, and utility of other services. The second objective is to investigate if additional capabilities that are not currently available in *OPUS-S,* but are available in other services, including the ability to post-process data collected at faster logging rates or the addition of GLONASS observables, in fact improve the accuracy of the resulting coordinates.

To accomplish these objectives, observational data files were collected on six passive marks in varying multipathing environments. First, the data files were prepared with GPS-only observables of durations ranging from 2 to 10 hours with a 30-second logging rate. These files were submitted to the aforementioned five services for post-processing, enabling a direct comparison of the services with identical inputs. The original data files were then prepared with GPS-only and GPS+GLONASS observables at logging rates of 30, 15, and 10 seconds. All of these prepared files were then submitted to *TrimbleRTX* and the resulting coordinates were evaluated and compared. Lastly, the GPS+GLONASS data files at a data logging rate of 30 seconds were also post-processed in *CSRS-PPP*.

Background on Online Post-Processing Services

Table 1 provides a summary of the five post-processing services tested in this study. It is worth noting that all evaluated services can be used globally, thus all of these services can be used for international applications.

The five services can be divided into two categories based on processing technique: relative positioning and precise point positioning (PPP). *OPUS-S* and *AUSPOS* use relative positioning techniques, whereas *CSRS-PPP*, *GAPS*, and *TrimbleRTX* use PPP techniques.

Relative positioning is a more-traditional method for high-accuracy GNSS data processing. The method relies on a minimum of two GNSS receivers that simultaneously observe common satellites. Resulting carrier phase-angle observables collected by the receivers are differenced in order to fix integer ambiguities and reduce common GNSS errors, such as those due to satellite orbit bias, atmospheric refraction, clock bias, and cycle slips. The differencing results in a baseline observation or vector between the receivers (Figure 1). By establishing at least one receiver over a reference station with “known” coordinates, it is then possible to use the vector(s) referenced from these coordinates in order to compute the coordinates of the “unknown” mark. Thus, any error in the coordinates of the reference station is propagated to the coordinates derived for the unknown mark.

PPP is a relatively new category and quite different from relative positioning as it only requires the use of a single dual-frequency GNSS receiver. PPP is based on the concept of absolute point positioning (APP) techniques because it only processes the satellite observations from the single receiver, as opposed to requiring at least two receivers. However, PPP is much more accurate than conventional APP techniques because it also employs corrections to reduce satellite orbit and clocks errors. Additionally, PPP requires dual-frequency GNSS equipment to decrease error from ionospheric delay and reduce ambiguities. Since only a single receiver is required, a baseline or vector is not generated (Figure 1). Thus, the coordinates at the observed mark are derived relative to the satellites and not relative to a reference station.

Relative positioning is commonly believed to produce more accurate results than PPP (especially for very short-duration GNSS observations); however, the development of PPP has grown significantly in recent years and, as will be later shown in this paper, the accuracy of services for post-processing GNSS sessions of at least 2 hours in duration using PPP algorithms rival the services that use relative positioning.

Relative Positioning Online Services

OPUS-S

OPUS-S is a GPS-only data processing service provided by NOAA NGS. A session of static, dual-frequency GPS data collected on a single mark can be submitted to *OPUS-S* for processing using its online portal. *OPUS-S* uses the NGS Continuously Operating Reference Stations (CORS) network or stations in the International GNSS Service (IGS) as reference stations to process data files from 2 to 48 hours in duration. NGS also provides a service for post-processing data files from 15 minutes to 2 hours in duration, known as *OPUS Rapid-Static*; however, note that this service was not assessed in this study.

When a data file is submitted, *OPUS-S* computes single, independent baseline solutions from up to five of the closest and available CORS or IGS stations to the observed mark using an NGS baseline processor named *PAGES* (Program for the Adjustment of GPS EphemerideS). *PAGES* employs a number of corrections for reducing distance-dependent errors in the baseline solutions, including corrections from a tropospheric delay error model, iono-free combinations from the dual-frequency data for reducing ionospheric delay, and precise ephemerides from the IGS for decreasing orbit errors. It then finds the average coordinates at the observed mark from the three most-precise single baseline solutions. In the conterminous United States (CONUS), over 1,600 active CORS and IGS stations are available for use as reference stations at a spacing of roughly 70 to 150 km; outside of CONUS, *OPUS-S* must use a more sparse number of CORS and IGS stations.

In each solution, *OPUS-S* provides “peak-to-peak” errors for each coordinate component that show the discrepancy between the three selected baseline solutions in terms of northing, easting, and up. Solution accuracy is stated to be within a few centimeters (National Geodetic Survey 2014). Soler et al. (2006) provide empirical equations for estimating the horizontal and vertical RMS of *OPUS-S* as a function of the duration of the observation and showed that *OPUS-S* can process baselines up to several hundred km in length to an accuracy of a few centimeters.

AUSPOS

AUSPOS is a GPS-only data processing service provided by Geoscience Australia. Static dual-frequency GPS data can be submitted and processed. When a data file is submitted, simultaneous session baseline processing is completed between the observed mark and the 15 nearest IGS and APREF (Asia-Pacific Reference Frame) reference stations using the *Bernese Software System*. The published coordinates of the reference stations are constrained to 1 mm horizontally and 2 mm vertically (assumed 68% confidence level). *AUSPOS* solutions provide positional uncertainties at the 95% confidence level for reference stations and the observed mark. Uncertainties are scaled using an empirical model based on data duration, quality, and geographic location (Geoscience Australia 2012).

Precise-Point Positioning Online Services

CSRS-PPP

CSRS-PPP is a GNSS post-processing software provided by Natural Resources Canada (NRCan). It is capable of processing both GPS and GLONASS observables as well as static and kinematic observations. It is also possible to process individual data files with logging rates as short as 1 second. *CSRS-PPP* states that horizontal and vertical accuracies of 1 cm and 2 cm (assumed 68% confidence level), respectively, can be achieved using dual-frequency static data (Natural Resources Canada 2014).

CSRS-PPP is the only service tested in this paper with the capability of batch processing multiple data files with variable GNSS antenna types and heights on more than one mark in a zipped archive. Additionally, users have an option to input custom ocean tidal loading files (Natural Resources Canada 2017).

GAPS

GAPS (GNSS Analysis and Positioning Software) is developed and maintained by the Department of Geodesy and Geomatics Engineering at the University of New Brunswick. *GAPS* uses PPP techniques for static and kinematic GNSS post-processing. Available GNSS constellations for *GAPS* processing include GPS, Galileo, and BeiDou.

While the other services tested in this study provide little functionality beyond post-processing, *GAPS* offers additional functions and processing options under an advanced submission portal. The user can estimate ionospheric and neutral atmospheric delays, receiver clock and inter-system biases, and code multipath. The user can select GNSS constellations to use in processing, set a-priori coordinates, window the observation, specify elevation cutoff angles, specify dilution of precision cutoff ranges, and more. *GAPS* is an ongoing project; the development team is working to improve error modeling and provide real-time PPP (University of New Brunswick 2016).

TrimbleRTX

Trimble RTX (Real Time eXtended) is a proprietary, dual-frequency static GNSS correction technology developed by Trimble, Inc. This technology is applied in several Trimble services. One of these services is known as *Trimble CenterPoint RTX Post-Processing*, a web-based GNSS post-processing service, which will be simply referred to in this paper as "*TrimbleRTX*." *TrimbleRTX* is capable of processing observables from GPS, GLONASS, QZSS, and BeiDou. It uses data from a global network of Trimble reference stations to compute satellite orbit, satellite clock, and other system corrections. These corrections can be transmitted to a receiver in real time via satellite or internet protocol. Post-processing can occur via webform or a client interface.

The minimum data logging rate is 60 seconds, but Trimble recommends using its highest processing rate of 10 seconds (Trimble 2017). *TrimbleRTX* states 2 cm or better horizontal and 6 cm or better vertical accuracy (assumed 68% confidence level) can be achieved for a 1-hour minimum observation. As the session duration approaches 24 hours, the accuracy (assumed 68% confidence level) approaches 1 cm horizontal and 3 cm vertical (Trimble 2014).

Previous Efforts Comparing Online Positioning Services

Some studies have been completed on comparing online positioning services and positioning techniques. The following section provides a brief summary on papers involving evaluations and comparisons of more than one to two online services.

Ghoddousi-Fard and Dare (2005) assessed accuracy versus observation duration at eight active stations around the globe. GPS-only data files at a 30-second logging rate with session durations from 1 to 24 hours were submitted to *OPUS-S, AUSPOS, CSRS-PPP, SCOUT,* and *Auto-GIPSY* (now *JPL-APPS*), using default settings. Additional submissions were made to *OPUS-S* and *SCOUT* using the advanced option wherein the user can specify which active stations to use as reference stations in the relative processing. For durations less than 6 hours, there were a few centimeters of disagreement with the published coordinates at the active stations. The accuracy of the coordinates hardly improved after session durations reach approximately 10 hours.

Ocalan et al. (2013) submitted 24-hour static, GPS-only data collected at eight active stations in Istanbul, Turkey, to *OPUS-S, AUSPOS, CSRS-PPP, SCOUT, GAPS, APPS,* and *magicGNSS*. They found all relative positioning solutions to be within 1 cm and PPP solutions to be within 2 cm when compared to a network solution computed in *Bernese Software*.

Tsakiri (2008) submitted multiple 24-hour static GPS-only data files from eight IGS stations on seven continents to *Auto-GIPSY* (now *JPL-APPS*), *SCOUT, AUSPOS*, and *CSRS-PPP*. The precision of the solutions for the multiple data files at each mark from each individual service was within 1-2 cm. The solutions generally had standard deviations in northing, easting, and up of 3 cm, 3 cm, and 5 cm, respectively. Additionally, they found that solution quality degrades for shorter duration observations (e.g., 6 hours or 1 hour).

Dawidowicz and Krzan (2014) used *CSRS-PPP* and *ASG-EUPOS*, a relative-positioning GNSS service, to process static GNSS measurements from 0.5 to 6 hours in duration at three sites in Poland with varying satellite visibility. The study showed that dual-frequency data is more accurate than single-frequency data, the addition of GLONASS improved results at sites with limited satellite visibility, and the two services yielded coordinates with similar accuracies, especially for files longer than 2 hours in duration.

There are other studies and articles that compared fewer services or data from fewer sites, such as El-Mowafy (2011), Martin et al (2011), and Silver (2013).

In addition to the aforementioned papers on comparisons of online services, other studies have been completed on how the inclusion of GLONASS with GPS affects the accuracy of the survey. Mohammed et al. (2016), Anquela et al. (2013), and Yigit et al. (2013) compared the accuracy of observations using GPS-only, GLONASS-only, and GPS+GLONASS. They generally concluded that GPS+GLONASS-derived coordinates were more accurate than GPS-only-derived coordinates, and both were more accurate than GLONASS-only for both static and kinematic observations using PPP techniques. Nevertheless, Yigit et al. (2013) found insignificant differences in the three constellation solutions at observation durations longer than 8 hours. Weaver et al. (2018) and Allahyari et al. (2018) showed that real-time observations using GPS+GLONASS allowed collection of fixed solutions at longer baseline lengths than can be obtained using GPS-only, and they showed that the inclusion of GLONASS with GPS improved accuracy, especially at sites with poorer satellite visibility. Bakula (2013) developed a method to obtain cm-level accuracies using GPS+GLONASS and multiple antennas on a special base at sites with some obstructed conditions.

The aforementioned studies provide a starting point for this project. However, due to the rapid development of GNSS and regular updates to the online services, some of the results are somewhat dated. In addition, many of these studies primarily used GNSS data from active stations, which are typically constructed at sites with ideal overhead conditions, rather than using data collected from a field survey campaign.

Differing from these previous works, this paper will evaluate several services using GNSS data collected from a field survey campaign, where some of the sites have less than ideal conditions that are commonly encountered in practice. It will evaluate the combined effects of observation duration, multipathing environment, data logging rates, and the inclusion of GLONASS observables.

Methodology

During a 2014 static survey campaign, GNSS observations were collected on 18 existing bench marks set in road corridors in western Oregon. During each of the 15 total sessions, five or six Leica GS14 integrated antenna/receivers were set up on 2-m fixed-height tripods on five or six marks. Then, for 10 hours per session, raw GPS+GLONASS observables were collected simultaneously at a 1-second logging rate and a 10 degree elevation mask (Gillins and Eddy 2015, 2016). Each of the 18 marks were observed for three to ten 10-hour sessions.

Gillins and Eddy (2016) described the procedure for post-processing all of the aforementioned data to generate most-probable geodetic coordinates for each of the 18 passive marks. In summary, each session was first post-processed in *OPUS-Projects* following recommendations in Armstrong et al. (2015). Note that *OPUS-Projects* only processes the GPS observables and decimates the data files to a logging rate of 30 seconds. Afterwards, the session solutions were uploaded to *ADJUST*, where a constrained least squares adjustment of the campaign-style survey network was performed by constraining the coordinates of seven CORS and setting weights on the constraints equal to the inverse of the published standard deviations of the coordinates of the CORS. The coordinates were then stored in the ITRF2008 reference system at the mean epoch of the observation.

By formal error propagation, the estimated horizontal uncertainties on the resulting coordinates for each mark ranged from 0.4 to 0.5 cm at 95% confidence, and the estimated vertical uncertainties (in terms of ellipsoid height) ranged from 1.1 to 1.3 cm at 95% confidence. Although the final coordinates have these estimated errors, they were held as "truth" or as a basis for evaluating the accuracy of the coordinates produced by the five online positioning services.

The GNSS data collected on six of the 18 marks in varying multipathing environments were compiled for future submission to the online positioning services. To provide some context of the type of environment at each of the six marks, Figure 2 shows terrestrial photographs of each mark used in this study.

Figure 3 presents overhead visibility plots of each of these six marks. These visibility diagrams were produced using *Skyplotter*, a custom Java application. To use this application, a camera equipped with a circular fisheye lens was mounted on top of the fixed-height tripod set up on each mark and a zenith photograph was taken. Then, each photo was uploaded in the application. *Skyplotter* maps the distorted circular image on an orthographic grid, draws vertical angle circles in increments of 15 degrees (from 0 degrees to 90 degrees), and depicts the azimuth lines in 30 degree increments.

Three of the marks (i.e., B726, GLAS, and LBCC), depicted along the top row of Figures 2 and 3, are in “moderate” multipathing environments, and three of the marks (i.e., BICK, Y683, U727), depicted along the bottom row of the figures, are in “minimal” multipathing environments.

The “moderate” multipathing environments include power lines, metallic street signs, and a wooden lamp pole in close proximity to the observed mark. At B726, power lines are overhead and a wooden lamp pole is within just one meter. At GLAS, a large metallic road sign is located within one meter and obstructed some view up to 45 degrees. At LBCC, a small metallic sign is within two meters. Although these items were close to the mark and pose multipathing potential, each of these six sites were still considered reasonably favorable for making GNSS observations. Mark U727 has worse satellite visibility than the other marks, but the tree tops shown in its visibility plot are over 20 meters from the mark and pose minimal likelihood for causing multipathing.

As per Table 2, a total of 35 10-h GNSS data files, in Receiver Independent Exchange Format (RINEX) version 2.11, were gathered from the 2014 survey. The RINEX files were then prepared and edited using the *TEQC* command line program developed by

UNAVCO. First, the data files were edited to only include GPS observables and decimated to a 30 second logging rate. This ensured the submission of identical data to each of the five services for direct comparison purposes since *OPUS-S* and *AUSPOS* are currently only capable of processing GPS observables at a 30-second logging rate. Each of the 10-h RINEX files were next windowed or divided to shorter durations of 2, 3, 4, 5, and 7 hours. This resulted in a total of 490 RINEX files, as listed in Table 2.

Each of the 490 data files were submitted to the five online services, with version numbers listed in Table 3. All five of the online services solved for geodetic coordinates for the observed mark in the ITRF2008 reference system at the mean epoch of the observation. These coordinates were differenced with the aforementioned "true" coordinates from the static survey campaign for each of the associated six marks, and the resulting differences in terms of northing (Δn), easting (Δe), and up (Δu) within a local geodetic horizon frame at each mark were computed and stored for later evaluation.

The next step was to investigate the effects of processing data collected at faster logging rates and/or with GLONASS observables. Of the five services tested, only *TrimbleRTX* and *CSRS-PPP* are capable of processing GPS+GLONASS observables. In addition, these are the only two services that are capable of processing data at faster logging rates. Trimble recommends processing data at its fastest data logging processing rate of 10 s when using *TrimbleRTX.* Therefore, we decided to process data files at 30, 15, and 10-second logging rates in *TrimbleRTX* in order to evaluate if, and by how much, processing data at faster logging rates improves its accuracy.

Thus, the original RINEX data files were prepared using *TEQC* such that they included either GPS-only or GPS+GLONASS observables at logging rates of 30, 15, and 10 seconds. Then, these data files were again windowed to the same shorter observation durations of 2, 3, 4, 5, and 7 hours, producing 490 RINEX data files for each of the six different permutations. All six permutations of the RINEX data files were submitted to *TrimbleRTX*, and the two permutations with GPS-only and GPS+GLONASS data files at a 30-second logging rate were submitted to *CSRS-PPP*. The resulting coordinates from all submissions were differenced with the "true" coordinates to find Δn, Δe, and Δu.

Results and Discussion

The differences in coordinates were calculated in terms of horizontal RMS (HRMS) and vertical RMS (VRMS) per Equations 1 and 2, where *n* is the total number of solutions from a service for each mark and for each session duration. These statistics were primarily used for evaluating each of the online services.

$$HRMS = \sqrt{\frac{\Sigma(\Delta n^2 + \Delta e^2)}{n}} \tag{1}$$

$$VRMS = \sqrt{\frac{\Sigma(\Delta u^2)}{n}} \tag{2}$$

In addition to calculating HRMS and VRMS, the RMS in northing (NRMS) and easting (ERMS) were computed. Furthermore, the range, mean, and standard deviations of Δn, Δe, and Δu were found for each service at each mark (see supplemental data).

Comparison of Online Services

Figures 4 and 5 show HRMS and VRMS versus observation duration, respectively, for each mark. Note that the six subplots in each of these figures are ordered in the same manner as in Figures 2 and 3, where the top row is for the marks in moderate multipathing environments and the bottom row is for marks in minimal multipathing environments.

For an unknown reason, *AUSPOS* produced wildly incorrect geodetic coordinates for two of the 10-hour data files, once for mark B726 and once for LBCC, both marks in moderate multipathing environments. The Δn, Δe, and Δu of these two solutions were in error as much as 75 m. Both of these data files were re-submitted to *AUSPOS*, but *AUSPOS* produced the same incorrect coordinates. The solution files from *AUSPOS* gave an indication that the coordinates were in error, because the files estimated unusually large standard deviations for the coordinates ranging from 15 to 18 m. These two solutions were removed as outliers prior to producing any of the statistics and figures showing the results. Oddly, *AUSPOS* appeared to successfully process these same data files when they were windowed to the shorter durations of 2, 3, 4, 5, and 7 hours.

Other challenges were discovered when processing the data using *GAPS*. Unfortunately, *GAPS* truncates all submitted data files to midnight in GPS Time. All of the 10-hour data files for the marks concluded 1 to 3 hours after GPS midnight because the local time in Oregon is approximately 7 or 8 hours behind GPS time. Thus, the plots in Figures 4 and 5 do not show any HRMS or VRMS values for *GAPS* for the 10-hour sessions. Compared to the other services, *GAPS* also produced solutions with significantly higher HRMS and VRMS values at mark B726 when the sessions were less than 5 hours in duration. For the 2-hour sessions on B726, *GAPS* produced an HRMS and VRMS values equal to 8.6 and 12.4 cm, respectively; for the 3-hour sessions on B726, the HRMS and RMS values equal 7.1 and 7.7 cm, respectively. Because of these challenges, solutions from *GAPS* were removed from further evaluation in this paper.

Aside from the poor HRMS and VRMS values for *GAPS* on mark B726, it is apparent that the HRMS and VRMS curves are similar for the marks in moderate or the minimal multipathing environments, except for an occasional spike which may be explained by the somewhat small sample sizes. Thus, residual differences of Δn, Δe, and Δu were pooled together according to either of the two multipathing environment categories, and new HRMS and VRMS values were computed for each service, except *GAPS*. The standard deviations for the residual differences, NRMS, ERMS, and other statistics for the pooled data were also calculated and listed in the supplemental data. Figure 6 shows HRMS and VRMS versus observation duration, where the curves on the left two subplots are for the pooled data from the three marks in minimal multipathing environments, and the curves on the right two subplots are for the three marks in moderate multipathing environments.

In general, the HRMS and VRMS values in Figure 6 appear similar for each of the four services. HRMS and VRMS for the sites in minimal multipathing environments rarely vary by more than 1 cm when comparing services. For the most part, the HRMS and

VRMS curves for *AUSPOS* are slightly lower or roughly equal to the other services, except for sessions less than or equal to 3 hours. For the sites in moderate multipathing environments, the HRMS and VRMS curves for *TrimbleRTX* tend to be slightly higher than the other curves.

One consistent pattern in Figure 6 is that the HRMS and VRMS values for sessions shorter than 5 hours are much higher for the sites in moderate multipathing environments than for the sites in minimal multipathing environments. However, when collecting more than 5 hours of data, the HRMS and VRMS values for both environment categories appear similar and the services vary by less than 1 cm. After 5 hours, there is limited improvement in the HRMS and VRMS values. Thus, a conservative recommendation is to collect 5 hours of data regardless of the two multipathing environment categories; a minimum of 5 hours of data is clearly beneficial for sites in a moderate multipathing environment. However, for sites in a minimal multipathing environment, the HRMS and VRMS hardly improve, especially after sessions as short as 3 hours.

Equations 1 and 2 showed how RMS can be computed as a function of the residual differences between the coordinates of a sample of data and the “true” coordinates of the spatial data. RMS is a popular statistic for evaluating spatial data because it is a function of both: (1) the bias or systematic error between the coordinates of the sample and the “true” coordinates, and (2) the precision of the coordinates in the sample. In other words, RMS can also be written in more general terms as:

$$RMS = \sqrt{\mu^2 + \sigma^2} \tag{3}$$

where μ is the aforementioned bias and σ is the standard deviation of the coordinates of the sample.

Of course, it is desirable for each service to produce solutions with unbiased coordinates. If $\mu = 0$ in Equation 3, then RMS will be equal to σ. If bias can be detected, either the service should be further scrutinized or the “truth” coordinates may be incorrect.

To assess the presence of bias in the solutions, μ was computed per Equations 4a – 4c using the samples of pooled residual differences organized by online service source, multipathing environment category, and session duration (see supplemental data).

$$\mu_n = \sqrt{|NRMS^2 - \sigma_n^2|} \tag{4a}$$

$$\mu_e = \sqrt{|\ ERMS^2 - \sigma_e^2|} \tag{4b}$$

$$\mu_u = \sqrt{|VRMS^2 - \sigma_u^2|} \tag{4c}$$

where μ_n, μ_e, μ_u are the bias in northing, easting, and up, respectively; σ_n, σ_e, and σ_u are the standard deviation in northing, easting, and up, respectively.

Values of μ_n, μ_e, and μ_u were found to be roughly constant at all observation durations for a given sample of data organized by service source and multipathing environment. Thus, the mean value of μ for all observation durations was computed according to service and multipathing environment, as illustrated in Figure 7. As shown, the values are typically sub-centimeter and approaching the estimated uncertainty of the “truth” coordinates. Values of μ_u for the solutions from *OPUS-S* are higher than the other services, and values of μ_n, μ_e, and μ_u are generally lower for the solutions from *AUSPOS*. Values of μ_n, μ_e, and μ_u are generally similar, but in some cases slightly lower, for moderate multipathing environments as compared to minimal multipathing environments. This may be due to a larger spread in the solutions from moderate multipathing environments, which seems to make it more difficult to detect a consistent offset from the truth coordinates.

For further investigation, statistical F-tests were performed, testing the null hypothesis that the difference in the square of RMS and the variance (square of the standard deviation) equals zero at 95% confidence. These tests were performed for three directions (i.e., northing, easting, and up) for each of the four services, at each of the six observation durations, and for the two multipathing environment categories, resulting in a total of 144 tests (see supplemental data). Table 4 summarizes the number of tests that passed and failed the F-test. When the null hypothesis cannot be rejected, it indicates that the square of the RMS and variance for a sample of data cannot be proven to be statistically different and implies that there is a lack of statistical evidence that a bias is present in the sample.

Approximately 74% of these tests did not reject the null hypothesis and therefore conclude that there is no evidence that the square of the RMS and variance values are statistically different (i.e., no statistical evidence of a bias). Of the 26% of tests that did reject the null hypothesis, 63% of rejections occurred in the northing direction. Of the 36 tests performed using *OPUS-S* data, 14 rejected the null hypothesis (39%). Eight of these *OPUS-S* rejections (57%) occurred in the northing direction. *CSRS-PPP* rejections predominantly occurred in the northing direction (8 of 16) and vertical direction (6 of

16). *TrimbleRTX* produced 6 rejections, all in the northing direction. Interestingly, *AUSPOS* produced the least number of rejections. It may be because *AUSPOS* processes data against 15 base stations, while *OPUS-S* starts with only five base stations and ultimately only uses three base stations as control. Use of such a small number of base stations as constraints appears to allow more bias in the coordinates of the control to shift or bias the solution at the observed mark.

Effects of Logging Rates using **TrimbleRTX** *and Addition of GLONASS Observables using* **TrimbleRTX** *and* **CSRS-PPP**

As mentioned previously, the effects of including GLONASS could only be tested in *TrimbleRTX* and *CSRS-PPP* because these are the only two services that are currently capable of processing GPS+GLONASS observables. For this paper, processing data at faster logging rates were only evaluated in *TrimbleRTX,* and future work could involve testing the effects of data logging rates in *CSRS-PPP*.

Figures 8 and 9 show HRMS and VRMS values, respectively, from *TrimbleRTX* versus observation duration for each of the six marks.

Similar to the previous section, the HRMS and VRMS curves are generally similar for the marks in moderate or the minimal multipathing environments. Thus, values of Δn, Δe, and Δu were pooled together according to either of the two multipathing environment categories, and new HRMS and VRMS values were computed. Figure 10 shows HRMS and VRMS versus observation duration for the pooled data.

It is clear that increasing the logging rate only marginally improved the HRMS and VRMS values at both the sites in moderate and minimal multipathing environments and for all session durations. Increasing the data logging rate from 30 seconds to 10 seconds only improved the RMS of the solution by an average of 5% vertically and 2% horizontally. Only one data point (Figure 8) for mark LBCC at a duration of 2 hours showed improvement in RMS more than 10% by increasing the data logging rate.

Although increasing the data logging rate showed little improvement, the addition of GLONASS observables reduced the HRMS and VRMS as much as 60% at some of the marks. The greatest benefit of adding GLONASS was for the marks in moderate multipathing environments. For the marks in minimal multipathing environments, lower HRMS and VRMS values are also noticeable for GPS+GLONASS sessions less than 5 hours in duration; after 5 or more hours, the GPS-only and GPS+GLONASS HRMS and VRMS curves are similar at these sites.

Figures 11 and 12 show HRMS and VRMS values, respectively, from *CSRS-PPP* versus observation duration for each of the six marks. Similar to the previous sections, the HRMS and VRMS curves are generally similar for the marks in moderate or minimal multipathing environments. Similar to the results for *TrimbleRTX*, the HRMS values from GPS+GLONASS were consistently smaller or negligibly different than HRMS values using GPS-only. However, surprisingly, VRMS values at B726 behave unexpectedly; except at $T = 2$ h, the GPS-only solutions are an average of 50% smaller than the GPS+GLONASS solutions. *CSRS-PPP* shows less improvement and less consistency in VRMS versus HRMS when comparing GPS-only versus GPS+GLONASS. VRMS for GPS+GLONASS are generally smaller than GPS-only at stations GLAS and BICK, negligibly different at Y683, and generally larger at B726, LBCC, and U727.

Again, values of Δn, Δe, and Δu were pooled together according to either of the two multipathing environment categories, and new HRMS and VRMS values were computed. Figure 13 shows HRMS and VRMS versus observation duration for the pooled data. HRMS is consistently improved by including GLONASS observables. When pooled, the curves for VRMS and HRMS look similar for *TrimbleRTX* and *CSRS-PPP*, where RMS values hardly improve after T = 5 h for sites in either multipathing category. But, for the GPS+GLONASS solutions, the VRMS values from *TrimbleRTX* are 10-20% smaller than from *CSRS-PPP*. Based on this finding, it seems that *TrimbleRTX* is combining GLONASS with GPS more effectively than *CSRS-PPP*.

Table 5 summarizes the percent reduction in HRMS and VRMS values when using GPS+GLONASS versus GPS-only for a data logging rate of 30 seconds using either service. The table presents the reductions for the marks in minimal and moderate multipathing environments and for each of the tested session durations.

Conclusions

The objectives of this paper were to compare the accuracy of five online services, namely *OPUS-S*, *AUSPOS*, *CSRS-PPP*, *GAPS*, and *TrimbleRTX*, by submitting identical GPS-only sessions of varying durations from 2 to 10 hours on six marks. Additionally, this paper investigated if processing data at faster logging rates using *TrimbleRTX* and/or including observables from GLONASS using *TrimbleRTX* and *CSRS-PPP* improved the accuracy of the results.

All five services generally produced similar results when processing identical GPS-only files at a 30-second logging rate. It was found that for session durations of 5 hours or greater, the HRMS and VRMS values between services vary by less than 1 cm. In addition, the HRMS and VRMS values are similar when comparing sites in moderate and minimal multipathing environments, and there is limited improvement in HRMS and VRMS values for longer durations. For sites in minimal and moderate multipathing environments, HRMS and VRMS values hardly improved beyond approximately 2 cm after 3 and 5 hours, respectively.

For the most part, the coordinates from each service's set of solutions were centered about the "truth" coordinates at a given mark that were derived from a static survey campaign. Note the coordinates held as truth have estimated horizontal uncertainties from 0.4 to 0.5 cm and vertical uncertainties from 1.1 to 1.3 cm, both at 95% confidence. If a set of solutions does not center about the truth coordinates, it indicates that there is a systematic error or bias present in the service or in the truth coordinates and this bias would have increased the RMS of the set of solutions. The majority of the statistical F-tests (i.e., 74%) could not reject the null hypothesis that the square of the RMS for a given sample of solutions from a service, organized by multipathing environment and observation duration, was equal to the variance of the sample. Thus, the majority of the statistical testing could not detect a bias between the solutions from each online service and the truth coordinates.

In addition to the comparison of the accuracy of each service, it is worthwhile to note that all of the evaluated services are easy to use and return similar solutions within an hour or two of submission. The services vary most in submission method and solution format. The authors preferred *CSRS-PPP* for ease of batch processing and the included solution information and figures. Each *CSRS-PPP* solution includes data file details, a 95% error ellipse, satellite tracks with residuals, and more. For high-accuracy work, surveyors should consider submitting data to multiple services, since they are easy to use. In any case, the user should review the information returned with the solution and check the quality of the statistics provided by the service. For example, *AUSPOS* estimated unusually large standard deviations (i.e., > 1 m) for the coordinates of the poor solutions for two of the 10-h data files; users should beware of solutions from any service which report large error estimates.

Using *TrimbleRTX*, it was also found that increasing the logging rate hardly reduced the HRMS and VRMS values for all session durations, at sites in both minimal and moderate multipathing environments. However, the addition of GLONASS observables substantially improved results using *TrimbleRTX*, especially at observation durations less than 5 hours and at sites in moderate multipathing environments. For sites in minimal multipathing environments, the average reduction using *TrimbleRTX* in HRMS and

VRMS is 18.1% and 9.2%, respectively. For sites in moderate multipathing environments, the average reduction in HRMS and VRMS is 39.6% and 19.0%, respectively.

CSRS-PPP GPS+GLONASS results also improved at observation durations less than 5 hours; VRMS and HRMS improved at sites in minimal multipathing environments and HRMS improved at sites in moderate multipathing environments. For the GPS+GLONASS solutions, the VRMS values from *TrimbleRTX* are 10-20% smaller than from *CSRS-PPP*. Based on this finding, it seems that *TrimbleRTX* is combining GLONASS with GPS more effectively than *CSRS-PPP*.

This study was limited to an evaluation of four to ten 10-h sessions of data collected on six bench marks in western Oregon. It is recommended that future research involves an evaluation of a much larger sample of data collected over multiple seasons and across a wider geographic area in order to reach deeper conclusions on the accuracy of the five services. Additionally, this study could be expanded to assess other available services (e.g. *SCOUT* and *JPL-APPS*), make use of other viable GNSS constellations (e.g., Galileo, BeiDou), and/or test the accuracy when using IGS rapid ephemerides versus final ephemerides.

Acknowledgements

NOAA funded a portion of this research study by cooperative agreement via the Cooperative Institute for Marine Resources Studies (CIMRS), award number

NA11OAR4320091. Leica and David Evans & Associates provided most of the survey hardware for the 2014 Oregon survey and some of the software for analysis. Former Oregon State University civil engineering students Michael Eddy, who led the 2014 static survey campaign, and Damon Houck assisted with submitting data files to the online services. Special thanks to Mark Armstrong (National Geodetic Survey, retired) for his advice and assistance, and Farid Javadnejad, Oregon State University graduate research assistant, for developing and running *Skyplotter*.

References

ADJUST [Computer software]. National Oceanic and Atmospheric Administration, National Geodetic Survey, Silver Spring, MD.

Allahyari, M., Olsen, M.J., Gillins, D.T., and Dennis, M.L. (2018). "Tale of Two RTNs: Rigorous Evaluation of Real-Time Network GNSS Observations," *Journal of Surveying Engineering,* 10.1061/(ASCE)SU.1943-5428.0000249, 144(2), 05018001.

AUSPOS [Computer software]. Geoscience Australia, Canberra, ACT.

Anquela, A. B., Martin, A., Berne, J.L., and Padin, J. (2013). "GPS and GLONASS Static and Kinematic PPP Results." *Journal of Surveying Engineering,* 139(1), 47-58.

Armstrong, M. L., Schenewerk, M. S., Mader, G., Martin, D., Stone, B., and Foote, R. (2015). *OPUS Projects: Online Positioning User Service Baseline Processing and Adjustment Software User Instructions and Technical Guide*, Ver. 2.5, National Oceanic and Atmospheric Administration, National Geodetic Survey, Silver Spring, MD.

Bakuła M., 2013, Study of Reliable Rapid and Ultrarapid Static GNSS Surveying for

Determination of the Coordinates of Control Points in Obstructed Conditions. Journal of Surveying Engineering, 139(4): 188-193. DOI:10.1061/(ASCE)SU.1943-5428.0000109.

CSRS-PPP [Computer software]. Natural Resources Canada, Ottawa, ON.

Dawidowicz K., Krzan G., 2014, Accuracy of single receiver static GNSS measurements under conditions of limited satellite availability, Survey Review, 46(337): 278 - 287. DOI: 10.1179/1752270613Y.0000000082

El-Mowafy A., 2011, Analysis of web-based GNSS post-processing services for static and kinematic positioning using short data spans. Survey Review. 43 (322): 535-549. DOI: 10.1179/003962611X13117748892074

GAPS [Computer software]. University of New Brunswick, Fredericton, NB.

Ghoddousi-Fard, R. and Dare, P. (2005). "Online GPS processing services: an initial study." *GPS Solutions,* 10(1), 12-20.

Gillins, D.T., and Eddy, M.J. (2015). *An Evaluation of NGS-58 and OPUS-Projects: Methods for Determining Accurate Ellipsoidal Heights with GPS*, National Oceanic and Atmospheric Administration, National Geodetic Survey, Silver Spring, MD, 136 pp.

Gillins, D.T., and Eddy, M.J. (2016). "Comparison of GPS Height Modernization Surveys Using OPUS-Projects and Following NGS-58 Guidelines." *Journal of Surveying Engineering*, 10.1061/(ASCE)SU.1943-5428.0000196, 143(1), 05016007.

Geoscience Australia (2012). "AUSPOS - Online GPS Processing Service" <http://www.ga.gov.au/scientific-topics/positioning-navigation/geodesy/auspos> (Apr. 21, 2017).

Martin, A., Anquela, A. B., Capilla, R. and Berne, J. L. (2011). “PPP Technique Analysis Based on Time Convergence, Repeatability, IGS Products, Different Software Processing, and GPS+GLONASS Constellation.” *Journal of Surveying Engineering,* 137(3), 99-108.

Mohammed, J., Moore, T., Hill, C., Bingley, R.M., and Hansen, D.N. (2016). “An assessment of static precise point positioning using GPS only, GLONASS only, and GPS plus GLONASS.” *Measurement*, 88, 121-130.

National Geodetic Survey (2014). “What is OPUS?” <https://www.ngs.noaa.gov/OPUS/about.jsp> (Apr. 20, 2017).

Natural Resources Canada (2014). “NRCan Precise Point Positioning (PPP) Service.” *Civil GPS Service Interface Committee,* Tampa, Fl.

Natural Resources Canada (2017). “Tools and Applications” <https://webapp.geod.nrcan.gc.ca/geod/tools-outils> (Apr. 22, 2017).

Ocalan, T., Erdogan, B., and Nursu, T. (2013). “Analysis of Web-based Online Services for GPS Relative and Precise Point Positioning Techniques.” Boletim de Ciências Geodésicas, 19(2), 191-207.

OPUS-Projects [Computer software]. National Oceanic and Atmospheric Administration, National Geodetic Survey, Silver Spring, MD.

OPUS-Static [Computer software]. National Oceanic and Atmospheric Administration, National Geodetic Survey, Silver Spring, MD.

Silver, M. (2013). “A Comparison of Free GPS Online Post-Processing Services.” <http://gpsworld.com/a-comparison-of-free-gps-online-post-processing-services/> (Jun. 1, 2015).

SkyPlotter [Computer Software]. Javadnejad, F., Gillins, D.T., Jenny, B. "SkyPlotter – Automated GNSS visibility diagrams."

Soler, T. (2011). “CORS and OPUS for Engineers: Tools and Mapping Applications.” American Society of Civil Engineers, Reston, Virginia.

Soler, T., Michalak, P., Weston, N.D., Snay, R.A., and Foote, R.H. (2006). “Accuracy of OPUS solutions for 1- to 4-h observing sessions,” *GPS Solut*, 10:45-55.

Trimble CenterPoint RTX Post-Processing (2014). “Welcome to the Trimble Centerpoint RTX Post-Processing Service” <http://trimblertx.com/Home.aspx> (Apr. 20, 2017).

Trimble CenterPoint RTX Post-Processing (2017). “Frequently Asked Questions” <http://trimblertx.com/Support.aspx> (Jan. 2, 2018).

TrimbleRTX [Computer software]. Trimble, Inc., Sunnyvale, CA.

Tsakiri, M. (2008). “GPS Processing Using Online Services.” *Journal of Surveying Engineering,* 134(4), 115-125.

University of New Brunswick (2016). “GAPS - GNSS Analysis and Positioning Software” <http://gaps.gge.unb.ca/> (Apr. 25, 2017).

Weaver, B., Gillins, D.T., and Dennis, M. (2018). “Hybrid survey networks: combining real-time and static GNSS observations for optimizing height modernization,” *Journal of Surveying Engineering,* 10.1061/(ASCE)SU.1943-5428.0000244, 144(1), 05017006.

Yigit, C.O., Gikas, V., Alcay, S., and Ceylan, A. (2013). “Performance evaluation of short to long term GPS, GLONASS and GPS/GLONASS post-processed PPP.” *Survey Review*, 46(336), 155-166.

Tables

Table 1. Summary of online services for post-processing static GNSS data

Service Name	Positioning Technique	Satellites	Minimum Duration (Recommended)	Fastest Logging Rate	Orbit Source	Batch Processing
OPUS-S	Relative	GPS only	2 hours (4 hours)	30 sec	IGS	Yes
AUSPOS	Relative	GPS only	1 hour (6 hours)	30 sec	IGS	No
CSRS-PPP	PPP	GPS, GLONASS	None (>2 hours)	1 sec*	IGS and NRCan	Yes
GAPS	PPP	GPS, Galileo, BeiDou	None (2 to 3 hours)	30 sec	IGS and NRCan	No
TrimbleRTX	PPP	GPS, GLONASS, QZSS, BeiDou	10 min (>1 hour)	10 sec	Trimble	No

*During batch processing, *CSRS-PPP* decimated our data files that were more than 4 hours in duration to a logging rate of 30 seconds. However, we found that *CSRS-PPP* processed our data files at a 1-second logging rate if they were uploaded individually to the service.

Table 2. Number of windowed RINEX files on each mark, organized by observation duration

Mark	Duration of Observation						*Total*
Name	2h	3h	4h	5h	7h	10h	
B726	20	12	8	8	4	4	*56*
GLAS	20	12	8	8	4	4	*56*
LBCC	35	21	14	14	7	7	*98*
BICK	50	30	20	20	10	10	*140*
Y683	30	18	12	12	6	6	*84*
U727	20	12	8	8	4	4	*56*
Total	*175*	*105*	*70*	*70*	*35*	*35*	***490***

Table 3. Software details for the five services

Service Name	Service Version	Underlying Software	Software Version	Solution Format(s)
OPUS-S	-	PAGES	page5 1209.04	Email, XML
AUSPOS	2.2	Bernese	5.2	PDF, SINEX
CSRS-PPP	V1.05_11216	-	-	PDF, CSV, SUM, POS
GAPS	v5.9.1	-	-	HTML, JPG, KML, etc.
TrimbleRTX	-	Trimble CenterPoint RTX	5.0.0.15127	PDF, XML

Table 4. Summary of F-test results for pooled observations

Service	# rejects out of 12			Total
	North	East	Up	
OPUS-S	8	2	4	*14 / 36*
AUSPOS	2	0	0	*2 / 36*
CSRS-PPP	8	1	7	*16/ 36*
TrimbleRTX	6	0	0	*6 / 36*
total	*24 / 48*	*3 / 48*	*11 / 48*	*38 / 144*

Table 5. Percent reduction in HRMS and VRMS from *TrimbleRTX* when using GPS+GLONASS observables instead of only GPS-observables at a 30-second data logging rate

Hours	*TrimbleRTX*				*CSRS-PPP*			
	% Reduct. HRMS		% Reduct. VRMS		% Reduct. HRMS		% Reduct. VRMS	
	Min	Mod	Min	Mod	Min	Mod	Min	Mod
2	19.2	22.8	23.1	27.4	24.2	41.1	14.0	29.7
3	19.6	27.8	15.6	21.3	20.3	32.7	14.3	-5.5
4	26.0	57.4	12.1	23.5	18.7	36.5	5.7	-1.6
5	19.5	44.6	0.2	14.8	23.2	43.6	18.7	-6.9
7	12.2	47.7	11.9	23.5	4.9	29.0	-9.9	-12.3
10	11.9	37.5	-7.3	3.3	5.0	19.1	-6.3	-16.7
mean	*18.1*	*39.6*	*9.2*	*19.0*	*16.0*	*33.7*	*6.1*	*-2.2*

Note: negative values indicate an increase in RMS rather than a reduction

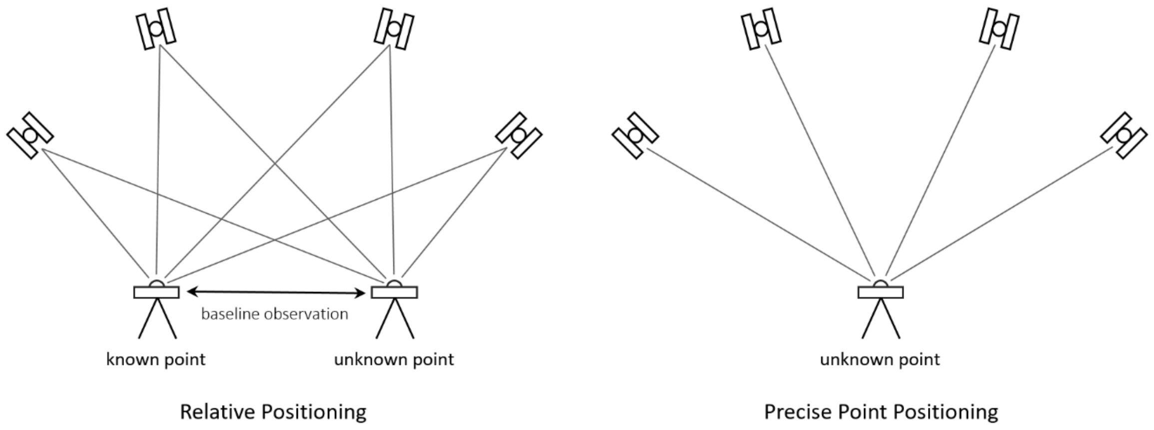

Figure 1. Schematic depicting (a) relative positioning vs (b) absolute point positioning


B726 - North

GLAS - East

LBCC - East

BICK - North

Y683 - North

U727 - West

Figure 2. Terrestrial photos of the setup at each of the six test marks, with approximate direction of the camera noted

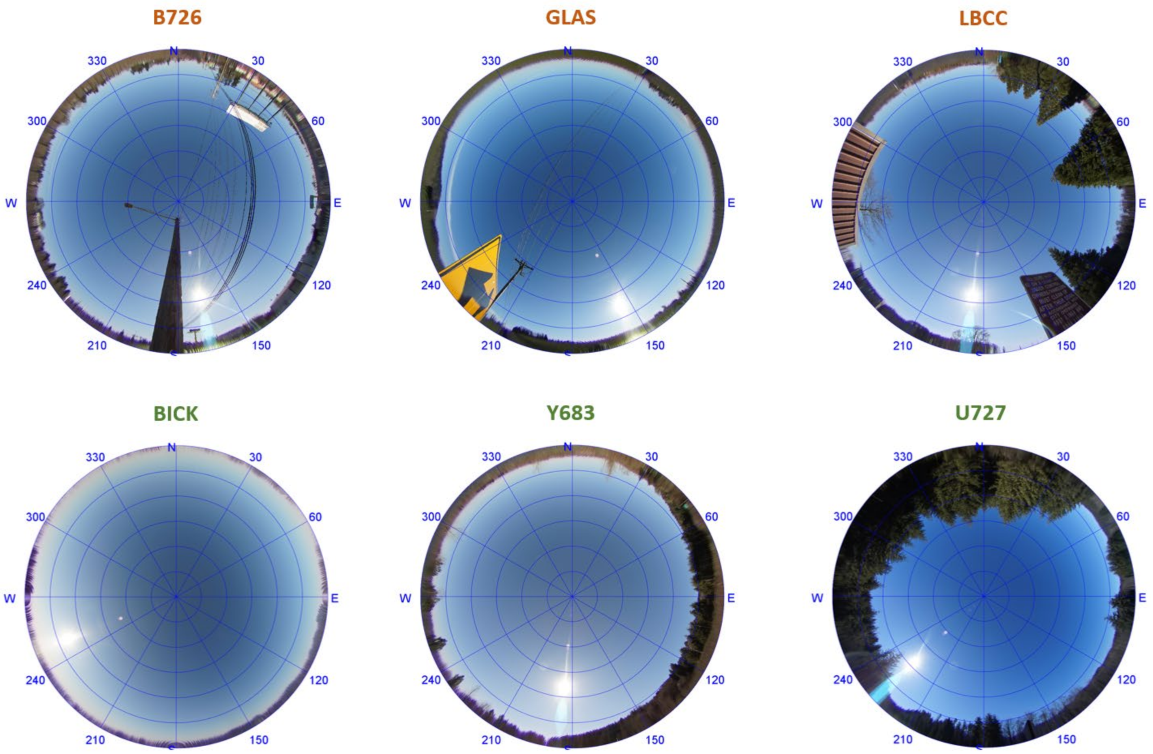

Figure 3. Visibility plots for the six test marks; the circles are shown in 15-degree vertical-angle increments from the top of the fixed-height tripod above each mark.

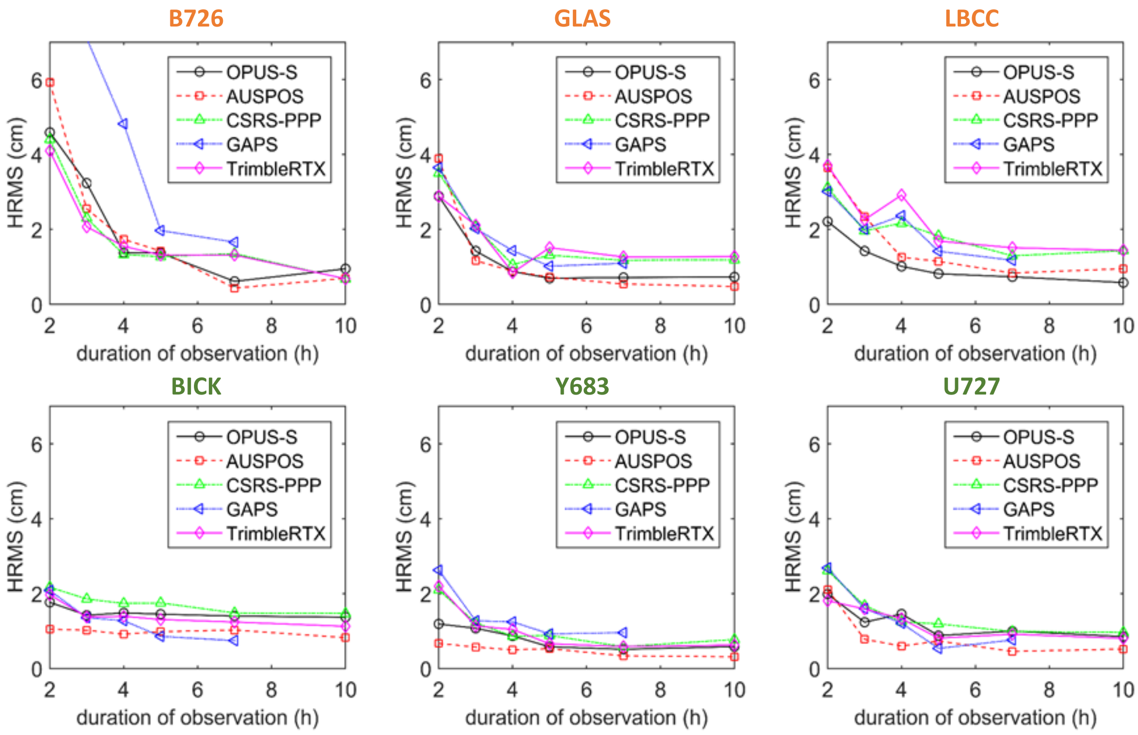

Figure 4. HRMS versus observation duration for each of the six test marks

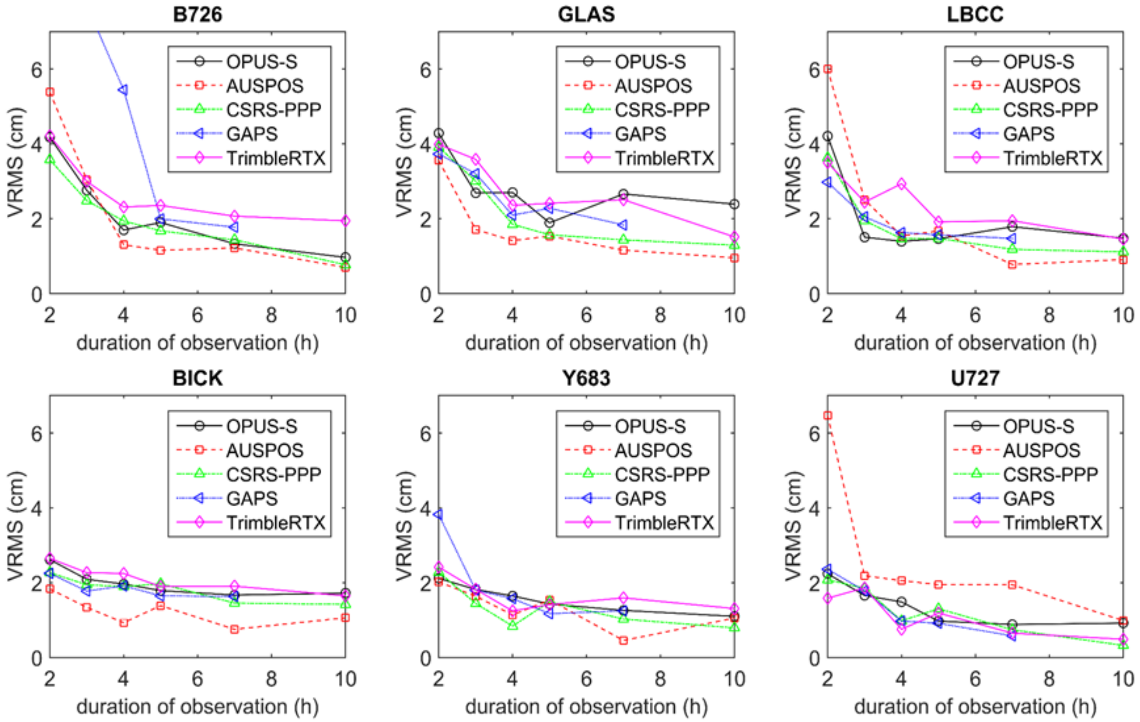

Figure 5. VRMS versus observation duration for each of the six test marks

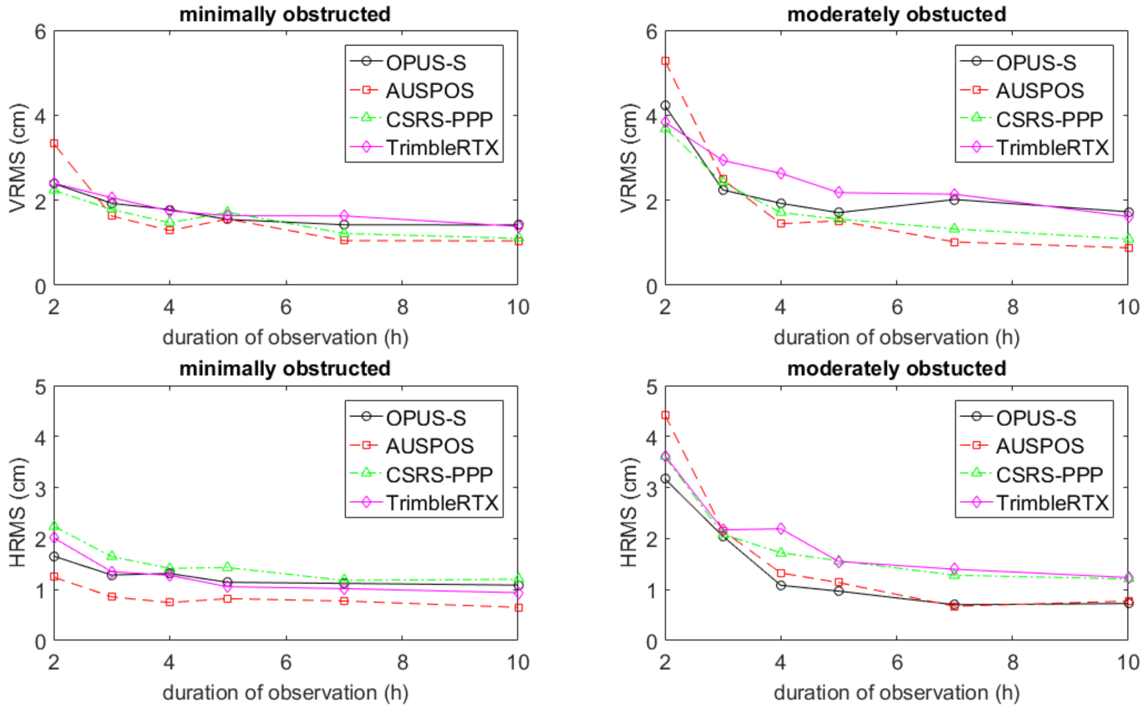

Figure 6. HRMS and VRMS versus observation duration, grouped by multipathing environment category

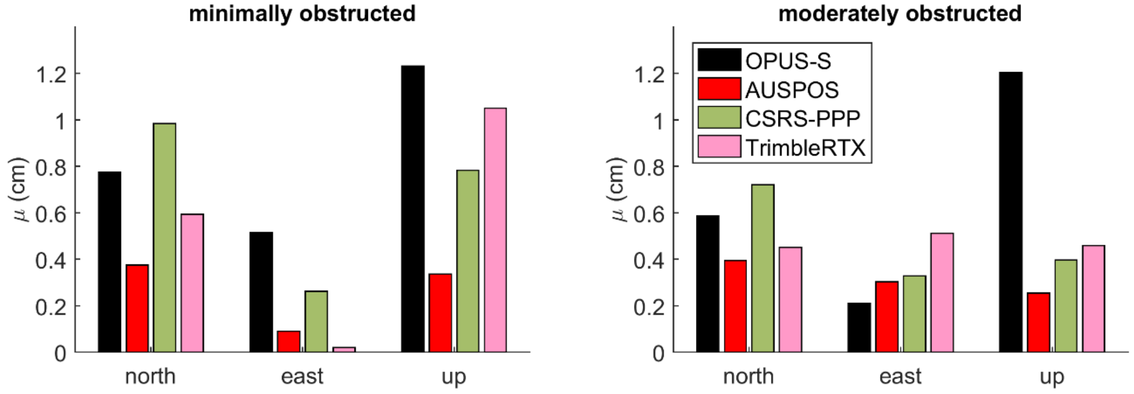

Figure 7. Mean values of μ for solutions from each service pooled by multipathing environment category

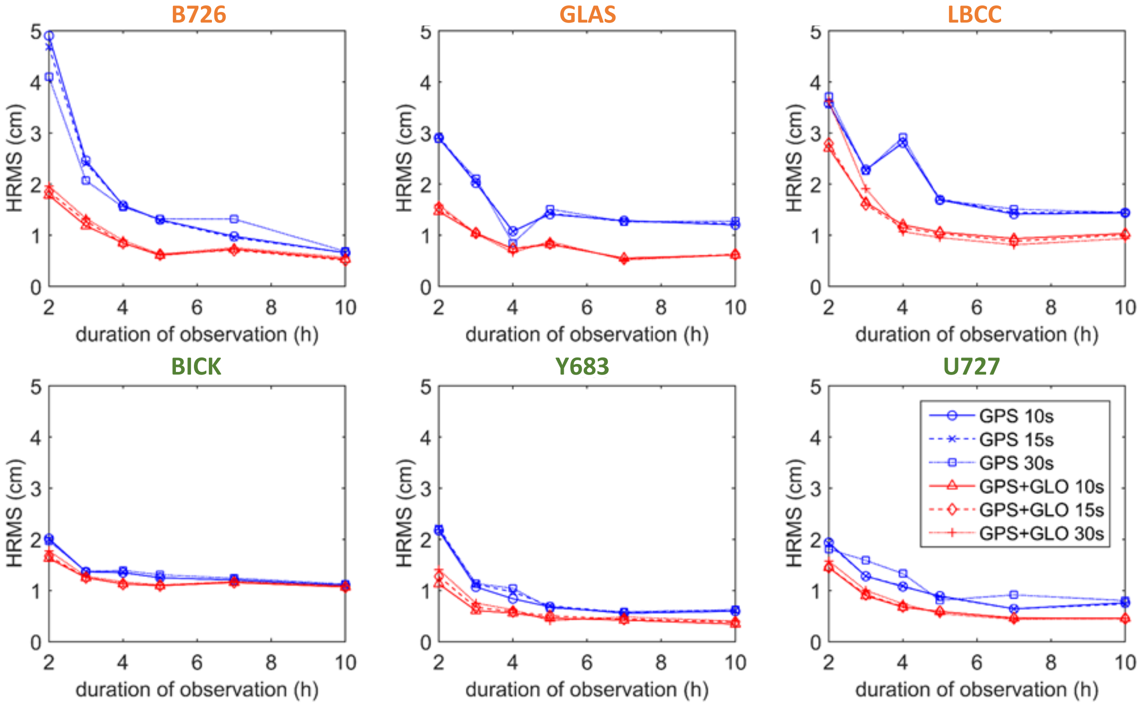

Figure 8. HRMS versus observation duration for each of the six test marks; all values are based on solutions from *TrimbleRTX*

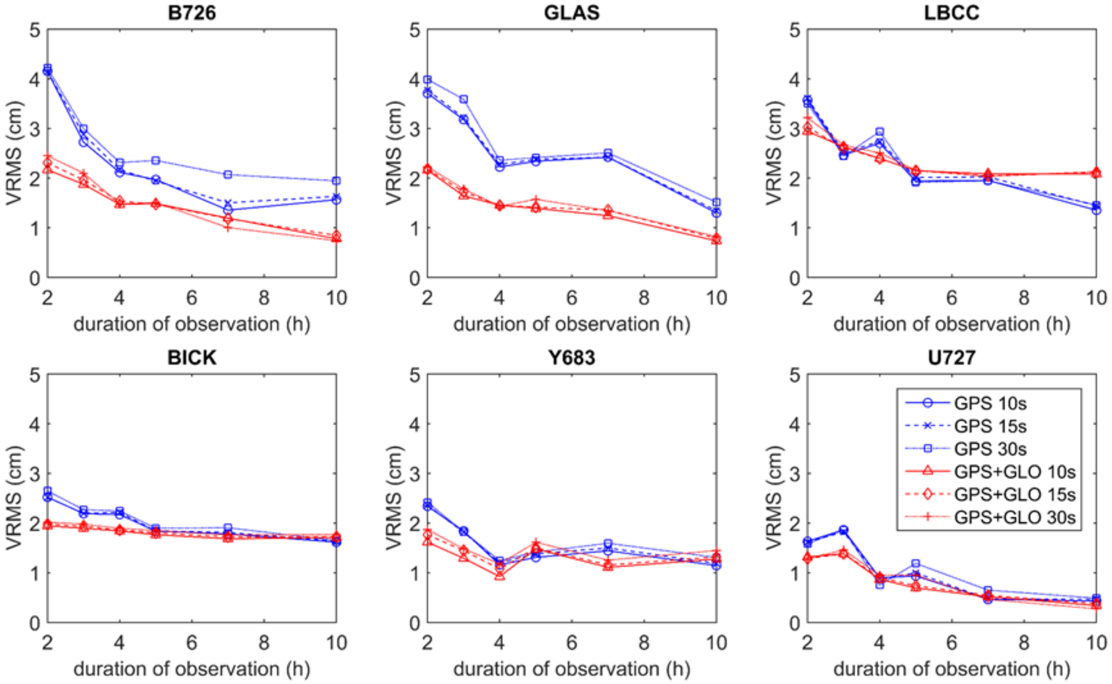

Figure 9. VRMS versus observation duration for each of the six test marks; all values are based on solutions from *TrimbleRTX*

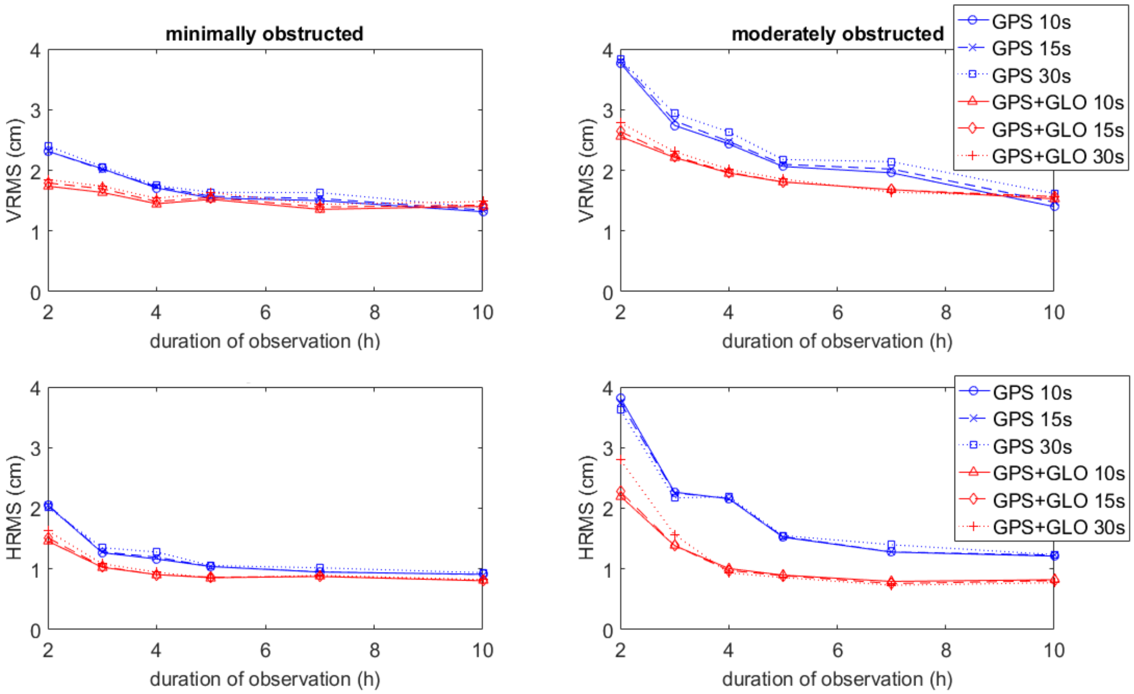

Figure 10. HRMS and VRMS vs observation duration, grouped by station multipathing environment; all values are based on solutions from *TrimbleRTX*