Evaluation of the Online Positioning User Service for Processing Static GPS Surveys: *OPUS-Projects*, *OPUS-S*, *OPUS-Net*, and *OPUS-RS*

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ABSTRACT

The National Geodetic Survey has developed four versions of the online positioning user service (OPUS) for post-processing dual frequency, static Global Positioning System (GPS) data. Each version was designed for a different application and outputs coordinates at a mark to varying accuracy. To compare the accuracy of these four versions, 88 10-h-duration GPS data files collected on 18 marks in Oregon were processed in *OPUS-Projects*, producing horizontal coordinates and ellipsoid heights at these marks with an estimated network accuracy less than 0.5 cm and 1.3 cm at 95% confidence, respectively. Then, these data files were windowed into sessions ranging from 20 min to 10 h in duration. The windowed files were processed in *OPUS-S*, *OPUS-Net*, and *OPUS-RS*, and the resulting coordinates at each mark were compared with the coordinates from *OPUS-Projects*. At a session duration of 2 h, *OPUS-RS* was found to be more accurate than both *OPUS-S* and *OPUS-Net*. For sessions less than 2 h, *OPUS-RS* frequently produced poor solutions with error messages. At a session duration of 4 h, *OPUS-S* and *OPUS-Net* produced coordinates with both horizontal and ellipsoid height error less than 3 cm at 95% confidence.

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Introduction

In 2001, the National Geodetic Survey (NGS) introduced the Online Positioning User Service (OPUS) which has become widely popular in the United States for surveying, engineering, geographic information systems, and mapping (Snay and Soler 2008). Users can upload a raw static or rapid-static data file from a dual-frequency Global Navigation Satellite System (GNSS) receiver for an observational session on a mark using a free, online portal, and OPUS will post-process the data and email back geodetic coordinates for the observed mark referenced to the United States' National Spatial Reference System (NSRS).

Currently, NGS has developed four different versions of OPUS, each with different capabilities. The recommended version depends on the duration of the GNSS observational session and the desired accuracy of the GNSS survey. It is worth noting that all of the current versions of OPUS are only capable of processing observables from the United States' Global Positioning System (GPS). Research is underway at NGS to develop new tools for processing GPS data plus data from other types of GNSS (e.g., Russia's GLONASS, European Union's Galileo, China's Beidou, etc.). In addition, all current versions of OPUS decimate data files to a 30-sec data logging rate.

For session durations of at least 2 h, NGS recommends the use of OPUS-Static (*OPUS-S*), which is currently the most popular and oldest version of OPUS. *OPUS-S* outputs geodetic coordinates for an observed mark by finding the (unweighted) mean of three separate, fully or partially fixed, single-baseline solutions computed by double-differenced, carrier-phase measurements to the observed mark from three active stations that contribute to the NGS' Continuously Operating Reference Stations (CORS) Network and/or the International GNSS Service (IGS) Network using NGS baseline processing software named *PAGES* (Soler 2011). *OPUS-S* cannot produce reliable coordinates for sessions shorter than 2 h in duration (Soler et al. 2006). Therefore, for a user who desires to observe a mark for only 15 min to 2 h in duration, NGS recommends OPUS-Rapid Static (*OPUS-RS*). Using *RSGPS* baseline processing software that was developed in collaboration with the Satellite Positioning and Inertial Navigation (SPIN) group at The Ohio State University, *OPUS-RS* outputs the geodetic coordinates of the observed mark by session baseline processing of double-differenced carrier phase measurements to the observed mark from three to nine CORS and/or IGS stations that must meet stringent geometric conditions (Schwarz 2008). These geometric conditions are required because *RSGPS* spatially interpolates the tropospheric refraction at the observed mark by fitting a plane to a minimum of three reference stations (Schwarz 2008).

In addition to *OPUS-S* and *OPUS-RS*, NGS has more recently developed two other versions of OPUS for processing GNSS data: *OPUS-Net* and *OPUS-Projects*. Both of these versions have different features and are advantageous for varying surveying and monitoring projects. *OPUS-Net* is an internal application developed by NGS for monitoring the position of the active GNSS stations in its CORS Network. *OPUS-Projects* is a web-based application designed for detailed, campaign-style GNSS surveys. *OPUS-Projects* is considered the most rigorous and accurate version of OPUS, and it is meant for managing, post-processing, and adjusting a static GNSS survey campaign involving multiple observations of at least 2 h in duration on numerous survey marks.

Since there are currently four versions of OPUS available for use, the objective of this paper is to first introduce the more-recently developed *OPUS-Net* and *OPUS-Projects*. Less details and background are given on *OPUS-S* and *OPUS-RS*, because several recent papers (e.g., Wang and Soler 2013; Smith et al. 2014; Soler and Wang 2016; Wang et al. 2017; Jamieson and Gillins 2018) and numerous other articles compiled into a book are available (i.e., Soler 2011). The second and main objective is to compare the accuracy of coordinates derived from processing GNSS survey data in *OPUS-S*, *OPUS-RS*, *OPUS-Net*, and *OPUS-Projects*. This comparison aims to improve understanding of the relative capabilities and limitations of each version of OPUS.

To accomplish the comparison, 88 10-h-duration GNSS data files were collected on 18 passive marks in western Oregon. All of these data files were first post-processed in *OPUS-Projects*, and the resulting GNSS vectors in the survey network were adjusted by least squares in the NGS application *ADJUST*. The resulting adjusted coordinates were then considered the "true" coordinates for each of the 18 passive marks and were used as a reference for evaluating the accuracy of the other versions of OPUS. Afterwards, all of the GNSS data files were windowed into mutually non-overlapping session durations of 20, 40, and 60 min, as well as 2, 3, 5, 7 and 10 h. The 2- to 10-h data files were then submitted to *OPUS-S* and *OPUS-Net*, and the 20-min to 2-h data files were submitted to *OPUS-RS*. The resulting solutions from *OPUS-S*, *OPUS-Net*, and *OPUS-RS* were then differenced with the adjusted coordinates derived using *OPUS-Projects* and *ADJUST*.

Background on *OPUS-Net*

As a monitoring effort, NGS has used *OPUS-Net* internally since 2011 for post-processing each daily (24-h-duration) static GNSS data file collected at each active station in its CORS Network. NGS computes the difference between the resulting daily geodetic coordinates from *OPUS-Net* with the "predicted coordinates" of the CORS, in terms of northing, easting, and up in a local geodetic horizon frame. NGS computes "predicted coordinates" of the CORS at a given time by starting with its published geodetic coordinates at its referenced epoch (for this project, in the IGS08 reference system at epoch 2005.0). Then, NGS adds to these published coordinates the product of the elapsed time since its referenced epoch with its velocity which was either computed from years of data collected at the CORS or estimated from an NGS tool named *HTDP*. NGS archives the daily differences between the coordinates from *OPUS-Net* with the predicted coordinates and plots them in short-term time-series plots.

Both *OPUS-S* and *OPUS-Net* applications use the NGS baseline processor *PAGES* (Schenewerk and Hilla 1999), and both are meant for processing a single static GNSS observation on an individual mark. In addition, both recommend that the GNSS sessions on the observed mark are a minimum of 2 h in duration. However, instead of computing the unweighted mean of three single-baseline solutions from the observed mark to three CORS or IGS stations like in *OPUS-S*, *OPUS-Net* produces a session baseline processing network solution from the observed mark to three nearby CORS and the 10 nearest active stations that contribute to the IGS Network (Weston and Ray 2011). The three nearby CORS are not constrained in the session solution, and they are only included for modeling tropospheric delay errors. Instead of constraining the coordinates of the three nearby CORS, the coordinates of the IGS stations are held fixed, and *OPUS-Net* then computes the geodetic coordinates of the one observed mark for the single session (Weston and Ray 2011).

Background on *OPUS-Projects*

Unlike *OPUS-S*, *OPUS-RS*, and *OPUS-Net*, *OPUS-Projects* is a baseline processing and network adjustment software meant for managing campaign-style static survey projects containing many marks observed in multiple GNSS sessions. *OPUS-Projects* is free, web-based software that allows users to manage large sets of static GNSS files, perform session baseline processing of simultaneous occupations on multiple marks, and conduct a least squares network adjustment of one or more sessions (Armstrong et al. 2015). Similar to *OPUS-S* and *OPUS-Net*, *OPUS-Projects* uses *PAGES* as its baseline processor. Users may choose from a list of output reference frames and associated geoid models, alter tropospheric modeling parameters, and change elevation mask cutoff angles. During session baseline processing, the user can add data collected at multiple CORS and IGS stations and can create custom network designs between these stations and the observed marks. During session baseline processing, different schemes are available for applying weights to the coordinates of the control.

Sessions in a project can be combined and adjusted within *OPUS-Projects* using an NGS application named *GPSCOM*. This application produces final geodetic coordinates for each project mark in the network (Weston et al. 2007).

Recently, NGS has added *ADJUST* to *OPUS-Projects* as another application for adjusting session baseline solutions. *ADJUST* is the official NGS software program for performing least squares adjustments of GNSS survey networks (Milbert and Kass 1993). For approximately three decades, NGS has used *ADJUST* for adjusting and preparing GNSS surveys for publication in the NGS Integrated Database (NGS IDB) following a process known as “Blue Booking” (NGS 2017b). Thus, including *ADJUST* within *OPUS-Projects* provides an efficient method for not only processing and adjusting a static GNSS survey campaign, but for also preparing the results for publication in the NGS IDB. The combination of *OPUS-Projects* and *ADJUST* (referred to hereinafter as "OP+ADJUST") are becoming popular for processing static GNSS survey campaigns according to NGS guidelines, such as for establishing geodetic control at airports and for GNSS height modernization surveys (Kerr 2015; Gillins and Eddy 2017; and Weaver et al. 2018).

Materials and Methods

Source of Data for Analysis

Raw GNSS data were gathered from a static, campaign-style GNSS survey conducted from October 7 to November 7, 2014, in the Willamette Valley, Oregon. During the campaign, static GNSS data were collected on 18 passive marks at sites considered suitable for making satellite observations.

For each of the 15 sessions of the survey project, five or six Leica Viva GS14 receivers with integrated antennas were set up to simultaneously observe five to six marks. Each antenna was placed on a calibrated 2-meter fixed-height tripod that was stabilized with three 14-kg sandbags. To account for minor errors due to eccentricities in the antenna phase center, the receiver antennas were always oriented north prior to starting the session. After each setup of the antenna, the level bubble on each fixed-height tripod was checked by rotating the center pole 180 degrees and verifying the bubble remained in the center of the bulls-eye ring.

Once each session started, static GNSS data were collected for at least the same 10-h period of time on all occupied marks. Both GPS and GLONASS observables were collected (although all versions of OPUS ignore GLONASS) at a 1-sec data logging rate with an elevation mask of 10 degrees, stored in Receiver Independent Exchange (RINEX) format, version 2.11. Mark D728 was observed for only 3 sessions, and the remaining marks were observed for at least four sessions. Upon completion of the survey schedule, a total of 88 10-h-duration RINEX files on the 18 passive marks were collected and prepared for evaluation. For additional details on the 2014 survey campaign, see Gillins and Eddy (2015, 2017).

OP+ADJUST Processing

Figure 1 presents the flowchart for processing all 88 of the 10-h static GNSS data files in *OPUS-Projects* in order to derive highly accurate geodetic coordinates on the 18 passive marks. This process was discussed in detail in Gillins and Eddy (2017), and it is based primarily on NGS recommendations in the *OPUS-Projects* User Manual (Armstrong et al. 2015). First, each 10-h static data file was uploaded to *OPUS-Projects* using the NGS online portal for *OPUS-S* and by specifying an *OPUS-Projects* Project Identifier.

Afterwards, 24-h-duration data files collected at seven CORS were added to each of the 15 sessions of the survey project. One major advantage of *OPUS-Projects* is that the user can select desired CORS and IGS stations for inclusion in a survey network. Practically any CORS or IGS station could be added to the project, but several criteria should be considered when deciding which ones to add to the project. For highest accuracy, data from poorer-quality active stations should be avoided because they could potentially introduce error in the network. In addition, active stations should be chosen to meet a recommended geometric design for session baseline processing in *OPUS-Projects*. An explanation of why the CORS for this project were chosen is based on the following recommendations from NGS.

For each session, Armstrong et al. (2015) recommends developing a hub survey network design (Figure 2). Per Armstrong et al. (2015), the user should do the following:

- Designate a single station within roughly 100 km of observed passive marks in the session as the hub. It is best practice to designate a CORS, temporary CORS, or other type of active station as the hub (so that the hub has a minimum of 24 h of static data for each session). The user may designate different stations as the session hub when processing multiple sessions; for such projects, ensure that a baseline observation connects all hubs in the survey network in every session.
- Add and use data from nearby and distant CORS or IGS stations for every session. Use of multiple nearby CORS or IGS stations helps reference the network to the geometric reference frame of the NSRS because such redundancy reduces possible bias that may occur if only a single CORS was used as control. In addition, the use of data from at least one long-distance (i.e., ~300 to 1,000 km) station helps *PAGES* solve for the wet component of its tropospheric delay modeling corrections (Ugur et al. 2013).
- Plan to process baselines such that every observed mark in the session is directly connected to the hub (per Figure 2). Designating an active station as the hub is ideal because its 24-h-duration data file helps ensure there is sufficient mutual satellite visibility between the hub and the distant CORS or other active stations for double differencing. Observations shorter than 24 h in duration are typically adequate for the shorter (i.e., < 100 km) baselines between the hub and the passive marks observed in the session.

Given these recommendations, a CORS named CORV roughly near the center (i.e., within 30 km) of all of the observed passive marks for our project was designated as the hub for every session. Data collected at six additional near and distant CORS (FTS5, ORK6, ORS2, RPT6, PPT6, and P054) were added to each session because each had static data available (except for an occasional, small data gap) during each of the 15 sessions and had computed velocities published by NGS. It is important to note that NGS computes velocities by processing years of continuous GNSS observations at active stations in the CORS Network. Some new or young active stations in the CORS Network do not have computed velocities. In addition, the coordinates for such CORS without computed velocities also do not have formal uncertainty estimates, and these stations should therefore be avoided.

In addition to the aforementioned reasons, the daily *OPUS-Net* solutions differenced with the predicted coordinates of each CORS, as depicted in short-term time-series plots (e.g., Figure 3), were evaluated for each of the seven CORS and were found to be satisfactory. These short-term time-series plots are computed and made available by NGS (NGS 2017a). Since ultimately the predicted coordinates of each of the CORS were held as control, CORS with time-series plots with large systematic daily residuals from their predicted coordinates (i.e., large offsets from zero in the time-series plot), spikes, gaps, or discontinuities during the time of the survey project should be avoided. The daily solutions of the selected CORS during the days of the survey project were consistent with the predicted coordinates of the CORS to ± 1 cm.

Each of the sessions in *OPUS-Projects* were next processed. During the session baseline processing, the tropospheric modeling was set to *piecewise linear* at a sampling interval period of 7200 sec, which fits line segments of 7200-s duration (approximately a smooth curve) across the average zenith delay versus time. Only CORV was selected as the hub, and its predicted coordinates in the IGS08 reference system at the weighted mean epoch of each session were held as control by selecting *normal* constraint weights. Normal constraint weights are preferred because they allow slight shifts on the same rough order as the typical accuracy of the published coordinates of the CORS (i.e., ~ 1 cm). The following *OPUS-Projects* data and solution quality thresholds were set and satisfied for all of the processed baselines: >80% observables used, >80% ambiguities fixed, and < 2.5 cm baseline processing root-mean-square error (RMSE).

Satisfied with the results of the session baseline processing, the session solutions were combined within *OPUS-Projects* with its network adjustment utility, *GPSCOM*. Figure 4 shows screen captures of the survey network displayed in OPUS-Projects. *OPUS-Projects* output the multiple, unadjusted GNSS vectors in a file known as a “G-file,” and it output the adjusted coordinates in another file known as a “B-file.” The G-file and B-file are required inputs for running NGS software, *ADJUST*, and their format is described in the NGS Blue Book (NGS 2017b). *ADJUST* estimates the a-priori geodetic coordinates of the marks in the network using the B-file; the G-file contains Earth-centered, Earth-fixed components of the GNSS baseline observations and variance-covariance (v-c) matrices of the session solutions.

OPUS-Projects output the vectors in the G-file in the IGS08 reference system. The vector components are also output at the weighted mean epoch for each observational session. Typically, *ADJUST* attempts to transform the vector components to the North American Datum of 1983 (NAD 83). However, the G-file was modified in order to disable this transformation so as to keep the data in IGS08 at the approximate weighted mean epoch of 2014.8. Then, the B-file and G-file were inputted in *ADJUST*, and a minimally constrained least squares adjustment of the network was performed holding fixed the predicted coordinates of CORV in IGS08(2014.8). Afterwards, a fully constrained network adjustment was performed by holding the predicted coordinates of all seven CORS in IGS08(2014.8), and by assigning weights that were inversely proportional to the square of the published standard deviations for the CORS.

ADJUST output the most-probable geodetic coordinates and their standard deviations for each station, as well as horizontal and vertical "network" accuracies at 95% confidence as defined by federal standards (FGDC 1998) using formal error propagation theory. The horizontal network accuracies for the 18 marks ranged from 0.4 to 0.5 cm, and the vertical network accuracies ranged from 1.1 to 1.3 cm (95% confidence). The resulting geodetic coordinates from the fully constrained least squares adjustment in ADJUST (i.e., "OP+ADJUST solution) were adopted as the "true" coordinates at each mark and were used as a basis for evaluating the accuracy of *OPUS-S*, *OPUS-Net*, and *OPUS-RS*.

It is worth noting that the network adjustments for this study were done outside of *OPUS-Projects* by loading the B-file and G-file into *ADJUST*, as described above. However, recent developments to *OPUS-Projects* have been completed at the time of this writing which enable users to run *ADJUST* within *OPUS-Projects*.

OPUS-S Processing

OPUS-S, *OPUS-RS*, and *OPUS-Net* have a simple user interface and significantly less options than *OPUS-Projects*. After simply uploading a single RINEX file, these three versions of OPUS post-process the GPS data and will solve for geodetic coordinates in the IGS08 reference system at the mean epoch of the observation. Such coordinates from these versions of OPUS were differenced to find the change in northing, easting, and up (Δn, Δe, Δu) in a local geodetic horizon frame with the coordinates of the mark from the OP+ADJUST solution. These differences form the basis for the statistics presented throughout the paper. Eckl et al. (2001) computed similar statistics when evaluating the accuracy of single-baseline GPS solutions post-processed in *PAGES*. Soler et al. (2006) used much the same method while evaluating the accuracy of *OPUS-S*.

To evaluate the accuracy of *OPUS-S*, all 88 of the 10-h GNSS data files collected on the 18 marks in Oregon were windowed into mutually non-overlapping sessions in order to produce sets of data files with observational durations of 10, 7, 5, 4, 3, and 2 h. (Note they were further windowed to durations of 60, 40, and 20 min for later submission to *OPUS-RS*, as discussed below.) All windowing of the data files was performed using the time binning options in the *TEQC* software toolkit (Estey and Meertens 1999).

All 1,232 of the resulting 2-h to 10-h RINEX data files were submitted to *OPUS-S* via its online portal at https://www.ngs.noaa.gov/OPUS/. When submitting the data files to *OPUS-S*, the three CORS in Oregon (ORK6, FTS5, and ORS2 in Figure 4) were selected for use as base stations. In addition to parsing the aforementioned IGS08 geodetic coordinates, other information was also taken from the *OPUS-S* solutions, including the peak-to-peak errors (the difference between the maximum and minimum value of a coordinate) from the three baseline solutions processed to the three CORS, the RINEX file name, date, start and stop time of the observation, number of observables used in the solution, percent fixed ambiguities, and the overall RMSE of the baseline processing.

OPUS-Net Processing

Similar to the data processing completed with *OPUS-S*, the identical data files submitted to *OPUS-S* were also submitted and post-processed in *OPUS-Net* via its internal NGS web portal. *OPUS-Net* was set to automatically choose its reference stations, which includes the ten nearest IGS stations (constrained) and three nearby CORS (unconstrained) from the observed mark. Again, Δn, Δe, and Δu for each *OPUS-Net* solution at each mark were computed with respect to the coordinates of the mark from the OP+ADJUST solution, and other similar data were parsed from the *OPUS-Net* solutions as were collected from the *OPUS-S* solutions.

Figure 5 illustrates an *OPUS-Net* solution for one of the processed data files collected on mark BEEF. As shown, baseline observations were processed to BEEF from 3 unconstrained, nearby CORS and 10 constrained IGS stations. In many cases, such as illustrated in Figure 5, the IGS stations were up to 4,000 km from the observed mark. As shown, two of the IGS stations were in Hawaii. The use of such long-distance IGS stations might be due to the fact that there are a limited number of IGS stations in the continental United States; sometimes, *OPUS-Net* must search a great distance to find ten IGS stations with available data.

OPUS-RS Processing

Similar to the data processing completed for both *OPUS-S* and *OPUS-Net*, all 88 of the 10-h GNSS data files were windowed into mutually non-overlapping sessions of 20, 40, 60, and 120 min. Then, the resulting 5,313 RINEX data files were uploaded to the online portal for *OPUS-RS* at https://www.ngs.noaa.gov/OPUS/. The default settings were chosen where *OPUS-RS* was allowed to use any available CORS or IGS station as a base station (i.e., no base stations were excluded). The results from *OPUS-RS* were emailed to the submitter, and *OPUS-RS* used from five to nine CORS as base stations in each solution. As discussed below, for a percentage of the data files, *OPUS-RS* failed to produce a solution and instead emailed an "*OPUS-RS* is aborting" message. The number of aborted messages as well as their error messages were counted and stored.

Otherwise, Δn, Δe, and Δu for each *OPUS-RS* solution at each mark were computed with respect to the coordinates of the mark from the OP+ADJUST solution in IGS08 at the mean epoch of the data file. In addition, other statistics were parsed from the *OPUS-RS* solutions, including any warning messages from *OPUS-RS*, the start and stop time of the observation, estimated standard deviation of the coordinate in each component (north, east, up), number of observables used in the solution, data quality indicators, and normalized RMSE of the baseline processing for the overall solution.

Results and Discussion

OPUS-S Results

Although a total of 1,232 RINEX files were submitted *OPUS-S*, only 1,149 (93.3%) solutions were kept for analysis. The reason is that for some of the solutions, *OPUS-S* did not use the requested CORS (i.e., ORK6, FTS5, and ORS2) as base stations. This was due to occasional gaps in the availability of the GPS data collected at these CORS. In addition, for 1% of the solutions, one or more of the single-baseline solutions generated by *OPUS-S* for a given data file did not use the entire duration of the GPS data collected on the observed mark. Again, this might be due to gaps in data availability at the base station. For example, sometimes a single-baseline solution from *OPUS-S* was only based on the first 2.3 h of the 3 h session since the latter 0.7 h of data were unavailable at a particular base station.

To eliminate this confusion, only *OPUS-S* results based on the mean of three single-baseline solutions using the full duration of the uploaded RINEX data file and using only the three specified CORS (i.e., ORK6, FTS5, and ORS2) as base stations were studied further. Table 1 summarizes the number of used *OPUS-S* solutions at each mark.

Figure 6 depicts values of Δn, Δe, and Δu, for each of the 1,149 *OPUS-S* solutions tabulated in Table 1. Overall, the data displays no obvious bias as the residuals in each component and duration interval are centered about zero. It is clearly seen that the residuals become closer to zero (i.e., more accurate) as the session duration increases. Keeping session durations (T) longer than 4 h is advantageous when using *OPUS-S*. For $T \geq 4$ h, none of the absolute values of Δn and Δe are greater than 3 cm, and only 10 (0.9%) of the absolute values of Δu are greater than 3 cm. At $T = 3$ h, 1 (0.1%), 3 (0.3%), and 18 (1.6%) of the absolute values of Δn, Δe, and Δu, respectively, are greater than 3 cm. At $T = 2$ h, 4 (0.3%), 26 (2.3%), and 65 (5.7%) of the absolute values of Δn, Δe, and Δu, respectively, are greater than 3 cm; moreover, some of the absolute values Δe and Δu exceed 10 cm when T is only 2 h. It is interesting that larger residuals occurred more frequently in easting than in northing, and perhaps this is related to local obstructions at the mark or due to poor estimation of the phase biases which are more correlated with the east component (Blewitt 1989).

OPUS-Net Results

Only a total of 1,010 (82%) of the 1,232 solutions from *OPUS-Net* were used in the analysis. Unfortunately, it was discovered that *OPUS-Net* truncates all data files at midnight (GPS time). The local time in Oregon was 7 or 8 h earlier than GPS time (ignoring leap sec and accounting for daylight savings time which began near the end of the survey), and all 88 of the original 10-h RINEX data files spanned across GPS midnight by approximately 1 h. As a result, no 10-h-duration solutions were obtained from *OPUS-Net*; rather, several 9-h-duration solutions were produced.

Table 2 lists the sample size of *OPUS-Net* solutions used at each mark, subdivided by duration interval. All solutions that were based on data truncated at GPS midnight were removed from the analysis unless they were within 6 min of the hour intervals listed in Table 2.

Figure 7 depicts values of Δn, Δe, and Δu, for each of the 1,010 *OPUS-Net* solutions tabulated in Table 2. Again, no obvious bias is present in the residuals, and the residuals become closer to zero (i.e., more accurate) as the session duration increases. The scatter for Δn and Δe at all duration increments, and the scatter for Δu at $T \geq 4$ h in Figure 7 look extremely similar to the scatter of the residuals found when using *OPUS-S* (Figure 6). Both applications appear to have produced similar results, which should not be a surprise because a large portion of the processing in both applications is identical.

However, when $T = 2$ or 3 h, the values of Δu from *OPUS-Net* look less accurate than values of Δu from *OPUS-S*. For instance, at T = 3 h, 25 (2.5%) of the absolute values of Δu from *OPUS-Net* exceed 3 cm; whereas 18 (1.6%) of the absolute values of Δu from *OPUS-S* exceed 3 cm. At $T = 2$ h, 86 (8.5%) and 65 (5.7%) of the absolute values of Δu from *OPUS-Net* and *OPUS-S*, respectively, exceed 3 cm. The range of all values for Δu at $T = 2$ h is 30.4 cm and 27.0 cm from *OPUS-Net* and *OPUS-S*, respectively. The poorer performance of *OPUS-Net* at $T = 2$ or 3 h might be related to its use of very long baselines, like > 2,000 km as illustrated in Figure 5, to IGS stations. There is reduced mutual satellite visibility at the ends of such long baselines for post-processing, and, of course, there are fewer satellite observables in general as the session duration is shortened. The reduction in low elevation observations results in poorer integer fixing and noisier solutions. Longer-duration observations (i.e., $T \geq 4$ h) help overcome this issue, yielding similar solutions from both *OPUS-Net* and *OPUS-S.*

OPUS-RS Results

OPUS-RS returned an email for each of the uploaded 5,313 RINEX data files. The majority of the emails included a solution or set of geodetic coordinates for the observed mark. Of the *OPUS-RS* emails, 19.9% included a solution, but the email included at least one type of "warning" message that indicated that the quality of the solution was weak or poor. Unfortunately, 6.7% of the emails did not include a solution and instead stated that *OPUS-RS* was "aborting." This percentage (6.7%) is the same as the number of *OPUS-S* solutions that did not use the requested CORS or did not use the full data file for one or more of the single-baseline solutions.

Table 3 lists the total number of *OPUS-RS* emails, subdivided by mark and session duration increment. It also clarifies the number of these emails with "aborting" or "warning" messages as well the number of emails where the solution was apparently fine because it did not have a warning message (i.e., solution with "no warning"). No pattern can be found relating the error and warning messages to factors for a specific mark, as emails with aborting or warning messages were generated at every mark in the survey. Figure 8 shows the relative frequency of the emails in these three categories according to observation duration. It is important to note that as the duration of the session increases, the frequency of solutions with aborting or warning messages decreases. Thus, increasing the session duration reduced the likelihood for *OPUS-RS* to fail or generate a poor solution. However, this finding is unfortunate, as *OPUS-RS* is meant for processing short-duration sessions.

Of the total of 358 emails with an aborting message, 93.6% provided error message number 6034: "The quality of the GPS data from the rover or nearby CORS sites was too noisy and below minimum standards to attain a meaningful solution." A small percentage (i.e., 6.4%)

of the aborting error messages stated that *OPUS-RS* stopped with an unspecified error in the RSGPS network solution or *OPUS-RS* failed to converge after 5 iterations. Of these 358 emails, 253 occurred (70.7%) when T = 20 min.

A total of 1,056 emails included at least one warning error message; some contained two or three warning error messages. Of the total number of warning error messages, 56% were error message number 6030: “one or both of the standard deviations associated with the horizontal coordinates is greater than 5 cm, and/or the standard deviation associated with the vertical coordinate is greater than 10 cm. That means the vectors used to determine your position did not agree as well as expected.” Twenty-three percent were error message number 6023: “The Quality Indicator for the network solution is less than 3.0. This is often a warning sign that the network solution was weak and tropospheric and ionospheric refraction in the project area were not strongly determined.” Finally, 22% were error message number 6024: “The Network Quality Indicator for the rover solution is less than 1.0. This is often a warning sign that one or more of the baselines involving your station were weakly determined.”

It is possible that the frequent aborting and warning messages from *OPUS-RS* is specific to the local survey project, and *OPUS-RS* may perform better in other locations. In Oregon, there are a sparse and limited number of available CORS as compared to some other locations in the US, and the base stations must meet stringent geometric conditions to satisfy *OPUS-RS* processing requirements, unlike *OPUS-S* (Schwarz 2008). As an example, NGS does not recommend the use of *OPUS-RS* near the coast due to the impracticability of installing base stations in the ocean. However, note that the passive marks tested in this study were more than 50 km from the coast, and Schwarz et al. (2009) stated that in the first 6 months of 2007 when *OPUS-RS* was released for operational use, approximately 15% of the 400,000 files submitted resulted in *OPUS-RS* aborting. In addition, roughly 5 of every 65 solutions generated in *OPUS-RS* included a warning message (Schwarz et al. 2009). Nevertheless, in 2007, there were roughly only half as many CORS as in 2014; the fewer CORS would have adversely affected *OPUS-RS* and may have been the reason for many of the aborting and warning messages.

From the online portal for *OPUS-RS*, NGS provides a map for viewing the estimated accuracy and availability of *OPUS-RS* in the conterminous US and Alaska. In 2014, this "*OPUS-RS* map" showed that *OPUS-RS* was available throughout the survey project, and it estimated that for a 1-h GPS data file collected in Corvallis, Oregon, the accuracy in northing/easting and ellipsoid height would equal approximately 0.7 cm and 2.4 cm, respectively. Note that it is best practice to view this online map at or near the time of the GPS survey, as NGS updates it when CORS are installed or decommissioned.

Figure 9 shows values of Δn, Δe, and Δu for all *OPUS-RS* solutions, including solutions with warnings. For $T \leq 60$ min, a number of the absolute values of the residuals exceed 10 cm. These large residuals are generally associated with solutions from *OPUS-RS* with warning messages. It is clear that users should be cautious when *OPUS-RS* sends a solution with a warning message.

To illustrate this point, Figure 10 shows values of Δn, Δe, and Δu, for only those *OPUS-RS* solutions without warning messages. The scatter for the residuals improves significantly as compared with Figure 9. (Note that the scale of the y-axis in Figure 9 differs greatly from the scale of the y-axis in Figure 10.) Again, no obvious bias is present in the residuals, and the residuals become closer to zero as the session duration increases.

The residuals in both Figures 9 and 10 at $T = 120$ min (2 h) look smaller or more accurate from *OPUS-RS* than from *OPUS-S* (Figure 6) and *OPUS-Net* (Figure 7), especially in the horizontal components. At this duration in Figure 10, none of the absolute values of Δn and Δe exceed 3 cm, and 36 (8.7%) of the absolute values of Δu exceed 3 cm.

All but five of the solutions from *OPUS-RS* without warnings had absolute values of Δn and Δe less than 5 cm. The majority, or 95%, were less than 2 cm. Although *OPUS-RS* was highly accurate horizontally, several *OPUS-RS* solutions without warnings still had absolute values of Δu greater than 11 cm when $T \leq 60$ min.

Comparison of Results for OPUS-S, OPUS-Net, and OPUS-RS

The RMSE in northing, easting, and up components were computed from the values of Δn, Δe, and Δu from the solutions from *OPUS-S*, *OPUS-Net*, and *OPUS-RS*. Figure 11 presents these RMSE values as a function of session duration. Two sets of curves are presented for *OPUS-RS* in Figure 11: (1) using all solutions, and (2) after filtering out those solutions from *OPUS-RS* with warning messages.

As shown in Figure 11, values of RMSE improve from each version of OPUS as the duration of the session increases. Interestingly, at $T = 2$ h, the RMSE in easting of all solutions from *OPUS-RS* are 60% and 65% smaller than the RMSE in easting values from *OPUS-S* and *OPUS-Net*, respectively. The RMSE in up values for all *OPUS-RS* solutions at $T = 2$ h are 8% and 32% smaller than the up RMSE values from *OPUS-S* and *OPUS-Net*, respectively.

The RMSE curves for *OPUS-S* and *OPUS-Net* are generally similar; however, when $T \leq 3$ h, the up RMSE values are smaller for *OPUS-S* than for *OPUS-Net*.

Figure 11 gives an opportunity to decide which version of OPUS is most optimal for achieving a certain level of accuracy. For example, suppose it is desired to measure the coordinates of a mark to a horizontal error less than 3 cm, 95% of the time. Assuming systematic error or bias was removed (which in this case is a safe assumption as noted earlier), then the RMSE curves presented in Figure 11 are nearly equivalent to uncertainties at 68% confidence. Using a bivariate distribution for horizontal error, 3 cm at 95% confidence should be divided by 2.45 to equal 1.2 cm at 68% confidence. Entering Figure 11, the RMSE in both northing and easting is less than 1.2 cm at T = 0.33 h (20 min) for *OPUS-RS* (assuming the solution will not contain a warning message). However, out of concern that a warning or aborting message is likely at T = 20 min, it may be more prudent to plan a longer session and avoid the cost of having to return to the field and re-observe the mark should *OPUS-RS* fail or produce a weak solution. At T = 2 h, the RMSE in both northing and easting of all solutions from *OPUS-RS* are less than 1.2 cm.

Extending this simple example further, at T = 2 h, the up RMSE for all solutions from *OPUS-RS* is equal to 2.4 cm. Suppose a user desires to measure the coordinates of a mark such that the error in *both* the horizontal and up (i.e., ellipsoid height) components are less than 3 cm, 95% of the time. This cannot be accomplished at T = 2 h in *OPUS-RS*. Using a univariate distribution for error in ellipsoid height, 3 cm at 95% confidence should be divided by 1.96 to equal 1.5 cm at 68% confidence. From Figure 11, the RMSE in both northing and easting is less than 1.2 cm and the up RMSE is less than 1.5 cm at T = 4 h using either *OPUS-Net* or *OPUS-S*. Based on the curves derived from this case study, T = 4 h is the minimum allowable duration for measuring the coordinates of a mark such that its error horizontally as well as its error in ellipsoid height are less than 3 cm at 95% confidence. For sessions longer than roughly 4 or 5 h, the values of RMSE decrease by only 1 or 2 mm and the RMSE curves appear to become asymptotic. Thus, sessions of 4 or 5 h appear to be most optimal for minimizing error both horizontally and vertically.

Conclusions

NGS has developed four different versions of OPUS for processing GPS data and referencing resulting coordinates to the NSRS. In this study, 88 static GPS data files that were 10 h in duration collected on 18 passive marks in western Oregon were post-processed in *OPUS-Projects*, *OPUS-S*, *OPUS-Net*, and *OPUS-RS*. All of the data were first processed in *OPUS-Projects* along with data from seven CORS. The resulting campaign-style survey network was adjusted by least squares in NGS software, *ADJUST*. The coordinates on the 18 passive marks from this adjustment we held as "true" coordinates for evaluating the accuracy of the other versions of OPUS as a function of session duration.

The GPS data files were windowed into session durations of T = 10, 7, 5, 4, 3, 2, and 1 h as well as 40 and 20 min. Afterwards, the thousands of data files that were at least 2 h in duration were submitted to *OPUS-S* and *OPUS-Net* for post-processing. In addition, the data files less than or equal to 2 h in duration were submitted to *OPUS-RS*. A number of findings were made in this case study:

(1) It appears that *OPUS-S* was generally as accurate as *OPUS-Net*, and it was more accurate than *OPUS-Net* at $T \leq 3$ h. The poorer performance of *OPUS-Net* for short sessions may be due to lack of mutual satellite visibility when processing long baselines to the sparse number of IGS stations which are held as base stations in the application. Of course, *OPUS-Net* was designed to process much longer sessions (i.e., T = 24 h) for monitoring the data collected at CORS while holding only IGS stations as control; interestingly, for sessions longer than 4 h, it produces both horizontal coordinates and ellipsoid heights with accuracies similar to *OPUS-S*.

(2) *OPUS-RS* failed to produce a solution (i.e., aborted) for 6.7% of the 5,313 uploaded GPS data files. It also produced a solution with a warning error message (i.e., a weak solution) for 19.9% of the uploaded files. Most (> 66%) of these aborting and warning messages were when $T = 20$ min. Such frequent failures could prove costly to users who would have to return to the field and collect new data. The frequency of the aborting and warning messages decreased as the session duration increased; thus, conducting longer sessions will mitigate the risk of needing to return to the field to re-observe marks when *OPUS-RS* fails. However, it is desirable to use *OPUS-RS* for processing short-duration sessions; thus, more work remains improving its reliability for processing short sessions. Only 6.5% of the uploaded GPS data files for $T = 2$ h resulted in an *OPUS-RS* aborting or warning message.

(3) Solutions from *OPUS-RS* with a warning message should be checked and used cautiously. These warning messages should not be ignored, as coordinates from these solutions were frequently in error more than 5 cm horizontally and 10 cm in ellipsoid height.

(4) At $T = 2$ h, all *OPUS-RS* solutions provided coordinates with a horizontal RMSE that was 61% smaller and an up RMSE that was 8% smaller than the horizontal and up RMSE of the coordinates generated from *OPUS-S*. At $T = 2$ h, *OPUS-S* more frequently output ellipsoid heights in error by more than 10 cm.

(5) A session of $T = 4$ to 5 h seems optimal for minimizing both horizontal and ellipsoid height errors. Both *OPUS-S* and *OPUS-Net* produced coordinates in error less than 3 cm both horizontally and in ellipsoid height at 95% confidence when $T \geq 4$ h. From $T = 5$ to 10 h, the RMSE of the solutions only improved by 1 or 2 mm.

(6) It is clear that increasing the observational session will improve the accuracy of the solution from *OPUS-RS*, *OPUS-S*, and *OPUS-Net*. Longer sessions also reduce the likelihood of a failure or weak solution. For high-accuracy projects, it is recommended to conduct longer-duration sessions as well as to conduct multiple repeat sessions per mark at different times of the day in order to check the repeatability of the results and detect possible outliers.

(7) This study was limited to GPS data collected on 18 bench marks in western Oregon. Future work should involve analysis of data from other geographies, climates, and elevations in order to expand the testing of the OPUS suite and evaluate the effects of varying tropospheric conditions. Additional tests could also be completed on how the design and interstation distance of the reference stations affects results.

(8) Comparisons were only presented between the different versions of OPUS in this paper. See Jamieson and Gillins (2018) for comparisons of the accuracy of OPUS-S with other online services, including the Canadian Spatial Reference System PPP (CSRS-PPP) service and the Geoscience Australia Online GPS Processing Service (AUSPOS). Jamieson and Gillins (2018) also investigated the effects of including GLONASS observables and data collected at faster logging rates.

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Table 1. Sample size of *OPUS-S* solutions involving the same three CORS as base stations for analysis, subdivided by mark and session duration

Mark	Session Duration (h)					
Name	**10**	**7**	**5**	**4**	**3**	**2**
B726	3	3	7	7	10	17
BEEF	4	4	8	8	12	20
BICK	10	10	19	19	29	47
CRVA	6	6	12	12	18	30
D728	3	3	6	6	9	15
E141	4	4	7	7	11	17
G287	4	4	8	8	12	20
GLAS	4	4	7	7	11	17
LANG	3	3	6	6	9	14
LBCC	6	6	13	13	19	32
OXOO	3	3	6	6	9	14
PT35	4	4	8	8	12	20
S714	3	3	7	7	10	17
T714	5	5	12	11	17	29
U727	4	4	8	8	12	20
WASH	6	6	12	12	18	30
Y683	6	6	11	12	18	29
Z714	4	4	8	8	12	19
Total	*82*	*82*	*165*	*165*	*248*	*407*

Table 2. Sample size of *OPUS-Net* solutions for analysis, subdivided by mark and session duration

Mark	Session Duration (h)					
Name	**9**	**7**	**5**	**4**	**3**	**2**
B726	3	4	4	8	11	17
BEEF	3	4	4	8	11	17
BICK	7	10	10	20	27	40
CRVA	3	6	6	12	16	24
D728	2	3	3	6	8	12
E141	3	4	4	8	10	17
G287	2	4	4	8	11	16
GLAS	3	4	4	8	10	16
LANG	4	4	4	8	11	16
LBCC	5	7	7	14	19	28
OXOO	4	4	4	8	11	16
PT35	3	4	4	8	11	16
S714	3	4	4	8	11	17
T714	5	6	6	12	18	25
U727	1	4	4	8	10	17
WASH	2	6	6	12	15	24
Y683	5	6	6	13	17	27
Z714	1	4	4	8	10	16
Total	59	88	88	177	237	361

Table 3. Sample size of *OPUS-RS results*, subdivided by mark, session duration, and if *OPUS-RS* aborted, provided a solution with a warning message, or provided a solution without any error or warning messages.

	Session Duration, T = 20 min			T = 40 min			T = 60 min			T = 120 min		
Mark ID	aborted	warning	no warning	aborted	warning	no warning	aborted	warning	no warning	aborted	warning	no warning
B726	12	46	60	4	16	39	3	4	33	0	1	19
BEEF	9	26	84	2	8	50	2	0	38	0	0	20
BICK	25	77	198	9	19	120	5	7	87	1	2	47
CRVA	6	34	139	1	12	77	1	2	57	0	2	28
D728	12	37	41	3	15	27	3	3	24	1	1	13
E141	5	33	82	1	10	49	0	5	35	0	0	20
G287	3	16	100	1	6	53	1	1	38	0	1	19
GLAS	13	35	72	4	8	48	1	7	32	1	1	18
LANG	20	40	60	6	17	37	1	9	30	1	1	18
LBCC	33	63	111	6	31	68	1	8	61	0	4	31
OXOO	17	39	64	7	14	39	3	7	29	1	1	18
PT35	11	26	83	2	14	44	2	1	37	0	0	20
S714	14	26	80	5	11	44	0	3	37	0	1	19
T714	28	54	112	5	23	69	4	12	48	0	3	29
U727	13	31	76	3	15	42	1	6	33	0	1	19
WASH	15	42	123	3	9	77	2	3	55	0	2	28
Y683	9	49	133	1	13	82	1	8	55	1	0	31
Z714	8	22	88	2	7	50	2	4	34	1	1	18
Total	*253*	*696*	*1706*	*65*	*248*	*1015*	*33*	*90*	*763*	*7*	*22*	*415*
Grand Total	***2655***			***1328***			***886***			***444***		

Figure Captions

Fig. 1. Flowchart used for developing, processing, and adjusting a survey network using OPUS-Projects and ADJUST; adapted from Gillins and Eddy (2016)

Fig. 2. Hub network design recommended for session baseline processing in OPUS-Projects

Fig. 3. An example NGS short-term time-series plot of a CORS named RPT6, Mar. 3, 2016. The top of the plot provides the mean and standard deviation (in parenthesis) of the depicted daily residual differences in northing (N), easting (E), and up (U).

Fig. 4. Screen shots of the GNSS survey network in *OPUS-Projects* with (A) baselines from the hub to both near and distant CORS; (B) baselines from the hub to the observed marks

Fig. 5. Illustration of an *OPUS-Net* solution for a static GNSS observation on a passive mark

Fig. 6. Distribution of residual differences between *OPUS-S* solutions and OP+ADJUST coordinates

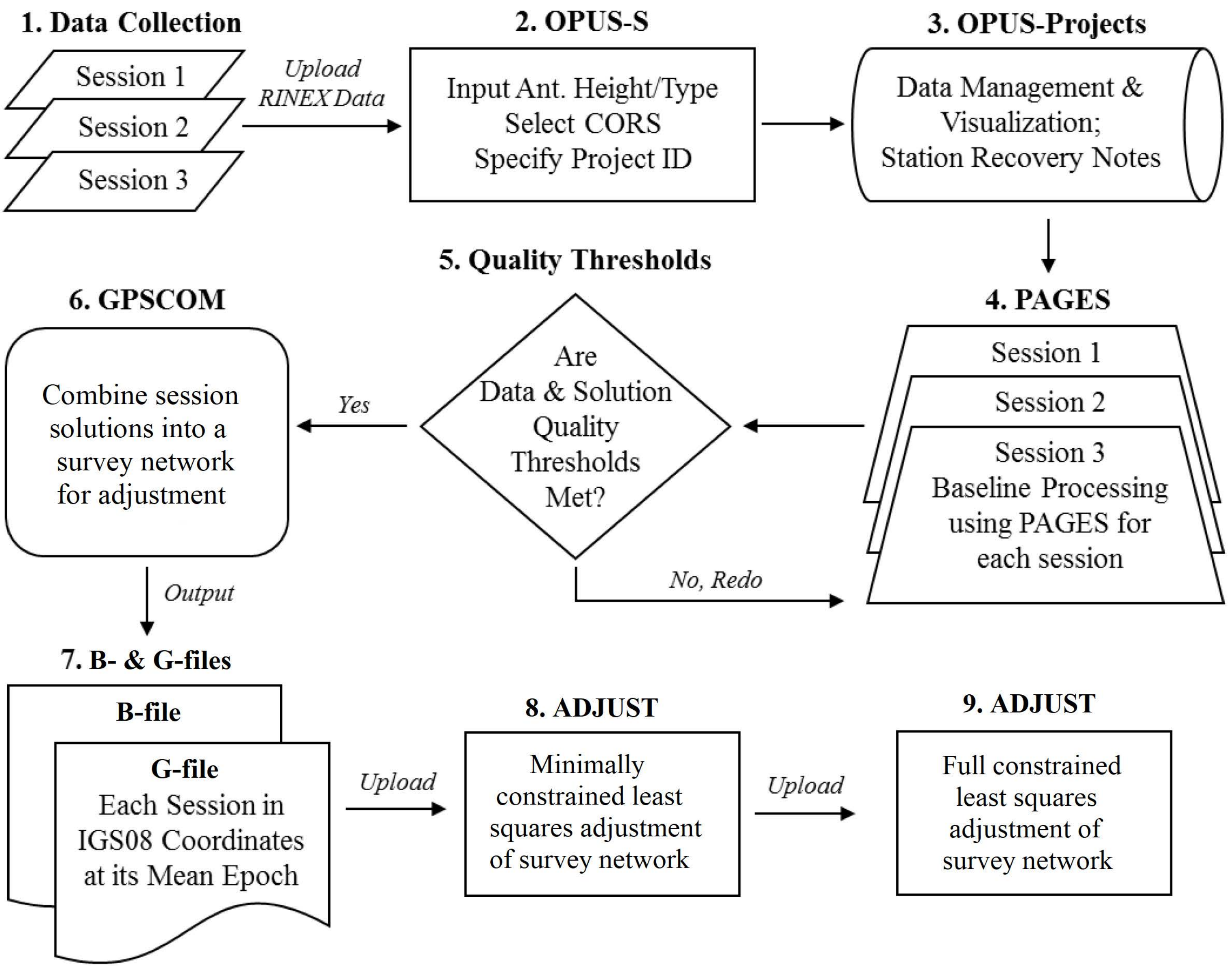
Fig. 7. Distribution of residual differences between *OPUS-Net* solutions and OP+ADJUST coordinates

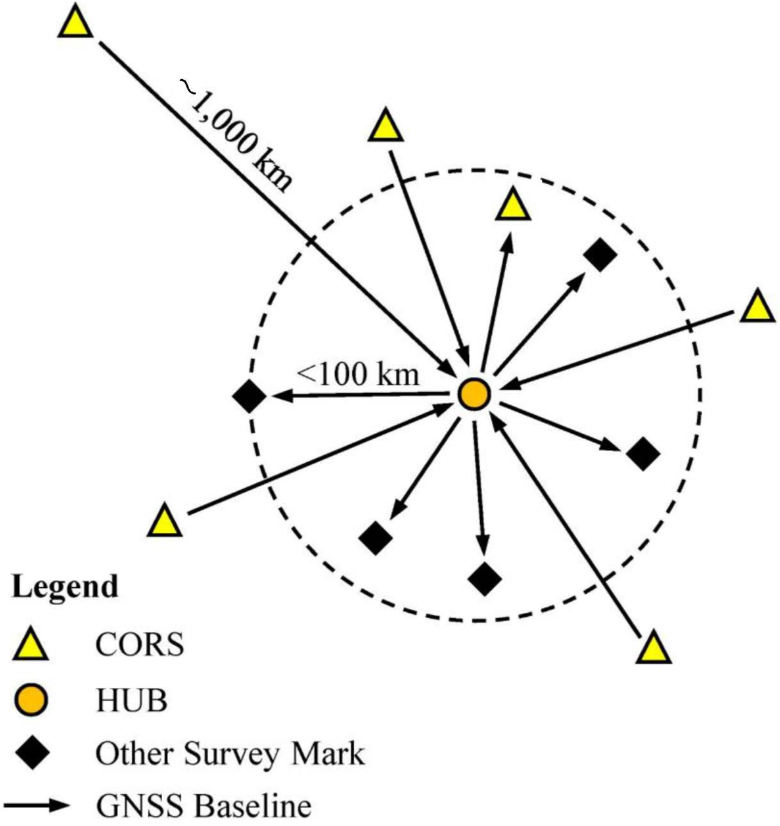
Fig. 8. Frequency of *OPUS-RS* aborted solutions, solutions with warnings, and solutions without warnings by observation duration.

Fig. 9. Distribution of residual differences between all *OPUS-RS* solutions (including solutions with warning messages) and OP+ADJUST coordinates

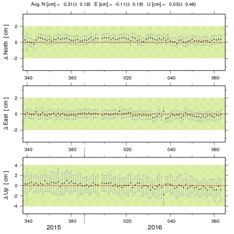
Fig. 10. Distribution of residual differences between only those *OPUS-RS* solutions without warning messages and OP+ADJUST coordinates

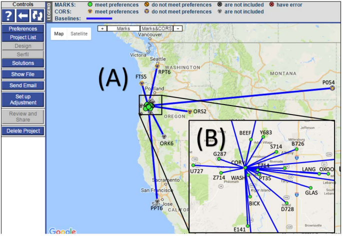
Fig. 11. Comparison of RMSE of solutions from *OPUS-RS*, *OPUS-S*, and *OPUS-Net*


1. Data Collection
Session 1
Session 2
Session 3
Upload
RINEX Data
2. OPUS-S
Input Ant. Height/Type
Select CORS
Specify Project ID
3. OPUS-Projects
Data Management &
Visualization;
Station Recovery Notes
4. PAGES
Session 1
Session 2
Session 3
Baseline Processing
using PAGES for
each session
5. Quality Thresholds
Are
Data & Solution
Quality
Thresholds
Met?
Yes
No, Redo
6. GPSCOM
Combine session
solutions into a
survey network
for adjustment
Output
7. B- & G-files
B-file
G-file
Each Session in
IGS08 Coordinates
at its Mean Epoch
Upload
8. ADJUST
Minimally
constrained least
squares adjustment
of survey network
Upload
9. ADJUST
Full constrained
least squares
adjustment of
survey network


~1,000 km
<100 km
Legend
CORS
HUB
Other Survey Mark
GNSS Baseline

RPT6 in US-WA: Daily minus Published IGS08 Position




Controls
Preferences
Project List
Design
Serfil
Solutions
Show File
Send Email
Set up Adjustment
Review and Share
Delete Project
LEGEND
MARKS:
meet preferences
do not meet preferences
are not included
have error
CORS:
meet preferences
do not meet preferences
are not included
Baselines:
Map
Satellite
Marks
Marks&CORS
(A)
(B)
RPT6
FTS5
P054
ORS2
ORK6
PPT6
BEEF
Y683
S714
B726
G287
CORV
T714
U727
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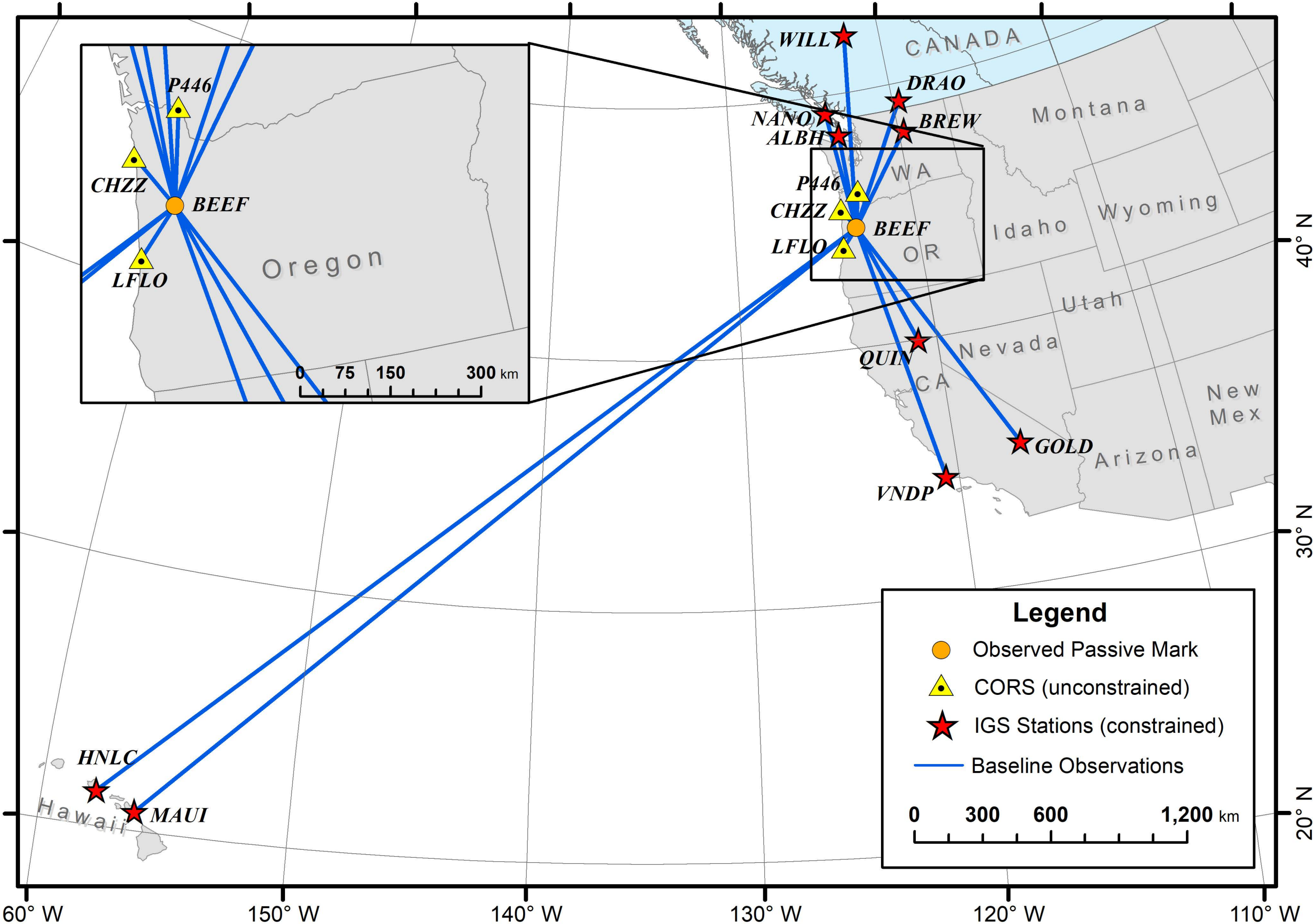
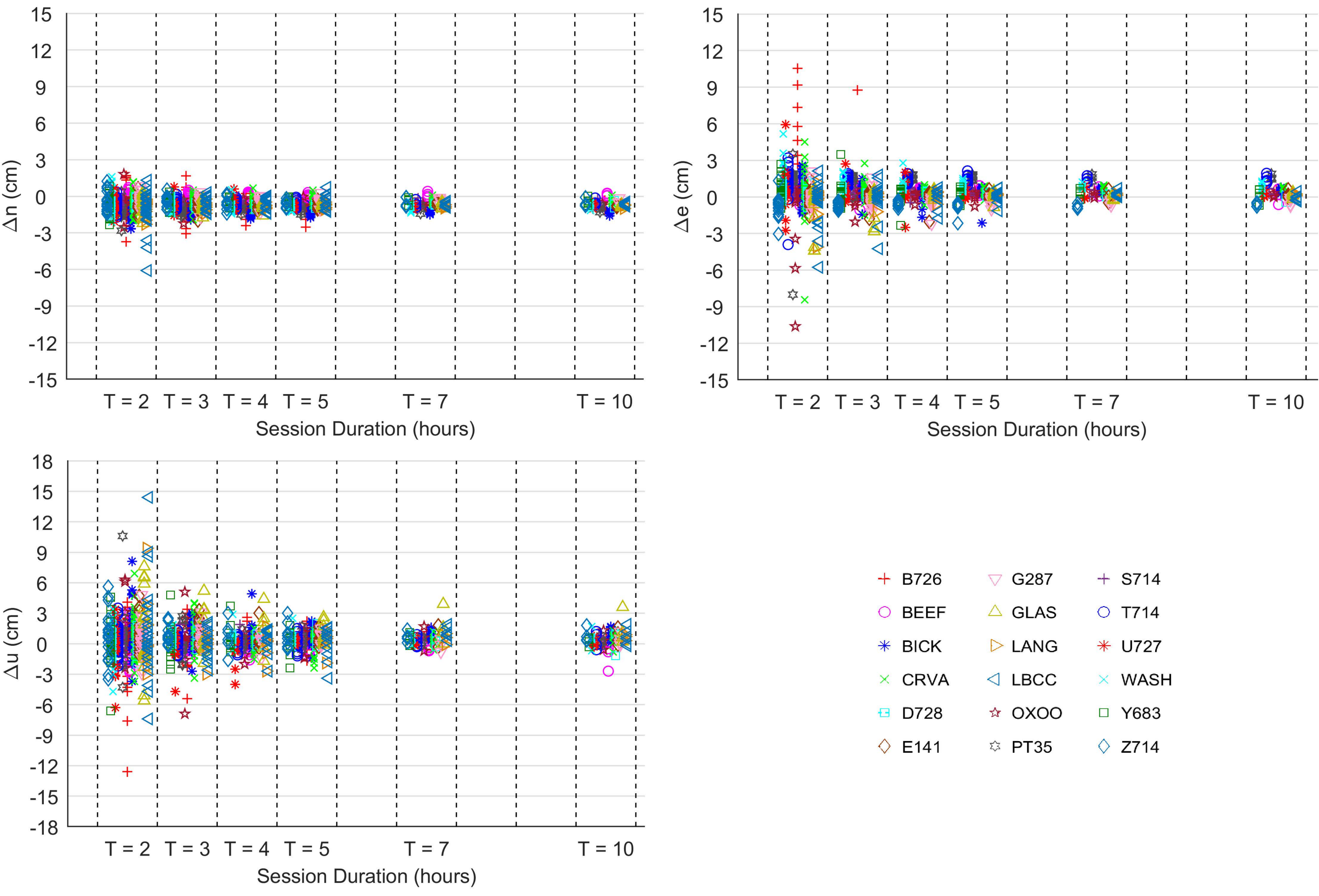
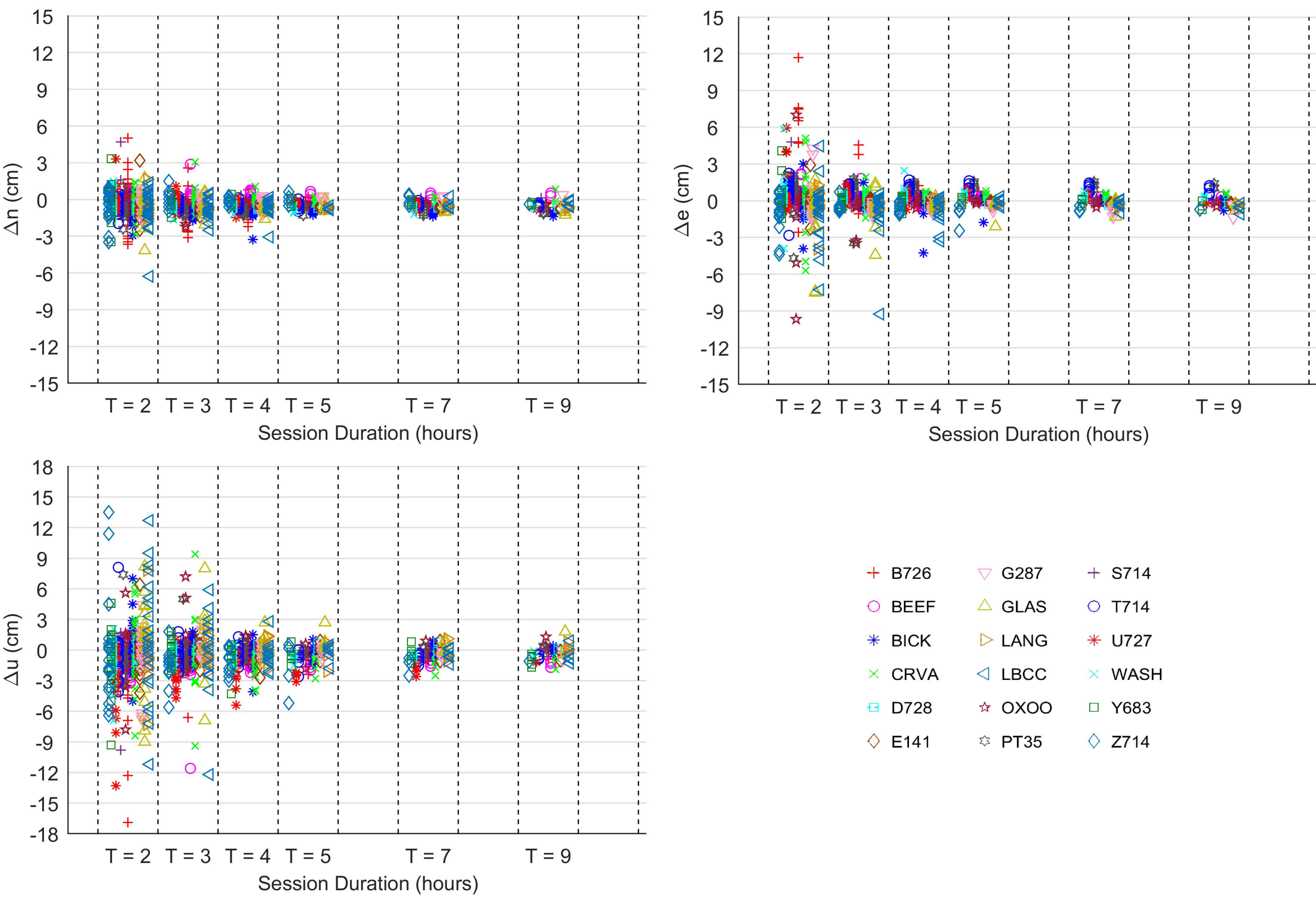
LANG
OXOO
GLAS
BICK
D728
E141

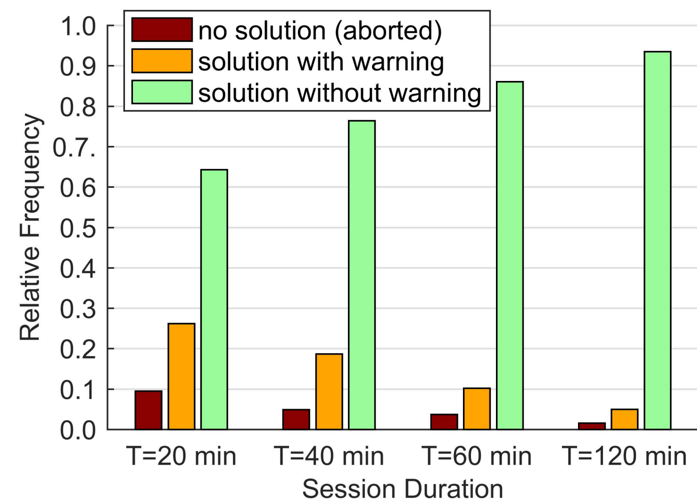


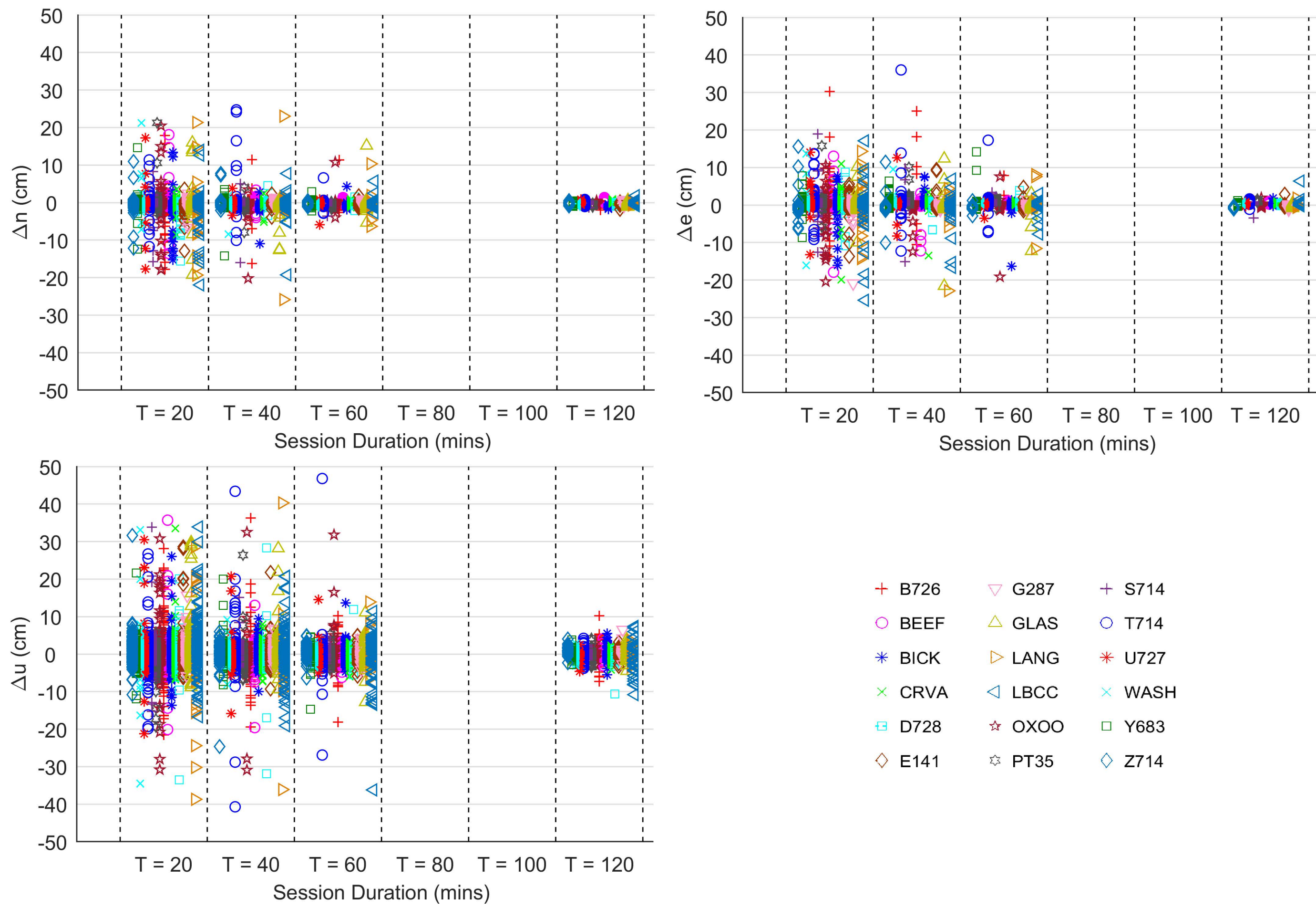
WILL
CANADA
DRAO
NANO
BREW
ALBH
Montana
P446
CHZZ
BEEF
LFLO
WA
OR
Idaho
Wyoming
Utah
Nevada
QUIN
CA
GOLD
VNDP
Arizona
New Mex
Oregon
0 75 150 300 km
HNLC
MAUI
Hawaii
Legend
Observed Passive Mark
CORS (unconstrained)
IGS Stations (constrained)
Baseline Observations
0 300 600 1,200 km
160° W
150° W
140° W
130° W
120° W
110° W
40° N
30° N
20° N



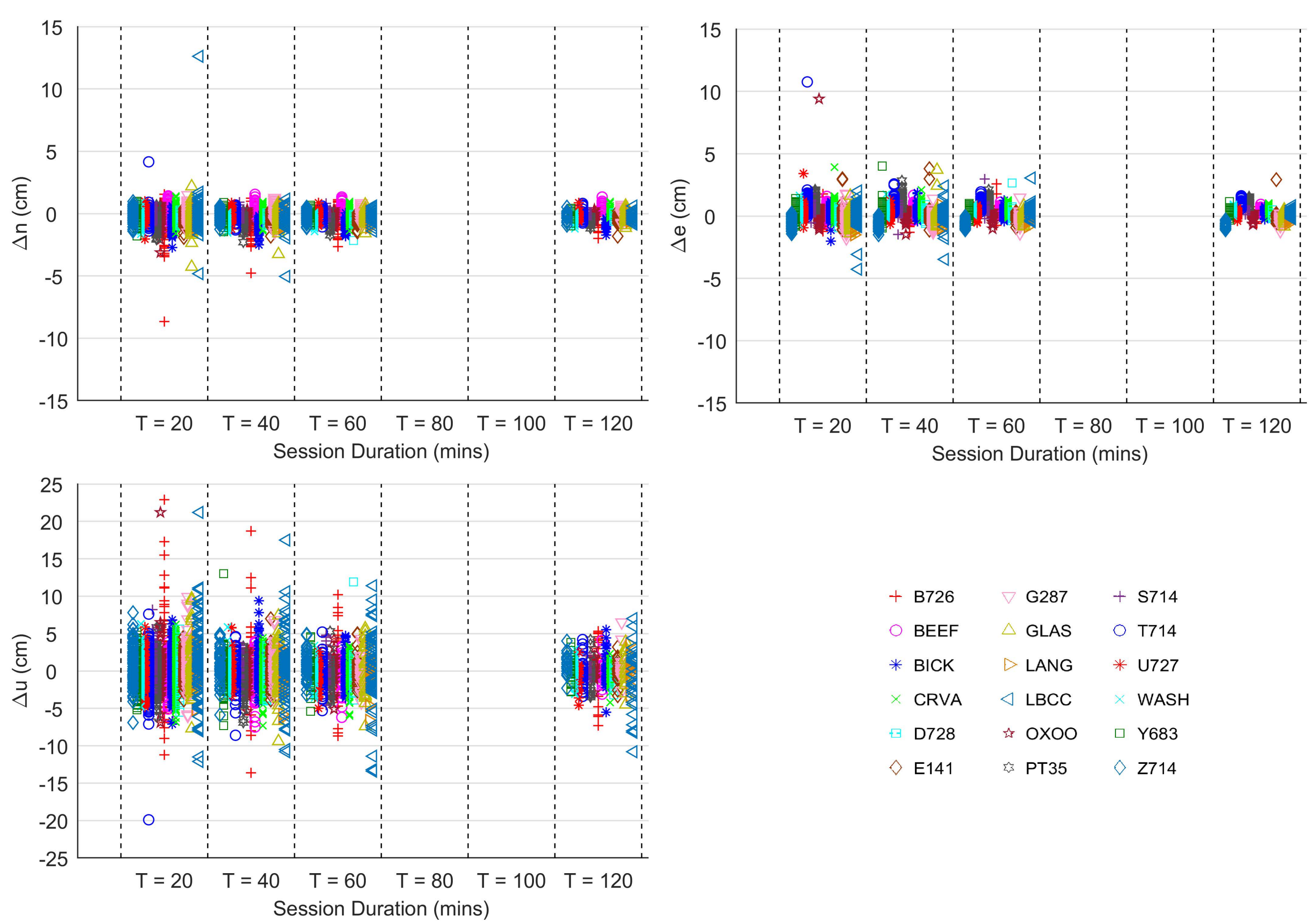
Δn (cm)
Δe (cm)
Δu (cm)
T = 2
T = 3
T = 4
T = 5
T = 7
T = 10
Session Duration (hours)
B726
BEEF
BICK
CRVA
D728
E141
G287
GLAS
LANG
LBCC
OXOO
PT35
S714
T714
U727
WASH
Y683
Z714

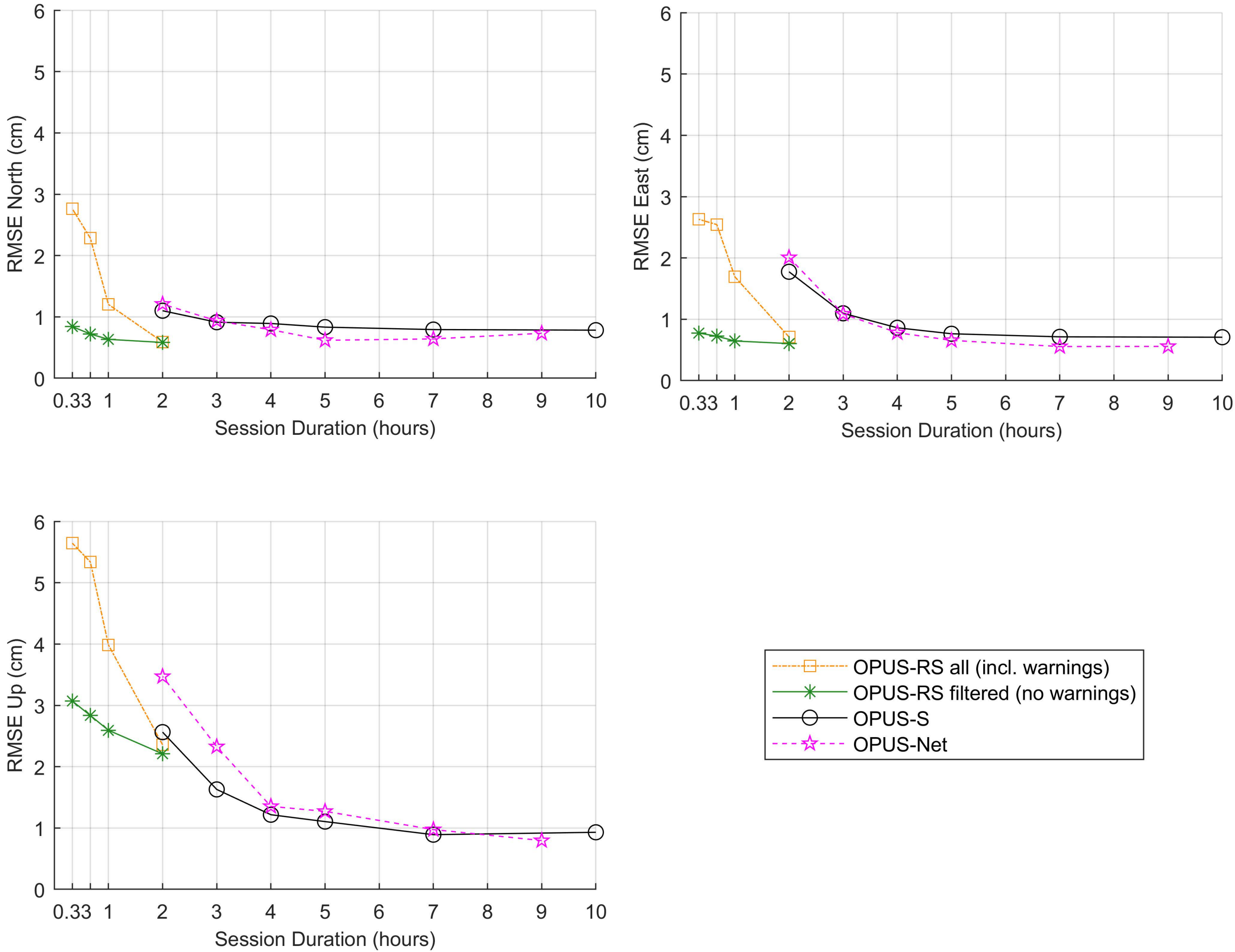

Δn (cm)
Δe (cm)
Δu (cm)
T = 2
T = 3
T = 4
T = 5
T = 7
T = 9
Session Duration (hours)
B726
BEEF
BICK
CRVA
D728
E141
G287
GLAS
LANG
LBCC
OXOO
PT35
S714
T714
U727
WASH
Y683
Z714


no solution (aborted)
solution with warning
solution without warning
Relative Frequency
1.0
0.9
0.8
0.7.
0.6
0.5
0.4
0.3
0.2
0.1
0.0
T=20 min
T=40 min
T=60 min
T=120 min
Session Duration



Δn (cm)
Δe (cm)
Δu (cm)
50
40
30
20
10
0
-10
-20
-30
-40
-50
T = 20
T = 40
T = 60
T = 80
T = 100
T = 120
Session Duration (mins)
B726
BEEF
BICK
CRVA
D728
E141
G287
GLAS
LANG
LBCC
OXOO
PT35
S714
T714
U727
WASH
Y683
Z714


Δn (cm)
Δe (cm)
Δu (cm)
T = 20
T = 40
T = 60
T = 80
T = 100
T = 120
Session Duration (mins)
B726
BEEF
BICK
CRVA
D728
E141
G287
GLAS
LANG
LBCC
OXOO
PT35
S714
T714
U727
WASH
Y683
Z714



RMSE North (cm)
RMSE East (cm)
RMSE Up (cm)
Session Duration (hours)
0.33
1
2
3
4
5
6
7
8
9
10
OPUS-RS all (incl. warnings)
OPUS-RS filtered (no warnings)
OPUS-S
OPUS-Net