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An examination of GNSS positioning under dense conifer forest canopy in the Pacific Northwest, USA

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ABSTRACT

Accurate positioning in the forest (e.g., less than 1–2 m horizontal error) is needed to leverage the potential of high-resolution auxiliary data sources such as airborne or satellite imagery, lidar, and photogrammetric heights used in forest monitoring. Unfortunately, typical short duration occupations in the forest with budget Global Navigation Satellite System (GNSS; GPS is the American constellation) receivers are generally inaccurate (horizontal errors >5–20 m). This study demonstrates that accurate GNSS positioning is feasible beneath 40 to 60 m-tall closed-canopy conifer forests of western Washington state, USA by using survey-grade receivers with at least 15-min occupations. We also demonstrate the effects of receiver height, occupation duration, base-station distance, and differential post-processing modes (e.g., autonomous, code, fixed-integer, and floating-point) on horizontal positioning accuracies in the forest.

A geodetic survey was our benchmark for accuracy estimation but is difficult to replicate by most other GNSS users in the forest. The difficulty in setting up a geodetic survey has led to common usage of naïve accuracy estimators based on within-occupation coordinate variation (e.g., the "accuracy" reported on the face of a handheld GNSS device). In this study we demonstrate the efficacy of two simple alternatives that outperform the naïve estimator; the naïve esimator was shown to perform poorly.

The findings in this study on GNSS performance and positioning accuracy estimation supports more effective use of GNSS technology in applications that require high-performance GNSS positioning in the forest.

1. Introduction

Accurate field-plot coordinates are needed to align field measurements with modern high-resolution remote sensing data (e.g., lidar) for the purpose of improving forest estimation and mapping (Andersen et al., 2022). Auxiliary information paired with in-situ forest measurements can enable both mapping and estimation capabilities which support a wide variety of forest monitoring objectives, such as fuel conditions (Mauro et al., 2021), carbon and biomass (Mauya et al., 2015), bole volume (Strunk and McGaughey,

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2023), and habitat parameters (Garabedian et al., 2018). Unfortunately, the same trees that we often wish to characterize with maps and estimates are also an impediment to the GNSS signals used for positioning (e.g., Gobakken and Næsset, 2009). For example, 1-hour occupations with survey-grade GNSS receivers, which are nominally expected to obtain better than 2 cm accuracies in the open, were demonstrated to only achieve ≈ 80 cm accuracy in a typical Pacific northwest USA forest forest (McGaughey et al., 2017). The recreational- and resource mapping-grade receivers commonly employed in forestry fare demonstrably worse than survey-grade receivers, with observed horizontal accuracies on the order of 5–20 m of horizonal error (e.g., Strunk et al., 2019; McGaughey et al., 2017; Frank and Wing, 2014).

In recent years, the information available from remote sensing has improved with respect to its ability to characterize vertical forest structure, e.g., lidar and photogrammetry from various platforms such as satellite (Zhang et al., 2022; Puliti et al., 2020), airplane (Puliti et al., 2020; Shoot et al., 2021), unmanned airborne vehicle (UAV; Cabral et al., 2023; McGaughey et al., 2024), and ground-based platforms (Gollob et al., 2020). We have also seen increased horizontal and vertical resolutions (e.g., 100s–1000s of points per square meter and cm-level ground sample distances or GSDs), and increased temporal resolutions such as daily Planet satellite imagery (Pascual et al., 2022) and sub-weekly lidar scans (Shcherbacheva et al., 2024). However, to obtain the most value out of high-resolution auxiliary datasets, the locations of field plots must be known with higher accuracy than is typically achieved with recreational- and resource mapping-grade GNSS receivers.

Increased positioning accuracy can have a substantial effect on integration with auxiliary information, enabling more accurate mapping, and improved estimation performance. For example, McRoberts et al. (2018) compared the results for the USA National Forest Inventory (NFI) nominal subplot coordinates (they did not use high-performance GNSS at that time) with those from survey-grade GNSS and found that the coarse locations had a dramatic 20% increase in model RMSE values. This is equivalent to a 30% reduction in efficiency. In other words, the use of coarse plot locations would be equivalent to losing 30% of field plots. Studies by Mauro et al. (2011), Frazer et al. (2011), Pascual et al. (2020), and (Gobakken and Næsset, 2009) also demonstrated deleterious effects of poor positioning accuracy on forest inventory. The study by Frazer et al. (2011) which simulated increased positioning error up to 5 m suggested that positioning errors on the order 1–2 m were acceptable for aligning lidar data with field measurements.

In contrast to high-spatial resolution remote sensing, there is a common expectation that poor quality field plot positioning is not problematic for low-resolution auxiliary information such as Landsat or Sentinel images. However, a simulation study based on USA NFI plots found that for typical levels of positioning error associated with recreational-grade GNSS receivers (the standard for USA NFI subplot coordinates at the time of the study in the early 2000's), that between 32% and 57% of plots would be misclassified or assigned to an incorrect environmental condition (McRoberts, 2010). Depending on the biome, the misclassification of pixels could have considerable implication on mapping quality and estimation efficiency.

In the United States, the NFI is conducted by the US Forest Service's Forest Inventory and Analysis program (FIA; Bechtold and Patterson, 2005). FIA collects, analyzes, and reports information on the status and trends of America's forests using a network of over 100,000 forested permanent sample plots. Tree measurements on NFI plots primarily come from a cluster of four 168 m^2 (7.3 m radius) circular subplots (small and large diameter trees may be measured on different sized nested areas). The clustered sample design is efficient from a sampling perspective, but it increases the need for accurate subplot coordinates due to the small areas of each subplot. For example, a nominal positioning accuracy of 10 m (e.g., recreational-grade GNSS) would result in only 20 percent overlap between remote sensing and NFI field measurements. With high-resolution, high-accuracy remote sensing data becoming widely available, accurate plot locations are needed to effectively link NFI field measurements with high-resolution auxiliary information. FIA has piloted the use of more accurate subplot locations since at least 2014 in the Pacific Northwest (PNW) FIA region (Andersen et al., 2022) and recently has begun rollout of survey-grade receivers to position all subplot centers for all forested NFI plots nationwide. The protocol requires survey-grade GNSS receivers, use of a tripod placed at the subplot center, a minimum of 15-min occupations (longer encouraged), and differential post-processing of GNSS files. However, there is still uncertainty in how field measurement and post-processing protocols affect positioning accuracies in forested conditions.

The added difficulty in GNSS positioning in the forested environment has been appreciated since at least the late 1980s (Ashjaee et al., 1989; Gerlach and Jasumback, 1988). Obtaining accurate plot positions under the forest canopy has proven to be a difficult endeavor, with numerous studies demonstrating the difficulty of GNSS positioning in forests around the globe (Shannon, 1992; Dominy and Duncan, 2002; Hasegawa and Yoshimura, 2003; Pirti, 2005; Andersen et al., 2009; Grala and Brach, 2009). Research has looked at numerous factors including receiver height (Brach and Zasada, 2014), occupation duration (Frank and Wing, 2014; Andersen et al., 2009; McGaughey et al., 2017), effects from forest attributes such as basal area (Frank and Wing, 2014; Bettinger and Merry, 2012), different processing modes (Grala and Brach, 2009), types of receivers (Andersen et al., 2009; McGaughey et al., 2017; McRoberts, 2010), distance to GNSS base station, effects of weather and topography, and various processing algorithms.

Unfortunately, much of the research on GNSS accuracy in the forest has focused on receiver technologies (especially recreational- or mapping-grade receivers) and protocols (especially short occupations) without the ability to achieve submeter accuracy in tall (>40 m) closed canopy forests, such as are common in the PNW region of the USA. Studies with mapping- and recreational-grade receivers in these conditions have typically seen accuracies in the range of 2–20 m in PNW for these types of receivers (Frank and Wing, 2014; McGaughey et al., 2017). The results from Andersen et al. (2009) and McGaughey et al. (2017) suggest that survey-grade receivers have the highest chance of achieving accuracies suitable for integration with forest monitoring data. Based on the current state of research on GNSS accuracy in the forest, there is a need to better understand the effects of data collection protocols (receiver height and occupation duration) as well as post-processing protocols (base station distance, number of base stations, and processing mode) on survey-grade GNSS receiver positioning accuracy.

A further impediment to effective GNSS usage by the forestry community is the difficulty in evaluating GNSS accuracy in the forest. The most common (and incorrect or "naïve") approach to evaluate GNSS accuracy is to use the positioning statistics reported, e.g., on the face of the device or in the output reports of post-processing software. These "naïve" accuracy estimators do not involve comparison with a benchmark or known survey monument, they instead rely on the variation among GNSS positions for a static position over a period of time. Unfortunately, while convenient, using this GNSS position internal variation as a naïve surrogate for accuracy is problematic because variation alone may have little agreement with actual positional accuracy. Andersen et al. (2009) and McGaughey et al. (2017) suggest that these naïve accuracy estimation approaches provide little or no information about receiver or positional accuracy. Furthermore, the most reliable method of accuracy estimation, comparison with a survey traverse, is typically impractical to implement for the great majority of forestry GNSS users.

One strategy to improve GNSS positioning protocols by the forestry community is to describe and evaluate simpler and reduced-cost accuracy estimation protocols that may be used to more easily evaluate GNSS accuracy by a broad community of GNSS users. We describe accuracy estimation protocols that are simpler to implement than traditional geodetic surveys, substantially reducing costs and barriers to usage, but they do have some practical limitations that are described in the methods section. The simplified protocols involve either repeated occupation of the same location at different points in time, or measuring the distances (e.g., with a laser range finder) between two field monuments and comparing field distances with GNSS distances.

Another strategy to improve the effectiveness of GNSS implementation in support of forest inventory and monitoring has been for a research body to commit to checking the accuracies of various types of receivers marketed to the forestry community. For instance, the USDA Forest Service Missoula Technology and Development Center (MTDC; USDA Forest Service Global Positioning System: MTDC Accuracy Reports, 2024) has evaluated nearly 200 receivers against survey monuments, the gold standard for positioning accuracy assessment. Their current evaluation protocols are geared towards short occupations, typically with budget receivers, and typically without post-processing. This focus makes sense practically because, arguably, the bulk of forestry GNSS consumers do not require high-performance positioning, but unfortunately it is not ideally suited for our application that requires accurate plot positions (better than 1-m median horizontal error) in the forest. The MTDC Accuracy Reports could be invaluable for users that do not require high-performance GNSS and can serve as a template for evaluation of high-performance GNSS positioning in the forest.

The objective of this study is to improve our understanding of high-performance GNSS positioning accuracy in the forested environment, especially the particularly difficult tall, dense conifer forests of the PNW USA. We specifically address the following three aspects of positioning accuracy in this environment:

1. Performances of both naïve and simplified accuracy estimators relative to the benchmark of geodetic survey-based accuracy estimation

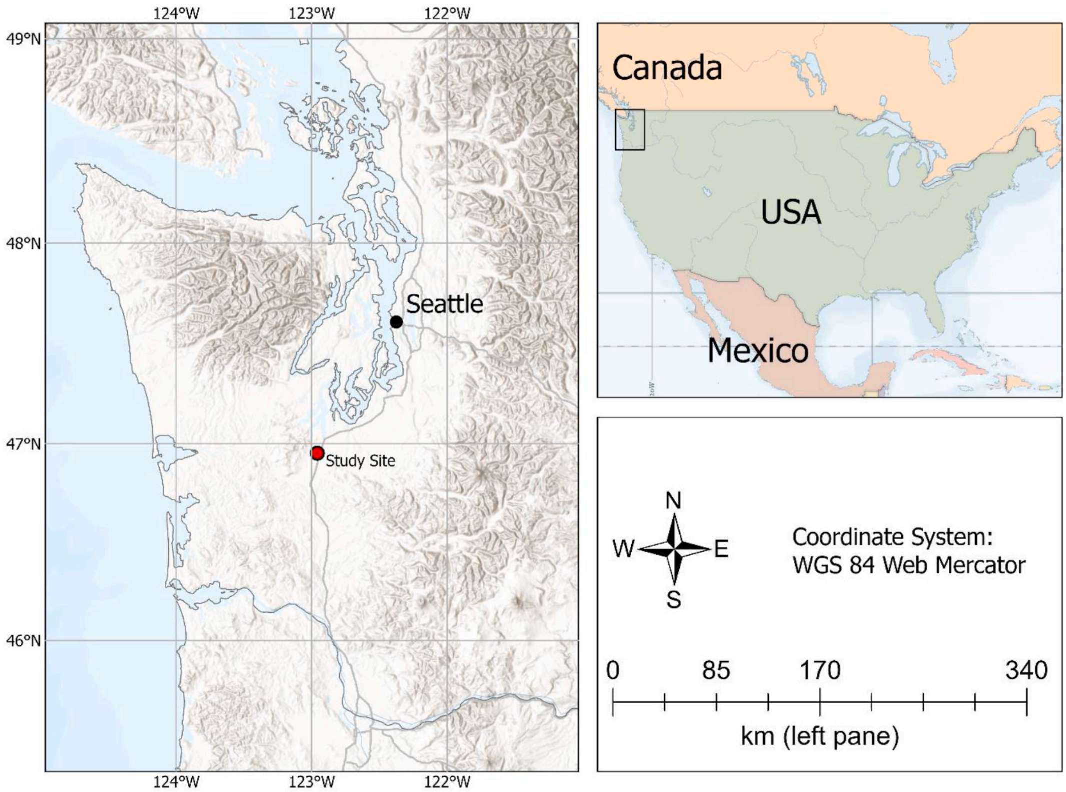

Fig. 1. Location of study area in western Washington state in the northwest conterminous USA.

2. Effects of GNSS data collection protocols, GNSS receiver height, and occupation duration on survey-grade GNSS receiver positioning accuracy
3. Effects of post-processing, base station distance, number of base stations, and processing mode on survey-grade GNSS receiver positioning accuracy.

These contributions enable a broad forestry audience to more reliably achieve high-performance plot positioning, even in some of the most difficult forested environments. In addition, the flexibility provided by the alternative accuracy estimators will further enable users to tailor their equipment and protocols to their own applications in a wide range of forested conditions. Finally, our findings further demonstrate the need for the forestry community to steer away from the inaccurate naïve types of horizontal accuracy estimators, which are commonly used and reported in the literature for lack of convenient alternatives.

This study uses horizontal positioning accuracy thresholds motivated by the PNW-FIA program (Andersen et al., 2022): 1) less than 1 m median horizontal error and 2) better than 2 m 95th percentile error. These statistics provide both a measure of central tendency, and an indication of the breadth of the distribution of horizontal errors. These statistics are also easily interpretable: the proportions of sample observations (50% and 95% respectively) that fall beneath the calculated values. A review of the literature suggests that at these thresholds there will be minimal impact on estimation and mapping of forest attributes when integrating high-resolution auxiliary information into forest inventory and monitoring. While the forestry literature commonly uses mean horizontal error, this metric can be quite unstable because it is very sensitive to even a single outlier. The horizontal root mean square error (HRMSE) is another commonly used metric, where RMSE is convenient in statistics because it is used in formulae for confidence intervals, but it is difficult to interpret practically in the context of positioning errors.

2. Methods

2.1. Study site

The study site is a small block (1.3 ha) of typical western-Washington state (USA; Fig. 1) coniferous forest on the southern half of the Olympia Forestry Sciences Laboratory campus. It is a topographically flat, primarily Douglas-fir (*Pseudotsuga menziesii* Mirb. Franco) dominated, stand with interspersed Western Hemlock (*Tsuga heterophylla* Raf. Sarg.), Western Redcedar (*Thuja Plicata* Donn ex D. Don), and other minor species. It is a closed-canopy forest with upper canopy trees typically in the 40–60 m range (see Figs. 2 and 3). The small patch of forest is surrounded on four sides by predominantly non-forest conditions.

2.2. Geodetic survey

Survey monuments from a geodetic survey were used as benchmarks for accuracy (Fig. 3). Points were surveyed with a total station and then tied into monuments established using long GNSS occupations (>1 h) with survey-grade receivers (horizontal error <2 cm expected in the open) for the two open-sky points (black points) in Fig. 3 with a 7 cm misclosure error that was distributed back to the traverse. In addition, there were a series of points clustered on the west side of the traverse that were collected with side-shots to each point (not part of the closed traverse). The surveyed coordinates of these side shots were also used as survey control for GNSS accuracy estimation. Between the GNSS positioning and survey traverse, we expect positioning errors in the control data on the order of 10 cm or

Fig. 2. Photos taken horizontally and vertically from the interior of the study area.

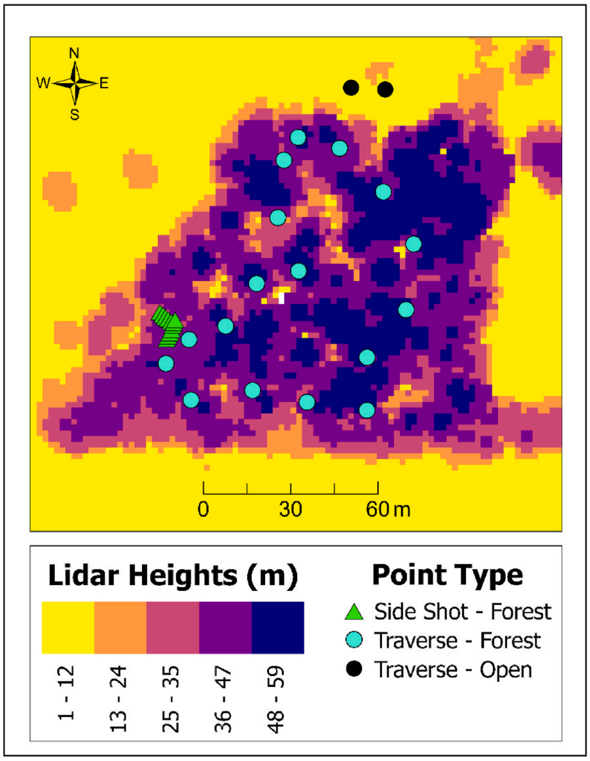

Fig. 3. Locations of survey points used as reference points for GNSS occupation accuracy evaluation overlaid on lidar height map (2 m ground sample distance).

better. This magnitude of error (10 cm) is roughly one-tenth of the magnitude of the positioning errors that we are aspiring to achieve with GNSS occupations in the forested environments.

2.3. GNSS data collection

A total of six separate sets of GNSS datasets were collected on each survey monument (Fig. 3) in the summer of 2018 using survey-grade (horizontal error <2 cm in the open) Javad Triumph 2 receivers (Table 1). Five of the datasets were collected for at least 15 min on each survey monument and one dataset was collected for at least 60-min on each survey monument. GNSS files were collected with a 1-second epoch rate.

To evaluate the effects of occupation duration on positioning accuracies, the original 15- and 60-minute occupation durations were clipped to exactly 1, 5, 10, and 15 minutes. The 60-minute occupations were also clipped to exactly 30, 45, and 60 minutes.

2.4. GNSS post-processing

Javad GNSS Justin 3 software was used to differentially correct GNSS occupations using a variety of processing modes described in Table 2. These processing modes are described in GNSS literature, but their implementation may be specific to Javad. Using these modes in other software will, most likely, not yield identical positions as those obtained with the Javad software. There are modes that are unique to Javad, including the “auto” and the “L1-only” modes, described in greater detail in Table 2. GNSS post-processing

Table 1
Summary of data collected with survey-grade Javad Triumph 2 receivers in the summer of 2018. Data for a particular dataset below may have been collected on multiple days throughout the summer.

Height (m)	Duration (min)	Receiver	Obs. Count
0	15	Triumph 2	29
0	15	Triumph 2	31
1.2	15	Triumph 2	30
1.2	60	Triumph 2	31
1.5	15	Triumph 2	31
2.7	15	Triumph 2	31

Table 2
Summaries of various GNSS processing modes.

Mode	Description
Code phase ("code")	Positioning that uses the time codes transmitted by GNSS satellites to estimate pseudo-ranges (distances) to satellites (L1 and L2).
[a]Differential correction	Use of GNSS data from a reference base station on a monument with a known coordinate to aid in correcting for atmospheric distortions in GNSS signals.
[a]Carrier phase	GNSS positioning approach which enables centimetric or better positioning accuracy. It uses the phase, or position on a single sine wave, to increase the resolution of the pseudo-range (distance to satellite) from the GNSS receiver. This approach uses either a "fixed-integer" or "floating-point" estimate of the count of the number of cycles to add to the phase measurement. Carrier phase processing is performed at the same time as differential correction in Javad software.
Fixed-integer ("fixed")	*(This term is not equivalent to a "satellite fix" which indicates a that a particular satellite signal is available to the receiver).* Carrier-phase processing approach in which an integer number of cycles (sine waves) is used to estimate the discrete number of cycles between the receiver and the satellite.
Floating point ("float")	Carrier-phase processing approach that uses a floating-point (continuous) approach to estimate the number of cycles between the receiver and the satellite (L1 and L2).
Auto	Javad-software specific processing mode which attempts to choose the best solution type from among fixed, float, and code solutions for a particular occupation (L1 and L2).
Autonomous	Autonomous positioning is simply the point average of all epoch-level coordinates using the code-phase pseudo-ranges and without differential correction (L1 and L2).
PPP	An autonomous positioning approach that uses improved satellite positions obtainable two weeks following GNSS survey to increase positioning accuracy (L1 and L2).
L1-only	In the Javad GNSS post-processing software, "L1-only" processing mode is equivalent to "auto", but uses only the L1 GNSS signal. The post-processing software does not have L1 only equivalents to "code", "fixed", and "float" processing modes exposed to the user.

[a] Not a processing mode in Javad software, but provides explanatory information needed for other approaches.

software typically also uses filters or logic that may not be transparent to the user and/or not described in the documentation. This proprietary logic and point filters, for example, affect which pseudo-ranges and epochs are considered sufficiently "good" to include in the final position calculation. These filters and logic are generally designed for GNSS positioning in the open and may not perform as well in the forested environment. Settings not visible to the user (filters and logic) can have a negative effect on the results, as is demonstrated in our results where we report positioning accuracy for various processing modes in the open versus in the forest.

Fig. 4. Example of field conditions encountered by an FIA field crew in Hawaii (2019) which are not conducive to installation of a geodetic survey for GNSS positioning accuracy tests.

2.5. Positioning accuracy

In this section we describe positioning accuracy estimation using four different approaches. The benchmark estimation approach for accuracy is comparison of rover GNSS coordinates with coordinates for geodetic survey monuments (“reference-point approach”). However, establishing a geodetic survey in real-world conditions (e.g., Fig. 4) is typically difficult and expensive. The second approach estimates point error using the within-point variance (labeled “naïve” accuracy estimation approach in this paper). The last two approaches: repeated rover-based accuracy estimation and reference-distance based accuracy estimation, are alternatives which do not require a geodetic survey.

Based on our review of relevant literature on GNSS positioning in forestry, horizontal positioning errors on the order of 1–2 m (e.g., Frazer et al., 2011, 645–648) are acceptable for aligning auxiliary high-resolution remote sensing data with field plots. In the context of FIA field plots, 1- and 2-m subplot positioning errors correspond to ≈ 91% and ≈ 83% areal overlap between field and remote sensing footprints, respectively. In the evaluation of field protocols and post-processing protocols, this study uses the magnitude of horizontal positioning accuracy to designate a positioning approach as “high-performance GNSS” (HPGNSS). Specifically, HPGNSS as defined here requires 1-m median horizontal error and better than 2-m 95th percentile error. Together, these criteria provide both a measure of central tendency and indicate the target error value in the upper tail of the distribution of horizontal errors. These statistics are also easily interpretable relative to some alternatives. While this study describes performance for a single receiver model in a small patch of forest, in practice to achieve HPGNSS positions one must consider the type of receiver used, the field protocol (especially epoch rate, duration, and receiver height), and post-processing protocol. These factors may also interact with field conditions (e.g., vegetation type and size, topography, rain or snow) to affect positioning accuracy.

2.5.1. Benchmark accuracy estimation

Arguably, the most credible approach to evaluate GNSS positioning accuracy is to compare GNSS rover positions with reference points in the forest that are expected to have (much) greater accuracy than the GNSS rover – typically the reference points are from a geodetic survey. Under forest canopy, the geodetic survey can be achieved by doing a closed survey traverse, perhaps with side shots. The survey traverse is then linked to known positions, e.g., long-occupation survey-grade GNSS monuments with an unimpeded sky view, or with cadastral survey benchmarks. In the reference-point approach to accuracy estimation, errors for individual rover positions are computed simply as the distances between the “true” coordinate (geodetic survey monument) and the GNSS position for some monument

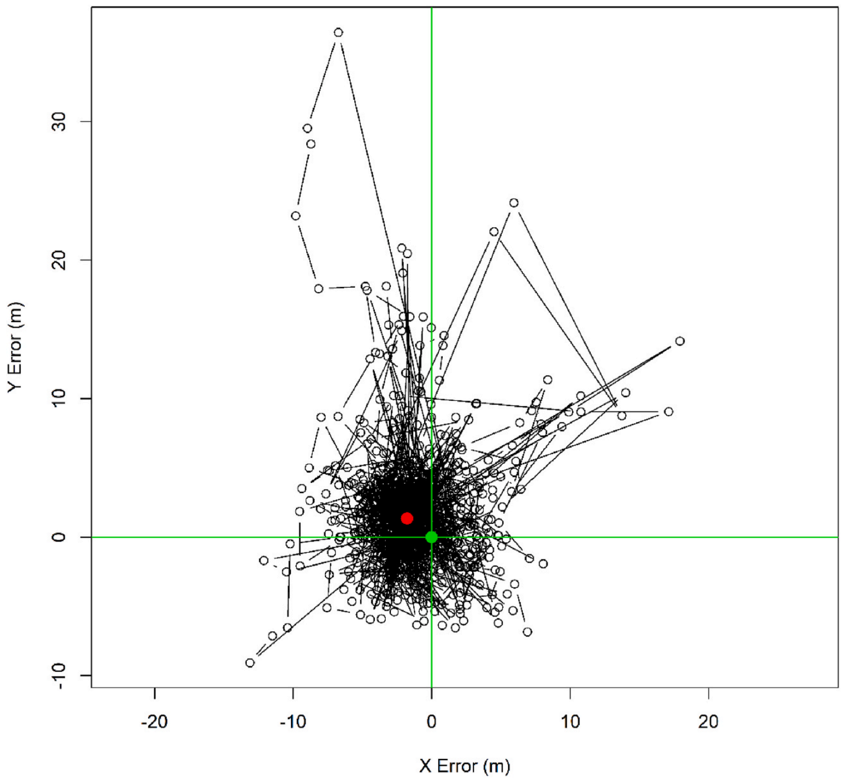

Fig. 5. Spatial distribution of 1-s epoch coordinate errors (black) and their median (red) for a single occupation relative to the “true” corresponding survey coordinate (green). Black lines connect sequential epoch coordinates.

$$e_i = \sqrt{(x_i - x_{0i})^2 + (y_i - y_{0i})^2} \tag{1}$$

e_i is horizontal error for monument i

x_i, y_i are rover GNSS coordinates for monument i

x_{0i}, y_{0i} are reference coordinates for monument i.

The distribution of errors can then be characterized in a number of ways, such as mean horizontal error, horizontal error percentiles, or horizontal mean squared error (HRMSE):

$$\text{HRMSE} = \sqrt{\frac{\sum_{i\in n} e_i^2}{n}}. \tag{2}$$

A limitation of the benchmark approach is the high cost, difficulty, and limited extent of geodetic traverses. The approach is effective in its ability to estimate the precision for one site, but it will not be very representative of the precision achieved across a broad range of sites and conditions. For example, to represent conditions across an entire state would require implementing tens of geodetic surveys with various canopy conditions. This approach to characterize GNSS positioning errors is not considered operationally viable for representing performances broadly across a wide range of forest conditions in most forest inventory applications. For this study, we placed a traverse in an accessible site that is representative of moderately difficult for HPGNSS positioning (closed canopy, multi-layered, 40–60 m height coniferous forest), but is not expected to represent the most difficult conditions; deep, narrow mountain canyons with tall dense forests in wet or snowy conditions are expected to be the most difficult in which to obtain GNSS positions.

2.5.2. Naïve accuracy estimation

Accurate GNSS positioning in the forest generally involves taking many GNSS positions over a period of time, e.g. 20 min, and using their average X, Y, and Z coordinates. This is also known as a GNSS occupation. Over that 20-min period, many GNSS coordinates are estimated for the occupation, e.g., 1-second intervals (Fig. 5), and are called 1-second epochs (0.01, 5, 10, 15, and 30-second epochs are also commonly used). In the naïve approach, the variations in coordinates from (e.g.) 1-second epochs around their mean are used to erroneously estimate accuracy, which is sometimes reported as "RMSE". In reality, such calculations are only standard deviations of the positions. Over such a short time period, the mean epoch coordinate is usually not sufficiently close to the true monument location to warrant use of the term RMSE. The naïve approach is common largely because it is easy to compute and the baseline reference-point approach is so difficult to implement.

The naïve approach to accuracy, e.g., with the Horizontal Root Mean Squared Deviation (HRMSD, although often incorrectly reported as Horizontal Root Mean Squared Error or HRMSE) shown in equation (3), is unfortunately a common approach used to characterize positioning error ("deviation" is used instead of "error", because "error" implies comparison with a known benchmark coordinate). Many GNSS users in forestry applications rely on naïve accuracy estimation to infer positioning accuracy both for receiver evaluations and to characterize GNSS positioning accuracy for receivers and individual GNSS occupations:

$$\text{HRMSD} = \sqrt{\frac{\sum_{i\in n} d_j^2}{n}} \quad d_j = \sqrt{(x_j - \bar{x})^2 + (y_j - \bar{y})^2} \tag{3}$$

d_j is deviation for the jth epoch collected on some point

x_j and y_j are coordinates for individual epochs

$\bar{x}, \bar{y}$ are the means of all x_j and y_j values respectively.

Nearly all consumer- and resource-grade receivers report naïve point-spread based estimates of positioning error, as do all post-processing software we have worked with. A limitation of this approach is that it only accounts for within-occupation variation, and not the bias of the spread. In Fig. 5 we can see that the naïve estimator is based on variation around the red point but would not account for bias (distance to green point) if collected for a short period of time (e.g., <2 hours). As a result, the naïve approach may not provide meaningful inferences about actual positioning accuracies. For example, one of the causes of positioning error is short-term systematic bias caused by satellite signal reflections off of trees (multipath and non line-of-sight signals, McGaughey et al., 2017) and atmospheric attenuation of GNSS signals. The naïve HRMSD, would not account for these sources of error. In addition, the sequential coordinates are correlated in time, and thus the software must account for temporal correlation in positions to be meaningful even for variance estimation. For a more detailed discussion of the mechanics of GNSS and its interaction with vegetation, there is a more thorough description of these topics in Andersen et al. (2022).

2.5.3. Repeated rover (2x) based accuracy estimation

Another approach to compute positioning errors is to simply return to the same monument on two separate occasions and collect two sets of rover data for the same point(s). The distances between two rover positions on some monument i collected at different points in time can be used to estimate horizontal error

$$\widehat{e}_{2x,i} = \sqrt{\frac{(x_1 - x_2)^2 + (y_1 - y_2)^2}{2}}$$

which can be generalized for two or more replications,

$$\widehat{e}_{mx,i} = \sqrt{\frac{m}{m-1} \times \left((x_j - \overline{x})^2 + \left(y_j - \overline{y}\right)^2 \right)}$$

$$j \in 2, .., m$$

a formulation that allows for any number m of repeated occupations on a single point. The $\widehat{e}_{2x,i}$ (or $\widehat{e}_{mx,i}$) values could then be used with any statistic used to characterize the error distribution such as mean horizontal error, error quantiles, or commonly, HRMSE (Eq. (2)), e.g.,

$$HRMSE_{2x} = \sqrt{\frac{\sum_{i \in s} \widehat{e}^2_{2x,i}}{n}}.$$

Unlike the reference-point approach, the error computed for a single point is only an *estimate* of the single point positioning error (instead of the observed error), which is why it has a hat.

The repeated-occupation (2x) approach is particularly relevant to the USA's NFI (Forest Inventory and Analysis National Core Field Guide, Volume I: Field Data Collection Procedures for Phase 2 Plots, 2021), in which a subset of permanent sample plots is re-measured in the field for accuracy assessment every year (the remeasured plots are called "quality assurance" or "QA" plots by FIA). At the time of repeated measurement, a new set of GNSS rover data files are also obtained. These repeated measurements with GNSS could be used with the repeated occupation (2x) approach to estimate GNSS accuracy associated within a region. The sampling intensity for QA plots is sparse, so the region of interest must be large, on the order of an entire western USA state (~180,000 km^2).

2.5.4. *Reference-distance based accuracy estimation*

The known distance between two GNSS rover points can also be used to estimate positioning accuracy when a geodetic survey is not feasible or convenient. In this approach the field-measured horizontal distance between two (perhaps temporary) monuments is compared with the distance computed from GNSS coordinates collected at each monument. The distance between two monuments can be measured with a tape and clinometer or, preferably, with a laser range finder. This approach does not require (but can use) a closed traverse or surveying instruments and does not require tying reference points into an established geodetic reference frame. This can also prove more convenient than the repeated occupation (2x) approach, since each point must only be visited a single time. A complication of this approach is that it does require accurate measurements of the distances between monuments (Fig. 6), which may not always be practical to obtain in dense vegetation, on steep or complex terrain, for long distances, or for one-person field crews.

The reference-distance based accuracy estimation approach first requires field measured distances, d_i, between two or more

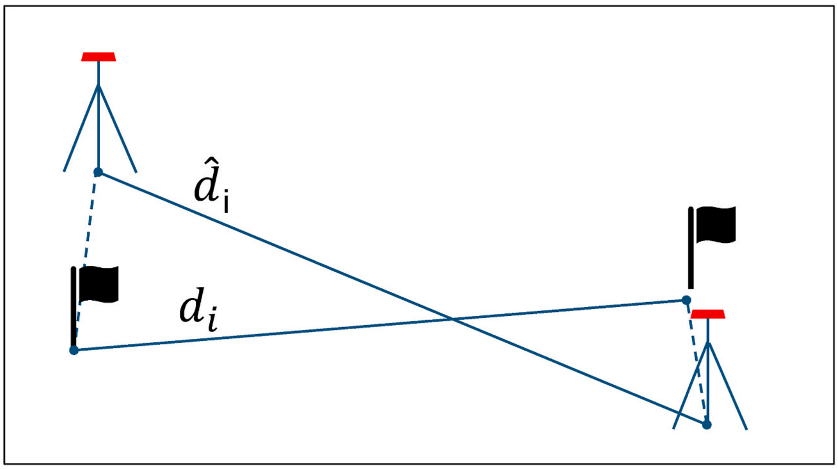

Fig. 6. Schematic of field- and GNSS-based distance measurements used to estimate horizontal accuracies. The true distance, $\boldsymbol{d_i}$, is measured in the field (distances between black flags) and compared with the apparent GNSS distance, $\widehat{\boldsymbol{d}}_i$, computed from the two corresponding GNSS occupations (distances between red GNSS receivers on survey tripods).

monuments. The field measured distances, d_i, are then compared to the GNSS based distances, $\widehat{d}_i$, between the same monuments, which allows us to estimate the positioning errors as

$$\widehat{e}_i = d_i - \widehat{d}_i.$$

Typical accuracy statistics such as mean horizontal error, horizontal error quantiles, and HRMSE are simply computed from the reference-distance based error estimates $\widehat{e}_i$. For example, the reference-distance based HRMSE is computed:

$$HRMSE_{dist} = \sqrt{\frac{\sum_{i \in s} \widehat{e}^2_{dist,i}}{n}}.$$

The reference-distance approach could be implemented in many ways. For example, a traverse or sets of paired observations distributed across a large area (e.g., Fig. 7). For this study, the reference-distance approach was implemented with the distances computed between adjacent monuments, which ranged from approximately 1 to 23 m apart. Adjacent points were generally collected within 30 min of each other, except when data collection was paused at the end of the workday and resumed on another day.

3. Results

3.1. Accuracy estimator performance

In this section we demonstrate performances for three alternative approaches to accuracy estimation which do not require a geodetic survey: 1) a naïve within-occupation-variation based accuracy estimator, 2) a repeat occupation (2x) accuracy estimator, and 3) a reference-distance based accuracy estimator. For each of these cases, the reference approach which compares GNSS coordinates with the geodetic survey coordinates serves as the benchmark for accuracy estimation. If there is a strong agreement between the benchmark accuracy and the alternative estimator accuracy estimators, then it suggests that the alternative accuracy estimation approach is effective. If they do not agree, then it suggests that the approach is not reliable and should not be used.

Accuracies for all processing and data collection configurations are compared for reference and naïve accuracy approaches in Fig. 8. These data indicated that there is little or no agreement between accuracies for the naïve approach and the benchmark reference-point approach. The vast majority of naïve 95th percentile horizontal error estimates are less than 4 m, while benchmark horizontal errors are broadly distributed between 0 and 10 m. Only 95th percentile errors are shown in Fig. 8 as the naïve median horizontal error and HRMSE are similarly uninformative. This suggests that the naïve accuracy estimation approach is not an effective accuracy estimation approach and should not be used to infer positioning accuracy from GNSS data, at least in in the forested environment.

Accuracies for the reference approach are compared with the repeat occupation (2x) approach in Fig. 9 and with the reference-distance approach in Fig. 10. In contrast to the naïve approach, both repeat occupation and reference-distance estimation approaches have strong agreement with the baseline reference-point accuracy approach for all three accuracy metrics. The point scatters are generally tightly scattered around the 1-1 line. Of the three horizontal error statistics reported in Figs. 9 and 10 (median, 95th percentile, and HRMSE), the agreement between reference and alternative horizontal error estimates are greatest for HRMSE. On the

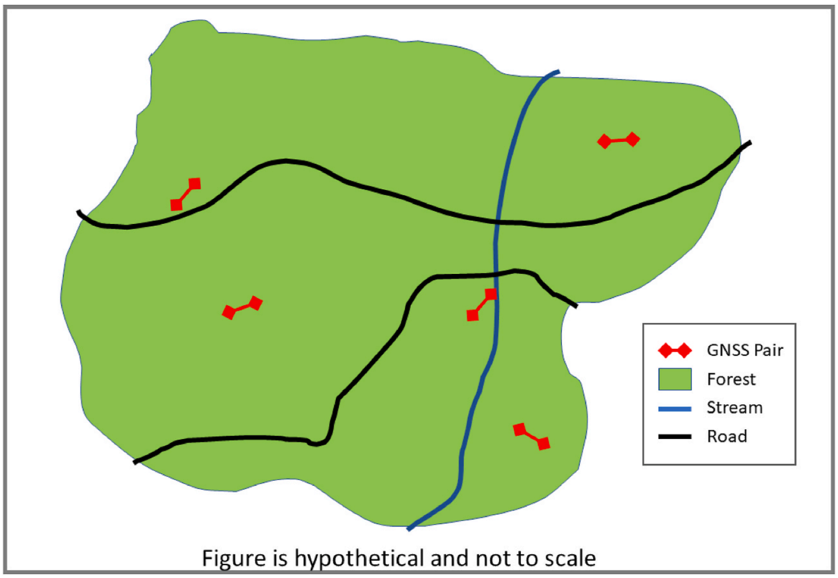

Fig. 7. Hypothetical spatial distribution of pairs of GNSS monuments spread across a variety of forest conditions.

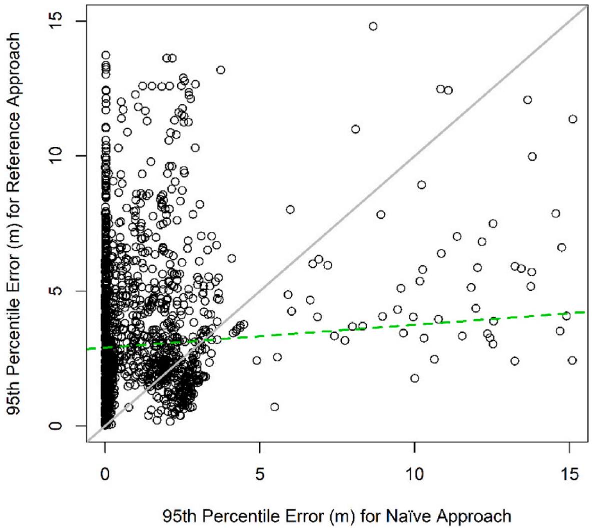

Fig. 8. Naïve accuracy estimation results for 95th percentile horizontal error relative to the benchmark reference point approach. Points are for individual GNSS occupations (1–60 min) with various processing configurations (base distance, number of base stations, processing mode). Solid gray line represents a 1-1 relationship, and the dashed green line represents the fitted line between values on x and y axes.

other hand, the 95th percentile and median horizontal errors are more interpretable with respect to distributional properties: estimates of 50th and 95th percentile horizontal errors. The median repeat occupation error (2x) error exhibits the greatest magnitude of bias (clustering on one side of the 1-1 line), but the bias is mild in the targeted accuracy range (0–2 m horizontal error) and represents a conservative, or over-estimation, of error, which is preferable to underestimation of expected errors. The high level of agreement between the benchmark horizontal accuracy approach and the two alternatives suggests that the repeat occupation (2x) and reference-distance based approaches can be used as more cost-effective alternatives to the benchmark approach.

The temporal arrangement of GNSS observations collected for this study is both sparse and clumpy (temporal arrangement not shown). This means these data are not ideally suited to estimate with fine temporal precision the number of hours needed between occupations to be able to effectively use the repeat occupation (2x) accuracy estimation approach. Due to the temporal limitations of the data, we binned accuracies into the coarse ranges 0–2 h and 2–12 h in Fig. 11, resulting in similar numbers of observations in each group (approximately 300). In the range of 0–2 h, it appears that there is temporal correlation between repeat occupations which causes a bias in accuracy estimates. This is evident from the fact that the fitted line between reference-point and 2x accuracies (green dotted line in Fig. 11) is above the 1-1 line, which, e.g., results in a 72 cm under-estimation bias for the 2x approach at 3 m versus the baseline reference-point approach. In the range of 2–12 h, there does not appear to be any temporal confounding of the 2x accuracy estimation approach. However, further data collection would be necessary with more precise temporal arrangement to effectively characterize the temporal correlation between GNSS positioning errors in time. Conservative guidance for use of the 2x accuracy estimator would be to wait at least 12 h between GNSS occupations. This recommendation works well with the FIA protocol for NFI plot QA measurements, which are typically measured on a different day than the original plot measurements.

3.2. Effects of processing and data collection configurations on accuracy

In this section the benchmark reference-point approach is used to evaluate a suite of post-processing and data collection configurations, primarily for the forested environment. The results are reported with custom boxplots that represent 95th percentile as the upper whisker, median as the central line on the box, and 5th percentile as the lower whisker. This implementation of whiskers is different from the “standard” boxplots that most readers are familiar with (whiskers at the minimum and maximum values) but is convenient in this case because it enables us to evaluate our target accuracy thresholds. For this analysis we set thresholds of 1 m for a target median horizontal accuracy, and 2 m as a target 95th percentile horizontal accuracy. These target accuracies represent thresholds that we expect, based on our experiences, to not contribute noise to area-based forest inventory modeling and estimation. To aid in our inferences, horizontal lines at 1 m and 2 m are superimposed on boxplots to show which combinations of processing and data collection configuration met our arbitrary thresholds. If the upper whisker falls below the 2 m line, and the central solid black line falls below the 1 m line, it suggests that the particular combination of processing and data collection configurations met our target accuracy thresholds.

3.2.1. Effect of processing mode on accuracy in open-sky and forest conditions

In Fig. 12 we can see the performance of various processing approaches when the base station is 160 km away from the GNSS rover and the receiver collects 15 min of data. For the open-sky condition, the fixed-integer processing approach is the most accurate approach, which agrees with generic GNSS guidance on differential correction: that fixed-integer processing is the most accurate

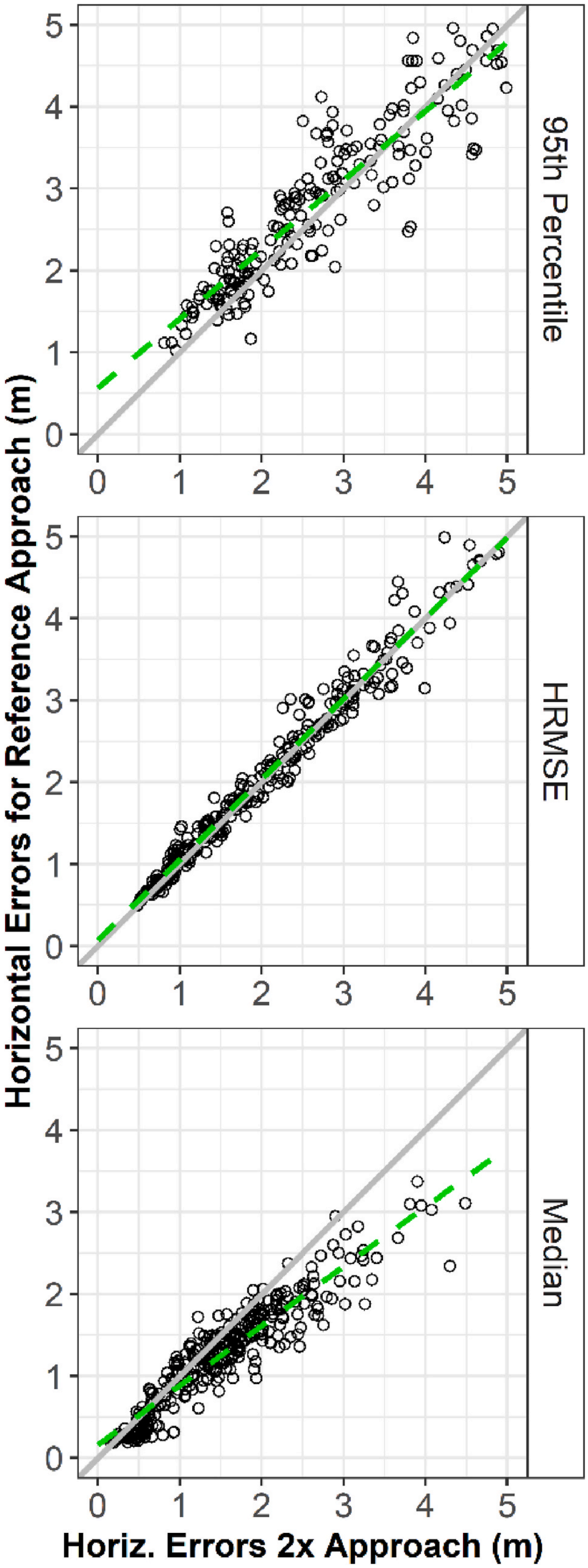
95th Percentile
HRMSE
Median
Horizontal Errors for Reference Approach (m)
Horiz. Errors 2x Approach (m)
0
1
2
3
4
5

Fig. 9. Comparison of HRMSE, 95th percentile error, and median horizontal error statistics for reference and repeated occupation (2x) approaches. Points are for individual GNSS occupations (1–60 min) with various processing configurations (base distance, number of base stations, processing mode). Gray solid lines represent a 1-1 relationship, and the dashed green lines represent the fitted lines between values on y and x axes. Data were clipped to a 0–5 m range.

approach, although in our case fixed, float, L1-only, auto, and Precise Point Positioning (PPP) had similar accuracies. Note that the PPP solution is an autonomous solution that does not utilize base station position data but rather GNSS satellite clock and orbit corrections collected at global reference stations. In contrast, in the forested condition with a 160 km base station, the L1-only processing mode is the most accurate approach, and it is demonstrably better than other processing approaches. At this base distance, the L1-only approach is the only approach that meets both of our target accuracy metrics: that the median horizontal error is less than 1 m, and that the 95th percentile horizontal error is less than 2 m.

PPP fared the worst amongst all processing approaches in the forested environment. This is not surprising as PPP processing does not utilize base station data to compute a differential correction for the rover position, but instead, relies on carrier phase processing that requires uninterrupted satellite signal reception which is difficult to achieve under heavy forest canopy. This suggests that the PPP approach, at least as implemented in Javad Justin 3 software with Javad Triumph 2 receivers, should be avoided in the forested environment.

3.2.2. Effect of base station distance on positioning accuracy

Our results indicate that GNSS positioning accuracy declines with increasing base station distances (Figs. 12 and 13). At 8 km away, auto, code, fixed, float, and L1-only all achieved better than our accuracy targets of 1-m median horizontal errors and 2-m 95th percentile horizontal errors. However, this quickly declines and at only 40 km away (Fig. 13) only code and L1-only processing achieve better than 1-m median horizontal errors and better than 2-m 95th percentile errors. At further distances, L1-only processing is the only approach to achieve both target thresholds and is minimally impacted up to 480 km away from the reference base station (the furthest distance tested).

3.2.3. Effects of receiver height on overall positioning accuracy

The results in Fig. 14 suggest that for 15-min GNSS occupations in the forest, that receiver height can affect positioning accuracy, but the magnitude of the effect is dependent on the processing mode used. For example, for auto, autonomous, code, fixed, float, and L1-only, the 0 m receiver height resulted in the poorest accuracy, and 2.7 m height tended to have the highest accuracy. In the case of L1 only processing, the processing mode that typically resulted in the highest accuracy, the magnitude of the effect appears to be the least pronounced and is the only case for which 0 m height receivers were still within the target accuracy thresholds. When broken out by height, code processing was the second least impacted by receiver height.

3.2.4. Effect of occupation duration on positioning accuracy

In this section we look at the effect of GNSS occupation duration on processing accuracy (see Fig. 15). GNSS accuracy improved with longer occupation times, where all the processing modes except for PPP achieved our target accuracies ($<$1 m median error, and $<$2 m 95th percentile error) with 45-min occupations or longer. The PPP approach fares poorly for all occupation durations, although the median accuracy achieved was less than 1 m for 60-min occupations. For 60-min occupations with the L1-only processing approach, even the 95th percentile error was less than 1 m.

3.2.5. Effect of number of base stations on positioning accuracy

Based on our findings here (Fig. 16), we see the surprising result that having a single base station resulted in better performance on average than using multiple base stations. Unfortunately, this finding cannot be broadly generalized. The reality could be that the quality of a single base station amongst the three used could have been inferior to the other two, or contrarily, that the single base station used was superior to the other two in some way (e.g., potentially a cleaner signal due to having a higher-quality antenna, or more precise reference location). In practice we have observed the phenomenon that some base stations simply appear to work better for reasons that are unclear to us. The main takeaway from the results in Fig. 16 is that there is not overwhelming evidence in favor of improved accuracy from using multiple base stations. We also cannot say that a single base station works better than multiple base stations, based on limitations to the comparison that was made. The findings were also not practically (magnitude of effect) or statistically significant (p-value $>$0.7) in a formal ANOVA test (results not shown) with explanatory variables: occupation duration, number of base stations, base station distance, and receiver height. A more robust inference would be possible by using a random assignment of base stations to each point that was processed. In this case, for logistical reasons, every point for a given base station distance was processed with the same single base station, and the same set of multiple base stations.

4. Discussion

The results from this study indicate that naïve accuracy estimation (using internal variation among GNSS epochs for a single point) is not suitable for positioning accuracy estimation, at least in the forested environment. This is operationally quite inconvenient, as many receivers and software report naïve accuracies, and many users rely exclusively on the reported naïve accuracy estimates. However, we found no agreement between the naïve accuracy estimates (e.g., as would be displayed on many GNSS receiver screens)

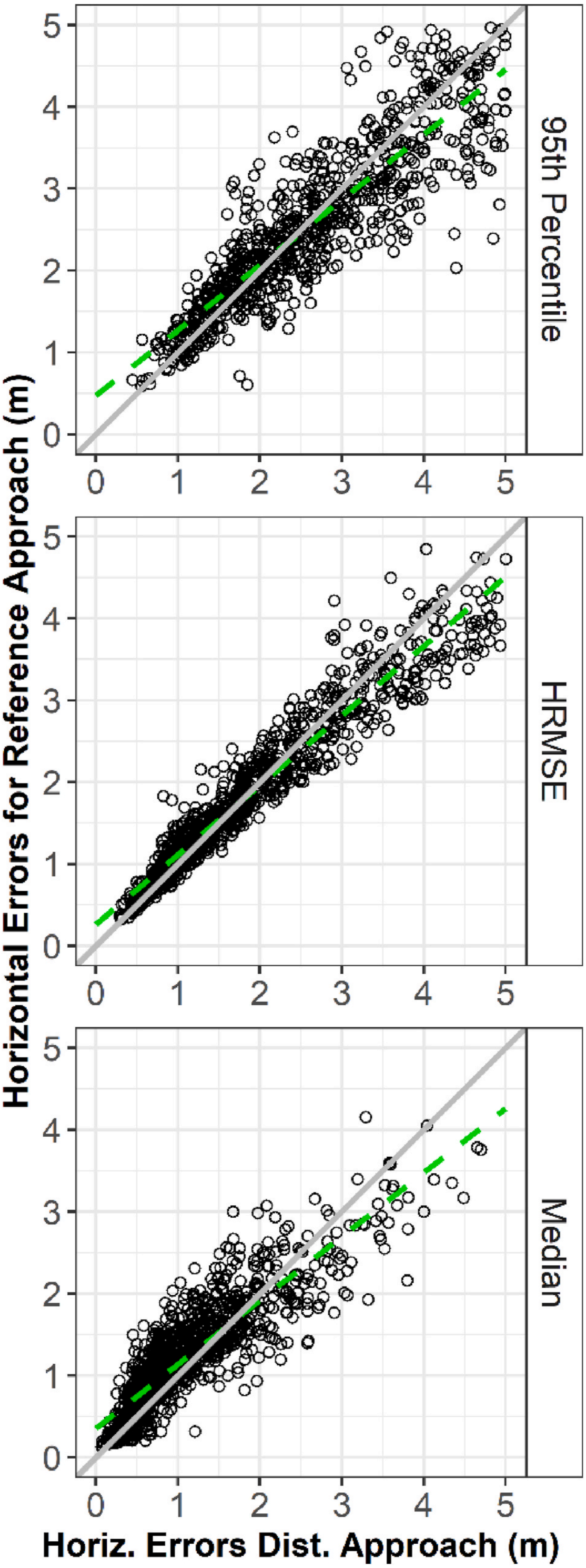
95th Percentile
HRMSE
Median
Horizontal Errors for Reference Approach (m)
Horiz. Errors Dist. Approach (m)
0
1
2
3
4
5

Fig. 10. Comparison of HRMSE, 95th percentile error, and median horizontal error statistics for reference and distance-based accuracy approaches. Points are for individual GNSS occupations (1–60 min) with various processing configurations (base distance, number of base stations, processing mode). Gray solid lines represent a 1-1 relationship, and the dashed green lines represent the fitted lines between values on y and x axes. Data were clipped to a 0–5 m range.

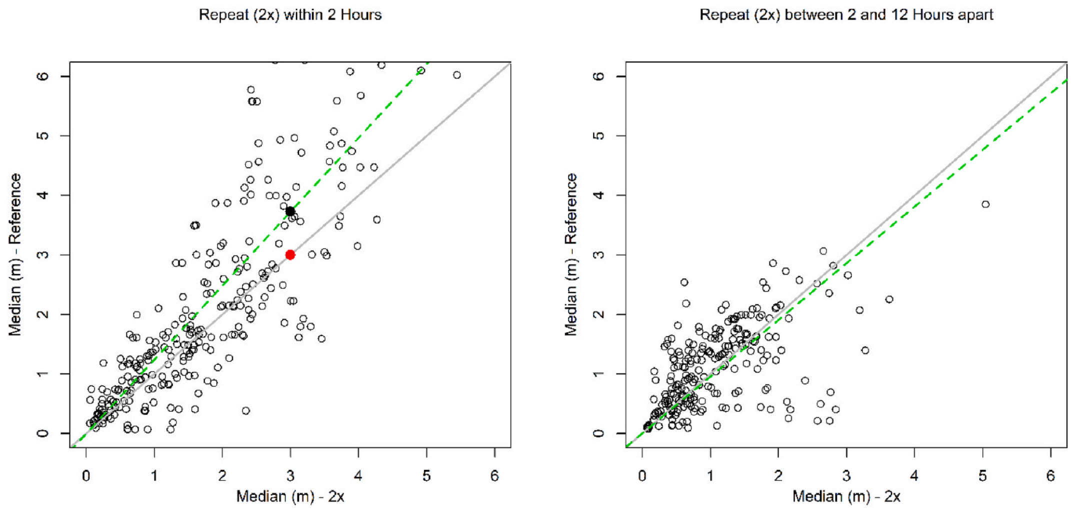

Fig. 11. Scatterplots of reference-point and 2x accuracy estimates for observations close in time (0–2 h) and further apart in time (2–12 h). The solid gray line is the 1-1 line between the two axes and the dashed green line is the zero-intercept OLS fitted line between values on X and Y axes. For the 0–2 h pane, the expected median 2x accuracy (red solid point) is 72 cm downward biased relative to the expected baseline reference-point accuracy (solid black point).

and actual accuracies computed with geodetic survey coordinates. The lack of agreement between naïve and actual accuracies with Javad receivers and software agrees with the results from McGaughey et al. (2017) for Trimble GeoXH6000 resource-mapping receivers. They found that the naive horizontal accuracies reported by Trimble Pathfinder office had no correlation with actual point accuracies.

In contrast to the disappointing findings with respect to naïve positioning accuracy estimation, two alternative accuracy estimators were both found to be highly effective for estimation of positioning accuracies. Repeated occupation (2x) and reference-distance based positioning accuracy estimation approaches were highly correlated with actual positioning accuracy statistics (HRMSE, median error, and 95th percentile error) and minimally biased. It is recommended that naïve accuracy estimators are abandoned in forestry applications, in favor of one of three alternatives:

1) Comparison with reference points in a geodetic survey (actual accuracy, but expensive)
2) Repeated occupations of the same points on separate days (less expensive than a geodetic survey, but ideally requires returning to locations on a separate day)
3) Comparison between GNSS distances and reference distances (less expensive than a geodetic survey, can be obtained on a single day, but requires accurate horizontal distance measurements between adjacent points).

This study is unique in comparing an L1-only GNSS post-processing approach to a variety of dual frequency post-processing approaches for a survey-grade receiver in the forest. Examination of L1-only processing was initially an attempt at completeness (to demonstrate all the processing modes offered by the software) but resulted in the L1-only approach achieving the highest performance of all the processing modes in the forested environment. There are other studies which have looked at multiple processing modes, including comparing L1-only and dual frequency devices (Kaartinen et al., 2015; Andersen et al., 2009), but not that have considered using L1-only data from a dual-frequency survey-grade receiver. The results of Grala and Brach (2009) may shed some light on this phenomenon, as they received fewer position fixes with fixed-integer post-processing than with floating-point solutions, although they achieved the highest accuracy with fixed-integer processing. However, their forest conditions were very open with relatively short trees compared to our study area. It may simply be that at some threshold of interference from vegetation (e.g., our 40–60 m tall closed-canopy conifer forests), that there are too few fixed-integer solutions to accurately estimate the receiver position relative to other processing modes.

We also observed as good or better performance for code and autonomous processing relative to fixed-integer and floating-point processing for occupations 30 min or less, and arguably similar results beyond 30 min. In a related result, Edson and Wing (2012) saw the highest accuracy for the code processing mode of GNSS positions in the forest, and autonomous positioning accuracy was slightly worse than carrier-phase processing (fixed-integer or floating-point modes were not differentiated by the authors). In our results, PPP

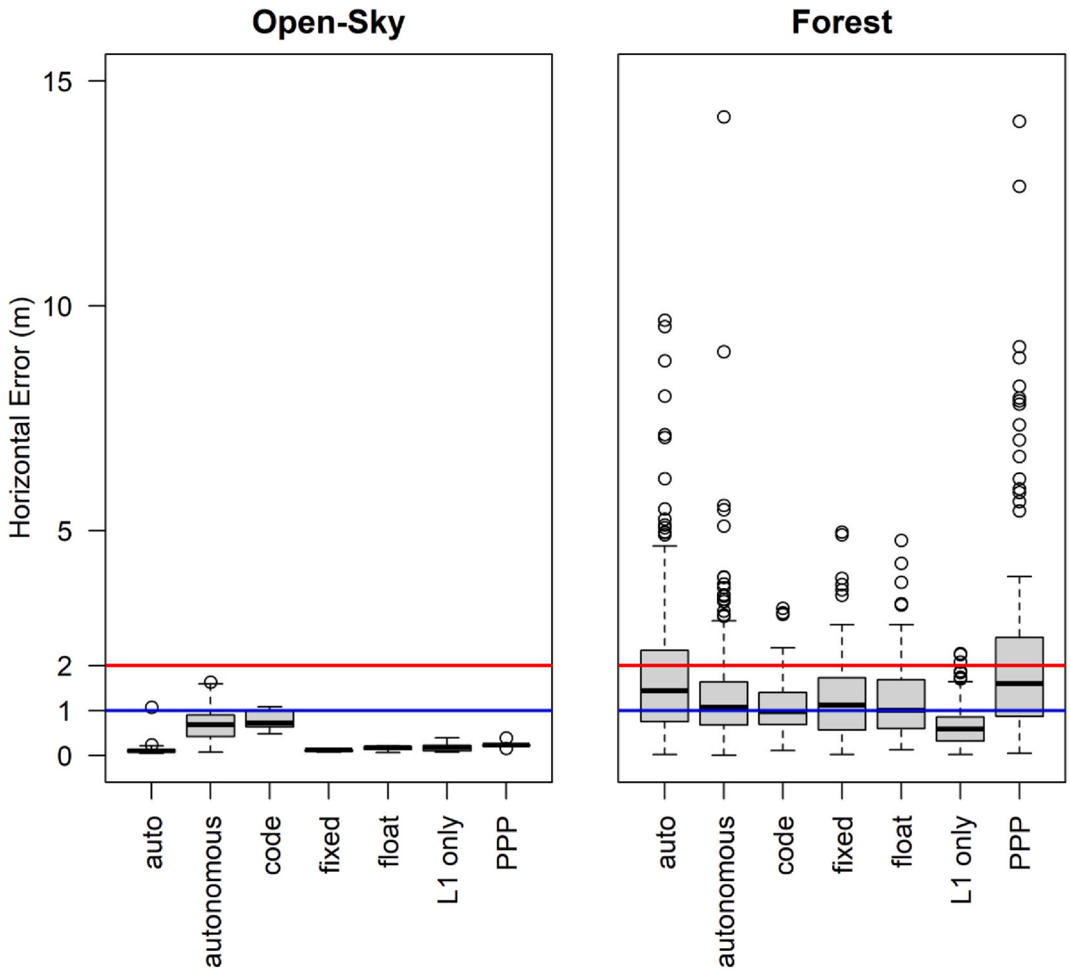

Fig. 12. Effects of various processing modes on positioning accuracy in open-sky and forest conditions when the base station is 160 km away and the receiver collects data for 15 min. Blue and red horizontal lines at 1 and 2 m represent the target levels of median and 95th percentile accuracies respectively. *PPP and autonomous positions do not use reference stations and thus the distance to reference station is not applicable – they are provided in each boxplot for comparative purposes.

processing was inferior to all other modes of processing. Næsset and Gjevestad (2008) also concluded that differential processing methods were preferred to PPP in the forested environment.

In this study we observed that increased base station distances resulted in poorer GNSS accuracy for differential post-processing approaches (which excludes PPP and autonomous approaches; Figs. 12 and 13), as was observed for GNSS positions in Alaskan forests (USA) by Andersen et al. (2009). In this study, the resulting decline in accuracy due to increased base station distance was dramatic for all post processing modes except for L1-only, even at only 40 km away. This may suggest an opportunity for users to set up their own temporary base station (e.g., a survey-grade receiver placed in a secure location with clear skies) for cases in which base stations are excessively far away. On the other hand, the L1-only mode was surprisingly robust to base station distances up to 480 km away.

As would be expected based on findings observed in other studies of occupation duration on GNSS accuracy in the forest (e.g., McGaughey et al., 2017; Næsset et al., 2000), we also observed that longer duration GNSS occupations had improved positioning accuracy. For 30-min occupations, all the processing modes except PPP and floating-point achieved our target high-performance positioning thresholds of a median error less than 1 m and 95th percentile error less than 2 m, even with autonomous positioning. This suggests that 30-min is a suitable occupation duration to be able to guarantee high-performance positioning, even in the absences of nearby base stations.

Our study also agrees with a number of other studies that suggest that increased receiver height contributes to increased positioning accuracy (e.g., Grala and Brach, 2009; Brach and Zasada, 2014) although the maximum height we considered was less than the minimum (5 m) considered in some other studies. While our results and those of other studies certainly indicated that elevating our receivers to 2.6 m (or even 10 m) would result in improved performance, our focus was instead to evaluate whether forest inventory crews, who may be already carrying tens of pounds of field equipment, could consider placing receivers on or near the ground. We were more interested in observing whether a receiver placed on or near the ground could provide positioning accuracies competitive with

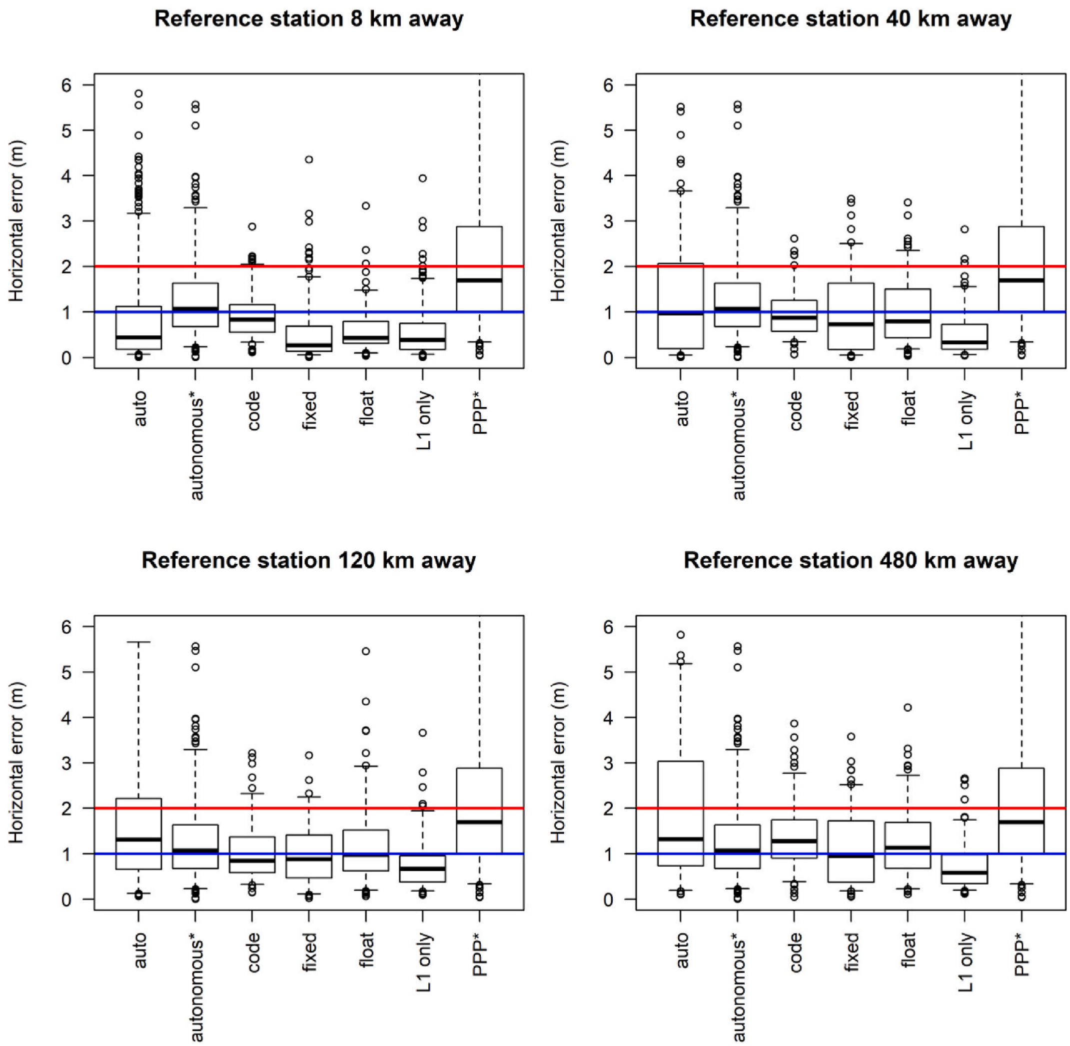

Fig. 13. Horizontal error distributions for different processing modes and base station distances. Boxplots represent data quantiles including box edges (0.25, 0.75), whisker bounds (0.05, 0.95), and bold black center lines for the medians – the y-axes are truncated at 6 m of horizontal error to aid in interpretation. Accuracies for 160 km away can be found in Fig. 12. Horizontal blue (1 m) and red (2 m) lines represent target median and 95th percentile accuracies. *PPP and autonomous positions do not use reference stations and thus the distance to reference station is not applicable – they are provided in each boxplot for comparative purposes.

those of a lightweight (≈ 0.5 kg) 1.2 m or 1.5 m camera tripod. We found that this was in fact feasible with the L1-only processing mode using at least 15 min occupations (other combinations of duration and height were not reported).

The results of this study are highly relevant to the implementation of HPGNSS in the context of the USA's NFI implemented by the USFS Forest Inventory and Analysis (FIA) program. Our findings suggest that the target accuracy thresholds (median horizontal error <1 m and 95th percentile error < 2 m) can be achieved in tall (40–60 m) closed-canopy coniferous Pacific Northwest USA forests with at least 15 min of data collection with survey-grade receivers (although longer durations are recommended). This is encouraging given that the vegetation conditions reflected in this study are relatively difficult compared to the majority of field plot conditions, especially with respect to the amount of vegetative biomass between the receiver and GNSS satellites. Further testing, however, will be needed in broadleaf canopy forests, in steeper terrain conditions, and in wet and snowy conditions to better understand the variability in accuracy as a function environmental conditions. The findings from this study also demonstrated that repeated GNSS occupations can be used in GNSS accuracy assessments. This aligns well with the FIA program's quality assessment (QA) data collection process which involves independent field measurements at a second point in time – an opportunity to also obtain independent GNSS occupations for positioning accuracy estimation.

5. Study limitations

One of the potential limitations of this study is that the data were collected approximately 6 years ago, while GNSS receivers,

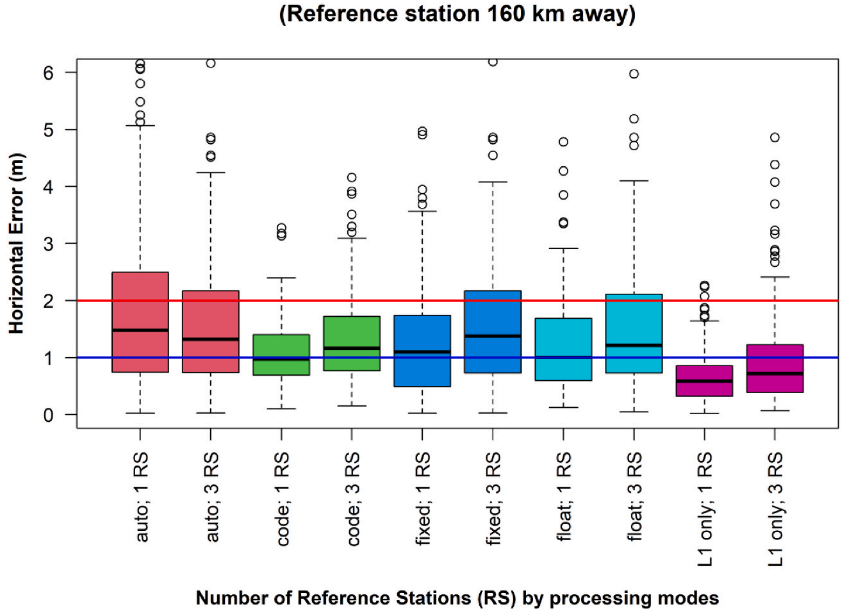

Fig. 14. Effect of receiver height on horizontal accuracy (m) for different processing modes following 15 min of data collection. Boxplots represent data quantiles including box edges (0.25, 0.75), whisker bounds (0.05, 0.95), and bold black center lines for the medians – the y-axes are truncated at 10 m of horizontal error. For the L1-only processing mode, the processing mode with the smallest horizontal errors, accuracy was estimated to improve ≈ 10 cm on average for a 1-m height increase (p-value ≈ 0.28). The base station distance is not applicable to autonomous and PPP processing modes.

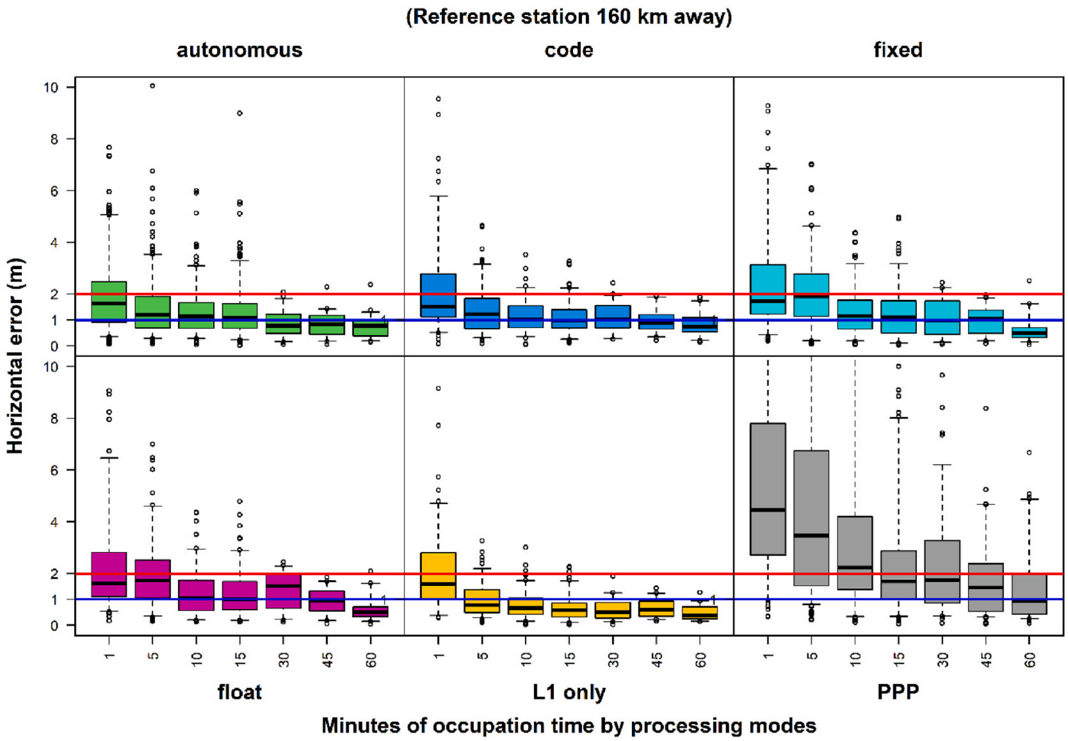

Fig. 15. Effect of occupation duration on horizontal error by processing mode. The base station distance is not applicable to autonomous and PPP processing modes. Boxplots represent data quantiles including box edges (0.25, 0.75), whisker bounds (0.05, 0.95), and bold black center lines for the medians – the y-axes are truncated at 10 m of horizontal error.

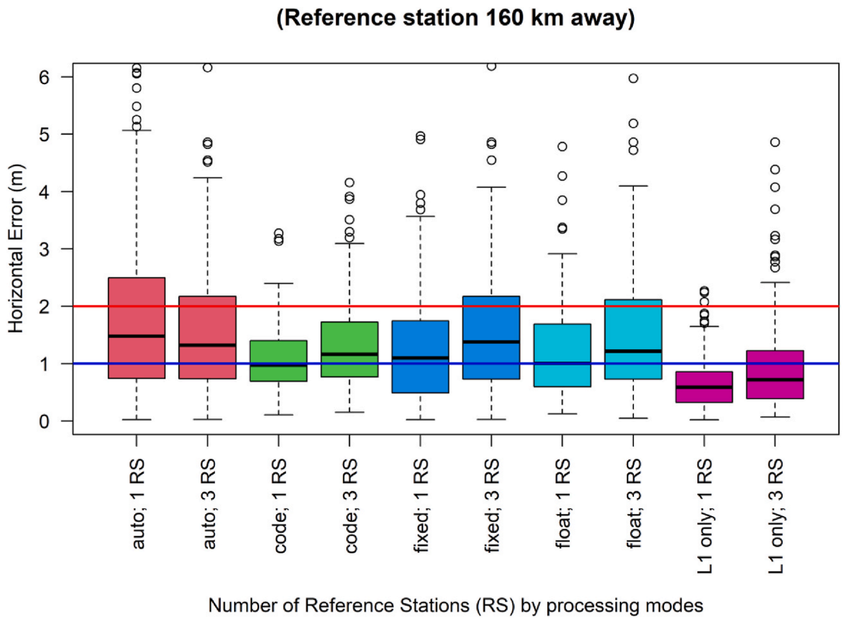

Fig. 16. Effect of number of Reference Stations (RS) on horizontal error by processing mode. Results are for 15-min occupations with 160 km away reference stations. Boxplots represent data quantiles including box edges (0.25, 0.75), whisker bounds (0.05, 0.95), and bold black center lines for the medians – the y-axis is truncated at 6 m of horizontal error.

satellites, and satellite constellations have changed and improved over that period. We expect the performances reported here to continue to be relevant, however, as updates take time to implement across satellites, base stations, and receivers used operationally. Ideally, GNSS performance has continued to improve, and the results presented here will represent conservative estimates of what is feasible. Continued testing will be needed, however, to determine whether the relationships among processing modes continue to favor L1-only processing.

A related limitation is that the results for the various processing modes are likely confounded by the internal filtering and logic used by Javad brand post-processing software. For example, fixed-integer processing fared worse in the forest than L1-only processing, but this could simply be due to the software filtering a greater proportion of epochs for the fixed-integer processing mode than for the L1-only mode. This would result in a smaller number of epochs to average, potentially yielding inferior results. Contrarily, in dense forests it could also be that GNSS data are simply too noisy to use L1 and L2 fixed-integer processing. The manufacturer suggested that the L2 band was more susceptible to interference in the forest. Unfortunately, from our findings it is not clear whether the effects of processing modes are specific to the Javad software implementation or are generic to the underlying GNSS processing modes.

Finally, the small size of our study site limits the extensibility of our findings. While the small patch of forest at the Olympia Forestry Sciences laboratory represents a difficult forest condition, it poorly represents the breadth of conditions that may be encountered, even in the Pacific Northwest of the conterminous USA. There is a need to understand positioning performances across a wider range of forest, terrain, and weather conditions (especially rain and snow). One finding from this study which facilitates the expansion of inferences to effects from forest, terrain, and environmental conditions on GNSS positioning errors is our demonstration of alternatives to the reference-point accuracy estimation approach. The repeated occupation (2x) approach is especially suited to evaluate GNSS positioning accuracy across the entire USA from repeated GNSS occupation on FIA plots. In addition, since the majority of forest conditions in the USA are expected to be less difficult from a GNSS positioning perspective (tree height and cover), our findings suggest data collection and post-processing methodologies that can support high-performance GNSS positioning in most forests.

6. Conclusions

High-performance positioning is important to forest inventory and monitoring to effectively leverage high-precision auxiliary information such as lidar and photogrammetric point clouds with field measurements of forest attributes. Unfortunately, consistently achieving positional accuracies better than 1–2 m is difficult and depends upon many factors, including the receiver (must be survey-grade), field protocol used (need long occupations), and post-processing approach (requires differential correction). Our results also suggest the unusual result that L1-only processing in the forest is more accurate and more robust with respect to base station distance and occupation length than other processing modes.

While the age of our study data and limited spatial extent represent limitations to the extensibility of our findings, we also demonstrate the effectiveness of two simple accuracy estimation techniques that do not require a geodetic survey. These methods can be used by the broader forestry GNSS community who may not have access to a geodetic survey in their desired forest conditions. The accuracy estimation approaches described can also help FIA to evaluate its operational GNSS accuracies across a wide range of forest conditions. Our results on the failure of naïve accuracy estimators, and demonstration of simpler alternatives to the reference point approach will also hopefully motivate people to adopt more reliable accuracy estimation approaches.

CRediT authorship contribution statement

Jacob L. Strunk: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Stephen E. Reutebuch:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Robert J. McGaughey:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Hans-Erik Andersen:** Writing – review & editing, Writing – original draft, Resources, Methodology, Conceptualization.

Ethical statement

We confirm that this work is original and has not been published or submitted for review elsewhere. We have no conflicts of interest to disclose and there were no outside sources of financial support for this work that could have influence the research outcomes. I, Jacob Strunk, also confirm that all co-authors have read and contributed to this manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

Andersen, H.-E., Clarkin, T., Winterberger, K., Strunk, J.L., 2009. An accuracy assessment of positions obtained using survey-and recreational-grade global positioning system receivers across a range of forest conditions within the tanana valley of interior Alaska. West. J. Appl. For. 24 (3), 128–136.

Andersen, H.-E., Strunk, J.L., McGaughey, R.J., 2022. Using high-performance global navigation satellite system technology to improve forest inventory and analysis plot coordinates in the pacific region. Gen. Tech. Rep. PNW-GTR-1000 1000: 44.

Ashjaee, J., Lorenz, R., Sutherland, R., Dutilloy, J., Minazio, J.-B., Abtahi, R., Eichner, J.-M., Kosmalska, J., Helkey, R., 1989. New GPS developments and Ashtech M-XII. In: Proceedings of the 2nd International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GPS 1989), Colorado Spring. CO, USA, pp. 195–198.

Bechtold, William A., Patterson, Paul L., Asheville (Eds.), 2005. The Enhanced Forest Inventory and Analysis Program - National Sampling Design and Estimation Procedures. U.S. Department of Agriculture, Forest Service, Southern Research Station, North Carolina.

Bettinger, P., Merry, K., 2012. Influence of the juxtaposition of trees on consumer-grade GPS position quality. Math. Comput. For. Nat. Resour. Sci. 4 (2), 81–91.

Brach, M., Zasada, M., 2014. The effect of mounting height on GNSS receiver positioning accuracy in forest conditions. Croat. J. For. Eng.: J. Theor. Appl. Forestr. Eng. 35 (2), 245–253.

Cabral, R.P., da Silva, G.F., de Almeida, A.Q., Bonilla-Bedoya, S., Dias, H.M., De Mendonça, A.R., Rodrigues, N.M.M., Valente, C.C.A., Oliveira, K., Gonçalves, F.G., Sarcinelli, T.S., 2023. Mapping of the successional stage of a secondary forest using point clouds derived from UAV photogrammetry. Rem. Sens. 15 (2), 509.

Dominy, N.J., Duncan, B., 2002. GPS and GIS methods in an African rain forest: applications to tropical ecology and conservation. Conserv. Ecol. 5 (2), 6.

Edson, C., Wing, M.G., 2012. Tree location measurement accuracy with a mapping-grade GPS receiver under forest canopy. For. Sci. 58 (6), 567–576.

Forest Inventory and Analysis, 2021. National Core Field Guide, Volume I: Field Data Collection Procedures for Phase 2 Plots, p. 484.

Frank, J., Wing, M.G., 2014. Balancing horizontal accuracy and data collection efficiency with mapping-grade GPS receivers. Forestry: Int. J. Financ. Res. 87 (3), 389–397.

Frazer, G.W., Magnussen, S., Wulder, M.A., Niemann, K.O., 2011. Simulated impact of sample plot size and co-registration error on the accuracy and uncertainty of LiDAR-derived estimates of forest stand biomass. Rem. Sens. Environ. 115 (2), 636–649.

Garabedian, J.E., Moorman, C.E., Peterson, M.N., Kilgo, J.C., 2018. Relative importance of social factors, conspecific density, and forest structure on space use by the endangered Red-cockaded Woodpecker: a new consideration for habitat restoration. Condor 120 (2), 305–318.

Gerlach, F.L., Jasumback, A.E., 1988. Evaluation of GPS instruments for resource management applications. In: Proceedings of the International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GPS 1988), Colorado Spring. CO, USA, pp. 503–509.

Gobakken, T., Næsset, E., 2009. Assessing effects of positioning errors and sample plot size on biophysical stand properties derived from airborne laser scanner data. Can. J. For. Res. 39 (5), 1036–1052.

Gollob, C., Ritter, T., Nothdurft, A., 2020. Comparison of 3D point clouds obtained by terrestrial laser scanning and personal laser scanning on forest inventory sample plots. Data 5 (4), 103.

Grala, N., Brach, M., 2009. Analysis of GNSS receiver accuracy in the forest environment. Roczniki Geomatyki 7 (2), 41–45.

Hasegawa, H., Yoshimura, T., 2003. Application of dual-frequency GPS receivers for static surveying under tree canopies. J. For. Res. 8 (2), 103–110.

Kaartinen, H., Hyyppä, J., Vastaranta, M., Kukko, A., Jaakkola, A., Yu, X., Pyörälä, J., Liang, X., Liu, J., Wang, Y., Kaijaluoto, R., Melkas, T., Holopainen, M., Hyyppä, H., 2015. Accuracy of kinematic positioning using global satellite navigation systems under forest canopies. Forests 6 (9), 3218–3236.

Mauro, F., Valbuena, R., Manzanera, J., Abril, A., 2011. Influence of Global Navigation Satellite System errors in positioning inventory plots for tree-height distribution studies. Can. J. For. Res. 41 (1), 11–23.

Mauro, F., Hudak, A.T., Fekety, P.A., Frank, B., Temesgen, H., Bell, D.M., Gregory, M.J., McCarley, T.R., 2021. Regional modeling of forest fuels and structural attributes using airborne laser scanning data in Oregon. Rem. Sens. 13 (2), 261.

Mauya, E.W., Hansen, E.H., Gobakken, T., Bollandsås, O.M., Malimbwi, R.E., Næsset, E., 2015. Effects of field plot size on prediction accuracy of aboveground biomass in airborne laser scanning-assisted inventories in tropical rain forests of Tanzania. Carbon Bal. Manag. 10, 1–14.

McGaughey, R.J., Ahmed, K., Andersen, H.-E., Reutebuch, S.E., 2017. Effect of occupation time on the horizontal accuracy of a mapping-grade GNSS receiver under dense forest canopy. Photogramm. Eng. Rem. Sens. 83 (12), 861–868.

McGaughey, R.J., Kruper, A., Bobsin, C.R., Bormann, B.T., 2024. Tree species classification based on upper crown morphology captured by uncrewed aircraft system lidar data. Rem. Sens. 16 (4), 603.

McRoberts, R.E., 2010. The effects of rectification and Global Positioning System errors on satellite image-based estimates of forest area. Rem. Sens. Environ. 114 (8), 1710–1717.
McRoberts, R.E., Chen, Q., Walters, B.F., Kaisershot, D.J., 2018. The effects of global positioning system receiver accuracy on airborne laser scanning-assisted estimates of aboveground biomass. Rem. Sens. Environ. 207, 42–49.
Næsset, E., Gjevestad, J.G., 2008. Performance of GPS precise point positioning under conifer forest canopies. Photogramm. Eng. Rem. Sens. 74 (5), 661–668.
Næsset, E., Bjerke, T., Bvstedal, O., Ryan, L., 2000. Contributions of differential GPS and GLONASS observations to point accuracy under forest canopies. Photogramm. Eng. Rem. Sens. 15 (111), 58.
Pascual, A., Guerra-Hernández, J., Cosenza, D.N., Sandoval, V., 2020. The role of improved ground positioning and forest structural complexity when performing forest inventory using airborne laser scanning. Rem. Sens. 12 (3), 413.
Pascual, A., Tupinambá-Simões, F., Guerra-Hernández, J., Bravo, F., 2022. High-resolution planet satellite imagery and multi-temporal surveys to predict risk of tree mortality in tropical eucalypt forestry. J. Environ. Manag. 310, 114804.
Pirti, A., 2005. Using gps near the forest and quality control. Surv. Rev. 38 (298), 286–298.
Puliti, S., Hauglin, M., Breidenbach, J., Montesano, P., Neigh, C.S.R., Rahlf, J., Solberg, S., Klingenberg, T.F., Astrup, R., 2020. Modelling above-ground biomass stock over Norway using national forest inventory data with ArcticDEM and Sentinel-2 data. Rem. Sens. Environ. 236, 111501.
Shannon, T., 1992. An Investigation of Single Channel, Global Positioning System Receivers for Forestry Applications. University of British Columbia. PhD Thesis.
Shcherbacheva, A., Campos, M.B., Wang, Y., Liang, X., Kukko, A., Hyyppä, J., Junttila, S., Lintunen, A., Korpela, I., Puttonen, E., 2024. A study of annual tree-wise LiDAR intensity patterns of boreal species observed using a hyper-temporal laser scanning time series. Rem. Sens. Environ. 305, 114083.
Shoot, C., Andersen, H.-E., Moskal, L.M., Babcock, C., Cook, B.D., Morton, D.C., 2021. Classifying forest type in the national forest inventory context with airborne hyperspectral and lidar data. Rem. Sens. 13 (10), 1863.
Strunk, J.L., McGaughey, R.J., 2023. Stand validation of lidar forest inventory modeling for a managed southern pine forest. Can. J. For. Res. 53 (2), 71–89.
Strunk, J., Packalen, P., Gould, P., Gatziolis, D., Maki, C., Andersen, H.-E., McGaughey, R.J., 2019. Large area forest yield estimation with pushbroom digital aerial photogrammetry. Forests 10 (5), 397.
USDA, 2024. Forest Service Global Positioning System: MTDC Accuracy Reports.
Zhang, S., Vega, C., Deleuze, C., Durrieu, S., Barbillon, P., Bouriaud, O., Renaud, J.-P., 2022. Modelling forest volume with small area estimation of forest inventory using GEDI footprints as auxiliary information. Int. J. Appl. Earth Obs. Geoinf. 114, 103072.