APPLICATIONS PAPER

Effect of Occupation Time on the Horizontal Accuracy of a Mapping-Grade GNSS Receiver under Dense Forest Canopy

Robert J. McGaughey, Kamal Ahmed, Hans-Erik Andersen, and Stephen E. Reutebuch

Abstract

A mapping-grade dual frequency GNSS receiver was tested under dense forest canopy to determine the effect of occupation time on horizontal accuracy. The U.S. Forest Service Forest Inventory and Analysis unit in the Pacific Northwest has been using 32 of these units to collect over 7,000 plot locations since 2013. In this study, one-hour GNSS static occupations were collected at 33 ground-surveyed positions with Trimble GeoXH6000 mapping-grade and Javad Triumph1 survey-grade receivers. Rover files were differentially post-processed and horizontal accuracy of each post-processed position was computed. Results indicated that 1.85 m accuracy (n = 990) could be achieved with the GeoXH6000 receiver with 15-minute occupations; however, maximum horizontal error was 7.01 m. Increasing occupation time to 20 minutes did not result in a significant improvement in accuracy. No correlation was found between the horizontal precision of a post-processed position reported by the postprocessing software and the field-measured horizontal accuracy of the positions.

Introduction

National Forest Inventories (NFI) are designed to produce and report estimates of forest resources. The types of estimates produced include forest area, volume, condition, removals, growth, mortality, and overall trends in land use. Estimates are generally summarized to represent various levels, including owner group (e.g., state, private, federal), ecological units, survey unit, forest type, and tree species. Inventory data have traditionally been used by public and private land managers, planners, and researchers to address a variety of information needs. NFIs are established in many countries around the world, providing information to the local government and commercial timber industry as well as supporting global efforts to monitor the effects of climate change, carbon emissions and sequestration, and biological diversity.

In the United States, The NFI is conducted by the Forest Service's Forest Inventory and Analysis program (FIA). FIA collects, analyzes, and reports information on the status and trends of America's forests: how much forest exists, where it exists, who owns it, and how it is changing, as well as how the trees and other forest vegetation are growing and how much has died or has been removed in recent years. FIA uses four related surveys to characterize different aspects of America's forests: forest monitoring, ownership survey, timber product output survey, and utilization studies. The forest monitoring component uses a three-phase sample with permanent sample sites located across the United States. Phase 1 uses remotely-sensed data for stratification and to identify whether or not a location is forested. Phase 2 consists of one sample site for every 6,000 acres, where field crews collect data on forest type, site attributes, tree species, tree size, and overall tree condition. Phase 3 utilizes a subset of the Phase 2 sample sites where crews measure a broader suite of forest health attributes including tree crown conditions, lichen community composition, understory vegetation, down woody debris, and soil attributes. FIA samples and summarizes data for the continental states, Alaska, Hawaii, and US Pacific Island Territories and Protectorates. The program includes over 323,000 phase 2 sample locations. Approximately 116,400 of these locations are forested and about 20,000 are measured each year (Vogt and Smith, 2017). The FIA database is one of the most comprehensive and complete samples of vegetation conditions in the world. For the sample sites, coarse locations are obtained using aerial imagery to guide crews to the site. In the field, crews typically record a location using a global navigation satellite system (GNSS). Plot confidentiality requirements limit the distribution of the actual plot locations. However, cooperators can obtain and use the actual locations after completing a formal spatial data request process and signing a non-disclosure agreement.

For FIA, the location (typically acquired using a low-cost, consumer-grade GPS unit) is primarily used to relocate the sample site. While an accurate position is always desirable, the position only needs to be good enough to help crews plan for travel to and from the site and to relocate the site each time it is measured. Accuracies for the GNSS receivers typically used by field crews range from a few meters to several decameters depending on the quality of the GNSS receiver, the forest conditions at the site, and postprocessing of the GNSS data (Bolstad *et al.*, 2005; Hoppus and Lister, 2007). This level of accuracy has been sufficient for FIA. However, the extensive area covered by FIA data, repeated measurements over time, consistent protocol, and general availability of the data make the plot data useful for a variety of applications many of which would benefit from more accurate locations. NFI data have been combined with a variety of remotely-sensing data to map characteristics over large areas and to help detect changes over time (Tomppo *et al.*, 2008; Zald *et al.*, 2014; Blackard *et al.*, 2008). Historically, rectification error present in the remotely-sensed data (Landsat TM) has been such that improving the accuracy of the GNSS location did not always result in improvements in analysis results (McRoberts, 2010). However, the remote sensing world is changing. High resolution digital

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imagery and lidar typically have horizontal registration errors of less than 1 m. When considering the size of the FIA subplot (circular plot with radius of 7.3 m), the effect of a 10 m error in location can have a significant impact on the ability to describe relationships between plot measurements and remotely-sensed attributes. For example, when developing relationships between lidar point cloud metrics and forest structure metrics, a plot position horizontal accuracy of 1 to 2 m ensures that ground measurements are reasonably well aligned with lidar data (Frazer *et al.*, 2011; Gobakken and Næsset, 2009).

Within FIA, GNSS receivers have been in common use for over 25 years. However, early receivers tracked few satellites (five channels) and did not allow differential correction of positions (Hoppus and Lister, 2007). Over the last decade, crews have relied on recreational-grade receivers that use the wide area augmentation system (WAAS) to improve the accuracy of positions. In 2013, FIA crews based in the Forest Service's Pacific Northwest Research Station (PNW-FIA is responsible for measurements in Alaska, California, Oregon, Washington, Hawaii, and U.S. Pacific Island territories and Protectorates) began using mapping grade GNSS receivers (Trimble GeoXH 6000 series standard edition with decimeter accuracy) that allow differential postprocessing of the collected rover files. As of 2016, 32 of the Trimble units were in use in PNW-FIA and locations had been collected for over 7,000 plots using the Trimble units. While these practices are intended to improve plot locations, even differentially-corrected static coordinates collected under forest canopy can have horizontal errors ranging from sub-meter to tens of meters, depending on many factors (e.g., density of canopy, number and geometry of available satellites, duration of data collection, type of receiver and antenna, local topography, availability of reliable base station data, and characteristics of differential processing software). Large errors often occur even when using survey-grade dual-frequency, multi-constellation receivers with moderately long occupation times (15-min to 1-hour) and with data from 10 or more satellites (Clarkin, 2007; Andersen *et al.*, 2009; Valbuena *et al.*, 2010). Næsset (2001) tested a dual-frequency GNSS (GPS and GLONASS) receiver under typical Scandinavian forest conditions and reported horizontal errors from 0.08 to 1.35 m with 2.5 to 20 min static occupations. Edson and Wing (2012) tested a mapping-grade GPS-only receiver in relatively low density conifer stands in Oregon with 30 second occupations and reported errors in the 2 to 3 m range. Frank and Wing (2014) tested a mapping-grade GPS-only receiver in low to high density conifer stands in Oregon with 1, 5, 10, 30, and 60 second occupations and reported errors in the 4 to 9 m range.

Large errors occur because of phenomena known as signal multipathing and non-line-of-sight (NLOS) reception when using GNSS receivers in forested environments. A multipath signal occurs when the direct line of sight signal from a GNSS satellite and a reflected signal from the same satellite are received by the GNSS receiver. In forested areas, the direct line-of-sight signal between a GNSS satellite and the GNSS receiver can be temporarily blocked by an object such as a tree bole. When this occurs, only a reflected signal (NLOS) may be received. The ranging distance for a NLOS signal is greater than the direct line-of-sight range from the satellite to the receiver; whereas, a multipath signal can either increase or decrease the range. If the multipath or NLOS signal is not detected by the receiver or postprocessing software the range can cause large errors in the computed position. Petovello (2013) provides a detailed discussion of multipath and NLOS signals and their effects on GNSS positioning.

Because the navigation satellites are not geostationary, the line of sight from the receiver to each satellite continuously changes during a static occupation. Relative to a point on the Earth's surface, a satellite moves through an arc of approximately 30 degrees an hour. The probability of a satellite's line of sight signal being blocked by a tree bole or foliage is proportional to the density of the canopy and canopy height. By using a GNSS receiver that tracks both GPS and GLONASS, the probability of tracking line of sight signals is increased at any instant in time. The longer GNSS data are collected at a point, the higher the probability that additional line of sight signals will be recorded as each visible satellite moves relative to canopy gaps. As the number of line of sight signals increases, the probability of computing an accurate position increases.

Figure 1a illustrates typical horizontal scatter in autonomous positions (before differential postprocessing) collected with a dual-frequency, dual-constellation (GPS and GLONASS) at a static point during a one hour occupation. Each marker represents the position at a given epoch (one second) computed using the pseudorange code (C/A code and P code). The red triangles correspond to a 9 second period of time when ample satellites (11) were being tracked, but one or more multipath or NLOS signals were present, resulting in large deviations from the average position both horizontally (Figure 1a) and vertically (Figure 1b). Given the wide scatter of positions over time shown in Figure 1a it is evident that the configuration of multipath and NLOS signals constantly changed as tracking of each satellite's signal was affected by reflective surfaces within the forest canopy.

When using a GNSS receiver to collect ground plot locations, one must balance the time spent collecting data with the marginal increase in horizontal position accuracy that is achieved by increasing occupation time (Næsset and Gjevestad, 2008). Several studies have compared the horizontal precision reported by the postprocessing software to the horizontal accuracy of a position under forest canopy to test whether reported precision provides some indication of accuracy of a postprocessed position (Andersen *et al.*, 2009; Valbuena *et al.*, 2010). Andersen *et al.* (2009) reported a very weak relationship in boreal forests. Valbuena *et al.* (2010) tested several GNSS receivers and concluded that differences in accuracy and precision between receivers are independent of forest canopy characteristics; however they did not report whether there was any correlation between horizontal precision and accuracy.

The objectives of this study were to:

1. Assess the horizontal accuracy of points collected under heavy forest canopy using the Trimble GeoXH6000 with varying static occupation times.
2. Estimate the minimum and maximum horizontal error associated with different point occupation times under heavy canopy.
3. Determine the minimum occupation time needed to collect data under heavy canopy that will provide differentially corrected 1 to 2 m horizontal error.
4. Determine if horizontal precision of a postprocessed position is correlated with the accuracy of that position.
5. Compare horizontal error associated with files processed in Trimble software as dual frequency (L1/L2) kinematic occupations to horizontal error associated with the same files converted to single frequency (L1) data and processed as static occupations in Javad software.
6. Compare horizontal accuracy of the Trimble GeoXH6000 receiver (mapping-grade) with the accuracy of a Javad Triumph1 receiver (survey-grade).

In the remainder of this paper we first present the methods including a description of the study site, field procedures, and post-processing of the GNSS receiver data. This is followed by a presentation of the results including statistical significance tests of the effect of increasing occupation times on position accuracy and comparisons of postprocessing strategies. We

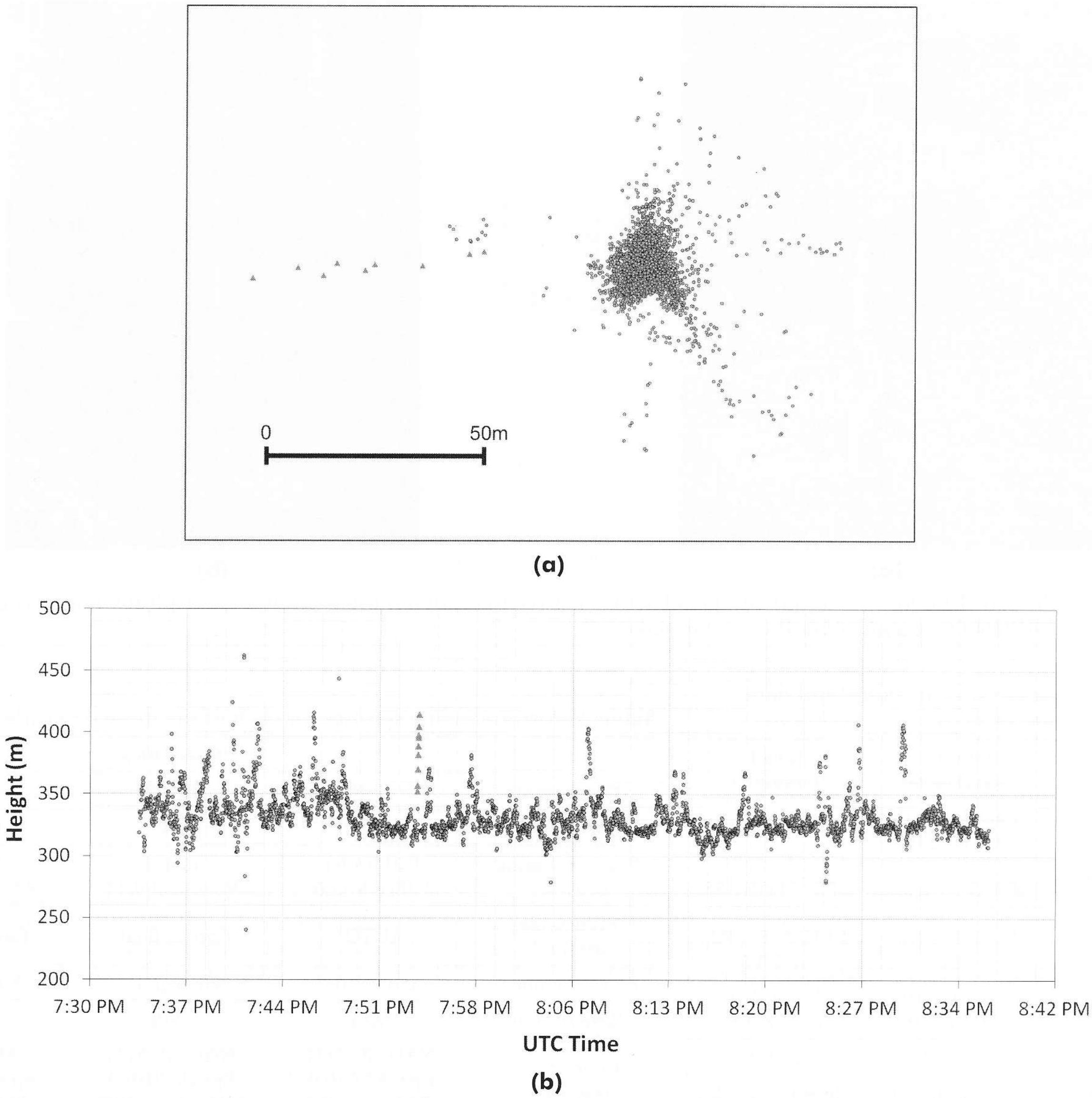

Figure 1. Typical horizontal (a) and vertical (b) scatter of GNSS autonomous positions collected with a Javad Triumph1 receiver during a 1-hour occupation of a static point under heavy coniferous canopy in western Washington.

end with a discussion of the significance of the results and conclusions and recommendations for a field protocol.

Methods

Study Site

The test was conducted in a 15 ha mature forest stand in western Washington (46°51'38"N, 123° 9'32"W). The stand was about 85 years old and composed primarily of mature Douglas-fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*). Dominant tree height is 50 to 60 m and tree density is approx. 275 trees per ha. The site has rolling mountainous terrain with elevation ranging from 300 to 350 m. Understory conditions vary from relatively open to extremely dense. A set of survey stakes were installed throughout the area. The position of each stake was surveyed using a traditional closed traverse with a Topcon 1-second total station. The closed traverse included two reference monuments that were installed by Washington State Department of Natural Resources surveyors using survey-grade GPS receivers. Final coordinates for each stake were computed using survey least-squares network adjustment software. Closure error was 10 cm which was distributed through the survey loop using least-squares adjustment.

Field Data

In summer 2013 1-hour occupations were collected at 33 survey stakes with Trimble GeoXH6000 standard edition with Floodlight enabled (rover files in SSF format) and Javad Triumph1 (rover files in JPS format) receivers. The receiver specifications and software settings used for collecting GNSS data are given in Table 1. Bipods were used during data collection to position receivers over surveys stakes (Figure 2).

GNSS Postprocessing

Because the distribution of multipath and NLOS signals is dependent on the near-random arrangement of canopy gaps in dense forests, 30 subsamples of a given occupation time were randomly selected from each of the GeoXH6000 1-hr SSF rover files. Barometric data were not included in the sub-sampled files. Thirty sub-sampled SSF files were created for each survey stake with occupation times of 5, 10, 15, 20, and 30 minutes. A total of 990 sub-sampled SSF files were


(a)


(b)

Figure 2. Trimble GeoXH6000 receiver (a) and Javad Triumph1 receiver (b) mounted on bipods. A plumb bob was used for centering the GeoXH6000 antenna over the survey stake.

Table 1. GNSS receiver specifications and data collection software settings.

Receiver	Trimble GeoXH6000	Javad Triumph1
Receiver edition	Standard with Floodlight	--
Constellations tracked	GPS, GLONASS	GPS, GLONASS
GPS signals	L1 C/A, L2C, L2E	L1 C/A, P1, P2, L2C, L5
GLONASS signals	L1 C/A, L1P, L2 C/A, L2P	L1 C/A, L2C, P1, P2, L3
Receiver firmware	V3.06.1	V3.5.1
Antenna type	Internal patch	Internal patch
Antenna height	1.8 m	1.8 m
Data collection software	TerraSync V5.40	Internal memory
Elevation mask	5 degrees	none
PDOP mask	99	none
SNR mask	14	none
Data record rate	1 second	1 second

Table 2. Postprocessing settings for each of the three rover file datasets.

File format	Rover files		
	SSF	RINEX	JPS
GNSS frequencies	L1, L2	L1	L1, L2
Post-processing software	Pathfinder Office V5.60	Justin V2.122.160.11	Justin V2.122.160.11
Processing method	AUTO[1]	Carrier float[3]	Carrier float
Elevation mask	Smart settings[2]	20 degrees	20 degrees
Base station	CXPF	CXPF	CXPF
Coordinate reference framework	NAD83(2011) Epoch 2010.0 UTM Zone 10N Meters	NAD83(2011) Epoch 2010.0 UTM Zone 10N Meters	NAD83(2011) Epoch 2010.0 UTM Zone 10N Meters

[1] PFO software automatically selects either a code or carrier float solution based on a proprietary algorithm.
[2] PFO software automatically selects sets elevation mask, SNR, and PDOP settings based on a proprietary algorithm.
[3] A carrier phase solution uses a floating point approximation of the number of carrier phase cycles between the receiver and each satellite, rather than solving for a fixed integer ambiguity solution.

created for each survey stake for a total of 4,950 SSF files. The 33 1-hr and 4,950 sub-sampled SSF files were postprocessed in Trimble Pathfinder Office (PFO). In PFO, all features, including point features are processed as kinematic (moving while collecting data) features. The continuously operating reference station (CORS) at Charles L. Pack Experimental Forest (CPXF) located near La Grande, Washington, approximately 70 km from the site was used for all postprocessing. CPFX base station files contain complete dual frequency (L1/L2) data for both GPS and GLONASS satellites. For each post-processed SSF file, horizontal error was computed by subtracting the post-processed coordinates from the ground surveyed coordinates (NAD83(2011) Epoch 2010.0). PFO also reported horizontal precision for each post-processed coordinate.

For the set of 15-minute occupations, the survey stake (T6P5) with the largest mean horizontal error and the stake (5A) with the smallest mean horizontal error were selected. The 30 sub-sampled SSF files for these stakes were converted to RINEX files using the Trimble SSF2Rinx program. Unfortunately, the SSF2Rinex program does not include L2 data in the RINEX output; therefore the GeoXH6000 RINEX files only contain L1 data.

Likewise, for the 15-minute occupations, 1 of the 30 sub-sampled SSF files were selected by random draw. This was repeated 30 times with replacement, resulting in 30 sets of 15-minute occupations for each survey stake. The mean horizontal error for the 33 stakes in each draw was computed. For the draw with the largest mean error (draw 21) the 33 sub-sampled SSF files were also converted to L1-only RINEX files.

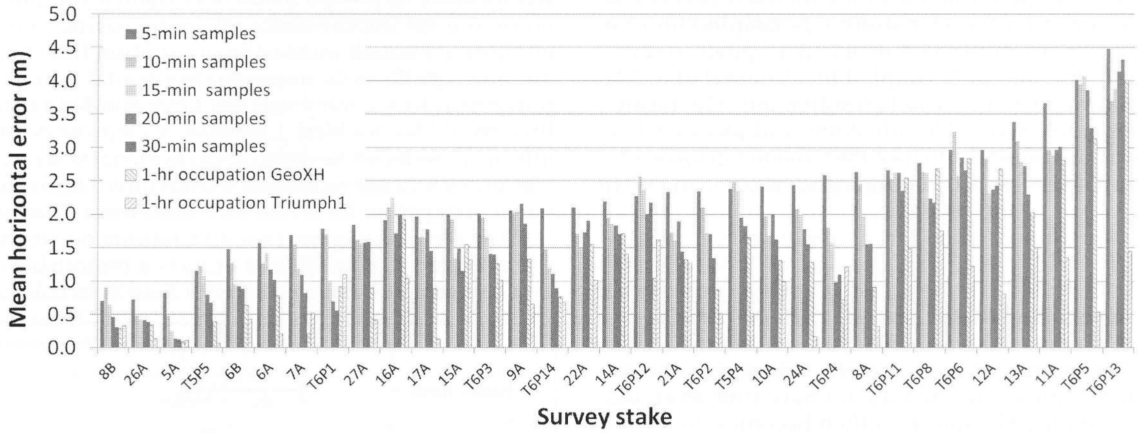

Figure 3. Mean horizontal error (n=30) for sub-sampled SSF and full 1-hour rover files by occupation time for individual survey stakes.

Table 3. Horizontal accuracy of GNSS positions bysub-sampled occupation time.

GNSS receiver	Occupation time (min)	Sub-samples per stake	Mean horizontal error (m)	Standard deviation of horizontal error (m)	Minimum horizontal error (m)	Maximum horizontal error (m)	RMSE horizontal error (m)
GeoXH6000	5	30	2.25	1.44	0.03	9.59	2.67
GeoXH6000	10	30	2.04	1.24	0.04	7.48	2.39
GeoXH6000	15	30	1.85	1.17	0.02	7.01	2.19
GeoXH6000	20	30	1.76	1.14	0.02	8.37	2.10
GeoXH6000	30	30	1.63	1.04	0.03	5.35	1.94
GeoXH6000	60	--	1.43	0.95	0.10	4.01	1.71
GeoXH_L1	60	--	1.05	0.85	0.02	3.35	1.34
Triumph1	60	--	0.83	0.51	0.07	1.75	0.97

The 15-minute GeoXH6000 L1-only RINEX files (GeoXH_L1) were then post-processed in the Javad Justin software as static occupations. The horizontal error of the GeoXH_L1 postprocessed static positions were compared to the horizontal errors of the L1/L2 PFO postprocessed kinematic positions.

The full 1-hr GeoXH6000 rover files were also converted to L1-only RINEX files. These GeoXH_L1 files and the 1-hr Triumph1 files were also postprocessed in Javad Justin software. Table 2 lists the postprocessing settings. For the 1-hr GeoXH6000 and Triumph1 files the Pearson correlation coefficient (r) was computed for the horizontal precision reported by the postprocessing software and the horizontal accuracy of each postprocessed position.

Results

The postprocessed mean, maximum, minimum, standard deviation, and root-mean-square-error (RMSE) of the horizontal errors for the 30 sub-sampled time periods and the full 1-hour occupations were computed. Table 3 lists a summary of horizontal accuracy by occupation time. Figure 3 displays the mean horizontal error by occupation time for the 33 survey stakes. Figure 4 displays the mean horizontal errors summarized by occupation sub-sample time. Figure 5 displays the maximum horizontal errors for each survey stake by occupation sub-sample time. Occupation times of 5 and 10 minutes had mean horizontal errors over 2 m. Occupation times of 15 minutes or greater had mean horizontal error less than 2 m.

Pairwise analysis of variance tests were performed to test for significant differences between the occupation time and mean and maximum horizontal errors (R Development Core Team, 2015). The ANOVA results are graphically summarized in Figures 6 and 7. As expected, longer occupation time resulted in both lower mean and lower maximum errors. Increasing occupation time from 5 to 10, 15, 20, or 30 minutes all resulted in significantly reduced mean horizontal error. Increasing occupation time from 10 to 15, 20, or 30 minutes also resulted in significantly reduced maximum horizontal error, as did increasing from 15 to 30 minutes. However, increasing occupation time from 15 to 20 minutes and from 20 to 30 minutes did not significantly improve mean horizontal error.

Increasing occupation time from 5 to 10, 15, 20, or 30 minutes all resulted in significantly reduced maximum horizontal error, as did increasing from 10 to 30 minutes. Increasing occupation time from 10 to 15 or 20 minutes did not significantly improve maximum horizontal error, and nor did increasing from 15 to 30 minutes.

A paired t-test was performed to compare the difference in mean horizontal error for the 33 survey stakes for the 1-hr GeoXH6000 files processed in PFO (1.45 m) and Triumph1 (0.87 m) occupations processed in Javad Justin software. The Triumph1 mean horizontal error was significantly lower than the GeoXH6000 mean (p = 0.0001). The 1-hr GeoXH_L1 (GeoXH SSF file converted to L1-only RINEX and then processed in Javad Justin) mean horizontal error (1.04 m) was also significantly lower than the GeoXH6000 PFO mean of 1.45 m (p = 0.0004). Finally, the Triumph1 mean was significantly lower than the GeoXH_L1 mean (p = 0.10).

A paired t-test was performed to compare the difference in mean horizontal error for the 15-minute sub-sampled files (n = 30) for survey stake T6P5 (stake with highest mean error) processed in PFO (4.06 m) and the same sub-sampled files converted to L1-only RINEX and processed in Javad Justin (3.23 m). The mean error of the files converted to L1-only RINEX and processed as static points was significantly lower than the mean error of the SSF files processed as L1/L2 kinematic features in PFO (p = 0.006).

A paired t-test was performed to compare the difference in mean horizontal error for the 15-minute sub-sampled files for survey stake 5A (stake with lowest mean error) processed in PFO (0.25 m) and the same sub-sampled files converted to L1-only RINEX and processed in Javad Justin (0.62m). The mean error of the files converted to L1-only RINEX and processed as static points was significantly higher than the mean error of the same files processed as L1/L2 kinematic features in PFO ($p = 0.000008$).

Discussion

As expected, when using the Trimble GeoXH6000 receiver, both mean and maximum horizontal error was lowest with full one-hour occupations. Unfortunately, field crews in production inventory situations often do not have time to collect such long occupations. The question then becomes: In areas of dense conifer forest canopy what is an appropriate occupation time that achieves mean horizontal accuracy in the 1 to 2 m range within reasonable field data collection limits?

The mean horizontal error for 5 and 10 minute occupations were greater than the desired horizontal accuracy for inventory plots of 1 to 2 m. Increasing occupation time to 15 minutes significantly improved mean horizontal error, but there was no significant improvement when increasing from 15 to 20 minutes. Although increasing occupation time from 15 to 30 minutes significantly improved horizontal accuracy, the improvement in accuracy was not large and field data collection time would be doubled. Likewise, 15 minute occupations significantly reduced the maximum horizontal error; and, there was no significant reduction in maximum horizontal error when occupation time was increased from 15 to 30 minutes.

These results suggest that a 15 minute occupation time when using the GeoXH6000 units is a reasonable compromise that balances accuracy goals with field data collection time

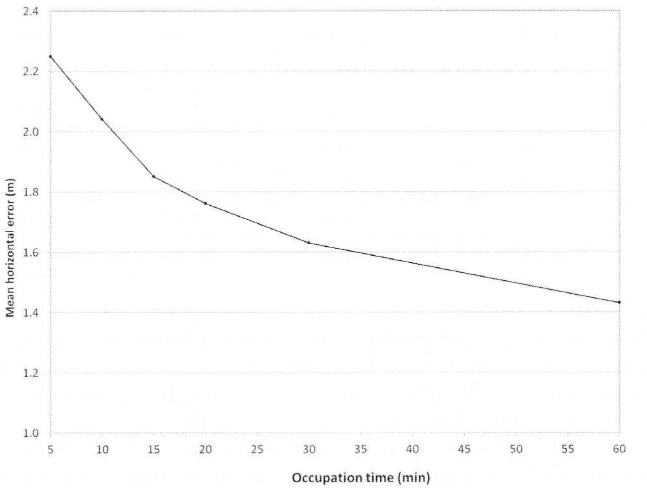

Figure 4. Mean horizontal errors computed for each sub-sampled occupation time and the 1-hr occupations for the GeoXH6000.

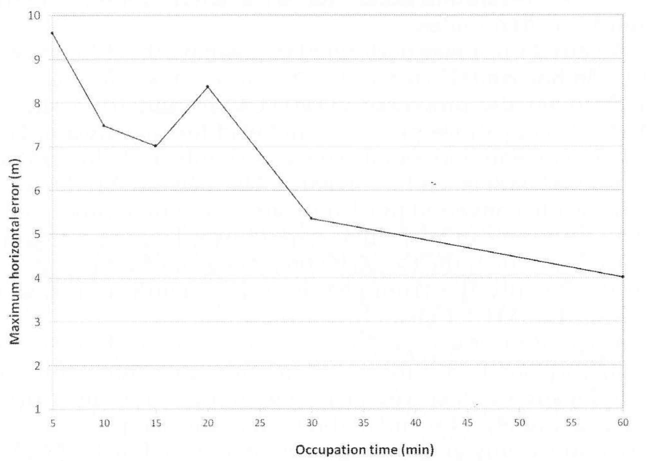

Figure 5. Maximum horizontal errors computed for each sub-sampled occupation time and the 1-hr occupations for the GeoXH6000.

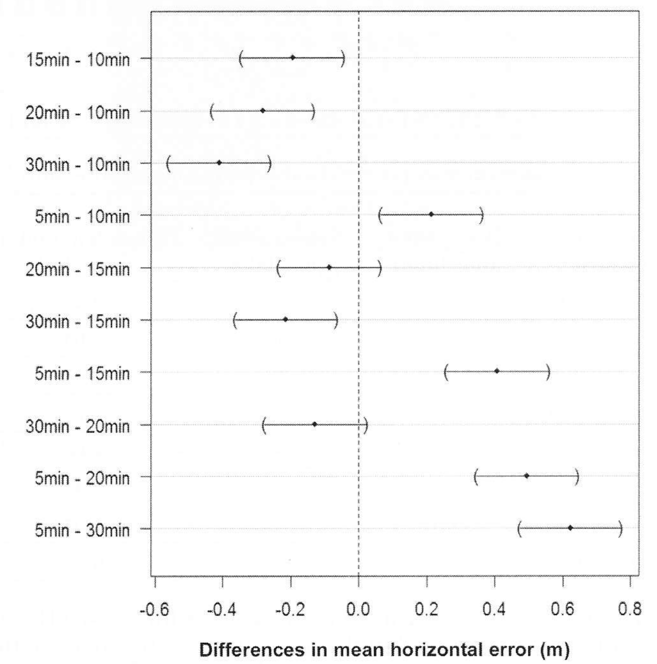

Figure 6. Pair-wise comparison of mean horizontal error (m) by occupation time.

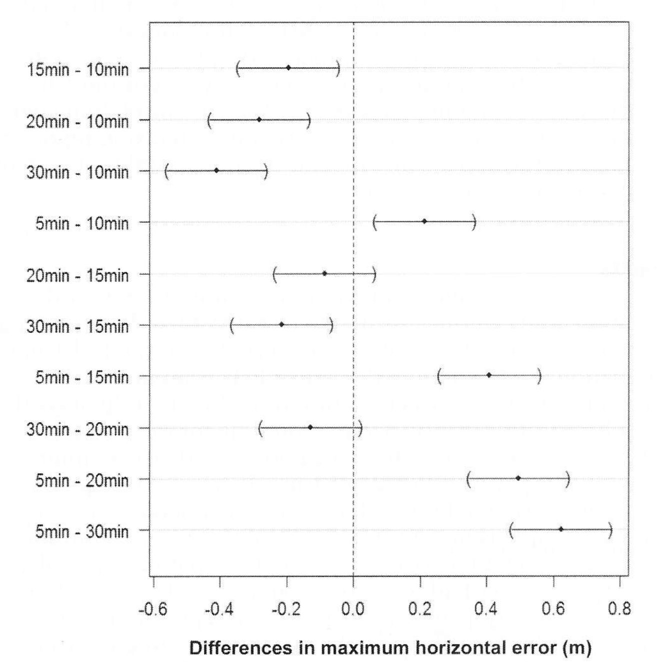

Figure 7. Pair-wise comparison of maximum horizontal error (m) by occupation time.

restrictions. Unfortunately, even with longer occupations, one can expect to occasional have errors that can exceed 5 m.

For 1-hour occupations, more accurate positions were obtained when the GeoXH6000 files are converted to L1-only RINEX and processed in Javad Justin software, in spite of the fact that the L1 RINEX files have only single frequency data. This suggests that by processing the files as static positions in Justin (as opposed to L1/L2 kinematic features in PFO), the solution is better constrained, thereby improves accuracy. Without the static constraint in the post-processing algorithm, PFO appears to not identify and eliminate many NLOS and multipath signals, resulting in the inclusion of these signals and their associated errors in the final point solution. This is supported by the differences in the mean number of satellites tracked versus the mean number of satellites used in the Justin and PFO post-processed solutions. Although the GeoXH6000 receiver tracked significantly more satellites than the Triumph1 (19.7 versus 18.2, $p = 0.02$), the Justin post-processing software, given the static constraint, identified and eliminated many more poor quality signals from its solutions than did PFO and used significantly fewer satellites to compute the postprocessed positions (9.9 versus 18.4, $p <$ 1e-04).

For the 15-minute occupations at the stake with the highest horizontal error (T6P5), again the L1-only RINEX solutions processed in Justin provided significantly lower mean error (3.23 m) than the PFO kinematic solutions (4.06 m). However, for the 15-minute occupations at the stake with the smallest horizontal error (5A), the PFO kinematic solution was significantly better. This is not surprising because error was quite low at this stake (due to relatively more open canopy at 5A located near the stand edge), indicating that NLOS and multipath signals were being identified and eliminated by both post-processing methods. This is supported by nearly equal numbers of satellites used in the solutions by PFO (14.8) and Justin (15.0). Furthermore, because the L1-only RINEX files used in Justin didn't have L2 data, one would expect the PFO solution (0.25 m) to be better than the Justin solution (0.62 m).

For the 1-hr GeoXH6000 positions processed in PFO and the 1-hr GeoXH_L1 and Triumph1 positions processed in Justin ($n = 33$) the correlation between horizontal precision and horizontal accuracy was 0.07 ($p = 0.69$), -0.09 ($p = 0.64$), and −0.005 ($p = 0.98$), respectively, indicating that there is no correlation between reported precision and actual accuracy with either postprocessing software.

We included positions from the Triumph1 to better understand how a survey-grade receiver performed under difficult conditions. In general, we would consider this the best available technology for obtaining positions yet we still observed an average horizontal error of 83 cm and a maximum error of 1.75 m. This illustrates just how difficult it is to obtain accurate positions under forest canopies.

Conclusions

The results of this study suggest that when using a dual-frequency, dual-constellation (GPS and GLONASS) GNSS receiver to collect point positions under dense conifer canopy like that found in forests of western Washington State, occupations should be at least 15 minutes if the desired average horizontal accuracy is 1 to 2 m. No correlation was found between the horizontal precision that was reported by the post-processing software and horizontal accuracy. Therefore, one cannot use the reported precision to infer anything about the actual accuracy of postprocessed positions measured under dense forest canopy. Results in this study, as with several other published studies, showed that horizontal accuracy increases with occupation time, leading the authors to suggest a simple field data collection guideline: the denser the forest canopy, the longer you should collect GNSS data. While this won't guarantee an accurate position, it is the easiest way to safeguard against the effects of signal multipathing and NLOS signals on position accuracy. In lower-density forests, where average GNSS accuracy is usually higher, longer occupation times can still increase the accuracy and reliability of positions. For FIA field crews, who typically spend several hours making plot measurements, collecting GNSS data for a longer period of time does not add to their overall time on the plot.

An important question not addressed in this study is: what accuracy could the GeoXH6000 achieve if point features could be processed as static points utilizing the full L1/L2 data in PFO, particularly given the large number of satellites tracked by the GeoXH6000? Unfortunately, the current version of PFO does not allow point features to be processed as static points.

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References

Andersen, H.-E., T. Clarkin, K. Winterberger, and J. Strunk, 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, *Western Journal of Applied Forestry*, 24(3):128–136.

Blackard, J.A., M.V. Finco, E.H. Helmer, G.R. Holden, M.L. Hoppus, and D.M. Jacobs, A.J. Lister, G.G. Moisen, M.D. Nelson, R. Riemann, B. Ruefenacht, D, Salajanu, D.L. Weyermann, D.C. Winterberger, T.J. Brandis, R.L Czaplewski, R.E. Roberts, P.L Patterson, and R.P.Tymcio, 2008. Mapping US forest biomass using nationwide forest inventory data and moderate resolution information, *Remote Sensing of Environment*, 112: 1658–1677.

Bolstad, P., A. Jenks, J. Berkin, K. Horne, and W.H. Reading, 2005. A comparison of autonomous, WAAS, real-time, and post-processed global positioning systems (GPS) accuracies in Northern forests, *Northern Journal of Applied Forestry*, 22(1):5–11.

Clarkin, T., 2007. *Modeling Global Navigation Satellite System Positional Error under Forest Canopy Based on LIDAR-derived Canopy Densities,* M.S. Thesis, College of Forest Resources, University of Washington, Seattle, Washington. 99 p.

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

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

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

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

Hoppus, M. and A. Lister, 2007. The status of accurately locating Forest Inventory and Analysis plots using the global positioning system, *Proceedings of the Seventh Annual Forest Inventory and Analysis Symposium, 2005* (R.E. McRoberts, G.A. Reams, P.C. Van Deusen, and W.H. McWilliams, editors), October 03-06; Portland, Maine, General Technical Report WO-77, Washington, D.C., U.S. Department of Agriculture Forest Service, pp. 179–184.

McRoberts, R.E., 2010. The effects of rectification and global positioning system errors on satellite image-based estimates of forest area, *Remote Sensing of Environment*, 114:1710–1717.

Næsset, E., 2001. Effects of differential single- and dual-frequency GPS and GLONASS observations on point accuracy under forest canopies, *Photogrammetric Engineering & Remote Sensing*, 67:1021–1026.

Næsset, E. and J.G. Gjevestad, 2008. Performance of GPS precise point positioning under conifer forest canopies, *Photogrammetric Engineering & Remote Sensing*, 74(5):661–668.

Petovello, M., 2013. Multipath vs. NLOS signals, *InsideGNSS*, Nov/Dec 2013, p. 40-44, URL: http://www.insidegnss.com/node/3789 (last date accessed: 06 November 2017).

R Development Core Team, 2015. R: A language and environment for statistical computing, *R Foundation for Statistical Computing*, Vienna, Austria.

Tomppo, E., H. Olsson, G. Stahl, M. Nilsson, O. Hagner, and M. Katila, 2008. Combining national forest inventory field plots and remote sensing data for forest databases, *Remote Sensing of Environment*,112:1982–1999.

Valbuena, R., F. Mauro, R. Rodriguez-Solano, and J.A. Manzanera, 2010. Accuracy and precision of GPS receivers under forest canopies in a mountainous environment, *Spanish Journal of Agricultural Research*, 8(4):1047–1057.

Vogt, J.T., and W.B. Smith. 2017. *Forest Inventory and Analysis Fiscal Year 2016*, Business Report, FS-1075, Washington, D.C., U.S. Department of Agriculture Forest Service, 73 p.

Zald, H.S., J.L. Ohmann, H.M. Roberts, M.J. Gregory, E.B. Henderson, R.J. McGaughey, and J. Braaten, 2014. Influence of lidar, Landsat imagery, disturbance history, plot location accuracy, and plot size on accuracy of imputation maps of forest composition and structure, *Remote Sensing of Environment*, 143:26–38.