PRECISION FORESTRY STUDIES: LASER CALIPERS AND GPS RECEIVERS

by

STEVEN ARCHIE WEAVER

(Under the Direction of PETE BETTINGER)

ABSTRACT

This thesis reports the findings of two *Precision Forestry* studies. In the first, a sector-fork and laser calipers were tested in three forest types. Mixed results were found that vary by forest type. They suggest direct diameter measurements can be significantly different than measurements collected at a distance with laser calipers. Sector-fork results were also varied; suggesting forest type can be a significant factor. Light conditions had no significant effect on caliper measurements, and results were mixed on the significance of forest type on measurement error. In the second study, the static horizontal accuracy of two GPS receivers was examined. Tests suggest forest type significantly affects accuracy. Season was a significant factor with the recreational-receiver but not the mapping-grade receiver, and the vertical holding position provided significantly lower error than other positions with the mapping-grade receiver. Further, environmental variables seemed to have no effect on position accuracy of both receivers.

INDEX WORDS: Forest measurements, accuracy, precision, error

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DEDICATION

I dedicate this work to my family and friends who have been with me through this process. I am especially grateful to my parents, William and Annie Weaver, whose constant love and support have been so vital in bringing my work to completion. I could never repay your love and kindness.

I also dedicate this thesis to Olivia Mangrum. Your patient encouragement over the past several months has been such a blessing. I couldn't have done it without you.

ACKNOWLEDGEMENTS

I would like to start by thanking Dr. Pete Bettinger. Pete has been instrumental in every way during this time. From accepting me as a student, to procurement of funding, to project development, to analysis and write-up, Pete has provided invaluable guidance in my thesis work and professional development. He has always been available and eager to assist, and without his help, this project would not have been possible. I am truly grateful for all his efforts.

I would like to thank my committee members, Dr. Michael Kane and Dr. Thomas Jordan, for their comments and advice on this project. While most of our interactions were through the classroom, I appreciate the time and effort the committed to me and the project. I would also like to thank Zennure Ucar, Krisha Faw, and Krista Merry. All of their help in conducting field work and write-up was invaluable. Their editing comments were particularly useful and definitely improved the quality of the work.

And last but not least, I would like to thank the Warnell School of Forestry and Natural Resources for providing my assistantship funding and access to the equipment and test site used in these studies. This would not have been possible without it. Thank you!

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

Introduction

What is *Precision Forestry*? A review of various definitions of this term might suggest that it involves the science or practice of accurately managing and caring for forests. This is a basic generalization and does not sufficiently define or describe *Precision Forestry*. Bruce Bare (2001), in his keynote speech at the First International Precision Forestry Symposium, described *Precision Forestry* as utilizing highly-detailed data to aid in site-specific decision-making allowing for repeatable measurements while protecting water quality, wildlife habitat, and a variety of other resources. In discussing the term *Precision Forestry* and its development in the southeastern United States, Taylor et al. (2006) defined it as "planning and conducting site-specific forest management activities and operations to improve wood product quality and utilization, reduce waste, and increase profits, and maintain the quality of the environment." Taylor et al. (2006) also discuss how improvements in technology are driving these activities where GIS and remote sensing or geospatial technology is a key component. This definition of *Precision Forestry* is the one that will be considered in this paper.

While *Precision Forestry* is still a relatively new term to the forest industry, a variety of research has been conducted in this area where developing technologies have been evaluated for their use and accuracy in forestry practices. For example, global positioning system (GPS) receivers were used to track wheeled skidders under different canopy conditions (Veal et al.

2001). GPS has also been used to evaluate the productivity of forest machines (Taylor et al. 2001). McDonald et al. (2006) performed a study evaluating herbicide application and seedling planting locations using GPS technology to generate maps to document the work.

Those studies represent only a small portion of the work having previously been performed. New technology for use in forestry is continually being developed, and I believe a continuous evaluation is necessary. Peter Farnum (2001) suggested that the precision of the technology is unimportant if it does not address the social and scientific concerns of forestry accurately. The social concerns involve sustainable management, commodity production, and the protection of ecological values, while the scientific concerns involve is the application of a rigorous experimental design to testing new technology. The studies presented in this paper are partially presented under this light to provide a scientific evaluation of new technology.

Dendrometer Literature Review

Examinations and tests of analog and digital tools for measuring tree diameters (dendrometers) have been reported in the literature for nearly 100 years. The main concerns associated with forest sampling procedures when using these instruments relate to efficiency, economy, and rationality (Rhody, 1975). Sophisticated instruments have been devised to measure trees from a distance or remotely (e.g., Henning and Radtke, 2006) and to measure trees with special characteristics, such as fluted basal swells (e.g., Parresol and Hotvedt, 1990). A range of results have been presented in comparing measurements of diameter directly obtained by using calipers or tapes. In some cases, practically no importance has been associated with the choice of instrument (Behre, 1926). In other cases, the differences between two types of measurements have been very small (Krauch, 1924), while others have found the differences to be statistically significant (Binot et al., 1995). Some have even suggested that the most accurate method is one that involves direct measurements of inside bark diameter (Chacko, 1961). Although most dendrometers can provide estimates of outside bark diameters that are adequate for a number of field inventory applications, when minor differences between measured tree diameters have been found among dendrometers, these differences can translate into significant variations in tree volume estimates (Parker and Matney, 1999).

In addition to precision dendrometers that are strapped or affixed to a tree (e.g., Yoda et al., 2000; Drew and Downes, 2009), panoramic (Rhody, 1975) and wide angle photography (Clark et al., 2000b) have also been tested for their ability to assist in diameter measurements. Optical sensor systems that use lasers have also been developed to count and determine the sizes of trees (Fairweather, 1994; Delwiche and Vorhees, 2003). A machine vision system has been recently tested that, through the detection of illuminated line segments, can count stems and determine diameters (Zhang and Grift, 2012). Further, tree diameters have been correlated with measurements obtained through the use of Lidar (Popescu, 2007). Skovsgaard et al. (1998) found that remote measurements tended to overestimate tree diameters by 2 to 5 %, with increasing deviations as measurement distance from a tree increased. On the other hand, Nicoletti et al. (2012) found the two optical dendrometers tested tended to result in an underestimation of stem biomass. Williams et al. (1999) also noted that the variability of measurements increases with the distance from a tree. While the sophistication of remote methods is increasing, results generated by some of these methods can be affected by the inability of a sensor to locate blocked tree stems or measurement errors arising from stem and bark irregularities (Bell and Groman, 1971).
For practical purposes, dendrometers need to be inexpensive, precise, and easy to use (Kalliovirta et al., 2005). Some efficient and reliable instruments may be expensive, complex (e.g., Parker, 1997), or too heavy (e.g., Liu et al., 1995) for regular field work. Laser

dendrometers might be suitable for use in practical forestry applications, yet the accuracy of the devices needs to be tested under typical operating conditions. The accuracy of some types of laser dendrometers may be associated with distance from a tree, measurement time, and tree diameter.

GPS Receiver Literature Review

Since the introduction of global navigation satellite systems 30 years ago, global positioning system (GPS) receivers have become a popular tool in natural resource management. Their integration has been somewhat slower in forestry because of difficulties in acquiring quality satellite signals under canopy (Wing 2008), but in general, this technology is steadily replacing traditional navigation and mapping techniques (Bettinger and Fei 2010). GPS receivers can be used for a variety of field work tasks. For example, they can be used for navigation, to locate permanent field plots, to map ownerships or management unit boundaries for use in geographical information systems, or to map points of interest for management or research. They are also frequently used in wildlife management research to track and locate GPS-tagged wildlife. A number of recent studies have been conducted to evaluate the static horizontal accuracy of GPS receivers in forestry applications (Wing et al. 2005, 2008, Danskin et al. 2009a, 2009b, Ransom et al. 2010). While GPS receivers have been shown to provide fairly accurate location information, several studies have found that vegetation type and canopy cover can have a significant effect on location accuracy (Veal et al. 2001, Wing and Karsky 2006, Wing et al. 2008, Andersen et al. 2009). Other factors that may affect location accuracy have been tested as well such as season and environmental variables such as air temperature and humidity (Bettinger and Fei 2010, Danskin et al. 2009a, 2009b) and post-process differential correction (Veal et al. 2001, Wing and Karsky 2006, Wing et al. 2008). As the desire for highly accurate location data increases and GPS technology changes, these receivers need to be continually reassessed to provide natural resource managers with a better understanding of the accuracy of this technology and the factors that influence it (Bettinger and Fei 2010).

Thesis Format

This thesis is written in the manuscript format, and it presents the results of two studies. Chapter 1 is an introductory chapter and provides a brief summary of previous research on dendrometers and GPS receivers. In Chapter 2, “Assessing the Accuracy of Tree Diameter Measurements Collected at a Distance,” three dendrometers were tested; the Haglöf Gator Eyes system mounted on an 18-inch Mantax Black caliper, the Bitterlich sektorkluppe or sector-fork, and a diameter tape. The Gator Eyes system consists of Class III green lasers mounted on the caliper jaws to facilitate the collection of diameter measurements at a distance, and the sector-fork uses perspective geometry to estimate diameters by placing the instrument on the tree bole at diameter at breast height. The main goal of the study was to examine whether there might be any bias between collecting direct or contact measurements versus collecting diameter measurements at a distance with the Haglöf Gator Eyes. The following are the hypotheses we attempt to examine:

1. There is no significant difference between direct and remote laser caliper measurements of tree diameters.
2. There is no significant difference between caliper (direct and remote) measurements and sector-fork measurements of tree diameters.
3. Light conditions have no significant effect on tree diameter measurements.

4. There is no significant difference between tree diameter measurement errors for data collected in different forest types.

In the second study (Chapter 3), “Static Horizontal Accuracy Assessment of a Mapping-Grade and a Recreational-Grade GPS Receiver,” we tested two GPS receivers; a Garmin Oregon 450t recreational-grade receiver and an F4Tech Flint mapping-grade receiver. Recreational-grade and mapping-grade receivers are the two most common types of GPS receivers chosen for use in forestry. These two receivers were chosen because they were relatively new releases of the technology at the start of the study. Static horizontal accuracy is the most common accuracy assessment performed on GPS receivers, and the goal of this study is to evaluate this for both receivers and examine if a variety of environmental factors, such as season and forest type, have any effect on accuracy. The following hypotheses will be examined for both receivers:

1. Horizontal position accuracy is not affected by season of data collection.
2. Horizontal position accuracy is not affected by forest type.

It was suggested by the supplier of the Flint receiver that the holding position of the receiver can affect data accuracy. The following hypothesis will only be tested on the Flint:

3. Horizontal position accuracy is not affected by receiver orientation during data collection.

Finally, Chapter 4 is a conclusion chapter with a review of each study’s conclusions and the management implications associated with each.

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CHAPTER 2

ASSESSING THE ACCURACY OF TREE DIAMETER MEASUREMENTS COLLECTED AT A DISTANCE[1]

[1] Weaver, S. A., Z. Ucar, K. Faw, P. Bettinger, K. Merry, and C. J. Cieszewski.

Submitted to the *Croatian Journal of Forest Engineering*.

Abstract

The ability to measure trees remotely or at a distance can increase the efficiency of forest inventory processes. Within three forest types (young pine, old pine, and hardwoods), we compared laser caliper measurements collected at distances up to 12 m from each tree, to direct contact laser caliper measurements and a Bitterlich sector-fork measurement. Diameter tape measurements were also collected solely for reference. We used a Wilcoxon two-sample test to evaluate three of our four hypotheses that suggest there are no significant differences between direct and remote diameter measurements, between caliper measurements and sector-fork measurements, and between diameter measurement errors across forest types. In general, most of the differences in diameters were small (0.8 cm or less) and observed within the 0 to 6 m measurement distance from each tree. These results suggest that forest characteristics and measurement distance may play a role in remote diameter measurement accuracy. We also performed a correlation analysis between light conditions and remote measurements. The correlation analysis suggested light conditions were not significantly correlated to diameter measurement accuracy. Although some significant differences were observed, measurements with laser calipers may reduce the time and costs of management, but these potential benefits have yet to be quantified.

Keywords

Dendrometer, precision forestry, Bitterlich sector-fork, Haglöf Gator Eyes, laser caliper, accuracy assessment

Introduction

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Kalliovirta et al. (2005), there is no relationship between the position of the dendrometer (when in use) and a person's eye with the laser caliper; therefore theoretically, the laser caliper should be more user-friendly than other laser dendrometer devices.

As with previous evaluations (e.g., Skovsgaard et al., 1998) our study is concerned with detecting possible bias when using remote and direct (contact) instruments for measuring outside bark tree diameters. The objectives of this research were to determine the relative consistency in measurements obtained using different techniques, remotely and directly, and whether there were significant differences between these. We attempt to examine several hypotheses:

1. There is no significant difference between direct and remote laser caliper measurements of tree diameters.
2. There is no significant difference between caliper (direct and remote) measurements and sector-fork measurements of tree diameters.
3. Light conditions have no significant effect on tree diameter measurements.
4. There is no significant difference between tree diameter measurement errors for data collected in different forest types.

Methods

Repeated measurements are necessary for obtaining statistical stability and for assessing accuracy and precision (Bruce, 1975). For this study, one hundred trees were randomly selected within each of three forest stands located at the University of Georgia’s Whitehall Forest; an older hardwood forest (60 to 70 years old), an older pine forest (60 to 70 years old), and a young pine forest (18 years old) (Figure 2.1). Further, three forest types with different characteristics

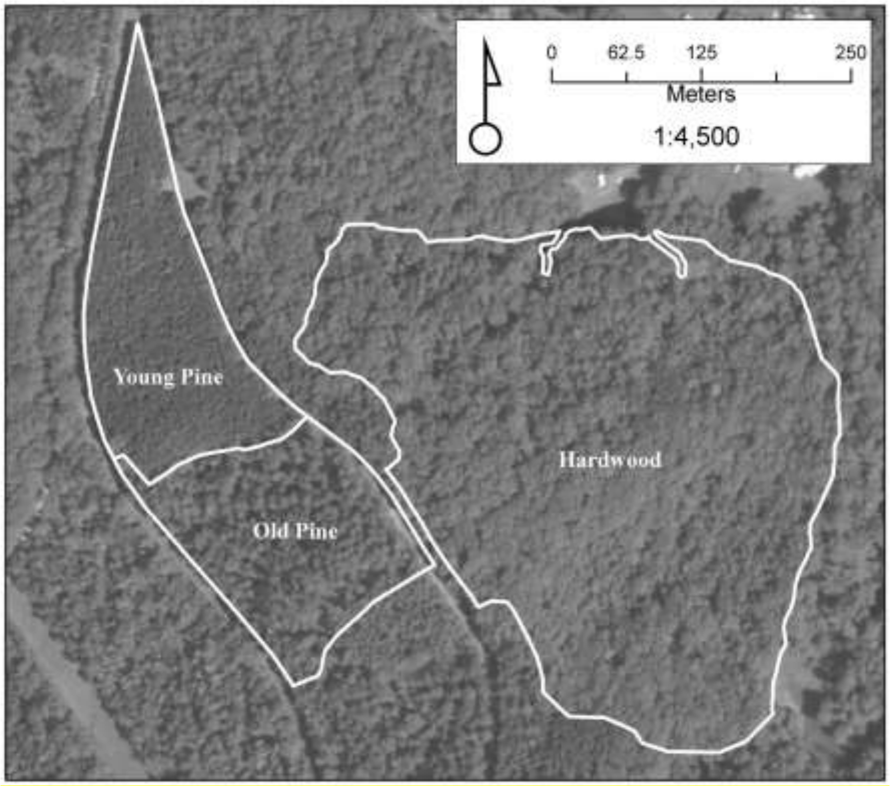

Figure 2.1. Aerial view of Whitehall Forest showing relative positioning of forest stands used in this study.

(Table 2.1) and diameter distributions (Figure 2.2) were included in this study to assess accuracy and precision differences with changes in light conditions (as a function of tree density and canopy closure) and bark characteristics (as a function of tree species, as suggested by Liu et al., 2011). Data were collected in the afternoon for 12 days (4 days per forest type) during October and November. Light conditions ranged between 101-60,000 lux with an average of 4,906.

We based our sample size, where the sample units were trees to measure in each of the three forest types, as a compromise between time availability and estimated precision of the population mean given 100 sample trees in each forest type. Of primary interest was the difference between the direct caliper measurement and the other four measurements made with

Table 2.1. Characteristics of the forested test areas.

Forest Type	Approximate Age (years)	Basal Area (m^2 ha^{-1})	Stem Count (trees ha^{-1})	Canopy Closure (%)
Young pine	18	35.4	1495.3	93
Old pine	65	22.9	303.4	85
Hardwood	65	26.2	421.7	94

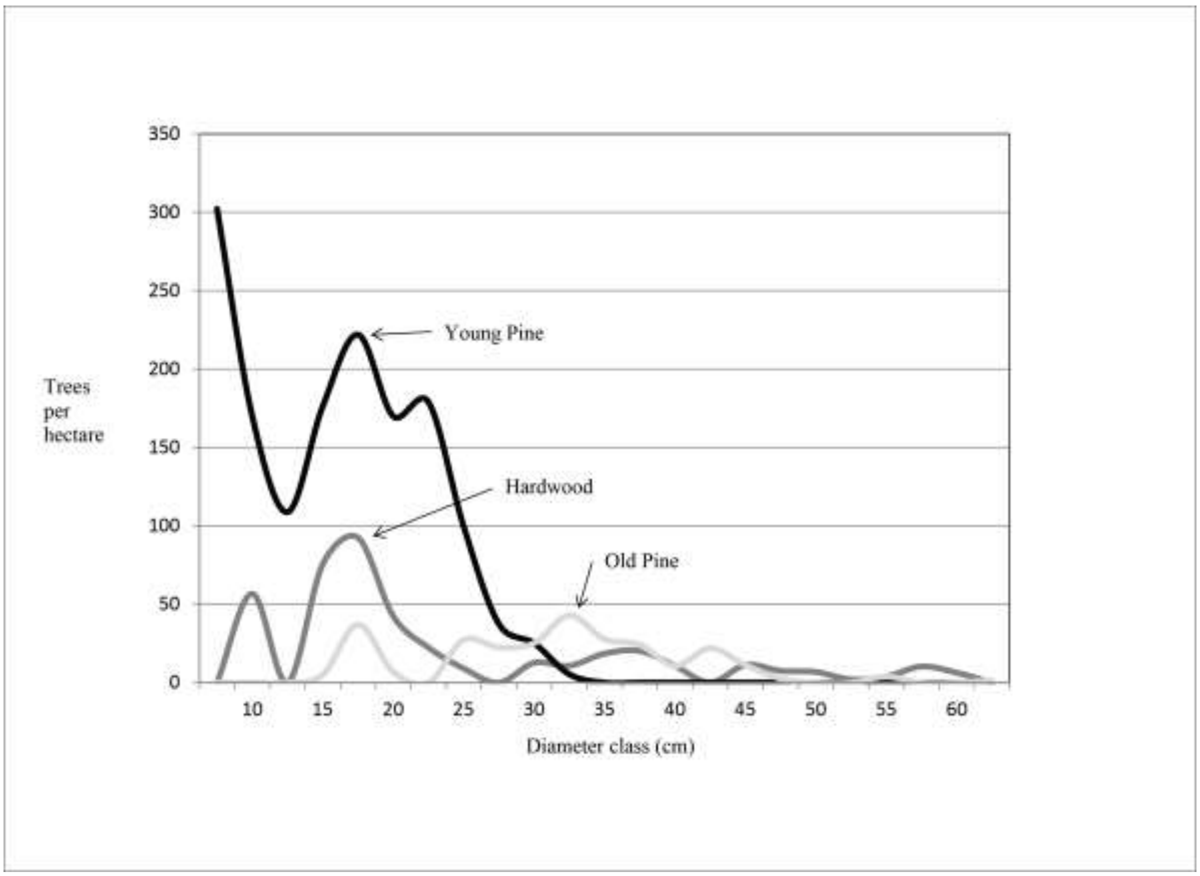

Figure 2.2. Diameter distributions of the young pine, older pine, and hardwood test areas.

the caliper at a distance. The computation of the deviation in diameter values, DEV_{idj}, or the deviation between the direct measurement and the measurement made for tree *i* at distance *d* in forest type *j*.

$$\mathrm{DEV}_{idj} = \mathrm{DBH}_{i0j} - \mathrm{DBH}_{idj}$$

DBH_{i0j} represents the direct caliper measurement for tree *i* in forest type *j*. DBH_{idj}, which could either be smaller or larger than DBH_{i0j}, represents the caliper measurement for tree *i* in forest type *j*, collected at distance *d*. This computation could lead to either positive or negative values of DEV_{idj}. A scale shift was considered, yet the standard deviation of the set of each for the three forest types is scale invariant. We assessed the sample size required for each distance and forest type (n_{dj}), assuming a desired 95% confidence interval, using the following sample size formula,

$$n_{dj} = \left(\frac{1.96\, s_{dj}}{E} \right)^2$$

where s_{dj} represents the standard deviation for deviations in values found at distance *d* in forest type *j*. The value *E* represents an assumed objective for estimating the population mean deviation in values between direct measurements and measurements collected at a distance (i.e., to within a certain number of units, represented by *E*). When we assume an objective of estimating the population mean deviation to be within 0.15 cm, we find that 100 samples is sufficient. This assumption (0.15 cm) was at worst, 33% of a single standard deviation representing the difference in direct and remote measurements. In only one case (the hardwood forest at the 12 m distance) was the suggested sample size larger than 100 trees (102 trees). This sample size (tree count) is also consistent with other recent work in the southern United States (Parker and Matney, 1999; Liu et al., 2011).

In all cases, the selected trees were measured along their stem to collect the diameter at breast height (DBH) outside bark at 1.37 m above ground. We used masking tape to mark the location just below where DBH would be measured so that measurements would all be made at the same place on each tree at the edge of actual bark (Figure 2.3). Each tree was visited one time during the study period to make all seven diameter measurements. Three measurements involved directly touching each tree (DBH tape, sector-fork, and a caliper measurement with the Mantax Black caliper), and the other four involved single remote measurements of DBH with the laser caliper along a consistent line of sight from the tree at 3 m, 6 m, 9 m, and 12 m (Figure 2.4). The sector-fork and direct (0 m) caliper measurements were also made along this same line of sight. For this study, the direct caliper measurement was assumed to be the best or the 'true' diameter. We allowed up to 30 seconds for each individual remote caliper measurement. The diameter tape measurements were made solely for reference purposes. Measurements made using diameter tapes have been shown to be different than those collected using calipers (McArdle, 1928), and they cannot be directly compared to single caliper measurements or sector-fork measurements given the irregular shape of most tree boles (Brickell, 1970; Moran and Williams, 2002).

While a variety of electronic dendrometers and scanning systems are available, due to availability, time, and cost limitations, the Mantax Black caliper and the sector-fork were chosen for testing. For the same reasons, all of the measurements were collected by one individual after several hundred practice measurements with the sector-fork and the laser caliper and after practice on fixed width, non-natural targets. This process helped avoid differences between

Figure 2.3. Diameter measurements conducted at a distance with the laser caliper dendrometer.

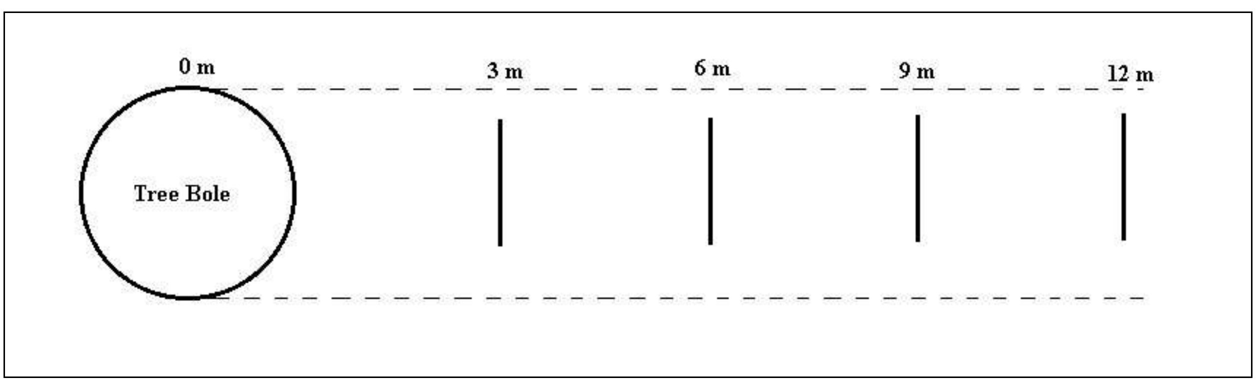

Figure 2.4. Diagram showing the layout of laser caliper measurements every 3 meters up to 12 meters along a consistent line of sight away from the sample tree (not drawn to scale).

individuals, although they could be small (Elzinga et al., 2005). The only environmental variable that was collected with the sampling of each tree was the incident light luminous emittance (lux) using a Mastech LX1330B light meter (Figure 2.5). This lux data were collected to determine if light conditions are correlated with remote diameter measurement accuracy.

Errors in successive measurements of tree diameters can occur with some instruments, and may be due to the following (McCarthy, 1924; Robertson, 1928):

1. Misjudging points of successive measurements.
2. Failing to place the instrument in its proper plane.
3. Measuring within close proximity to tree deformations.
4. Failing to account for differences in the tension of bark on trees.
5. Misreading instrument divisions.
6. Failing to notice weathering and scaling of tree bark.
7. Failing to know that instruments can be out of adjustment.

To limit potential errors such as these we developed a set of standard methods for data collection. These methods included measuring the diameter of a sample tree all seven times in a single visit within approximately five minutes, using the same person to collect all of the measurements, and conducting six of the seven measurements from the same perspective with respect to the tree; the exception involved the use of the diameter tape. The caliper tongs were also closed after each measurement to avoid biasing the next measurement.

While direct caliper measurements can be subject to error described by Abbé's Principle, remote caliper measurements will not (Clark, 2003). This principle states that measurement

Figure 2.5. Light conditions being measured using the Mastech LX1330B light meter.

errors with calipers will increase as the object being measured moves away from the device causing the caliper's tongs to bend outward, which introduces error. This would require the measured item to be within the jaws of the caliper. To minimize potential errors when using the caliper to make direct measurements of tree diameters, the bole of the tree will be placed as close as possible to the caliper bar, reducing the bending force on the jaws. When larger trees are measured, this type of error may be introduced when pressure from the tree bole is placed further out on the jaws. We do not employ a correction factor in these instances, and given that the caliper is relatively new, we assume that the forces acting on the jaws, perhaps requiring them to bend outward rather than to slide naturally along the caliper bar, will be minimized.

Ideally, the set of laser caliper measurement deviations for a specific distance *d* (direct measurement - distance *d* measurement) in a forest type *j* should be normally distributed around zero (no deviation). However, the ability to place the laser lights exactly on the edge of each tree at exactly the same time was difficult, perhaps due to a combination of general light conditions, bark conditions, and shadows within the crevasses of the bark. While we test the correlation between accuracy and general light conditions, the other potential factors were not tested. What we found was that the set of deviations developed by comparing the direct and remote measurements was not statistically significant with respect to representing a normal distribution in 10 of the 12 cases, according to Chi-squared, Anderson-Darling, or Kolmogorov-Smirnov tests (Palisade Corporation 1996). Therefore, a non-parametric method, Wilcoxon's matched-pairs signed-ranks test, was used to determine whether pairs of sample sets arose from the same population having the same location. When applying this test, if the rank sums of the paired samples are approximately the same, we would expect that they are not significantly different (Sokal and Rohlf, 1995). Although we initially assumed they are different, we applied this test to assess the difference between DBH tape measurements and other direct measurements. In applying this test for an analysis of Hypothesis 1, the test statistic was the tree diameter, and we compared the remotely obtained caliper measurements (3 to 12 m) to the direct caliper measurement (0 m) within each forest type. In applying this test for an analysis of Hypothesis 2, the test statistic was again the tree diameter, we compared the sector-fork measurements to all caliper measurements (direct, 3 to 12 m) within each forest type. In assessing Hypothesis 3, Pearson's product-moment correlation coefficient was computed for the association between illuminance (lux measurements at DBH) and the deviations computed for remotely measured tree diameters using the caliper (direct measurement - remote measurement). Both the actual deviation (positive or negative value) and the absolute value of the deviation were assessed in this correlation analysis. For Hypothesis 4, we attempted to determine whether the test statistic, the deviation in diameters (direct - remote) and the absolute values of the deviations, was significantly different across the three forest types at each distance using the Wilcoxon test.

Results

The average diameters measured within each forest type and the associated measurement process are shown in Table 2.2. In general, the diameters estimated using the DBH tape were significantly greater ($p < 0.05$) than direct measurements of diameters estimated using other methods. However, the other methods only considered one viewing perspective of a tree, thus do not fully account for irregularities in the shape of tree boles. The general pattern of results within a forest type is similar, yet the use of the sector-fork consistently produced a lower mean diameter when compared to the other measurements. Variation (standard deviation) among the sets of diameters, show there is more diversity among tree sizes in the deciduous forest than in the two pine forests (Table 2.3). Interestingly, 12 m remote caliper measurements were consistently slightly smaller with regard to the standard deviation than diameter measurements collected with the other processes.

Since the diameter distribution of trees within each forest type is different, another way to view the results is to compare the deviation in diameters with respect to the 0 m caliper measurement (Table 2.4). All of the remote measurements within the young pine stand tended to overestimate tree diameters, and the sector-fork measurements across all forest types tended to underestimate tree diameters. The variation (as reported by standard deviation) in measurement deviations (Table 2.5) also suggest that the use of the sector-fork tended to result in a noticeably larger amount of variation across forest types. In general, the variation in caliper measurement

Table 2.2. Average tree diameter by forest and measurement type.

	Forest Type		
Sample Measurement	**Young pine (cm)**	**Old pine (cm)**	**Hardwood (cm)**
DBH Tape	18.36	34.64	30.11
Sector-fork	17.88	33.74	29.50
Caliper – 0 m	18.03	34.35	29.79
Caliper – 3 m	18.07	34.34	29.56
Caliper – 6 m	18.11	34.35	29.69
Caliper – 9 m	18.24	34.34	29.67
Caliper – 12 m	18.31	34.26	29.68

Table 2.3. Variation (standard deviation) among diameters by forest and measurement type.

	Forest Type		
Sample Measurement	**Young pine (cm)**	**Old pine (cm)**	**Hardwood (cm)**
DBH Tape	4.87	8.42	14.04
Sector-fork	4.68	8.62	13.69
Caliper – 0 m	4.79	8.52	13.98
Caliper – 3 m	4.72	8.52	13.77
Caliper – 6 m	4.68	8.45	13.75
Caliper – 9 m	4.63	8.41	13.63
Caliper – 12 m	4.56	8.38	13.56

Table 2.4. Average deviation[a] in diameter measurement from the 0 m caliper measurement.

Sample Measurement	Forest Type		
	Young pine (cm)	Old pine (cm)	Hardwood (cm)
DBH Tape	-0.33	-0.29	-0.32
Sector-fork	0.16	0.60	0.29
Caliper – 3 m	-0.04	0.00	0.23
Caliper – 6 m	-0.08	0.00	0.09
Caliper – 9 m	-0.21	0.01	0.12
Caliper – 12 m	-0.28	0.08	0.11

[a] (0 m caliper measurement - other sample measurement)

Table 2.5. Variation (standard deviation) in deviation of diameter measurement from the 0 m caliper measurement.

Sample Measurement	Forest Type		
	Young pine (cm)	Old pine (cm)	Hardwood (cm)
DBH Tape	0.36	0.88	0.92
Sector-fork	0.55	3.60	2.05
Caliper – 3 m	0.43	0.49	0.40
Caliper – 6 m	0.45	0.60	0.45
Caliper – 9 m	0.55	0.68	0.60
Caliper – 12 m	0.64	0.72	0.77

deviations (as compared to the 0 m caliper measurement) tended to increase slightly the farther one moved away from the tree.

When examining the differences between the direct caliper measurement and the remote caliper measurements within the hardwood stand, we reject the null hypotheses ($p < 0.05$) that samples obtained at 3m, 6m, and 9m from each tree are the same as the direct measurement. However, the 12 m remote measurements ($p > 0.05$) were not significantly different from the direct caliper measurement. Therefore, in assessing Hypothesis 1, we found mixed results from measurements collected in the hardwood stand. When examining the differences between direct and remote caliper measurements within the older pine stand, there are no statistically significant ($p > 0.05$) differences between the direct and remote measurements. Therefore, we could not reject the null hypothesis that the samples arose from the same population. The same can be said about the direct and 3 m remote measurements obtained from the young pine stand. However, measurements obtained from 6-12 m were statistically significantly different than the direct measurement ($p < 0.05$); therefore, we reject the null hypothesis in these cases.

In comparing the caliper measurements to the sector-fork measurements, we found no statistically significant differences ($p > 0.05$) in the hardwood stand. For the older pine stand, we found statistically significant differences between the sector-fork measurements and the direct caliper and 3 m caliper measurements ($p < 0.05$); all other comparisons of diameters collected remotely in the older pine stand with the calipers were not significantly different than the sector-fork measurements. According to the results obtained from the application of the Wilcoxon two-sample test, the sector-fork data collected within the young pine stand were considered statistically significantly different ($p < 0.05$) than the data collected at all distances with the calipers.

The correlation analysis between illuminance (lux) and the deviation in remote caliper measurements from direct caliper measurements indicated very weak relationships in many instances (Table 2.6). In this analysis the deviation could be either positive or negative, and therefore it is assumed that light characteristics may force an overestimate or underestimate of the tree diameter when measured remotely. However, based on the p-values of this analysis, illuminance has no significant correlation to the deviation in diameter measurements between the direct measurement and the remote measurements. We also assessed the correlation between illuminance and the absolute value of the difference between remote caliper measurements from direct caliper measurements, assuming that the direction of the deviation (either an overestimate or underestimate of the tree diameter) is not necessarily forced by illuminance, but that changes in illuminance simply cause a deviation one way or the other (Table 2.7). As with the prior analysis, it does not appear that illuminance has any significant correlation to the differences in diameters based on the *p*-values ($p > 0.05$).

In assessing differences between forest types using the deviation between direct and remote measurements as the test statistic, at 3 m we found that there were significant differences between the hardwood stand and both pine stands ($p < 0.05$), yet no significant difference between the pine stands. When using the absolute value of the deviation, the only significant difference was observed between the hardwood and older pine stand. In comparing the deviations in 6 m remote measurements, the only significant differences were observed between the hardwood and the young pine stand. When the absolute value of the deviations was used in the analysis, significant differences ($p < 0.05$) were observed between all three stands. There were no significant differences in the 9 m measurement deviations among forest types. However, when the absolute value of the deviations were assessed, significant differences ($p < 0.05$) were

Table 2.6. Pearson's product-moment correlation between illuminance (lux) and the deviation in remote caliper measurements from direct caliper measurements.

	Forest Type		
Remote Distance	**Young pine**	**Old pine**	**Hardwood**
3 m	0.126	0.025	0.042
6 m	0.074	-0.070	-0.062
9 m	0.092	-0.021	-0.103
12 m	0.075	-0.007	-0.117

Table 2.7. Pearson's product-moment correlation between illuminance (lux) and the absolute value of the deviation in remote caliper measurements from direct caliper measurements.

	Forest Type		
Remote Distance	**Young pine**	**Old pine**	**Hardwood**
3 m	0.048	0.045	-0.013
6 m	-0.100	0.101	-0.027
9 m	-0.076	-0.077	-0.057
12 m	-0.108	-0.113	-0.004

observed between the young pine stand and the other two forest types. Similarly, there were no significant differences in the 12 m measurement deviations among forest types. When the absolute value of the deviations was assessed, significant differences ($p < 0.05$) were observed between the young pine stand and the other two forest types.

Discussion

The ability to remotely measure the diameter of trees has practical value for field technicians in that travel time to individual trees at sample locations can be reduced, and perhaps the efficiency of data collection processes can be increased. Further, upper-stem diameters necessary to understand the extent of merchantability within a tree can be estimated more reliably, as these otherwise generally are ocularly estimated. We found significant differences in diameters measured using a DBH tape and using the calipers. We recognize that it is commonly accepted that DBH tape measurements will likely lead to different results than caliper or sector-fork measurements, due to variations in tree bole and bark shape (McArdle 1928). Two or more sector-fork or caliper measurements acquired from different perspectives of the tree bole can alleviate some of these concerns. However, in this work we assumed that only one direction (or perspective) of a tree bole would be used in conjunction with the laser calipers. This assumption arises from the notion that a field technician should be able to stand in the middle of a circular measurement plot and use the laser calipers to remotely measure all of the trees in the plot without having to move away from the plot center. We further only measured tree diameters with the sector-fork from one perspective in order to be consistent with, and to comparable to, the laser caliper measurements. These limitations in measurement standards do not detract from the practical value of collecting remote measurements, and associated decisions were made to accommodate the study design.

In our work, we did find that the use of the sector-fork resulted in greater variation among the deviations from the direct (0 m) caliper measurement conducted at the same point on a tree and viewed from the same perspective. In fact, on average, the sector-fork diameter measurements were slightly smaller than the caliper measurements. We attribute a great deal of this problem to the scale of each device. Cummins (1937) found that differences in scale between instruments can contribute to differences in diameter measurements. The calipers have a graduated scale in 0.25 cm (0.1 inch) increments, yet the sector-fork scale has a graduated scale in 1 cm increments, and diameters were estimated to the nearest 0.5 cm. The scale on the sector-fork is also non-linear, and larger diameter measurements seemed to be more difficult to refine, while the caliper scale is linear and consistent (Figure 2.6).

One issue that could have potentially introduced error into the measurement of tree diameters with the laser calipers was the ability of the person performing the measurements to consistently measure a tree diameter at the same height and same angle perpendicular to the tree bole. The calipers, while not overly heavy (weight), needed to be held steady for 10-20 seconds each time a diameter was measured. If fatigue sets in after numerous repeated measurements, this practice can become a burden on the field technician and possibly affect the quality of results. Further, any uncertainty on behalf of the field technician regarding where the tree diameter should be measured can affect the person's ability to position the laser points correctly on the edge of a tree bole. The extra time required to ensure the correct position of the laser points on a tree bole could affect the increase in efficiency expected when using a remote instrument and perhaps lead to greater error. Therefore, one drawback to our analysis was the time limit we placed on measuring diameters when the calipers were used remotely. While effort was made to apply similar amounts of time at each stage in the measurement collection process, there may

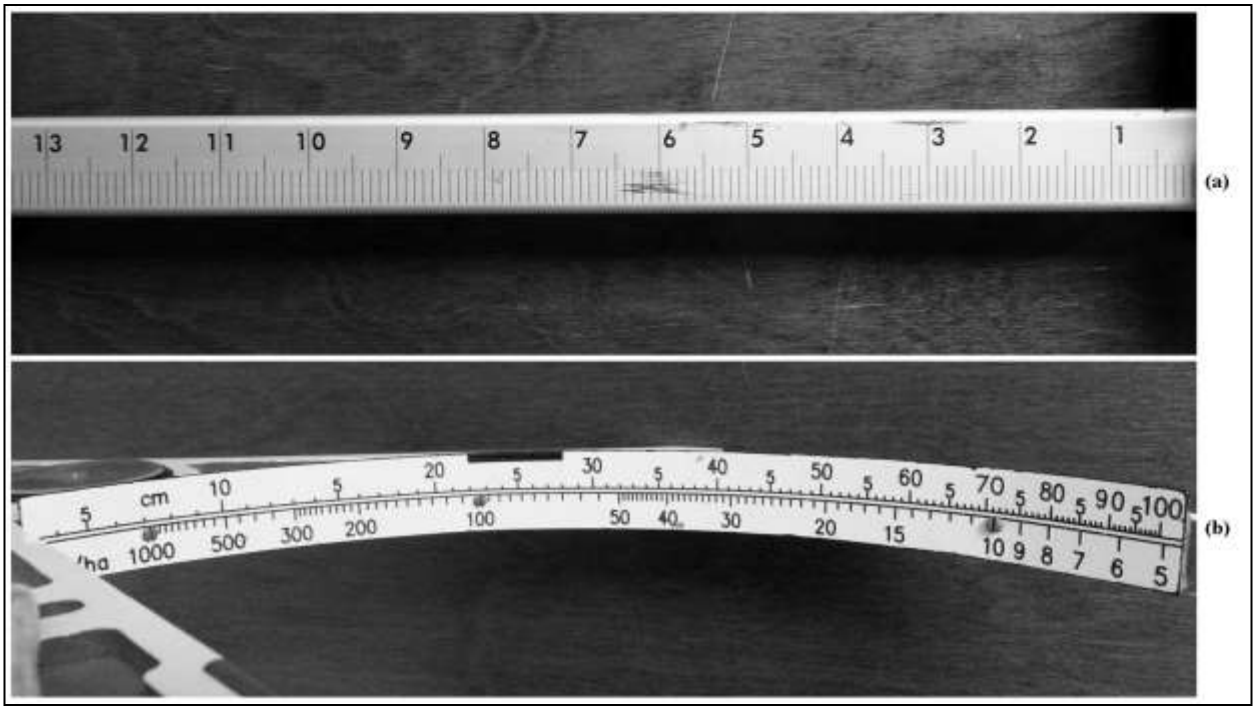

Figure 2.6. Photos showing the linear 0.1 in scale of the laser calipers (a) and the non-linear 1 cm scale of the sector-fork (b).

have been an association between measurement time and measurement accuracy for which we are unaware.

Another issue that may have introduced error during the measurement process was fatigue or distraction on behalf of the operator of the equipment. Although the laser calipers are relatively light weight, placing the calipers on top of a monopod during data collection might lessen the carry time and reduce fatigue. Setting the monopod to a specific height might also help ensure consistent measurements along the tree bole. One particular distraction was glare caused by the sun. At times, depending on the arrangement of the field technician, the tree, and the sun, the laser points were difficult to see on the edges of tree boles. Although the field technician practiced using each device for several weeks prior to the onset of the study, not all environmental factors could be replicated during the practice period. This potentially introduced error into the analysis.

One issue we discovered through a review of the literature was that over the course of a study period (and even over the course of a day) tree diameters may change slightly due to cambial growth, water balance, or due to the angle from which the remote measurements were made (Haasis, 1934; Pesonen et al., 2004; Devine and Harrington, 2011). Paired comparisons in our analysis were made with measurements that were collected within about five minutes of each other during each visit to a tree; therefore, this issue should have been minimized through the study design. We also understood that there may be some aspects of understory vegetation, bark color, stem density, and forest type in general that could cause error and affect the ability to distinguish bark edges with a high level of accuracy. For example, slight variations in tree or bark condition could act to trick a field technician into collecting remote measurements that do not necessarily represent the true edge of a tree bole. Tree lean and the shape of a tree's cross-sectional area may have also contributed to the variations in measurements between instruments (Grosenbaugh, 1963). The differences between forest types with respect to these types of issues appear to be most pronounced at distances of 6 m or less to the target tree, after which there are no significant differences in remote measurements.

Conclusion

The ability to collect tree diameter information remotely can improve the efficiency of forest inventory systems. Tree diameters are one of the main components of forest volume estimation processes. Assuming the same level of sampling intensity with and without remote measurements of tree diameters, if remote measurements can accurately represent forest conditions, management costs can be reduced. While laser caliper measurements were only collected with respect to one viewing perspective of a tree, they were consistently smaller on average than diameter measurements collected with a DBH tape. While it seemed that most of the significant differences in remote measurements were observed within the first 6 m of trees, based on a nonparametric statistical test, these differences were rather small (0.8 cm or less). The direction of the difference (over or under the direct caliper measurement) was different for each forest type, which if consistently observed, might suggest the use of a small correction value for each type of forest measured. However, reasonably accurate remote measurements may be attractive to field personnel for the time saved not having to travel to and physically touch each tree. While significant differences were found, the small differences found in this study may not make a significant difference in field practice when tree diameters are grouped into one inch DBH classes. The laser calipers are able to provide accurate diameter readings at a distance within 12 m, and measurements that are traditionally collected remotely (e.g., upper stem diameters, or lengths of the merchantable portion of a stem) can perhaps be estimated or measured more accurately.

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CHAPTER 3

STATIC HORIZONTAL ACCURACY ASSESSMENT OF A MAPPING-GRADE AND A RECREATIONAL-GRADE GPS RECEIVER[1]

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Abstract

The static horizontal accuracy of a recreational-grade GPS receiver and a mapping-grade receiver was tested in two forest types and two seasons. A Student's *t*-test was used to evaluate two hypotheses for both receivers that suggest there is no significant difference in accuracy between seasons and between forest types. A third hypothesis, suggesting there is no difference between holding position during data collection, was also tested for the mapping-grade receiver. In general, both receivers were found to have average errors within the ranges typically expected for these general types of receivers (3 to 5 m for the mapping-grade receiver on average and 7 to 10 m for the recreational-grade). The *t*-test results suggest season has a significant effect on accuracy with the recreational-grade receiver but not the mapping-grade receiver. Forest type was found to have a significant effect on accuracy for both receiver types, and the vertical holding position was shown to provide significantly lower error with the mapping-grade receiver. The correlation results suggest the atmospheric variables had a weak correlation to accuracy. Since holding position was found to be significant with the mapping-grade receiver, it may be beneficial to have an understanding of antenna positioning within the receiver to achieve the greatest accuracy during data collection.

Keywords

Static horizontal position accuracy, global positioning system receiver, root mean squared error, global navigation satellite system

Introduction

Since the introduction of global navigation satellite systems 30 years ago, global positioning system (GPS) receivers have become a popular tool in natural resource management. Their integration has been somewhat slower in forestry because of difficulties in acquiring quality satellite signals under canopy (Wing 2008), but in general, this technology is steadily replacing traditional navigation and mapping techniques (Bettinger and Fei 2010). GPS receivers can be used for a variety of field work tasks. For example, they can be used for navigation, to locate permanent field plots, to map ownerships or management unit boundaries for use in geographical information systems, or to map points of interest for management or research. They are also frequently used in wildlife management research to track and locate GPS-tagged wildlife. A number of recent studies have been conducted to evaluate the static horizontal accuracy of GPS receivers in forestry applications (Wing et al. 2005, 2008, Danskin et al. 2009a, 2009b, Ransom et al. 2010). While GPS receivers have been shown to provide fairly accurate location information, several studies have found that vegetation type and canopy cover can have a significant effect on location accuracy (Veal et al. 2001, Wing and Karsky 2006, Wing et al. 2008, Andersen et al. 2009). Other factors that may affect location accuracy have been tested as well such as season and environmental variables such as air temperature and humidity (Bettinger and Fei 2010, Danskin et al. 2009a, 2009b) and post-process differential correction (Veal et al. 2001, Wing and Karsky 2006, Wing et al. 2008). As the desire for highly accurate location data increases and GPS technology changes, these receivers need to be continually reassessed to provide natural resource managers with a better understanding of the accuracy of this technology and the factors that influence it (Bettinger and Fei 2010).

GPS accuracy can be assessed in two general ways: horizontal accuracy and vertical accuracy. Vertical accuracy involves comparing GPS position fixes collected over a known control point (both horizontally and vertically) at a specific height above ground. Horizontal accuracy is generally assessed by static position and dynamic position analyses. Dynamic analysis is so named because the user is typically moving while collecting position fixes, such as when a user walks a boundary line to map an area feature. Static horizontal accuracy assessments are the most common accuracy analyses, and this type of analysis will be the focus of this study. A static horizontal accuracy assessment is generally performed by the user holding the GPS receiver over a known control point and collecting position fixes. These are then compared to the known control point coordinates to estimate accuracy.

GPS receivers can generally be divided into three categories: recreational-grade, mapping-grade, and survey-grade. Recreational-grade receivers typically range in price from $100 to $700 USD. Wing (2011) reported a static horizontal accuracy range for such receivers of 5-10 m depending on the environmental conditions with the best performing receivers capable of accuracies within 2 m under open-canopy conditions. Mapping-grade receivers generally cost in the range of $1,000 to $9,000 USD, are typically more powerful than the recreational-grade receivers, and have a higher static horizontal accuracy in the range of 1-5 m. Most mapping-grade receivers are small enough to be hand-held but are not quite as compact as recreational-grade receivers. Survey-grade receivers are the most expensive type. They typically cost $10,000 USD or more, but they also provide the highest accuracy. Generally, they are able to provide sub-meter to centimeter levels of static horizontal accuracy. They are typically only used for property surveys since these receivers are not as easily carried as mapping-grade or recreational-grade receivers, and they are usually positioned over sample points from several minutes to several hours to attain these levels of accuracy (Bettinger and Merry 2012). Mapping-grade and recreational-grade receivers have become most common in forestry applications due to cost, desired accuracy, and mobility. However, it has been suggested that some recreational-grade receivers should not be used to map permanent sample plots due to their higher levels of location error (Andersen et al. 2009). Recommendations on the type of receiver to utilize should be based on the desired level of accuracy and cost (Bettinger and Fei 2010, Wing et al. 2005).

As noted previously, as GPS technology improves and new receivers are placed on the market, a continued assessment of their accuracy seems necessary. A number of studies have been performed to examine the accuracy of survey-grade receivers (Hasegawa and Yoshimura 2003, Andersen et al. 2009), but the goal of this study is to examine the static horizontal accuracy of two relatively new GPS receivers, a recreational-grade receiver and a mapping-grade receiver. The recreational-grade receiver is a Garmin Oregon 450t, and the mapping-grade receiver is a F4Tech Flint. These types of receivers were chosen for this study because they are the two general types of receivers most commonly used in forestry applications, and these models are relatively new designs. We will evaluate the effect on accuracy of a variety of environmental factors, including season and forest type. Of all the studies done, receiver orientation or holding position during data collection has not been mentioned or studied. Therefore, receiver orientation during data collection will also be examined for the Flint model. In sum, the following hypotheses will be tested for both receiver types:

1. Horizontal position accuracy is not affected by season of data collection.
2. Horizontal position accuracy is not affected by forest type.

Since a supplier of the Flint receiver suggested that the receiver holding position during data collection may influence accuracy, the following hypothesis will be tested solely with the Flint receiver:

3. Horizontal position accuracy is not affected by receiver orientation during data collection.

Methods

For this project, we evaluated the static horizontal accuracy of two GPS receivers: a recreational-grade Garmin Oregon 450t, and a mapping-grade F4Tech Flint. Both utilize touch-screen technology, are relatively light-weight (< 8 oz.), and are considered rugged devices. While both receivers have navigation, waypoint and track mapping functions, the Flint receiver also includes advanced data collection capabilities through a variety of software add-ons. When collecting GPS data, field personnel may encounter a variety of field conditions. Since seasonal variations in accuracy were of interest, both GPS receivers were tested in leaf-off (January 19 - February 2) and leaf-on (May 21-24) vegetation conditions, and to examine potential accuracy differences from forest types, test points within two different stand types were chosen. Six control points were chosen from the Whitehall Forest GPS test site in Athens, GA, U.S.A. This test site is based on a set of survey monuments established using an Ashtech Locus survey-grade GPS receiver and using the appropriate protocols (static data, 4 hours of data collection, etc.) to be accepted as National Spatial Reference System (NSRS) positions. The control points used in this study were originally established by registered surveyors using a Topcon GTS-211D instrument and the surveyed NSRS monuments as a base. Three points were located within an older pine stand (60 to 70 years old, 22.9 m^2 ha^{-1} basal area, 303.4 trees ha^{-1}), and three control points were chosen by topographical position within an older hardwood stand (60 to 70 years old, 26.2 m^2 ha^{-1} basal area, 421.7 trees ha^{-1}) (Figure 3.1). These control points have a surveyed location or "true" location that is known to be within about 2 cm. All six control points were visited 10 times resulting in 30 visits to the pine stand and 30 visits to the hardwood stand for each season.

Within each season, visits between forest types and points within each forest type were randomized to avoid bias. For each visit, the GPS receivers were positioned atop a 1.2 m wooden staff directly above the control point using a plumb bob while the researcher stood on the North side of the point during data collection. Effort was made to ensure the internal antenna of each receiver were directly above the control points during data collection. Each day of data collection both GPS receivers were allowed to warm-up (approximately 5 min) to ensure enough satellites were available for use. Both receivers were set to receive the wide area augmentation system (WAAS) satellite signal if it was available, but it was unclear how often it was used. At each visit, 50 position fixes per point were collected at 2-second intervals. This process was completed with an automatic function on the Flint receiver. However, each of the 50 fixes had to be manually saved on the Garmin receiver. Due to a problem in the first and last fixes collected at each point for the Garmin receiver, only 48 position fixes per point were used in the Garmin data. Many of the first fixes were found to be abnormal, and the last fix on some visits were omitted. These were discarded to have a consistent 48 fixes for each point visit. A range of position fixes have been suggested for estimating GPS accuracy in previous literature. Sigrist et al. (1999) suggested that 300 position fixes should be used for tests under forest canopy. A study by Bolstad et al. (2005) later found that one position fix may not be significantly different than an average of 300. Yet, Wing et al. (2008) found horizontal accuracy increased as the number of

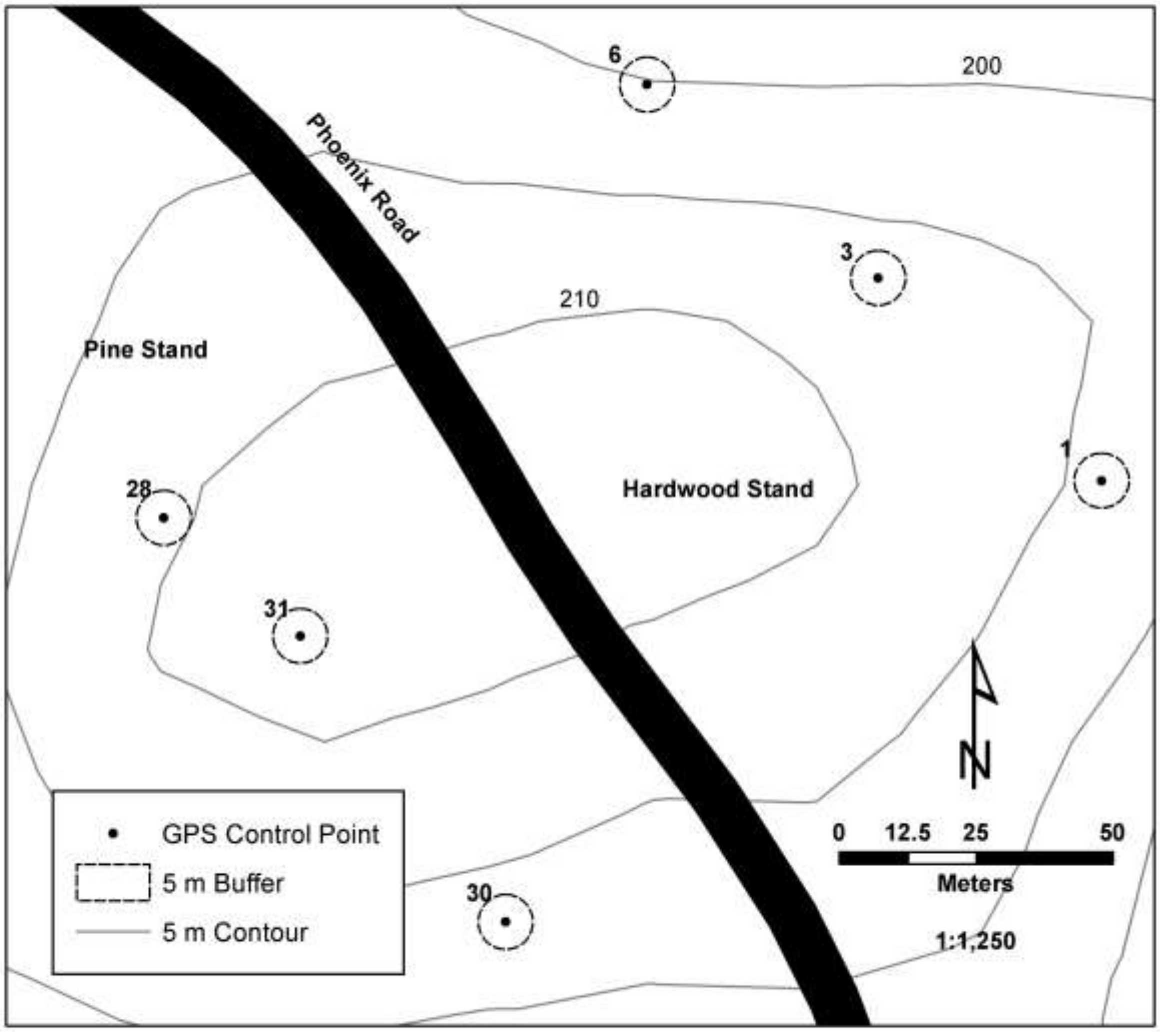

Figure 3.1. The surveyed control points, with a 5 m buffer shown, located at the Whitehall Forest GPS test site in Athens, GA.

position fixes increased from 1 to 30 when testing a mapping-grade receiver. Danskin et al. (2009a) later suggested that a minimum of 50 position fixes were necessary to provide an accurate position in forested conditions. Static horizontal position accuracy has also been found to be about the same when one position fix is used for a point as it is when an average of 60 position fixes are used (Wing and Karsky 2006). In a study performed by Bettinger and Merry (2012) utilizing a recreational-grade receiver, it was suggested that the first position fix may provide a position that is not significantly different than an average of the first 50. It was also suggested, however, that a larger set of position fixes may be required to reach the desired level of accuracy in younger, denser coniferous forests. An example of one point visit for the Garmin receiver is shown in Figure 3.2. We chose 48 or 50 position fixes per point visit to be conservative considering the wide range of suggestions from the literature and to account for this “walking” behavior shown in Figure 3.2.

The holding position of the Flint receiver during data collection was also an area of interest during this study. Because of the design of the Flint unit and the orientation of the antenna within it, some have suggested that holding the receiver in a vertical orientation during data collection would result in more accurate data (Darian Yawn, personal communication). To test this hypothesis, three holding positions were used for the Flint receiver: vertical, angled (approximately 45°), and horizontal (Figure 3.3). Holding position was also randomized to avoid bias in addition to randomizing the sampling order for stand type and points. Data was collected for 30 visits per season for the Flint receiver (10 visits to each forest type for each holding position). These holding positions were not tested for the Garmin receiver. The Garmin receiver was tested in a “normal” or a more natural, angled holding position.

Root mean square error (RMSE) was chosen to evaluate the accuracy of these GPS receivers as it has been a useful measure to assess the accuracy of GPS receivers in previous studies. There are two possible ways of calculating RMSE: (1) calculate the squared error for the set of position fixes at each control point for each visit and determine the square root of the mean squared error, or (2) average the set of position fixes and calculate the square root of the squared error of this value. For this study we chose the first method to report the RMSE. The RMSE values for each point visit will be used to evaluate our hypotheses. We also report circular error

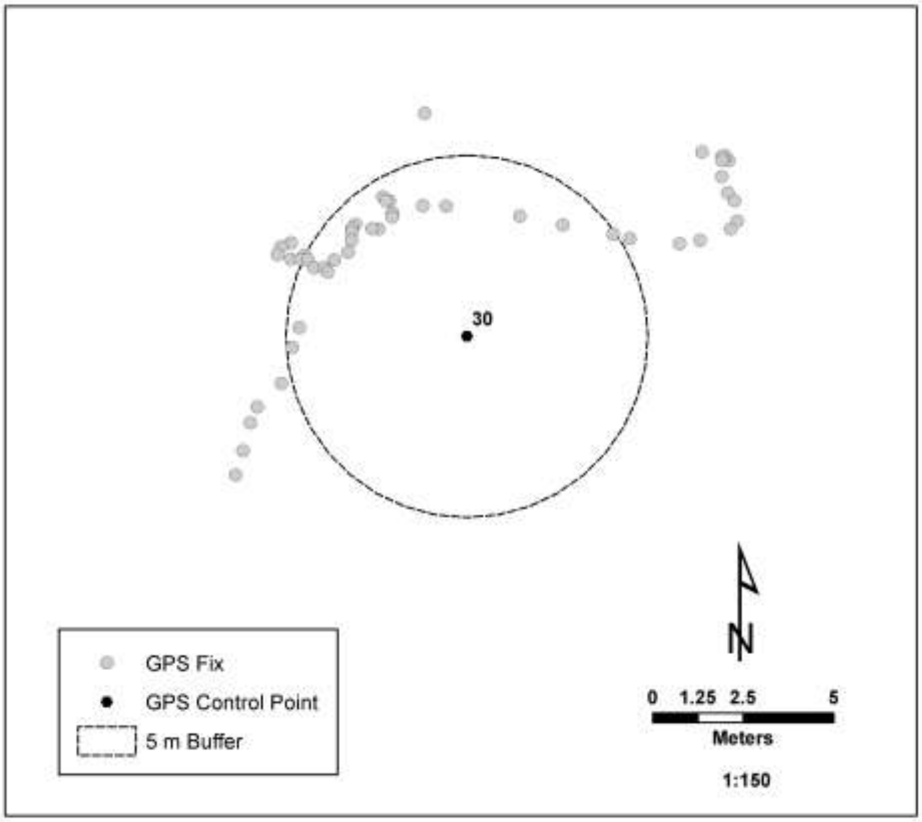

Figure 3.2. The "walking" behavior observed during one point visit with 48 point fixes for the Garmin receiver with a 5 m buffer shown.

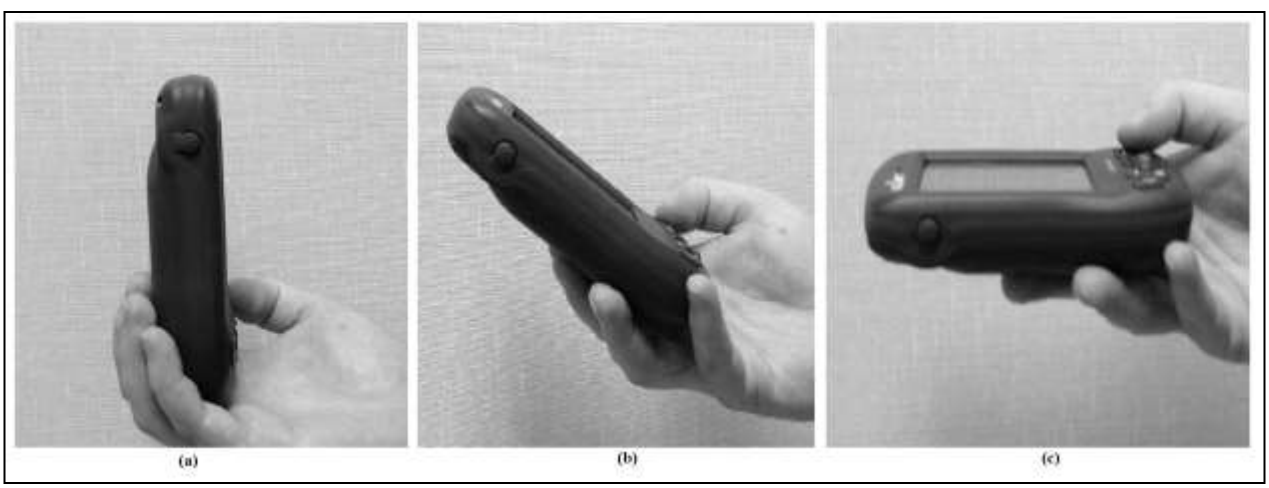

Figure 3.3. Examples of the three Flint holding positions used in this study; (a) vertical, (b) angled, and (c) horizontal.

probable 50 (CEP50) which represents the radius of a circle around the known control point in which 50% of the position fixes occur.

In addition to position coordinates, the Flint receiver also recorded horizontal dilution of precision (HDOP), positional dilution of precision (PDOP), satellite used (SATUSED), and signal-to-noise ratio (SNR) values for each fix. These values are of interest because they relate to satellite availability, signal quality, and satellite geometry quality. The values for each fix were then used to calculate averages for each point visit. Air temperature, relative humidity, and barometric atmospheric pressure data were also obtained for each point visit from the local weather station (Athens, GA airport). These variables were chosen because of their potential influence on the GPS signal as it passes through the atmosphere. The weather station only reported these values in one hour intervals. Therefore, a linear change was assumed between hourly observations from the weather station so values might be obtained for each point visit time. For the Flint receiver data, a Pearson correlation analysis was performed between the RMSE values and average HDOP, PDOP, SATUSED, SNR, air temperature, relative humidity, and atmospheric pressure values. The only data collected by the Garmin that was utilized were the position coordinates. For the Garmin, we used Trimble's online GNSS planning tool to acquire a *planned* PDOP for each point visit (Trimble Navigation Limited 2013), and as with the Flint receiver, air temperature, relative humidity, and barometric atmospheric pressure were obtained for each point visit from the Athens, GA airport. A Pearson correlation analysis was performed for the RMSE values, *planned* PDOP, air temperature, relative humidity, and atmospheric pressure.

Normality of RMSE values were evaluated using BestFit software (Palisade Corporation 1996). The majority of the data sets were normally distributed. Therefore, a Student's *t*-test was used to compare each sample set. To test hypothesis 1, no significant difference in accuracy between seasons, pine winter values vs. pine summer values and hardwood winter values vs. hardwood summer values were compared. Pine winter values vs. hardwood winter values and pine summer values vs. hardwood summer values were compared to test for significant differences in accuracy between forest types or hypothesis 2. For hypothesis 3, holding positions of the Flint receiver were compared within each stand and within each season.

Results

The mean values found for the Flint receiver in the hardwood stand are shown in Table 3.1. Average RMSE for both seasons were in the 3 to 5 m range. However, the vertical receiver position had a noticeably lower average RMSE value in both seasons, as much as 1.5 m lower on average. Mean CEP50 had a similar pattern. Both PDOP and SNR showed very little variation throughout the sampling period. PDOP only ranged from 1.79 to 1.97, and SNR remained in the range of 30.93 to 32.59 in the hardwood stand. Average air temperature, relative humidity, and barometric atmospheric pressure values recorded for the hardwood sampling period are shown in Table 3.2. The leaf-on season had temperatures in the 26-27 °C range with 55-57 % humidity on average. Leaf-off temperatures were around 11 °C with 35-36 % humidity. Atmospheric pressure for both seasons averaged between 29.9 and 30.3 in.

A similar pattern was found for the Flint receiver in the pine stand (Table 3.3). RMSE averages were in the range of 3 to 4 m. The vertical receiver position also had a lower RMSE on average in the pine stand, as much as 1 m difference. PDOP values were in a similar range (1.73 to 2.05) as the hardwood stand, but the SNR values were a little higher at 32.64 to 34.43. The environmental variables for the pine stand are shown in Table 3.4. Since data were collected for both stands on the same days these values are very similar to those for the hardwood stand.

Table 3.1. Average error and PDOP values for the Flint GPS receiver in the hardwood stand (n=30)

Season	Receiver Position[a]	Mean RMSE (m)[b]	Mean CEP50 (m)[c]	Mean PDOP[d]	Mean SNR[e]
Leaf-On	V	3.78	3.74	1.97	32.59
	H	4.57	4.66	1.83	30.93
	A	4.61	4.63	1.79	31.51
Leaf-Off	V	3.43	3.37	1.82	33.37
	H	4.52	4.62	1.89	31.01
	A	4.95	5.02	1.89	31.98

[a] V – vertical, H – horizontal, A – angled

[b] RMSE – root mean squared error

[c] CEP50 – circular error probable 50

[d] PDOP – positional dilution of precision

[e] SNR – signal to noise ratio

Table 3.2. Average environmental variables during data collection with the Flint receiver in the hardwood stand

Season	Receiver Position[a]	Mean Air Temperature (°C)	Mean Relative Humidity (%)	Mean Atmospheric Pressure (in)
Leaf-On	V	26.9	55	29.98
	H	26.6	57	29.99
	A	26.6	56	29.99
Leaf-Off	V	11.2	36	30.29
	H	11.3	35	30.30
	A	11.2	36	30.30

[a] V – vertical, H – horizontal, A – angled

Table 3.3. Average error and PDOP values for the Flint GPS receiver in the pine stand (n=30)

Season	Receiver Position[a]	Mean RMSE (m)[b]	Mean CEP50 (m)[c]	Mean PDOP[d]	Mean SNR[e]
Leaf-On	V	3.14	3.16	1.78	34.43
	H	4.14	4.20	1.86	33.05
	A	3.94	4.06	2.04	34.17
Leaf-Off	V	3.08	3.12	1.73	33.52
	H	3.76	3.78	1.93	32.64
	A	3.84	3.80	2.05	33.63

[a] V – vertical, H – horizontal, A – angled

[b] RMSE – root mean squared error

[c] CEP50 – circular error probable 50

[d] PDOP – positional dilution of precision

[e] SNR – signal to noise ratio

Table 3.4. Average environmental variables during data collection with the Flint receiver in the pine stand

Season	Receiver Position[a]	Mean Air Temperature (°C)	Mean Relative Humidity (%)	Mean Atmospheric Pressure (in)
Leaf-On	V	26.8	56	29.98
	H	26.5	58	29.99
	A	26.5	57	29.99
Leaf-Off	V	11.1	36	30.30
	H	11.3	35	30.30
	A	11.1	36	30.30

[a] V – vertical, H – horizontal, A – angled

The averages found during the Garmin receiver assessment are presented in Table 3.5. In general, leaf-off season shows higher mean RSME than leaf-on season (8.5 m vs 7.1 m for the pine stand and 9.9 m vs 7.2 m for the hardwood stand), and the point data for the hardwood stand had a higher RMSE than the pine stand regardless of the season (7.2 m vs 7.1 m in leaf-on and 9.9 m vs 8.5 m in leaf-off). Mean RMSE is not considerably different between stands during the leaf-on season; however, position accuracies within the hardwood stand were 1.4 m better on average than those within pine stand during the leaf-off season. The same result can be seen for mean CEP50. Average air temperature and relative humidity are also much different between the seasons as expected (11.9 °C, 33.4% in leaf-off vs 26.1 °C, 59.2% in leaf-on), but atmospheric pressure showed very little variability (about 30 in).

Since the vast majority of the horizontal position accuracy data for the Flint and Garmin receivers were normally distributed, no transformations were applied, and a Student's *t*-test was used to determine any significant differences. Using an alpha (α) value of 0.05, only one test for the Flint receiver was found to be significant. Leaf-off hardwood vertical position accuracy was found to be significantly different ($p = 0.012$) with a lower average error than leaf-off hardwood angled position accuracy. Although, no other tests were found to be significant when $\alpha = 0.05$, several other tests were significant when $\alpha = 0.1$. One test found significantly lower average error in the pine stand when compared to the hardwood stand during the leaf-off season ($p = 0.081$), and three tests found the vertical holding position accuracy to be significantly different, with a lower average error, than the horizontal or angled position accuracies, regardless of season or forest type ($p = 0.058$ to 0.092).

When testing for differences in the Garmin data, only one test was significant when $\alpha = 0.05$. Hardwood leaf-off horizontal accuracy error was found to be significantly greater than

Table 3.5. Summary statistics for the Garmin Oregon 450t receiver

Season	**Stand**	**Mean RMSE (m)**[a]	**Mean CEP50 (m)**[b]	**Mean *Planned* PDOP**[c]	**Mean Air Temperature (°C)**	**Mean Relative Humidity (%)**	**Mean Atmospheric Pressure (in)**
Leaf-on	Hardwood	7.21	6.91	2.34	26.2	59	29.97
	Pine	7.14	6.73	2.58	26.1	60	29.98
Leaf-off	Hardwood	9.94	9.65	2.53	11.9	34	30.28
	Pine	8.53	8.22	2.44	11.9	33	30.28

[a] RMSE – root mean squared error

[b] CEP50 – circular error probable 50

[c] PDOP – positional dilution of precision

hardwood leaf-on accuracy error. However, when $\alpha = 0.1$ two other comparisons were also found to be significantly different as well. One test found hardwood leaf-off horizontal error to be significantly greater than pine leaf-off error ($p = 0.063$), and the other test found pine leaf-off error to be significantly different and greater than pine leaf-on error ($p = 0.1$).

The *r* values of the correlation result for the Flint receiver were typically in the range of -0.4 to 0.4 showing a weak correlation or none. For most of the comparisons there does not seems to be a very consistent result. Some values are positive while other tests show a negative correlation. One notable *r* value outside this range was 0.5 for RMSE vs humidity. This may suggest some moderate correlation, but the mix of results make this suggests otherwise. Correlation results for the Garmin receiver had a similar range with *r* values in the range of -0.3 to 0.3, which also shows either no correlation or a weak correlation. *Planned* PDOP vs RMSE *r* values were typically in the range of 0.0 to -0.2. Temperature vs RMSE values were 0.0 to -0.3, and atmospheric pressure *r* values were in the range of 0.0 to 0.3. These tests showed only very weak or no significant correlations. An example of both Flint and Garmin correlation results is shown in Table 3.6.

Discussion

In general, the Flint receiver static horizontal positions had an average RMSE of 3.08 to 4.95 m with the best error value collected from a single point being 0.04 m, while the worst error was 11.59 m. A test on the same site several years prior to this study found a 1.6 to 2.1 m accuracy for two mapping-grade receivers without post-processing differential correction of the data (Ransom et al. 2010). Another study found an error range of 5.6 to 8.9 m, depending on slope position and season, for the mapping-grade unit tested. After post-processing, the static horizontal errors improved to the 2.0 to 3.1 m range (Danskin et al. 2009b). Comparing the Flint

Table 3.6. Example correlation results for the Flint, vertical holding position, in the pine stand leaf-on season and results for the Garmin in the hardwood stand leaf-off season

	HDOP	***Planned* PDOP**	**PDOP**	**SATUSED**	**SNR**	**TEMP**	**HUMIDITY**	**PRESSURE**
Flint RMSE	-0.246	-	-0.142	-0.109	-0.256	0.008	-0.106	-0.037
Garmin RMSE	-	-0.228	-	-	-	-0.289	-0.070	0.123

[a] RMSE – root mean squared error

[b] HDOP – horizontal dilution of precision

[c] PDOP – positional dilution of precision

[d] SATUSED – satellites used

[e] SNR – signal-to-noise ratio

[f] TEMP – mean air temperature

results to these studies, we find the Flint error values to be consistent with other assessments and within the error range that is expected of a mapping-grade receiver even without post-processing differential correction.

The *t*-test results showed no significant difference in static horizontal position errors with the Flint receiver between seasons (leaf-on vs. leaf-off). The average RMSEs between seasons were < 1 m different. This contrasts with other studies that have shown there is a significant difference in accuracy between seasons (Danskin et al. 2009a, 2009b). Forest type did however have a significant effect on accuracy between the pine-angled-leaf-off condition vs. hardwood-angled-leaf-off. The pine stand had an average RMSE of 3.84 m vs a 4.95 m error in the hardwood stand. This significance may be attributed to differences in stand structure, such as trees ha^{-1} or canopy cover. However, Ransom et al. (2010) did not find a significant difference in forest type. Interestingly, several tests in this study, in both forest types and seasons, showed a significant difference in holding position with the Flint receiver. The vertical holding position static horizontal position errors in several tests were found to be significantly lower, typically 0.7 m to 1.5 m, than horizontal or angled holding position errors. From personal communication with a Flint distributor, the orientation of the GPS antenna within the receiver seems to affect the static horizontal position accuracy and makes the vertical orientation the most accurate data collection orientation for the Flint receiver. Orientations away from vertical may block GPS signals reducing the number of available satellites or quality signals for use in position calculation.

The Garmin receiver had average RMSE values of 7.1 to 9.9 m with a best point visit error of 2.6 m and a worst error of 19.2 m. Bettinger and Fei (2010) tested a recreational-grade receiver for one year and found average errors of 6.6 m, 7.9 m, and 11.9 m across three forest types with a worst single error of 46.2 m. Wing (2008) tested six recreational-grade GPS receivers and found static horizontal position accuracies in the range of 5.6 m to 12.7 m in older forest conditions. Although the Garmin unit tested is a newer model, the positional accuracies found appear to be consistent with previous findings for recreational-grade receivers.

Based on the *t*-test results, we found that season had a significant effect on accuracy. The most notable difference season made was in canopy cover. During the leaf-off season the hardwood stand had lost all leaf cover. Bettinger and Fei (2010) found that season did not seem to matter when testing a recreational-grade receiver. However, Danskin et al. (2009a, 2009b) found season did have an effect on static horizontal position accuracy. Interestingly, we found an anomaly within the Garmin average RMSE values. Leaf-on errors were significantly lower than leaf-off error values. Typically, it would be assumed that greater leaf cover during the leaf-on season would contribute to greater multipath error, but we found the average leaf-on RMSE value to be 1.5 m to 2.7 m lower than leaf-off errors. While it is uncertain why this is the case, perhaps signal quality and satellite geometry are the most significant factors. However, correlation results of accuracy with *planned* PDOP values were low and negative. We would have expected the values to be high and positive. We also found the Garmin receiver accuracy to be significantly affected by forest type. This influence may be due in part to the forest stand structure and canopy cover differences between the two forest types tested. This is also consistent with recent tests of recreational-grade GPS receivers.

The correlation results for both the Flint and Garmin receivers were inconclusive. While several might be considered moderately correlated (0.5 for RMSE vs humidity for the Flint), most comparisons between RMSE and the atmospheric variables showed a weak correlation or no correlation. The few who did show a higher *r* value may hint at a connection, but there were no clear results from these correlation tests. Bettinger and Fei (2010) also found no correlation between static horizontal accuracy and the atmospheric variables; air temperature, atmospheric pressure, and humidity.

A number of factors could have affected the results of this study. Although the data was not examined for any influence, the proximity of the researcher during data collection may have introduced some bias. This is mentioned because a study performed by Bettinger and Fei (2010) found nearby trees to have some influence on static horizontal accuracy, which may also have influenced the data in this study. Control point location may also have been a factor. While the control points were chosen to be as consistent as possible in terms of forest conditions and elevation, there were some differences in aspect. Some points were on more northern and eastern aspects while others were on a more southerly aspect.

There was also no pre-planning or mission planning performed to schedule data collection at times with the best predicted PDOP. Collecting data during these times may have provided better accuracies or at the very least, more satellite availability and signal quality, but other responsibilities limited the available times for data collection. WAAS signal availability should also be a consideration. Both receivers were programmed to utilize the WAAS signal if it was available, but neither receiver recorded when the signal was used or what impact it had on these results. One might expect however that accuracy would increase with the use of WAAS. Danskin et al. (2009b) found improved accuracy from recreational-grade receiver positions in the range of 0.1 – 17.3 m depending on season. However, Wing et al. (2008) found no statistically significant differences when WAAS was utilized with mapping-grade receivers. Another concern is the use of only one of each receiver type. Wing (2009) suggests that equal performance among similar receivers is not guaranteed in all cases and should not be assumed. Due to time and receiver availability, only one receiver of each type could effectively be tested in this study.

Conclusion

This study and its results were consistent in many ways with previous studies testing mapping-grade and recreational-grade GPS receivers. We found season had a significant effect on the Garmin static horizontal accuracy, but we did not find a significant difference in accuracy due to season with the Flint receiver. This may be due to the Flint receiver handling multipath signals in response to canopy cover more efficiently. RMSE was found to be significantly different between forest types. This could be attributed to differences in forest density and canopy cover. The results presented here are related to the canopy conditions and forest structure studied. As canopy and stocking conditions change within a forest type, changes in static horizontal accuracy should be expected as well. For example, in forest stands with greater stocking and canopy cover, RMSE would be expected to increase due to greater multipath potential and blocked GPS signals. We also found that using the Flint receiver in a vertical orientation during data collection provided a significantly lower static horizontal position error when compared to a horizontal or angled orientation. This is probably due to antenna placement and orientation within the Flint receiver.

While only one receiver of each type was tested, we are confident in suggesting these receivers can be expected to provide similar accuracies as other mapping-grade and recreational-grade receivers under the same conditions. It may also be important to understand how the GPS antenna is placed within the receivers and what orientation provides the best accuracy during data collection. Otherwise, the receivers may not be utilized to their greatest potential.

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CHAPTER 4

CONCLUSION

With the expectation of continued development of *Precision Forestry* technology, a continuous assessment seems necessary to ensure the technology is useful and accurate. In this thesis, two types of instruments were examined; laser calipers and GPS receivers, and we have attempted to provide a scientific evaluation of the accuracy of these instruments.

The study in chapter 2, “Assessing the Accuracy of Tree Diameter Measurements Collected at a Distance,” reports the results of a test of three dendrometers in three forest types; the Haglöf Gator Eyes system mounted on an 18-inch Mantax Black caliper, the Bitterlich sektorkluppe or sector-fork, and a diameter tape. The goal of the study was to examine any potential bias between collecting direct measurements and collecting diameter measurements at a distance with the Haglöf Gator Eyes. The following hypotheses were examined:

1. There is no significant difference between direct or contact laser caliper measurements and laser caliper measurements of tree diameters collected at a distance.
2. There is no significant difference between caliper (direct and at a distance) measurements and sector-fork measurements of tree diameters.
3. Light conditions have no significant effect on tree diameter measurements.
4. There is no significant difference between tree diameter measurement errors for data collected in different forest types.

Hypothesis 1 had a mix of results. Diameter measurements were collected at distances of every 3 m up to 12 m. When the measurements at a distance were compared to the direct (0 m) measurement, most diameters at a distance were found to be significantly smaller on average in the hardwood stand compared to the direct measurement, and most diameters at a distance were significantly larger on average in the young pine stand. No significant differences were found in the older pine stand. Understory vegetation, bark shape and color, stem density and other factors may contribute to this mix of results. No differences were found between the sector-fork measurements and the caliper measurements within the hardwood stand. Compared to the sector-fork measurements, only one caliper measurement (at 3 m) was found to be significantly different (larger average diameter) within the older pine stand, and all caliper measurements were significantly larger within the young pine stand. This may have been influenced by stem size and bark shape. The analysis between light conditions (illuminance) and the deviations in remote caliper measurements and direct caliper measurements suggested no significant correlation. Hypothesis 4 also had a mix of significant comparisons with no clear pattern. With so many tests showing significant differences, it might be argued that forest type could be a significant factor in affecting accuracy at a distance.

In chapter 3, "Static Horizontal Accuracy Assessment of a Mapping-Grade and a Recreational-Grade GPS Receiver," two GPS receivers were tested; a Garmin 450t recreational-grade receiver and a F4Tech Flint mapping-grade receiver. The primary goal of this study was to test the static horizontal accuracy of these receivers, which is the most common accuracy assessment performed, and examine if accuracy is affected by a variety of environmental variables. The following two hypotheses were examined for both receivers:

1. Horizontal position accuracy is not affected by season of data collection.
2. Horizontal position accuracy is not affected by forest type.

Holding position of the Flint receiver during data collection and its effect on accuracy was also of particular interest. The following hypothesis was tested on the Flint:

3. Horizontal position accuracy is not affected by receiver orientation during data collection.

A Pearson correlation analysis was also performed to examine any correlation between RMSE and atmospheric variables such as air temperature, barometric atmospheric pressure, and relative humidity.

RMSE values for the Flint receiver ranged from 3.0 to 4.9 m on average, and the Garmin accuracy was in the range of 7.1 to 9.9 m on average. Season was found to have a significant effect on the static horizontal accuracy of the Garmin receiver, but it was not a significant factor for the Flint. Interestingly, the leaf-on season Garmin data provided a significantly lower RMSE than the leaf-off season (about 1.5 to 2.5 m on average). Typically, a GPS receiver might be expected to provide greater accuracy in leaf-off conditions due to less canopy closure. While it is not clear why this happened, we attribute this anomaly to potential differences in GPS satellite geometry and signal quality. Forest type was a significant factor in affecting accuracy for both receivers. Leaf-off conditions showed the greatest difference between forest types for the Garmin receiver. The pine stand had a RMSE of 8.5 m, 1.4 m less than the hardwood stand on average, and in general, the errors for the Flint in the pine stand were between 0.2 to 1.1 m less than the hardwood stand errors. The vertical holding position was also found to have a significant effect on the static horizontal accuracy of the Flint receiver. On average, the vertical position had an error between 0.7 to 1.5 m less than the horizontal and angled positions. It is thought these differences are due to the orientation of the GPS antenna within the receiver, and the vertical holding position allows for better satellite signal reception. Only very weak or no correlations were found between RMSE and atmospheric variables.

While similar studies on dendrometers and GPS receivers have been performed in the past, this thesis represents the first test of the Haglöf Gator Eyes laser caliper system and the sector-fork. Although significant differences were observed in this study when comparing diameter measurements collected on tree versus those collected at a distance with the laser calipers, the differences were typically small (0.8 cm or less). Only one perspective was used to collect diameters at a distance, but the laser calipers were able to provide fairly accurate diameter measurements. The small differences in diameter measurements observed may not have a significant impact in typical field use when trees are categorized into 1 inch DBH classes. The time saved from collecting measurements at a distance may also be attractive even with the small differences observed, and measurements that are typically collected at a distance, such as upper stem diameters, may be measured more accurately.

Chapter 3 is also the first test of the significance of holding position on static horizontal accuracy for mapping-grade GPS receivers. The GPS receivers examined in Chapter 3 were found to provide accuracies within the ranges that have come to be expected of these general types of receivers; 3 to 5 m with the Flint mapping-grade receiver and 7 to 10 m with the Garmin recreational-grade receiver. However, these tests suggest holding position of the receiver during data collection can have a significant effect on accuracy. This is probably due to the GPS antenna positioning within the receiver. To fully utilize the positioning capabilities of these receivers, particularly the Flint, it may be necessary to have an understanding of GPS antenna design and orientation within the receiver. The receiver could then be held in the most optimal orientation during data collection to ensure collection of the most accurate data possible.

These studies have provided a scientific accuracy assessment of these instruments and some factors that may significantly affect it. Hopefully, these findings will assist foresters and other natural resource managers in selecting tools to utilize in various management activities and in developing sampling protocols to collect the most accurate data with these instruments.

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