ASSESSING GPS ACCURACY, WAAS, AND A CHOKE RING ANTENNA SOLUTION IN A SOUTHERN HARDWOOD FOREST

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ABSTRACT

Interest in Global Positioning Systems (GPS) has grown widely in recent years, due in part to improved acquisition of GPS signals, development of more effective GPS technologies, increased accuracy, and lower equipment costs. While these developments have been made for applications under open sky conditions, how these improvements affect applications under forest canopies is not clearly understood. We assessed the performance of several receivers ranging from recreation- to mapping-grade for signal acquisition, accuracy, and precision. Data were collected over 24 closed and 3 open sites at the Warnell GPS Test Network, Athens, Georgia. Multiple sampling events were used to account for the impact of changing satellite geometry, and seasonal variation in Leaf Area Index (LAI). Vegetation sampling was also conducted at each point to capture the effect of stand type, density, height, and canopy openness. Data were compared using Root Mean Square Error (RMSE) and Circular Error Probable (CEP) for all position fixes, and linear regression to assess the effect of stand variables.

KEYWORDS. GPS, receivers, multipath, accuracy assessment.

INTRODUCTION

Interest in Global Positioning Systems (GPS) has grown widely since its availability to civilian applications. Developed by the Department of Defense in the late 1970's and released publicly in 1983, the NAVSTAR (NAVigation System with Timing And Ranging) GPS network consists of a constellation of at least 24 active satellites orbiting the earth at 20,200 km and at a 55º inclination angle to the equator (Kilroy et al., 1999; Tsui, 2000). This configuration guarantees that three or more satellites will be available at any given time to ground receivers at any location worldwide. Early applications focused on open-sky conditions with limited obstructions to satellite signals, including marine navigation, surveying, and agricultural studies (Gerlach and Jasumback, 1989, 1990). The potential of adopting GPS technology for forestry use was also explored early but with limited application (Kruczynski and Jasumback, 1993; Holden et al., 2001). These initial investigations in GPS accuracy under forested conditions were few (Gerlach and Jasumback, 1989) but have proliferated recently in response to improvements in technology

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and the abrogation of Selective Availability (SA) in 2000. Improvements in non-differentially corrected GPS accuracy have increased ten-fold, from errors ranging up to 100 meters reduced to within 10 meters. Additionally, advances in antenna and GPS receiver technologies and the development of real-time differential correction services, most noticeably the Wide Area Augmentation System (WAAS), have led to increased investigation of the error sources in GPS positioning data attributed to forest environments.

Sources of positional error can be broadly categorized into two classes: system error and environmental error. System error includes that associated with satellites, clocks, evil waveforms, jamming, and receiver and antenna effects (Faghri and Hamad, 2002; MacGougan et al., 2002). Some of these errors can be minimized using differential correction, including satellite error, clock error, and jamming. Others cannot be known or controlled by the end user. Fortunately, under optimal conditions these errors may collectively range from less than one to several centimeters, while only occasionally increasing to one hundred centimeters or greater depending on the health of the system (Olynik et al., 2002; Liu et al,. 2004).

Environmental error includes signal-to-noise ratio, satellite configuration (Dilution of Precision, or DOP), ionospheric delays, and multipath (in this study associated with forest vegetation effects). Differential correction techniques may reduce some error from all these sources. However, since the majority of receiver error realized originates from environmental sources, most notably from multipath effects, there is a decreasing return of how well accuracy can be improved by these techniques. Errors associated with signal-to-noise ratio and satellite configuration can be monitored and measured to some extent through internal controls of GPS receivers and proper mission planning of collection periods. Ionospheric delays exhibit large diurnal, monthly, and solar cycle variations and have become an area of increased interest (Van Dierendonck, 1999; Kunches and Klobuchar, 2001) . Many new ionospheric correction models have been developed to improve differential techniques by more directly correlating space/weather measurements to changes in ground reference station observations (Coster and Doherty, 2004). Multipath is caused by the reflection of satellite signals from nearby objects, including ground and water surfaces, buildings, topography, vegetation and other sources (Ge et al., 2000). In this study, multipath was primarily caused by vegetative obstructions, from both mid-and upper canopy tree cover.

Forest vegetation effects are the specific components of multipath (the reflection of satellite signals delaying arrival of signals to a receiver) that account for the majority of error in GPS applications in forestry, and can be broadly categorized into the following: canopy closure (%), stand density (stems/ha), stand basal area (m^2/ha), stand height (m), species, stand age, and season. Other factors influencing GPS accuracy, including DOP (horizontal, positional and others), Signal-to-Noise Ratio (SNR), ionospheric interference, and receiver error, have been researched to a lesser extent in natural resource applications, and developing technologies are reducing some of these errors within the receivers themselves (Xu, 2003; FAA, 2004). Not unexpectedly, there exists a great disparity between the rate at which GPS technologies are developed and the assessment of their application in real-world conditions. Therefore, the continual evaluation of GPS accuracy in forestry applications, and the development of new methods to mitigate the aforementioned sources of error and improve its overall value, will be necessary to fully realize the potential of this rapidly changing technology.

The objectives of this study are twofold; to examine how forested environments affect positional accuracy of several receivers ranging from mapping- to recreation-grade with respect to use of Wide Area Augmentation System, and to explore the use of choke ring antenna technology to better estimate the total enhancement in positional accuracy related to local environmental variables.

METHODS

Several different receivers were considered for inclusion in this study. Models were desired that were representative of wide classes of receivers, ranging from recreation- to mapping-grade, and were also commonly known to a wide audience of users. Additionally, we wanted to sample receivers from the major producers of GPS equipment to account for potential variations in accuracy attributable to different software applications. Table 1 highlights the receivers used in this study that meet the above criterion.

Table 1. Comparison of receivers reviewed in this study.

Receiver	**Price ($)**	**Reported Accuracy (m)**	**WAAS Enabled**
Trimble ProXR	5,000	0.01 –0.5, with tracking	No
Thales Mobile Mapper	1,500	<1	Yes/Fulltime only
Garmin GPS Map60c	500	<3	Yes
Garmin eTrex	<150	<3	Yes

Study Site

Research was conducted at the Warnell School of Forest Resources' Whitehall Forest research facility in Athens, Georgia (Figure 1). Sampling for GPS positional accuracy utilized 24 points within an approximately eleven acre test course, the horizontal coordinates of which are known to approximately 2 cm accuracy. Permanent GPS monuments were installed over a 6 ha area, and under varying stand and elevation conditions ranging from bottomland hardwood to mixed upland forest types. Additionally, three open-field condition benchmark points are located within Whitehall Forest, and were used to assess baseline accuracy of receivers. Future expansion of the test course may include installation of additional points in adjacent pine stands under different silvicultural treatments and age classes.

Vegetation Sampling Design

To assess the effects of vegetation on GPS position accuracy, sampling was conducted to include a significant portion of vegetation present at each site. Thus, sampling of within-forest vegetative conditions utilized the surveyed GPS monuments as center points for circular plot sampling. Since receivers are limited to satellites within a 150^o field of view above a 15^o elevation mask (Figure 2), canopy length (the distance the signal is required to travel through the canopy to the receiver) could be calculated based on estimated average upper canopy tree and understory tree height respectively, and their tangential influence. Plot sizes could then be selected to ensure inclusion of the majority of trees responsible for signal degradation.

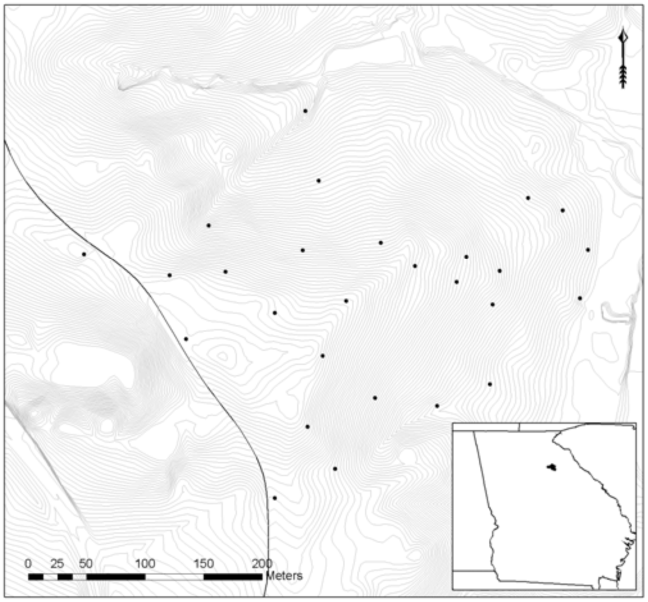
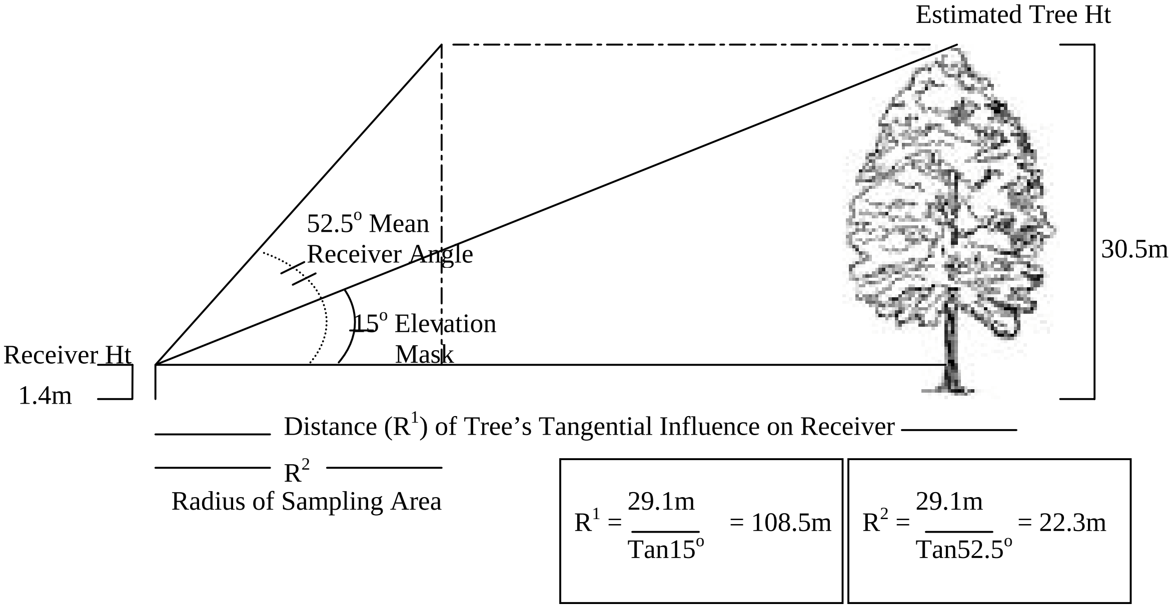


Figure 1. The Warnell GPS Test Course facility, Athens, Georgia.

All woody stems >7.62 cm (3 inch) diameter at breast height (DBH) were measured within a circular 0.2 ha plot (radius = 25.23 m). Additionally, stems ranging in the 2.54 -7.62 cm (1-3 inch) class were measured within a circular 0.025 ha (radius = 8.92 m) to capture local understory effects. For each tree, DBH and species were recorded, as well as distance and azimuth from plot center. Canopy closure was measured using hemispherical photograph analysis techniques suggested by Englund et al. (2000).



$$R^1 = \frac{29.1\text{m}}{\text{Tan}15^{\circ}} = 108.5\text{m}$$

$$R^2 = \frac{29.1\text{m}}{\text{Tan}52.5^{\circ}} = 22.3\text{m}$$

Figure 2. Determination of study area based on potential receiver interference.

GPS Data Collection

To record GPS location data consistently at each point, a custom-built GPS receiver stand was built which, through incorporation of a laser level, maintains a receiver's antenna directly over a given survey point in the test network. Due to topographic and environmental effects, height of the stand ranges from 1.3m to 1.6m above each point. The design of the stand also accommodates accurate placement of the choke ring ground plane when coupled with the Trimble ProXR data logger. In this study, we used a Topcon Model CR4, a JPL specification choke ring with a Dorne-Margolin element made available from Topcon Position System Inc.

Individual location samples, or fixes, were taken for each receiver at each of the 24 survey points within the test network. In addition, a subset of 9 points was sampled with the choke ring antenna, which represented sites typical of low-, mid-, and upper-slope positions. For the purpose of this study, only the receiver data collected at the subset of 9 sites were used. Fixes were also collected at three open-site monuments to establish a baseline performance of each receiver. Collection events took place under both leaf-on and leaf-of conditions, and each monument was visited twice to reduce the risk of data capture during isolated periods of high satellite system error. When possible receivers were programmed to record fixes every 2 seconds until 200 fixes have been recorded. Since not all of the receivers used in this study are programmable to automatically record fixes at a constant rate (Garmin eTrex, GPS MAP 60C), manual logging of fixes was conducted until 100 fixes were recorded at each point for both WAAS-on and WAAS-off operation. The timing of the collection events was randomly selected to avoid biasing the results.

Fixes collected from the Trimble ProXR were differentially corrected for the standard beacon antenna and choke ring, representing the highest order of accuracy available from all equipment tested. Accuracy of each fix was assessed using both Root Mean Square Error (RMSE[95]) and 50% Circular Error Probable (CEP_{50}).

RESULTS

Results are presented in two parts: the general performance of GPS receivers and use of WAAS signals compared to non-WAAS configuration under varying forest conditions and slope positions, and the performance of the Topcon choke ring antenna in mitigating multipath signals.

Receiver Performance and Vegetation Effects

The results of sampling in open field sites showed variation in the performance of individual receivers, WAAS enabling, and to a lesser extent the positional accuracy across the different sites (Table 2). For example, while all three open-site locations were considered to represent optimal conditions for signal acquistion, monument R3 was situated farther from any obstructions in the surrounding area, possibly allowing for higher positional accuracy at that site.

Most noticeably, the Thales Mobile Mapper showed the poorest positional accuracy at monument R3, which partially accounts for its low average score for open-site conditions. With WAAS enabled, performance improved for all GPS devices. Following differential correction, the data collected with the ProXR using either the standard beacon antenna or the Topcon choke ring antenna equally showed the highest level of data precision with sub-meter accuracy.

Table 2. Comparison of receiver performance in open-site conditions.

	Monument R3		**Average of open sites**	
Receiver Type	*CEP50 (m)*	*RMSE^{95}(m)*	*CEP50 (m)*	*RMSE^{95}(m)*
ProXR w/ Choke Ring	0.199	0.315	0.245	0.324
ProXR w/ Beacon	0.233	0.401	0.277	0.428
Thales Mobile Mapper	22.411	36.908	15.771	19.300
Garmin Map60c	5.837	11.669	14.331	21.787
Garmin Map60c w/ WAAS	3.208	8.535	5.039	11.440
Garmin Etrex Vista	1.865	6.08	3.457	9.901
Garmin Etrex Vista w/ WAAS	1.483	2.969	3.291	4.147

Results of vegetation sampling across the three slope positions were spurious. Overall vegetation conditions did not significantly change across slope position for each group of points sampled. This may be an effect of sample area, which tends towards homogenization of site conditions as sample area increases. However, a slight increase in canopy openness was observed, as well as changes in species composition.

Measurement of signal acquisition was approximated with the Thales Mobile Mapper, as it continually operates with full WAAS-enabling. Both Garmin products allowed manual operation of WAAS-enabling, but did not include information in the data string designating signal acquisition or signal type. Reception of WAAS signals was 83.2%, 65.7% and 89.4% for the low-, middle-, and upper slope positions respectively under leaf-on conditions. For leaf-off conditions these values lowered to 63.9%, 68.2% and 72.3% respectively. These values were unexpected, as position dilution of precision (PDOP) values were significantly improved during leaf-off conditions. Improvements to horizontal accuracy with WAAS enabled were found with all receivers across slope positions. Accuracy for all receivers without WAAS enabled improved slightly across an increasing slope gradient, as did the improvement to accuracy from WAAS-enabling.

Results of Choke Ring Evaluation for Mitigating Multipath

Choke ring antenna design consists of a series of concentric rings milled from a single billet of aluminum, which surround an antenna receiver located at ring center. Through wave impediment, these rings essentially create a zone of low multipath signals over the antenna center. Due to weight, size, and cost of the devices, they have been used most extensively in high accuracy reference networks, at base stations, and in precision engineering applications. Forests are extremely high-multipath environments, and expectations of choke ring improvement to positional accuracy were limited.

Results of the open-site testing showed choke ring use for improving accuracy were similar to the ProXR standard beacon antenna. Under forested conditions we saw a significant reduction in the performance of the beacon antenna, ranging from ~20m to 15m RMSE^{95} across an increasing slope gradient. In contrast, accuracy improvement from choke ring data increased to only 2m to 3m RMSE ^{95} regardless of slope position.

DISCUSSION

Previous studies in GPS accuracy have often focused on one or two factors that contribute to positional error. These factors commonly range from open versus closed canopy, seasonal variations, and to a lesser extent canopy closure. Research methods of collecting GPS receiver data have lacked uniformity, and have been limited by time, DOP conditions, or adequate variation in stand conditions. In this study, we attempted to examine multiple factors affecting positional accuracy; however these factors are often correlated making it difficult to isolate the contribution to positional error from individual factors.

Vegetation sampling over a large area immediately surrounding GPS monuments has provided an apparently overwhelming amount of data. This may suggest that vegetation conditions most significant to signal degradation and reduction in positional accuracy occur much more locally, or potentially are influenced by other factors, such as topographic position. Further examination of local stand conditions will be conducted using the azimuth and distance information collected to the respective nearest stems.

The relatively recent emergence of a fully operation WAAS signal in 2002 (FAA, 2004) has limited the number of WAAS studies available. Bolstad (2005) found improvements in positional accuracy with WAAS, but had limited signal acquisition due to sampling at higher latitudes. Since WAAS satellites are geostationary, the high signal acquisition we experienced at the Warnell Test Course may be due largely to our closer proximity to the equator, which elevates the reception angle of the signal. Future development and improvement of WAAS includes increasing the number of both ground stations and broadcasting satellites, as well as increasing the strength of the WAAS signal itself. These developments will likely improve signal acquisition in high multipath environments, and future operations with low-cost WAAS-enabled GPS devices may provide adequate positional accuracy for many forest activities.

Improvements to positional accuracy from choke ring antenna resulted in the highest accuracy experienced. Regular use of choke ring antenna technology, in its current design stage, is impractical for many reasons, including cost, size, weight, and setup requirements. However, the use of choke ring antennae in selective research applications is promising. By reducing a large amount of multipath in a relatively short collecting period, choke ring antennae seem well suited for developing error profiles for specific forested conditions. In addition, these error profiles may potentially be used to infer forest structure from GPS sampling events.

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